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Development of a flax-fibre reinforced, cement-stabilized rammed earth housing solution (Uku) for rural Māori communities

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A thesis submitted in complete fulfilment of the requirements for the degree of
Doctor of Philosophy (PhD) in Civil and Environmental Engineering,
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Abstract

The research presented in this thesis develops the Uku flax-fibre reinforced, rammed earth housing method. The research was conducted using a kaupapa Māori research methodology and integrated Māori culture, structural testing of Uku, and the Mauri Model decision making framework, to empower Māori from the rural community of Ahipara, New Zealand, to implement a 102 m² Uku dwelling on their ancestral lands. The thesis is presented in three parts. The first part involved gathering the local perspectives in Ahipara regarding the holistic sustainability of rural Māori housing solutions. The second part reported investigations into the material strength and seismic performance of Uku test specimens and full-sized panels. Finally, the third part documented the process of the Ahipara whanau designing and building an Uku dwelling.

Using the Mauri Model decision making framework, a survey was conducted to ascertain the perceived holistic sustainability of Uku rammed earth and light timber-framed housing as a rural Māori housing solution. A holistic assessment was attained by using an intrinsic measure of sustainability ‘mauri’ to evaluate the housing methods in the four dimensions of environmental, social, cultural and economic. Individuals from five groups, the rural Māori community, environmentalists, Far North District Council, Community Housing Aotearoa, and Housing New Zealand Corporation, were surveyed. The Uku housing method was determined to be sustainable by individuals belonging to all five groups surveyed whilst the light timber-framed was perceived to be sustainable by two groups and unsustainable by the remaining three.

Compression and flexural tests on Uku rammed earth specimens were conducted. The test results provided data upon which the rate of strength gain rate could be predicted and improved understanding regarding the relationship between material density and strength. Comparisons of flexure and shear strengths with compressive strength were made to evaluate empirical relationships specified in the New Zealand Earth Building standards. The assumption that 10% of compressive strength was equivalent to the flexural strength of rammed earth was supported by the test results, and the assumption of 7% of compression strength being equivalent to the shear strength of rammed earth was found to be conservative.

Pseudo-static cyclic tests conducted on full-sized Uku rammed earth panels, and a 3-panel wall assemblage, showed the panels had considerable non-linear strength capacity. The
Ductility measured from the load-displacement plot of the Uku assemblage was 1.5 and 2.8 in the two directions of loading whilst the results for single panel tests ranged 2.6 to 5.8. A structural ductility value of 1.25 was thus recommended for the design of Uku structures.

The testing of panels, both in the laboratory and onsite in Ahipara, showed the importance of onsite testing. The laboratory panels were 31-50% stronger than predicted while the fourth onsite panel tested reached a maximum of 90% of the design load. The first three onsite panel tests exhibited low strengths due primarily to issues of onsite test methods, onsite construction methods, and worker experience. The onsite test experiences were invaluable as they helped to identify unavoidable issues when building and testing in an outdoor, isolated environment, with individuals from the local community. A test setup comprising of a large excavator as a reaction frame was described and is recommended for future onsite tests of Uku rammed earth walls.

The implementation of an Uku dwelling, which was driven by Māori from Ahipara and was conducted in adherence to Māori values and cultural practices, was used to identify and develop solutions to common housing obstacles experienced by Māori when developing on their ancestral lands. In the Appendix documents which would assist other Māori whanau develop Uku housing on their ancestral lands have been shared and include, communication with the Far North District Council regarding building consent issues, a copy of the main engineering calculations for the Ahipara Uku dwelling, and a full set of architectural plans.

The doctoral research has shown that the use of a kaupapa Māori research methodology was an effective way to conduct research within a Māori community, and to develop a housing solution for their benefit. The Uku housing method was also shown to be an appropriate and viable housing solution through the successful implementation of an Uku dwelling in Ahipara during the doctoral research period.
Dedication

This doctoral thesis is dedicated to:

Uncle Steven Tok

Darius Tan

Raymond & Quan Low

Mr. (David) Stillaman [Avondale College]

Thank you for believing in me before I could believe in myself.

Thank you for investing in me.

Thank you for speaking life giving words into my life.
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# Glossary of Selected Māori Terms

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<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Aotearoa</td>
<td>Māori name for New Zealand. Translates as “land of the long white cloud.”</td>
</tr>
<tr>
<td>Hui</td>
<td>Meeting</td>
</tr>
<tr>
<td>Kaitiaki</td>
<td>Trustee, guardian, custodian, keeper</td>
</tr>
<tr>
<td>Kanohi-ki-te-kanohi</td>
<td>Face to face</td>
</tr>
<tr>
<td>Kaumatua</td>
<td>Elder</td>
</tr>
<tr>
<td>Kaupapa Māori</td>
<td>Ideology incorporating the philosophy, knowledge, skills, attitude and values of Māori</td>
</tr>
<tr>
<td>Māori</td>
<td>Indigenous peoples of New Zealand</td>
</tr>
<tr>
<td>Marae</td>
<td>The open area in front of the wharenui. Often used to refer to the group of buildings around the wharenui</td>
</tr>
<tr>
<td>Mauri</td>
<td>Well being, life force</td>
</tr>
<tr>
<td>Pākehā</td>
<td>New Zealanders who are not of Māori blood lines</td>
</tr>
<tr>
<td>Te Tai Tokerau</td>
<td>One of the 16 administrative regions in New Zealand. It is the northernmost region.</td>
</tr>
<tr>
<td>Wananga</td>
<td>Seminar, conference, forum</td>
</tr>
<tr>
<td>Whakapapa</td>
<td>Genealogy, lineage, decent</td>
</tr>
<tr>
<td>Whānau</td>
<td>Extended family</td>
</tr>
<tr>
<td>Wharenui</td>
<td>Meeting house, large house</td>
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<tr>
<td>Whareuku</td>
<td>Earth house</td>
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<tr>
<td>Uku</td>
<td>The name given to the rammed earth housing method developed</td>
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Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 9 largely based on a Journal Article published in Construction Materials Volume 165, Issue 6, Titled "Evaluating shear test methods for stabilised rammed earth"

Nature of contribution by PhD candidate: Writing the journal paper

Extent of contribution by PhD candidate (%): 90

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<tr>
<td>Andrew Heath</td>
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<tr>
<td>Kepa Morgan</td>
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Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 10.1 Introduction from the Ahipara whanau by Rueben Taipari Porter, 2-3 pages

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## CO-AUTHOR(S)

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<tr>
<td>Rueben Taipari Porter</td>
<td>Wrote the pepeha, description of the land, and significance of the Uku housing research</td>
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## Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and
- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

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<tr>
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Last updated: 25 March 2013
Chapter 1. INTRODUCTION

*Tūngia te ururua, kia tupu whakaritorito te tupu o te harakeke*

*Clear the undergrowth so the new shoots of the flax will grow*

*The proverb is an encouragement to overcome whatever hinders progress. It is used to encourage innovation and a willingness to change.*

There are Māori in rural communities throughout New Zealand (NZ) who live in substandard and overcrowded housing conditions (Housing New Zealand 2005). In visits by the researcher to the rural community of Ahipara many locations where Māori lived in illegal and temporary dwellings, tents, and garages converted into living areas were seen. Though the majority of such housing was hidden from public view, local individuals pointed out numerous derelict structures located on main roads, some between housing developments which have been occupied for decades. Such examples represented the worst of housing situations in the rural community of Ahipara but the occurrence of such poor housing situations was not rare, and was evidence of the local issue of housing for rural Māori in Ahipara. Even amongst the Māori families that could afford to build and live on their ancestral lands in consented dwellings, they still lived in substandard housing conditions. Building issues relating to the lack of house maintenance, as well as issues with overcrowding, were observed. Current obstacles to developing housing on Māori land are often found to be insurmountable by land owners.

1.1. Obstacles to Māori Land Development

Morgan and Hoskins (2006) have identified financial difficulties, legal obstacles and the urbanisation of Māori as three significant factors that have hindered rural Māori land development. Obstacles to Māori land development relating to the three factors identified by Morgan and Hoskins are detailed in more depth in Appendix A.1.

1.2. Rural Māori Housing Options

Light timber framed housing solutions have been the preferred housing method for rural Māori communities because they best meet the criteria of government housing providers and are relocatable. The relocatable property of the housing method is significant because Māori land is inalienable and cannot be used as a security for a mortgage.
Light timber frame housing however has been identified as a suboptimal solution because of a number of reasons. Firstly, many rural Māori cannot afford to build and maintain a timber framed house on their land. These houses have high maintenance requirements and a shorter lifespan than other more permanent building materials. Secondly, the houses often are kitset houses with a set 2 or 3 bedroom floor plan which often does not suit the lifestyle requirements of Māori well (Hoskins et al. 2002). Māori living in light timber framed houses experience problems with dampness, poor air quality and a lack of insulation. These issues have long term implications on the health and life opportunities of the occupants.

Earthen housing solutions have been identified by a number of Māori communities around NZ as a promising alternative housing method. Earth has been used for millennia as a construction material in many differing housing forms, and has shown to provide a superior living environment yet remain an affordable and accessible housing method. Some positive attributes of earthen housing methods include the long term permanence of earth, the possibility of using locally sourced materials, indoor temperature stability, and the potential for end-users to reduce the build costs and increase self-sufficiency by building their own home.

1.3. Facilitation of Research

Māori wellbeing has been a focus for Nga Pae o te Maramatanga, a key funder of the Uku flax-fibre reinforced, rammed earth housing research. Research funding from the Foundation for Research, Science and Technology (FRST) and Nga Pae have supported this research in earlier investigations regarding the suitability of rammed earth and the construction of trial buildings to assess social acceptability of rammed earth housing methods to Māori. In order to achieve the outputs required by the research funders, researching in partnership with Māori end-users during the research and the use of a Māori research methodology was appropriate and necessary.

1.4. Research Focus

The foci of the doctoral research were;

- to further investigate the suitability of earth housing for Māori using an inclusive decision making framework to evaluate rural Māori housing methods;
to determine the characteristics of fibre reinforced rammed earth made using local earth sources from Te Tai Tokerau (the northernmost administrative region of NZ);

- to better understand and predict the behaviour of the Uku rammed earth wall system when subjected to seismic loads; and

- to support and enable a Māori whānau in Te Tai Tokerau to implement the Uku housing method.

1.5. Research Methodology

When conducting research in indigenous cultural contexts, additional obligations exist, that require approaches that are able to be inclusive of the relevant indigenous ontology and epistemology. Thus, the doctoral research was obliged to use an approach that would result in a tangible housing benefit to Māori and those participating in the research. These obligations were fulfilled by researching alongside Māori throughout the doctoral research, by providing a precedent of how to implement a rammed earth dwelling locally, and by supporting a Māori whānau (extended family) located in Ahipara, to design and build an Uku rammed earth dwelling on their ancestral lands.

In this case, the Kaupapa Māori research methodology was used for the doctoral research. Use of the methodology was appropriate because the research required the participation of Māori and because the development of housing solutions for Māori would have a significant impact on Māori self-determination. In retrospect, it was hard to envisage how the research could have been conducted locally, and how the research outputs achieved could have been achieved if a non-Māori research methodology was used.

1.6. Research Questions

The purpose of this doctoral research was to contribute to the development of the Uku rammed earth housing system for rural Māori communities. The following four questions were the focus of this doctoral research.

1. Is a rammed earth housing solution acceptable to organisations involved with the provision of housing and Māori end users in Te Tai Tokerau?

2. Is the rammed earth material, made using local materials from Te Tai Tokerau, strong and durable enough for structural use in housing?
3. How does the Uku rammed earth wall system perform when subjected to seismic loads? What is a suitable ductility factor to assume for the wall system in design?

4. How practical and accessible is the Uku housing method to implement on rural Māori land? Can the Uku rammed earth housing method be implemented by an interested Māori group or whānau in Te Tai Tokerau?

The research questions were identified as key issues that needed to be answered in order to develop a viable housing solution for Te Tai Tokerau. The first question addressed the conceptual acceptability of a rammed earth housing solution to end-users in Te Tai Tokerau and to those involved with the provision of housing in the area. If a rammed earth housing solution was not acceptable conceptually to individuals and stakeholders then there would be little tangible benefit to pursue further research and development. The second question focused on establishing the strength of rammed earth made from local earth sources so that the performance of rammed earth panels could be ascertained and dwellings could be designed using them. The third question was an extension of past material tests and seismic tests conducted on Uku rammed earth. The question focused on verifying specific design parameters regarding the ductility of individual Uku rammed earth panels and wall assemblages. The fourth question focused on the practical implementation of the Uku housing method and examined the practicality of Māori using the method to develop on Māori land. The implementation of an Uku dwelling in a specific context (with the Unaiki Mare Trust residing Ahipara) enabled the whole house implementation process to be examined and documented. The implementation of an Uku dwelling in Ahipara began at the decision making stages within the whānau and community, and progressed through the stages of developing a house design, conducting soil and strength tests, performing engineering calculations, obtaining a building consent, and finally building the dwelling using locally available labour, equipment, and materials.

1.7. Earth as a Structural Housing Material

Earth has been used as a housing material for many thousands of years and evidence of earth housing can be found around the world. Houben & Guillaud (1994) estimated that more than a third of the world’s population live in earthen dwellings. Earth remains a widely used and important structural material because of its accessibility and intrinsic advantages as a housing material (Bariola and Sozen 1990; Houben and Guillaud 1994; Minke 2000).
There are many methods of building with earth, such as cob, wattle and daub, adobe, pressed brick, poured earth and rammed earth. The rammed earth method, upon which the Uku housing method is based, is the second most widely used method worldwide after adobe (Easton 1996). Rammed earth walls are constructed by compacting earth within a set of formwork, in layers, up to the desired height. The large majority of rammed earth structures which have been built are single or double storeys structures, but higher rammed earth structures have been built. Examples include a seven storey building in Weilburg, Germany (built 1828), and hundreds of circular and rectangular communal homes three to five stories high in Fujian, China (built as early as 1000 AD). A modern example is the Kooralbyn Valley Resort Hotel in Kooralbyn, Australia which is four stories high (built 1992 and shown in Figure 1).

![Kooralbyn Hotel Resort in Kooralbyn, Australia](image)

In NZ and other countries in the developed world, interest in rammed earth construction has increased over the last few decades. NZ is amongst the world’s leading countries in developing standards and conducting research for modern earth buildings. The New Zealand Earth Building Standards (NZS 4297, NZS 4298, NZS 4299) were amongst the earliest national building standards issued around the world, and the Earth Building Association of New Zealand (EBANZ), with over 10,000 members, is one of the largest earth building associations globally.

Earth is a good material for housing and has many environmental advantages over other more processed building materials. Earthen construction has become more popular and recognised in response to the introduction of sustainable development goals and the need to use more
sustainable construction methods (Houben and Guillaud 1994). Earthen structures are built typically using locally available resources. The Chinese are known to have added such components as brown sugar and rice water into their rammed earth structures (Zhang 2012) and rammed earth from other regions commonly incorporate locally abundant agricultural by-products.

More recently, developed building materials have been incorporated into rammed earth construction methods as they have become more affordable and available. Lime stabilization of earth gained popularity in the United State of America in the 1920s, and in recent decades the use of cement and steel reinforcing bars have been used in the construction of modern rammed earth structures (Gharati 2006). The use of manufactured materials, like cement, in rammed earth mixtures increases the cost and embodied energy of the composite, but improves material strength and durability. In the NZ context, the inclusion of cement in the earth mixture used for rammed earth makes it considerably easier to meet the strength and durability requirements of the NZ Building Code and NZ earth building standards.

1.8. Research History of the Uku Rammed Earth Housing Concept

Research exploring the concept of using a rammed earth housing method on Māori land began in 1996. Since then, a number of funders, research organisations and individuals have contributed to the Uku housing research. A brief history of past Uku research is provided below. Although the test methods and observations are described below, the test results and a more detailed account of specific tests conducted by past researchers involved with the Uku research are provided in the literature review of fibre reinforced rammed earth in Chapter 5.

The idea of developing Uku, an innovative construction material comprised of flax-fibre reinforced rammed earth, was conceptualised by Dr. Kepa Morgan following a research tour to North America in 1994. The tour was funded by the Inaugural Housing Industry Association Award for Special Contribution to Housing which Kepa received in 1993. During the tour, alternative house construction materials for Māori land development were investigated to address the issue of escalating domestic timber prices which resulted from an increasing export demand for Pinus Radiata. Earthen dwellings were identified as a potential alternative housing solution for Māori communities. The benefits of earthen dwellings are well known and documented however the lack of seismic capacity to resist earthquakes in such dwellings limited its application in NZ.
In 1996, the Earth Building Composites Using Indigenous Fibres project was initiated by Te Rūnanga o Ngāti Pikiao in collaboration with SCION, formerly known as the Forest Research Institute (Te Rūnanga o Ngāti Pikiao 1997). The initial research was funded by a grant from the Foundation for Research, Science, and Technology (FRST) and Kepa Morgan was the Principal Investigator for the research. The research focused on optimising earth recipes for rammed earth construction and the identification of preferred flax cultivars. Two full-sized rammed earth panels were built using the identified earth mixture and shear tests were conducted. The results of the research showed that flax-fibre reinforced rammed earth was strong enough to be used as a structural building element (Morgan 2005).

In 2003 the Centre of Research Excellence Nga Pae O Te Maramatanga (NPM), was established and it commissioned three demonstration projects to profile the relevance of Māori-centred research. Examining the environmental, social, economic and cultural appropriateness of using Uku flax-fibre reinforced rammed earth construction for Māori land development was one of these projects. With Kepa Morgan as Principle Investigator, the research sought to verify the cultural and social acceptableness of the Uku housing concept for Māori. NPM required the research to be conducted in a way which would address Māori housing needs in a tangible manner and would show Māori responsiveness to the housing concept.

To achieve these goals a Māori Community Reference Group (MCRG), consisting of potential end-users of the rammed earth technology, was formed. The group convened kanohi ki te kanohi (face to face) on a number of occasions to establish relationships between parties, and to set goals and requirements for the rammed earth housing concept. Some of the desired aspects of a housing solution established through the MCRG meetings were:-

- Designs requiring a minimum of input by professional engineers,
- A design-life of six generations (150 years),
- Construction technology that was readily able to be adopted by a non-technical workforce,
- Construction technology not overly dependent on large, complex machinery,
- Low-cost, easily transferable, construction technology.
During the research, two 6 metre by 6 metre rammed earth dwellings were built on Māori land. One dwelling was built in a rural area (Waimango, on the Firth of Thames) and the other in an urban area (Otara, Auckland) as shown in Figure 2. The dwellings were successfully built by members from both the rural and urban areas. In both cases the initial designated uses for the dwellings were upgraded. The dwelling built in Otara was initially made to be a shed for a ride-on mower but became a meeting area for students of the school on site and was later used as the arts and crafts room. The dwelling built in Waimango was initially designated to be a laundry room but at the request of kaumatua (elders), it became their sleeping area. The building has been given the name Te Ahuone and has since been used as a place to hold significant events such as a tangihanga (funeral) in 2012 where a kaumatua, the architect and founder of Royal Architects in Christchurch, was laid in state within the dwelling.

![Map of Auckland Featuring Otara and Waimango Research Sites](image)

In 2004, a second research grant was given by FRST to develop the Uku housing concept to a stage where the constructability of the concept could be proved through full implementation and the thermal performance of an Uku dwelling could be measured. The research project consisted of three phases. The first phase was to conduct material tests on rammed earth made from earth sources near Auckland, and to evaluate the strength benefit of reinforcing rammed earth with flax-fibres. During this phase of research it was demonstrated that flax-fibre reinforced rammed earth specimens were on average 46% stronger than unreinforced rammed earth specimens in compression (Morgan 2005). In 2005 the research organisation SCION were contracted to conduct bending and compression tests on the rammed earth specimens and on full-sized panels.
The second stage of research examined the constructability of the Uku method in Māori communities, using local unskilled labour. Key findings from this stage of research included:

- Experimentation with formwork systems. Initial construction of the Waimango Uku dwelling in 2004 used the David Easton formwork system. Construction of the Otara dwelling in 2005 used a custom made modular formwork system designed by Kepa Morgan. The modular formwork was used from this point onwards in the Uku research because it was safer to build with and produced wall panels that were as good as panels made with the Easton formwork. The formwork change was required because several injuries were incurred during the formwork dismantling process during the construction of the Waimango dwelling.

- Incorporation of flax-fibres into the rammed earth construction process. The two single room dwellings were built predominantly with unreinforced rammed earth wall panels. Flax-fibres were included for the construction of only a few panels to test the difficulty of processing and mixing the fibres into the earth mixture. The inclusion of flax-fibres to the rammed earth construction process was found to be easy and straightforward to do and was used in wall panels built thereafter.

- The implications of using local unskilled labour were evaluated and it was decided to progress with the use of local unskilled labourers to build the Uku structures. The labourers were able to build the Uku dwellings to a high quality standard.

- The sourcing of earth material onsite was possible for the Waimango site but not for the Otara site. Earth from a local quarry was instead used for the Otara site. Assessments comparing between using on-site earth sources or earth from quarries were performed and showed that the more suitable and cost-effective earth source was not necessarily the on-site earth.

The third phase of the research involved building two houses on Māori land in Rotoiti, Bay of Plenty. Both houses had a similar floor plan, similar architectural details, two bedrooms and a floor area of 92 m². One house was built using the Uku rammed earth method and the other house was built using light timber frame construction (Morgan 2005). In 2007, after the completion of both houses, the data collected during the construction periods were used to compare the housing methods in terms of cost and constructability. Using thermal iButtons,
which were been placed at specific locations in both houses, the thermal performance data was gathered from both houses over the next 3-4 years.

The construction and monitoring of the two houses established the following:-

- The cost to construct the 92 m² Uku rammed earth dwelling in Rotoiti, Bay of Plenty, was $84,889. The equivalent structure built using light timber framed walls cost 15% less ($72,437). Even though the rammed earth construction method was more expensive, further cost savings were anticipated as the rammed earth housing method was improved and the houses were built using a larger scale of production. A breakdown of costs and the process of construction of the Rotoiti Uku dwelling are reported in Appendix A.2.

- Thermal performance comparisons during the winter month of August showed that the average indoor temperatures in both the rammed earth and the light timber framed dwelling were similar. The rammed earth dwelling performed better than the light timber framed dwelling because internal temperatures varied less. The indoor temperature of the rammed earth dwelling was warmer during the morning and night but cooler during the afternoon and evening (Khoo 2008).

- The viability of using 150 mm thick rammed earth walls for the construction of Uku dwellings. All internal and external rammed earth walls in the Rotoiti Uku dwelling were 150 mm thick. Previous construction of the two single room Uku dwellings had 280 mm thick walls.

- A full set of architectural drawings and engineering calculations for an Uku rammed earth house were produced for the Rotoiti dwelling.

In 2005, under the FRST research project, a mobile flax stripper was designed and built by Dr. Krishnan Jayaraman, Dr. Xun Xu and Master of Engineering student Micheal Segetin. The device enabled large quantities of flax leaves to be processed into flax fibres by the researchers at any site. Prior to the construction of the mobile flax stripper, flax fibres were obtained by transporting harvested flax leaves to a flax mill for processing.
1.9. The Uku Rammed Earth Housing Method

There are many variations of rammed earth construction and Uku rammed earth is a specific variant in terms of material composition and with respect to the other structural elements in an Uku wall system such as vertical reinforcing steel within the panels, and reinforced concrete bond beams and foundation beams connect to the panels.

The Uku rammed earth housing method has been developed to make use of labour and material resources that are assets possessed by a whānau or local community, and which can be contributed towards the construction of the house. One of the largest costs of using a labour intensive construction method like rammed earth is to pay wages for labourers. However, if family members or people from the community provide their own labour, then labour costs can be considerably decreased. Individuals who are lacking in building skills can be trained in a short period of time to build rammed earth wall panels.

The use of local labour is an important part of the Uku housing concept because the monetary value of the labour contribution can be quantified and used as part of the upfront financial down payment required to obtain a mortgage. Saving enough money to pay the down payment for a mortgage is a common financial obstacle for Māori. The concept of using labour as a part of the financial contribution of the home owner is known as sweat equity. It is the value that is contributed to the project as a result of the effort and work of the owner or owners. The work done by the end-user is effectively the same as the end-user having upfront capital to pay someone else to do the work. Similarly, the provision of materials for the project, by the end-user, has a monetary value and is equivalent to having upfront capital to purchase building materials with. The provision of flax fibres, earth, machinery, labourers and tradesman skills are examples of such resources which many Māori whānau have access to and should be able to use as a portion of the upfront financial down payment required to obtain a mortgage. If Māori are able to provide a part of the upfront financial down payment required for a mortgage through the contribution of their own labour and provision of resources, a large financial barrier for Māori housing development will be removed.

From a structural perspective, Uku rammed earth panels are built on reinforced concrete foundation beams and the finished dwelling has a reinforced concrete bond beam cast over the top of all rammed earth panels. A light timber roof structure is built over the Uku walls which feature an exposed rafter roof which is designed as a timber diaphragm. The rammed earth panels are also reinforced with vertical steel bars 12-16 mm in diameter on both sides of
each panel. Additional reinforcing bars are embedded within Uku panels that are wider than 1.5 metres or when required from a structural design perspective. The Uku rammed earth mixture comprises of flax fibres cut to lengths of between 40-60 mm and in proportions of 0.075% to 0.3% (by dry weight of soil) and includes a cement proportion of between 6-8% (by dry weight of soil). Uku rammed earth wall panel thicknesses vary between 150 mm and 200 mm.

1.9.1. Method of Rammed Earth Construction

Uku rammed earth panels are made with an earth mixture comprising of between 45-80% gravel and sands, 10-30% silt and 5-20% clay. The earth is brought to its optimal moisture content before the mixture is rammed into earth layers that are 50-100 mm thick. Additional layers of earth are added and rammed until the wall panel has been built to the desired height.

Uku rammed earth panels are built using the custom formwork system shown in Figure 3. The formwork for a rammed earth panel is made using timber planks and sheets of plywood. The plywood sheets are reinforced along its height with scaffold planks wedged tightly between the plywood and a steel frame.

![Figure 3 Formwork Set Up in Preparation for the Construction of an Uku Wall Panel](image)

1.9.2. Categorisation of Uku Rammed Earth

There are many methods and variations used to build rammed earth walls. The methods used have often been adapted by earth builders and contractors to make use of local resources and skills available in an area.
The cross sectional shape, thickness, and height, of rammed earth walls have varied through the centuries. Historic construction of rammed earth walls had low aspect ratios and usually featured a taper. The 7 storey rammed earth building in Weilburg, Germany was built with a base wall thickness of 750 mm which decreased to 400 mm at the top. The Shanhaiguan section of the Great Wall of China (construction began in 1381) was built using the rammed earth method and has an average wall height of 12 meters and a thickness of 10 metres. The three metre wide boundary walls of the Arg-é Bam (Bam citadel, built 500 BC), in Iran, were noted to be up to 9 metres tall (Blondet and Aguilar 2007).

Over the centuries the aspect ratios of rammed earth walls increased and wall thicknesses decreased as rammed earth construction methods were revised, earth mixes were refined, and new material additions became available. François Cointeraux (1740-1830) developed several methods of building stabilized rammed earth walls and published these methods in four cahiers (booklets) in 1790 and 1791, which were widely translated. His methods were widely used and influenced the development of rammed earth significantly (Minke 2006). He also founded a school in 1788 to promote the use of rammed earth and is considered to be the developer of a widely used rammed earth method known as pisé de terre (Easton 1996). Pisé de terre walls were built on 450 mm wide masonry foundations which were raised to a height of 600 mm above ground level. A common detail for a two storey pisé de terre building used a base wall width of 460 mm which tapered off to 380 mm at the top (Lewis 2006).

Modern rammed earth building methods have been developed by many different individuals and companies. Bulletin 5 Earth-Wall Construction (Middleton 1952) resulted in the widespread use of a cement stabilized rammed earth method in Australia, particularly in Western Australia (Moor and Heathcote 2002). David Easton (1996) is another well known developer of a rammed earth method. His modular rammed earth formwork system is known as the Easton method. Easton advocated for the use of cement stabilization to improve moisture resistance and to add ‘a much needed psychological and mathematical safety factor.’ Individual rammed earth contractors continue to develop and refine their own rammed earth methods. Contractors like TERRAFIRMA Earth Building Co Ltd in NZ advertise their ability to build a wall “to almost any shape and thickness” including curved walls and arches. There are many methods and materials that can be used in rammed earth construction. Understanding the difference between rammed earth construction methods allows for more meaningful comparisons to be made with other rammed earth research and existing structures. The key aspects of the Uku rammed earth method are outlined in Table 1.
## Table 1 Characteristics of the Uku Rammed Earth Method

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Uku rammed earth</th>
<th>Common variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Stabilized</td>
<td>6-8% cement (by dry soil weight)</td>
<td>• Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lime / Other</td>
</tr>
<tr>
<td>Admixtures</td>
<td>0.075-0.3% flax-fibres (by dry soil weight)</td>
<td>Various fibres, binders and chemicals</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>150-280 mm</td>
<td>Usually 200 mm or thicker</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td>Continuous vertical steel reinforcing bars (12-16 mm in diameter)</td>
<td>• None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vertical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vertical &amp; Horizontal</td>
</tr>
<tr>
<td>Wall construction</td>
<td>Modular panels</td>
<td>• Modular panels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• One course around the building at a time</td>
</tr>
<tr>
<td>Foundation</td>
<td>Reinforced Concrete</td>
<td>• Reinforced concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Masonry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Other</td>
</tr>
<tr>
<td>Bond Beam</td>
<td>Reinforced Concrete</td>
<td>• Reinforced concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Timber</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• None</td>
</tr>
<tr>
<td>Earth composition</td>
<td>45-80% Gravel &amp; sand 10-30% Silt 5-20% Clay</td>
<td>Various</td>
</tr>
<tr>
<td>Labour force</td>
<td>Non-technical labour</td>
<td>• Non-technical labour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Professional contractors</td>
</tr>
<tr>
<td>Number of stories</td>
<td>Single</td>
<td>• Single</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Double</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Multiple</td>
</tr>
</tbody>
</table>

The key distinguishing characteristics of Uku rammed earth wall panels are that they:-

- Are cement stabilized and reinforced with flax-fibres;
- Are made using local and unskilled labour. Locally available machinery and equipment are also used where possible;
- Have wall panel thickness that are thinner than most other rammed earth walls at 150-200 mm;
- Are enclosed between a reinforced concrete bond beam and foundation beam. The earth is rammed in situ around continuous vertical steel reinforcing bars cast into the
foundation beams. The ends of the steel bars are cast into the bond beam after the earth has been rammed.

1.10. About Ahipara and Research Partners

The research was conducted in partnership with a Māori whānau from Ahipara which is henceforth referred in the doctoral thesis as the Ahipara whānau. Members of the Ahipara whānau have strong links to the area which date back to when their ancestors landed in the area after immigrating to Aotearoa New Zealand from Hawaiki. Māori have a definition of family which is wider than the Western nuclear family. For Māori, children of uncles and aunts are their brothers and sisters. References to the Ahipara whānau include their extended family. Due to the long history of particular Māori tribes living in the area over many generations, most Māori living in the area are related in some way through genealogy, marriage or historic events.

The Ahipara whānau is an active participant within their local community. Prior to the housing research project, the whānau was involved with the operation and improvement of local Māori schools, held classes training Māori to develop agricultural skills and to bring back the cultivation of traditional varieties of crops like the peruperu (Māori potato). They also regularly organise hui (meetings) with kaumatua (elders) to learn traditional songs, chants, and lore, and they actively monitor and protect local fisheries and beaches. The Ahipara whānau actively engaged in local decision making processes and at a political level also. Improving the housing condition of their people has been a desire of the Ahipara whānau for over a decade, but due to a lack of expertise and knowledge, they were unable to effectively improve the housing standard of local Māori on their own until the opportunity arose to partner with Uku researchers from the University of Auckland.

Ahipara is a rural region located 14 km south west of Kaitaia. The population of Ahipara was 1125 as of the 2006 census (Statistics NZ 2006) and is equally represented by European and Māori ethnicities. Ahipara has a sub-tropical climate and receives abundant sunshine; approximately 2000 hours per year. Ahipara has an average temperature of 15 degrees Celsius and a moderate annual rainfall of 1194 mm (Climate-Charts.com 2013; NIWA 2013).


1.11. Thesis Structure

The research presented in this thesis is presented in nine chapters excluding the Introduction and Conclusion. Each chapter is outlined below.

Chapter 2 Sustainable Development Trends – Holistic Decision Making and Localized Solutions

In recent decades, the issues of sustainable living and how to achieve sustainable development goals have received considerable attention. It is clear that the negative impact on the environment brought about by human activities has to be reduced if current and future generations are to continue to meet their needs. Defining global sustainable development and the steps that nations, business and individuals need to take in order to achieve sustainable development goals has been the subject of a number of world sustainability conferences.

The definitions and goals of sustainable development have changed over time as a result of an increased understanding regarding key issues and the complexity surrounding identified problems. The chapter focuses on two trends that globally set sustainable development goals are increasingly supportive of. The first trend is to move from sustainable development initiatives being implemented at the national level with solutions being devised at a government level, to an implementation process that enables and empowers communities and individuals to develop and implement sustainable development within their local areas. The second trend is towards broader and more holistic evaluations in sustainability decision making. Instead of viewing sustainable development purely in terms of economic benefits and controlled environmental exploitation, there is an increasing recognising that long term sustainable development also requires the consideration of dimensions such as societal impacts and cultural issues as well.

Chapter 3 Research Methodology

There are many ways of conducting research and establishing knowledge. Conventional research assumes that there is only one true way to understand a phenomena and the best way of establishing knowledge is through the use of repeatable, unbiased observation. The experience of many Māori involved with conventional research was that the results and outcomes of the research often did little to address or alleviate the Māori issues researched. Research would be published and presented at conference while the issues that Māori experienced remained.
Before Pākehā colonised NZ, Māori had their own way of researching that was centred on benefitting their communities and culture. Māori research methods were also much more participatory and inclusive than conventional research methods used today. Research conducted in the traditional Māori way is known as Kaupapa Māori research.

The overarching goal of the housing research was to improve the living conditions of Māori. To achieve this goal, the use of a kaupapa Māori research methodology was deemed to be more appropriate than the use of a conventional research approach. The key aspects of kaupapa Māori research in existing literature are reviewed, and the ways that the research methodology influenced the doctoral research are detailed.

**Chapter 4 Mauri Model Survey of Housing Perspectives**

At the outset of the research, perspectives were sought from people, groups and organisations that had an interest in the provision of rural Māori houses in Te Tai Tokerau. In particular, perspectives for evaluating the sustainability and appropriateness of light timber framed houses and rammed earth houses as rural housing solutions were sought. Rather than using technical housing reports or relying on the expertise of housing professionals, a survey of housing performance using the responses from individuals from all segments of the housing provision chain was conducted.

Individual perspectives regarding the performance of light timber framed and rammed earth dwellings were gathered using the Mauri Model decision making framework. This framework used the Māori concept of mauri, which is a holistic concept and a measure of sustainability, to evaluate housing performance. Use of the Mauri Model housing survey enabled individuals, regardless of background and professional expertise, to meaningfully contribute to the housing assessment in a fair, equal, and transparent manner.

Survey results were gathered from the following five groups:-

1. Housing New Zealand Corporation - Government
2. Community Housing Aotearoa – A not for profit housing advocacy organisation
3. Local council
4. Environmental groups
5. Local Māori
Chapter 5 Literature Review of Fibre Reinforced Soils

Earth materials lack tensile strength and fail in a brittle manner. In this chapter the findings of researchers who examined the improvement of earth properties resulting from the inclusion of fibre reinforcement in earthen materials is presented. In particular, research which examined the behaviour and influence of fibre reinforcement on the internal mechanics of earthen composites, and the influence of fibre reinforcement on overall composite strength characteristics and shrinkage were reviewed.

A summary of research, examining material strength, conducted on Uku flax-fibre reinforced rammed earth over the past 17 years is given at the end of the chapter.

Chapter 6 Material Testing of Flax-fibre Reinforced Rammed Earth

Compression, flexural and shear tests on rammed earth specimens were conducted throughout the doctoral research. A number of different test methods and test specimens were used. The results are used to provide insights and show trends of how the strength of rammed earth varies with age and water content, and when different test methods are used.

Chapter 7 Pseudo-static Cyclic Testing of Flax-fibre Reinforced Rammed Earth Panels in the Laboratory and Onsite

Full-sized wall panel were subjected to pseudo-static cyclic tests to test assumptions regarding the failure mechanisms that would result when Uku rammed earth panels and Uku wall assemblages were subjected to seismic loads. In total, six Uku wall panels were tested:

- 2 wall panel tests were built and tested in the laboratory,
- 4 wall panel tests were built and tested onsite in Ahipara.

Chapter 8 Pseudo-static Cyclic Testing of a Flax-fibre Reinforced Rammed Earth Assemblage with Openings

A full-sized wall panel assemblage comprising of three rammed earth wall panels, built on reinforced concrete foundations, with a concrete bond beam cast over the top of all the panels, and with a window and door opening, was built and tested in the laboratory. The test was conducted to verify assumptions regarding wall panel failure mechanisms, and to measure the capacity of the Uku wall system as an assemblage.
Chapter 9 Evaluating Shear Test Methods for Stabilized Rammed Earth

Shear failure was the most common failure mechanism observed in cyclic tests involving full-sized Uku wall panels. The seismic tests showed that the shear strength of rammed earth was the most important strength property to be able to establish. A reliable method to measure the shear strength of rammed earth panels was required in order to efficiently design Uku structures to withstand major seismic and wind events. Due to the lack of a standard shear test method for rammed earth, many different test methods have been used by earth researchers.

The triplet shear test method (for masonry) and the triaxial test method (for soil testing) were used to evaluate the same rammed earth material in order to determine the better of the two for conducting shear tests on rammed earth. The merits and disadvantages of using each shear test method were identified. The triaxial test method was identified as the better shear test method of the two for shear testing of rammed earth.

Chapter 10 Implementation of the Ahipara Whareuku

The results and conclusions attained from the surveys of housing perspectives, and the soil, material and full-sized panel tests, were used to inform the process of implementing a rammed earth dwelling in Ahipara. The construction of the house linked the decision making research and the structural research with the overarching research objective to improve housing conditions and housing options for Māori.

The chapter was written for the benefit of researchers of rural Māori housing solutions and to provide insight for Māori regarding how to implement the rammed earth method within their communities and on Māori land. Many obstacles were encountered and overcome during the process of implementation. Each step of the housing process and the lessons learnt along the way were recorded.

1.12. Media Coverage

The Uku research project has received significant media publicity nationally and internationally in the form of newspaper and magazine articles, radio interviews and television coverage. The attention received showed that the public were interested in the research and that the research was valuable and novel. A list of selected media coverage is described below to show the range of media coverage the research received.
The Uku research has been regularly published in magazines and newspaper articles and media interest has been ongoing since the beginning of the project. Two magazine articles and five newspaper articles published in July 2009 are reproduced in Appendix A.3

Radio interviews of the Uku research have been aired on radio stations around New Zealand including:

- bFM (29 April 2008)
- Te Hiku 94.4FM / NgatihineFM 96.8 / Radio Tautoko FM (3rd and 7th July, 2009)
- Radio Australia and ABC Radio (7 October 2008)
- Tautoko Radio (31 December 2008)
- Radio Waatea 603AM (14 July 2009)
- Radio NZ (15 July 2009)

The Uku research has been covered a number of times on television including:

- National Geographic Channel documentary “China’s Lost Pyramids” in a section describing the science behind the rammed earth construction method
- Asia Downunder documentary (12th September 2010)
- Te Karere News broadcast (9th July 2009) and on four other occasions
- Te Kaea News broadcast an estimated 5 times
- Whare Māori architecture series (8th May, 2011)
- Project Mātauranga science series (9th November, 2012)

The housing research has featured in associated projects such as:

- An art exhibition called “One Quarter of a Whare.” In a collaboration between fine art and engineering students, Uku wall panels were built and used in an art gallery exhibition at George Fraser Gallery
- The SHaC09 Sustainable Habitat Challenge as Team WhareUku. SHaC09 was a two year nationwide sustainable housing competition held to help groups and institutions
physically implement their sustainable housing concepts. The aim of the competition was to demonstrate and publicize a variety of housing concepts which could be implemented, in a practical way, using current technology and existing knowledge. Team WhareUku was the only team that achieved high commendations in all four categories of the competition; Vision “low-cost housing for rural North Island”, collaboration “student-led team including engineering, a fine-arts exhibition and film crew”, communication “deep involvement of local community” and innovation “for earth walls strengthened physically and culturally with flax fibres, providing a literal connection to the land” (Bishop 2013).

1.13. Additional Notes

The presentation style used in this thesis assumes that the reader has a basic knowledge level of Māori culture and values. An appreciation of the history of interaction between Māori and Pākehā (white migrants to Aotearoa NZ) is also helpful to understand the underlying contexts upon which the Uku housing research and this doctoral research have been designed upon. For those wishing to gain a basic understanding of Māori, their culture, and their history, the following two books are recommended:

- *Tikanga Whakaaro. Key concepts in Māori culture* by Barlow (1992),
Chapter 2. SUSTAINABLE DEVELOPMENT TRENDS – HOLISTIC DECISION MAKING AND LOCALIZED SOLUTIONS

Hutia te rito o te pā harakeke. Kei whea te komako e ko?

If you destroy the flax, from where will the bellbird sing?

As the challenges of achieving global sustainable development goals have become more understood, the methods endorsed and the philosophy regarding the implementation of sustainable development have changed. Two trends observed in sustainable development approaches were the endorsement of using a broader, more holistic decision making and assessment process, and the support of sustainable development initiatives at the local community level. The developments of these two trends are considered in this chapter.

2.1. Transition towards a Holistic Decision Making Process

Holistic living and decision making practices can be observed in many cultures and communities around the world. The use of economically biased decision making seemed to become the norm in developed countries around the time of the industrial revolution (circa 1780). During this time new science and inventions resulted in rapid and sustained economic growth. Perspectives changed in the industrialized world from seeing humankind as a part of nature, to being separate from it. Developed nations perceived the environment as something that could be controlled and used for human benefit (Carson 1962). This perspective of the environment resulted in the exponential and sustained growth of the global economy as shown in Figure 4.
Economic growth resulted in negative effects such as large scale resource exploitation, waste creation and consumption being clearly evident by the 20\textsuperscript{th} century. Although many individuals and groups mobilised to protect the natural environment and oppose development throughout the industrial revolution, the support by the general public of developed nations for conservation was small. At the beginning of the 20\textsuperscript{th} century as the environmental consequences of economic growth become more evident, the numbers of individuals and groups who actively fought for reform grew. However, but it was not until a number of environmental catastrophes occurred during the middle of the 20\textsuperscript{th} century that the environmental movement become big enough to significantly affect government policy. These catastrophes triggered the propagation and publication of numerous influential books by researchers which identified the threat to the environment and humanity. Some significant events are detailed in Table 2.
The environmentalism movement gained a large public following in the 1950s and showed the concern that many individuals had regarding the state of the natural environment and the damage being caused to it as a result of human actions. The negative consequences could be seen in both the built and natural environment and showed that the use of new discoveries and inventions were not without costs and consequences. Negative outcomes also revealed the short-sightedness of the decision making processes used to evaluate impacts and justify use of new science and technology (Carson 1962). The demand for decision making processes to return to a broader and holistic form was a result of individuals realising the real costs of post-industrial economic development and the limited resilience of natural systems and human communities to withstand further degradation. In response to the issue of unsustainable development global forums have been held and nations have drafted legislation to require governments, businesses and individuals to adopt more sustainable practices.

‘Sustainable development’ is a term that represents and describes the change that is required if global sustainability is to be achieved. However, defining the term has been difficult. One definition of sustainable development, which was defined during the UN World Commission on Environment and Development (WCED), is quoted below:

*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

- WCED (1987)
Sustainable development has since been defined and redefined many times. A lot of effort has been invested to produce and update documents to assist governments, businesses and individuals to become and live more sustainably. In 1972 the United Nations held an international conference on sustainable development referred to as the UN Conference on the Human Environment. During this conference, a declaration was made which consisted of 26 principles that every nation would need to adhere to, if global sustainable development was to be achieved. In 1992 at the UN Conference on Environment and Development (UNCED) the Rio Declaration was made which refined the goals determined at the previous sustainable development conference using 27 principles. It is necessary that sustainable development is continually redefined because our understanding of sustainable development and what is required to achieve it is still developing. Newer definitions of sustainable development are becoming more similar to the holistic views of sustainability that are held by many indigenous groups already.

The holistic practices of many indigenous groups provide examples of ways to sustainably evaluate impacts and make decisions. Ways of living symbiotically with nature can be seen in the culture and practices of indigenous peoples and how they interact with the natural environment. Although sustainable development has become a major issue in the 21st century, it is an issue that all civilisations have needed to overcome.

Before NZ was officially founded in 1840 by the British, Māori had lived in the country for at least eight centuries. Based on radiocarbon dating, a number of NZ historians estimate the date of first settlement to be between 800-1000 AD (Davidson 1983). Over the centuries, Māori adapted to the NZ environment and developed ways of living that were sustainable. From their surroundings Māori were able to meet the needs of their people for many generations without depleting natural resources. When Māori took from the environment it was important culturally to improve or maintain the ‘mauri’ of the resource. Mauri is a concept used by Māori which has some similarity to the concept of well-being and is described in more detail in Section 2.1.3.

Every life-form or life supporting thing has mauri. When required, Māori protected the mauri of a resource by placing rāhui (temporary bans on harvesting) on a resource or over an area. Rāhui was often placed on resources during times of growth or breeding. Māori also had an appreciation and reverence for the resources taken and associated the provision of goods with the benevolence of deities. Often karakia (prayers) were offered, to acknowledge deities and
ask for permission, before taking from the environment. It was common for acts of reciprocity to be performed in return for the resource. For example, Māori wood carvers would return wood chips produced during the carving process back to the location where the tree was felled. An act of tā koha (reciprocal gift) was shown by the carvers of the meeting house Te Noho Kotahitanga who erected a carved post in the Kaingaroa forest, from which logs for carving were taken (Morgan 2007). The way that Māori valued their natural environment and the way that this influenced their decisions and interactions with it, ensured the long-term health of the resources used and thus the survival of the tribe. This behaviour resonates with the goal of sustainable development.

Sustainable development approaches and concepts should acknowledge and nurture the intrinsic value of eco-systems, but also need to be defined in a way that is acceptable and practical for governments and businesses to follow. Haque (2000) states that although it may be possible to define a more authentic model of sustainable development, the greater challenge was to get top policy makers and decision makers to implement sustainable development.

2.1.1. A Definition of Sustainable Development

A review of sustainable development documents and definitions made during international conferences emphasised two objectives:-

1. Preserve the environment

2. Ensure continued economic growth

The modern approach of sustainable development had an in-built assumption that continued positive economic growth was a requirement to meet human needs. Phrases such as “the possibility for a new era of economic growth” resulting from the change towards sustainable development in the main conference publications show the aspiration for continued economic growth (WCED 1987).

More specifically the goal of sustainable development seemed to be to achieve economic growth whilst limiting the impacts on non-economic dimensions such as cultural values, the environment and social systems. Using this understanding of sustainable development the optimal aspiration was to harvest natural resources at the maximum rate at which they could sustainably replenish, and thus achieve the greatest sustainable economic benefit. Lesser
consideration was given to the benefit or improvement of non-economic dimensions. The secondary place of the environmental dimension to the economic dimension in sustainable development approaches is clearly illustrated in documents such as the Brundtland Report. In the section defining sustainable development, it was written:

“Every ecosystem everywhere cannot be preserved intact. A forest may be depleted in one part of a watershed and extended elsewhere, which is not a bad thing if the exploitation has been planned and the effects on soil erosion rates, water regimes, and genetic losses have been taken into account”

- WCED (1987)

The excerpt from the Brundtland Report quoted above condones the degradation of a resource for the purpose of exploitation so long as the damage was controlled. This perspective of sustainable development conflicts with other views of sustainable development, particularly indigenous perspectives and perspectives that value non-economic outcomes.

Achieving economic growth without consideration for the growth or improvement in other non-economic dimensions is unsustainable. Market-based economic growth has historically exacerbated ecological problems, resource shortages and intensified unsustainable development (Redclift 1987). Former Secretary General of the Commonwealth Shridath Ramphal (1992) clearly locates the issue of human consumption, which is the basis of modern economic growth, as a central issue of the environmental crisis. Many of the environmental issues caused by unsustainable practices cannot be solved unless a more holistic approach to the problem is used.

Sustainability issues are complex and need to be addressed within a complex system (Adebowale 2002). In recognition of the complexity of sustainability issues a broad array of issues and effects such as education, crime, human rights, governance and health care (Horlings and Padt 2011; Quental et al. 2011) are now covered in global sustainable development conferences. At the Rio sustainable development conference emphasis was given to the issue of alleviating poverty in order to be able to preserve eco-systems. Many of the world’s poor are forced to over cultivate small plots of land or clear forests to cultivate land in order to survive. This is one example of how the issues of poverty and inequality need to be dealt with if the problems of land degradation, deforestation and declining biodiversity are to be improved (Haque 2000).
2.1.2. Indigenous Perspectives on Sustainable Development

Indigenous knowledge provides insights that can facilitate progress towards achieving sustainable development. Indigenous practices are examples of sustainable development and are increasingly recognised as such. Principle 22 of the Rio Declaration describes the vital role that local and indigenous communities have regarding sustainable development due to their traditional practices and knowledge (UNEP 1992). The UN Declaration on the Rights of Indigenous Peoples adopted in 2007 recognised that indigenous knowledge, traditions and culture promoted proper environmental management and sustainable development.

The knowledge and understanding possessed by indigenous peoples can also improve the health and yield of resources. One example is illustrated in Māori flax harvesting techniques. The flax harvesting method used by Māori was shown by Atkinson (1921) to result in a greater yield when compared with the method used by non-Māori flax millers. The non-Māori method involved cutting the plant across all leaves, eight inches above the ground. In contrast, Māori harvested the leaves outside of the two inner sheaths. The principle is embedded in Māori culture which likens a flax plant to a family unit as is encapsulated in the common Māori saying reproduced below.

Hutia te rito o te harakeke, Kei whea te kōmako e kō?
Kī mai ki ahau; He aha te mea nui o te Ao?
Māku e kī atu, he tāngata, he tāngata, he tāngata
If the heart of the flax plant was removed, where will the bellbird sing?
If I was asked, what was the most important thing in the world;
I would be compelled to reply, It is people, it is people, it is people!

The rito (child) inner leaf would be left to grow, and the awhi rito (parent) leaves around it were left to protect the rito. Harvesting procedures followed by Māori were found to be a safer process of harvesting flax, produce a higher quality flax product and result in much quicker plant recovery (Ngairimu 2005).

2.1.3. Mauri – a Māori Indigenous Concept of Sustainability

Māori have a concept of sustainability called ‘mauri.’ The concept is intuitive and simple, yet can be used meaningfully to assess the health of any object, resource or action. Mauri has been described as the binding force between the physical and spiritual (Barlow 1992). Mauri
is a measure of an object’s life-force or its capacity to support a healthy ecosystem (Morgan 2008). Marsden (1980) described mauri as “the life-force which generates, regenerates and upholds creation”. As an example, spring water typically has a good life supporting capacity and thus is associated with a strong mauri. Wastewater by comparison is not able to sustain an ecosystem well and thus is associated with a poor or degraded mauri. For Māori, the sustainability assessment is of the intrinsic value or health of the resource.

2.2. A Localized Definition of Sustainable Development

Documents produced from global sustainable development conferences are often comprehensive and are written to apply to a wide range of settings, however, as a result they are also often large and difficult to understand. While such documents are useful for national governments, they are less meaningful to individuals and business owners who are the ones implementing sustainable development initiatives in their communities.

Péti (2011) argues that a regional definition of sustainable development is more pragmatic and meaningful than a global or national definition. A regional definition would be more acceptable to local communities because views of sustainable development can vary from person to person and change over time (OECD 2001). Sustainability perspectives are influenced by the history and characteristics of each community. Addressing sustainable development for a specific region or community would result in the development of more meaningful goals for individuals and business owners. At the local level, the many different stakeholders in the community can interact and contribute effectively to the process of defining and implementing sustainable development locally.

It is by the action of individuals from communities that sustainable development is most effectively implemented. A process that places decision making as close to the individual as possible empowers local individuals to take responsibility for achieving sustainability locally and motivates action (du Plessis and J.Cole 2011). In four case studies of environmentally focused initiatives undertaken in the UK, Selman (1998) showed the unique benefits and positive effects of giving individuals in a local community the opportunity to participate in and control the decision making process in a range of local sustainability initiatives. Some of the most significant outcomes he noted of using a localized approach when implementing sustainable development initiatives were the strengthened local democracy, increased social capital and the ownership taken by local individuals of the responsibility to protect the
environment. Other case studies by Dongier et al. (2002), Mansuri & Rao (2004), Harris-Roxas & Harris (2011) and Mulligan et al. (2011) support Selman’s observations and showed that community driven projects encouraged local participation, assisted the development of self-sufficient communities, better met community-specific needs and demands, and had cost advantages compared to centrally administered programmes. Péti (2011) concluded that community driven initiatives helped to develop a local identity and found that the development of a local sense of ownership was one of the most important non-financial drivers to promote sustainable change.

2.2.1. Local Capability to Implement Sustainable Solutions

Locally based groups and individuals are able to find and implement solutions to issues in their own communities when given the opportunity and adequate guidance (Selman 1998; Péti 2011). Péti noted that individuals from a community were well aware of the local issues and in some cases were more aware and informed than local authorities. Knight et al. (2002) elaborated on the desire and expectation from individuals to be involved in decision making processes and to genuinely influence decisions that affected their lives. In a review of sustainable development initiatives that used the community driven approach developed at the Rio Summit (known as Local Agenda 21), Selman identified that genuine participation from those in the community was best promoted when local authorities did not have the lead role in the process. In particular the ability of individuals from the community to set the priorities of the initiative and to decide on the actions to be implemented was important. Not only were individuals from the local community found to be capable of the task, they desired the opportunity to improve their community.

Evaluating intangible considerations such as social capital, mana (prestige, standing), and kaitiakitanga (the role of enhancing mauri) in the decision making process and incorporating them into existing decision making processes has been difficult as concepts such as these are not easily assessed and quantifiable. Also, information related to these considerations is often not readily available or accessible. Even so, local stakeholders have shown that they are capable of recognising and implementing sustainable development solutions which improve intangible considerations such as social capital, equity and cultural values (Cuthill 2010).
2.2.2. Local Community Resistance to Top-down Sustainable Development Solutions

The NZ government has implemented sustainable development through sustainable development legislation. These are implemented in communities predominantly through initiatives run by territorial authorities or through monetary subsidies or incentives to induce behaviour change and promote the use of new green technologies.

Selman (1998) found initiatives by territorial authorities to be commonly met with indifference or resistance from the community because “traditional local policy documents were seen to be boring and largely irrelevant to the person in the street.” He observed that there was a widespread disillusioned perception of local government policies which were seen to be self-serving and ineffective which led to an apathy and distrust in individuals of local government. Similar sentiments were found in an Australian study (Cuthill 2010) and in a separate UK study (Moffatt et al. 2000).

One example of a sustainable development initiative to protect NZ forests which was poorly received was the use of aerial drops of sodium fluoroacetate poison tablets (known as 1080) over large areas of forest to reduce the population of the introduced and invasive brush-tail possum. The possums are a threat to NZ native wildlife, plant life and cattle farmers (The Pest Control Education Trust 2013). Aerial drops of 1080 poison pellets over large sections of forest was deemed by the Department of Conservation to be the most practical and effective solution for pest control. Māori opposed the aerial drop of poison pellets over their lands and into their waterways. The action also caused cultural offense for Māori because land features like mountains are considered as their ancestors and are sacred places. The dropping of poison pellets over these areas has caused much anguish for Māori. One of the main alternative solutions put forward by Māori was to train and employ members from NZ communities to become professional trappers. This proposal would have created much needed jobs in rural areas and been a viable long-term solution for controlling pest populations in the forests surrounding the communities. Apart from the ecological, ethical and practical benefits, it was also an opportunity to involve individuals within NZ communities in the implementation of sustainable development. Despite the efforts of many, 1080 poison drops were used, and continue to be used, as the solution to NZ’s possum problem. The 1080 issue continues to be a source of Māori angst against the government and illustrates how top-down solutions can result in disillusionment of those influenced by, but not able to influence, decisions made.
Local individuals should be encouraged to contribute towards the sustainable development decisions in their area. The literature shows that the development of a sense of ownership and responsibility for local sustainability and sustainable development is viable and has more potential to achieve sustainable outcomes than a situation where the responsibility for achieving sustainability is devolved primarily to territorial authorities and governmental organisations.

2.2.3. Challenges of a Community Driven Approach

Despite the potential benefits of community driven approaches to sustainable development, the use of such approaches are not widely used or accepted. The reasons for this include a lack of suitable decision making tools to facilitate the decision making process, the lack of a clearly defined process, and a resistance to deviate from existing approaches (Sahota and Jeffrey 2005; Harris-Roxas and Harris 2011).

In particular, gathering a comprehensive and representative community perspective that is credible to and accepted by all local stakeholders is a challenge. For community driven decision making, an inclusive approach to decision making is more suitable. Ideally, a unanimous decision should be reached on how to proceed by all stakeholders. In order to achieve a credible and acceptable compromise, all stakeholders need to have the opportunity to present their perspective and to hear the perspectives of other stakeholders during the decision making process. Participatory methods that have these elements often take more time and resources than non-participatory methods. Though many novel participatory techniques are available, like focus groups, opinion polls and citizens’ panels, they are not as well established as a decision process based on conventional representative democracy decided by majority vote where an elected person participates in the decision making process on behalf of a group or community (Selman 1998). Participatory techniques also tend to be subjective, less formal and less technically rigorous than assessments produced by professionals. Participatory techniques have been criticized particularly as an oversimplification of existing methods, such as impact assessments (Wood 2010).

In order for a community driven approach to be successfully implemented, a willingness was required from local authorities to share their decision making power with a wide range of stakeholders (Cuthill 2001). Selman (1998) observed resistance from councillors to change to a novel innovative process in which they had less control and from which there were no clear short term results to objectively gauge value. A minority of councillors were observed to
genuinely support community driven approaches. Selman noted that while it often took longer for community driven initiatives to produce measurable value to the community and to justify the investment of resources, improvements did occur in the long-term and came with many intangible benefits such as the strengthening of relationships within the community, improving attitude from both individuals and agencies towards sustainable development, and an openness of those in the community to new ideas.

Development of methods, tools, and processes, to support community driven approaches are in an early stage of development. From the case studies reviewed it was apparent that the processes and methods currently being used could be refined. Through usage in a project, the advantages and shortfall of each method were better understood. In incorporation of social and cultural dimensions in decision making is also relatively new and will take time to be included effectively into decision processes. Social dimensions of sustainable development have only begun to be formally recognised in decision making over the last decade (Cuthill 2010) while cultural and indigenous considerations have been recognised in decision making processes for an even shorter period of time. Even though cultural concepts have been included in NZ’s Resource Management Act (RMA) (1991) for two decades, there is less use and acceptance of cultural values and considerations in decision making than for economic, environmental and social considerations (Awatere et al. 2008).

Despite the difficulties and criticisms of the community driven process there are clear benefits that result from involving and empowering the local community in sustainable development initiatives. Given NZ’s history and commitment to bi-cultural development, the use of an inclusive community driven approach is particularly appropriate. A community driven approach to sustainable development has the potential to be an effective and practical way to meet the requirements as specified in the RMA (1991), to consider the four dimensions (economic, social, cultural and environmental) in the decision making process, and to implement holistic and lasting sustainable solutions.

2.3. NZ Sustainable Development Legislation

NZ has enacted legislation over the past few decades to achieve the goal of sustainable development which has the effect of legally requiring sustainable development to be considered in all projects. To improve the management of the environment the NZ Government set up the Ministry for the Environment (MfE) in 1986 under the
Environmental Act (1986). The act was the first to acknowledge “the intrinsic value of ecosystems”. The purpose of the MftE was to advise and inform the NZ government on environmental policies and carry out a range of responsibilities associated with monitoring the natural environment and promoting environmental policies to the public. The Resource Management Act (RMA) (1991) made it a requirement to consider the four dimensions of economic, environmental, social and cultural in decision making processes. The RMA applied to any activity that had an impact on natural or physical resources. Projects which impacted on the environment were required to have resource consent to proceed and a common requirement of such a consent was an Assessment of Environmental Effects (AEE) which identified the effects of a proposed project on the environment. The Local Government Act (2002) further supported local and holistic decision making by defining two purposes for local government:-

1. To enable democratic local decision-making and action by, and on behalf of, communities; and

2. To promote the social, economic, environmental, and cultural well-being of communities, in the present and for the future.

2.4. Limitations of Impact Assessments

The use of various impact assessments to inform the decision process is a commonly used method to evaluate the sustainability of a project and show that the requirements of the RMA have been met. However, one limitation of using impact assessments was with assessing intangible considerations. Cultural and social dimensions often have some degree of subjectivity. Pertinent data and records may not exist. Examples of intangible considerations include a project’s impact on mana (prestige, standing) in the community, long-term health effects, and the maintenance and continuation of cultural practices.

Impact assessments (IAs) cover a wide range of considerations and a significant amount of time, resources, and expertise is required to assess all the effects resulting from a project (Wood and Djeddour 1992). Due to the resource requirements, IAs are typically only done for a few alternative solutions. Due to the time required to carry out an IA, the findings are also often not available during initial planning stages of projects where they could most effectively influence the decisions that are made.
Simpler assessments that were less costly and quicker to conduct, such as the Sustainability Appraisal (SA) which is used in the UK, were developed in the 1990s. A SA would be used to assess the economic, environmental and social dimensions of a project by evaluating the project using a number of key objectives for each dimension, for example, the capacity of the project to provide everyone in the area with a decent home. A SA analysis is less rigorous than an impact assessment but is able to provide enough direction to guide decision making to better achieve the sustainability goals of the project. The SA indicated how well the project would achieve key objectives in terms of whether it would be positive or negative, and how significant the effect was likely to be. The SA was used iteratively and was able to produce useful measures of each metric in the short, medium and long term of each proposed solution (Cumbria County Council 2006). Because the assessment could be completed quickly, it could also be conducted on all alternative solutions. The SA has been criticized as an overly simplified and inadequate method of analysis (Hulme and Taylor 1999; Counsell and Haughton 2001) but it is still used because the assessment enables alternative solutions to be meaningfully compared and can provide early direction for a project, guiding it towards sustainability.

2.5. Achieving Sustainable Rural Māori Housing Development in NZ

In NZ communities, it is difficult for individuals from a local community to influence the decision making process of territorial authorities and government. More often than not, professional are used and relied upon by local and government authorities to make informed decisions and to provide high-quality, fair and long-term solutions (Hill and Lorenz 2011). In housing, this has resulted in a number of generic timber and masonry housing forms and layouts which can be used most locations. They have worked adequately in many localities, such as in suburban areas and rural townships, but they have not worked well in rural Māori communities. An overview of Māori housing in NZ by Awatere et al. (2008) showed that Eurocentric housing methods have been promoted to Māori and have been built in Māori communities with little consideration of the housing needs, lifestyle, and cultural values of Māori.

Due to the inadequacy of existing housing options Māori have been seeking to develop and provide housing solutions for their own communities. The positive results of Māori-led initiatives to address Māori issues show the value and effectiveness of developing solutions for Māori from a Māori world view. Positive examples of Māori-led initiatives can be seen
particularly in Māori health and education. The development of a housing solution by Māori has great potential to realise an accessible, culturally appropriate and holistic housing solution for Māori. The Uku housing research was unique compared to other Māori housing initiatives initiated by government in that the research was initiated by Māori, predominantly used Māori as researchers, and used a research process that acknowledged Māori customs and protocol. The doctoral research has continued this approach by using a Māori research methodology.
Chapter 3. RESEARCH METHODOLOGY

I nāianei, e rua ngā pūtea mātauranga kei mua i a tātou, te Māori: ko tā ngā koroua me tā te Pākehā. He ōrite te hua kei roto I ngā kete e rua: he ātaahua, he kino, nā reira, whāia te mea ātaahua

Nowadays we have two sources of knowledge, that belonging to the Māori and that belonging to the Pākehā. The fruits of these are the same, both good and bad, but you must seek that which is good.

- Cleve Barlow

The involvement of Māori as participants and researchers in this doctoral study was central to the success of the project. A Māori research methodology was used in this doctoral research to facilitate the involvement of Māori and develop an accessible, culturally appropriate housing solution for rural Māori communities.

3.1. Methodological Context

In a national sense Māori, as the indigenous people of NZ, are seeking to regain control of their future as Māori in NZ. The desire of Māori for self-determination is supported as a fundamental right by a number of commitments that NZ has agreed to which are listed in Table 3. Durie (1998) describes Māori self-determination as “the advancement of Māori people, as Māori, for the protection of the environment for future generations.” Since the colonisation of New Zealand, Māori have had to struggle to retain their place in New Zealand society. After enduring a period of great depopulation at the end of the 19th century, followed by a period of redefining their unique ethnic identity in the 20th century, the focus is now for Māori self-determination (Durie 1998). The housing research conducted in this doctoral thesis was conducted within this cultural movement to improve Māori self-determination.
Table 3 List of Commitments Made by NZ Which Support the Right for Māori Self-determination

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<thead>
<tr>
<th>Commitment</th>
<th>Year the commitment was joined or endorsed by NZ</th>
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<tr>
<td>Charter of the United Nations</td>
<td>1945</td>
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<tr>
<td>International Covenant on Civil and Political Rights</td>
<td>1966</td>
</tr>
<tr>
<td>International Covenant on Economic, Social, and Cultural rights</td>
<td>1966</td>
</tr>
<tr>
<td>Vienna Declaration and Program of Action</td>
<td>1993</td>
</tr>
<tr>
<td>Declaration on the Rights of Indigenous Peoples</td>
<td>2010</td>
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The ability of Māori communities to house their own people is a key issue at present because the lack of adequate housing is preventing Māori from being able to fully utilize their lands and to live as full citizens of NZ. Substandard housing is prevalent in rural Māori communities and has an associated detrimental effect on the health and education of Māori. The lack of affordable and good quality housing is also preventing the return of many urban Māori to their ancestral lands. A member of the Ahipara community mentioned the importance of improving the housing situation of Māori because it is not commensurate with the role that Māori have in NZ.

“Māori are rangatira (chiefs), so we need to live in houses fit for rangatira. Our people shouldn’t live in illegal or substandard housing.”

- Heeni Hoterene (Ngāti Hine, Ngāti Raukawa)

One research implication of Māori self-determination is the aspiration for research to be conducted by Māori. Although this requirement for research seems ethnically insular and needlessly exclusive to Māori, it was a conclusion reached largely because of two observations:-

1. The inadequacy of social services provided by government to meet the needs of Māori, and

2. Consistent use of an approach that focused exclusively on addressing the comparative shortfalls of Māori and not on positive Māori development.

The recurrence of government-provided social service failures has diminished Māori confidence in the state’s ability to understand and solve Māori issues. Reid (1999) observed that “the theoretical approaches of a variety of disciplines fall well short of being able to
address Māori needs or give full recognition of Māori culture and values systems.” Māori recognised that solutions to Māori problems would be more likely to succeed if they were developed from a Māori perspective. The ‘by Māori, for Māori providers’ health initiative and the Kōhanga reo movement to provide Māori language preschool education were examples of Māori actions which benefitted Māori significantly. These two initiatives are described in more detail in Section 3.3.1

Māori desired more emphasis into the positive development of Māori but government approaches focused exclusively on addressing the comparative shortfalls of Māori in areas like crime, health and employment (Durie 1998). Since taking the lead and responsibility for Māori development, Māori have been able to lift their political influence by setting up their own political parties and have introduced other initiatives which have promoted Māori culture and strengthened the identity of Māori in NZ. The increasing numbers of native Māori speakers, through kōhanga reo, and non-native Māori speakers, through the availability of free Māori language classes to members of the public, and the development of Māori media on television and radio, are other examples of progressive and positive Māori development. The flax-fibre reinforced rammed earth housing research developed in this doctoral thesis is part of a larger Māori research initiative responding to housing needs and the escalating cost of timber-frame construction.

3.1.1. Types of Doctoral Research

There are three types of doctoral research as defined by Phillips & Pugh (1987).

- New science explorative research
- Testing out research – seeks to extend existing theories
- Problem solving research – focus on achieving tangible results and in ‘the real world’ and implementing the research solutions in the community.

Although all three types of research were conducted during this doctoral study, the research was best classified as a problem solving research project. The overarching goal of the research was to develop a tangible housing method for use in rural Māori communities.

Due to the lack of established design processes, structural performance theory, and test methods for rammed earth, the research conducted on rammed earth was of an exploratory nature. The material strength testing adapted a variety of test methods developed for other
construction materials such as concrete masonry and reinforced concrete. Pseudo-static cyclic tests conducted in the doctoral research on rammed earth panels and assemblages were designed based upon test methods reported in research literature for the seismic assessment of unreinforced masonry wall panels and assemblages.

In order to develop and research a solution that would be suitable for implementation in a rural Māori community, members from the community of Ahipara were involved in the research. Individuals from the Ahipara whānau were involved in defining the research, conducting soil and material tests, constructing the rammed earth test specimens, and constructing the Ahipara Uku dwelling.

3.1.2. Continuums of Inquiry Paradigms

A range of ontological approaches were used during the doctoral research. Ontology is described in the Merriam-Webster dictionary as the branch of metaphysics that deals with the nature and relations of being. Ontology defines what can be known about. Ratima (2004) outlines a range of ontological perspectives with a realist perspective at one end, and a relativist perspective at the opposing end. The unique attributes of each perspective are summarised in Table 4.

A realist approach recognises a single reality. A relativist perspective acknowledges that there are multiple realities or perceptions of reality which are influenced by cultural, historical and social backgrounds. An objective approach has an in-built assumption that everyone’s experience of knowledge is the same whilst a subjective approach has an in-built assumption that the experience of knowledge is personal and differs from individual to individual (Vygotsky 1978; Guba and Lincoln 1994; Merriam et al. 2001). Objective research data is collected using human sensory experiences (i.e. what can be seen, touched, smelled, etc…). Logical and mathematical methods are used to process and interpret the data, and observations are made by a researcher who is unbiased and independent from the researched group. Subjective research data is constructed locally between the researcher and the researched group or thing. The knowledge generated is subjective and reflects the values of those involved in the research.
Although positivist research is the most common and accepted form of research inquiry, other research approaches can be more appropriate for research which is exploratory or for problem solving research where the implementation of a solution in a complex context is sought. Guba et al. (1994) commented that while positivist research increased the theoretical rigour of a study, a negative aspect of such research was that it reduced the relevance or generalisability of the results because the research outcomes were only accurately when applied in a specific context or in a contextually stripped situation. Positivist research focuses on verifying or falsifying specific hypotheses using experiments and by obtaining results which can be repeated and validated by other researchers. The use of divergent research methodologies that cannot be validated the same way are poorly regarded by mainstream researchers in comparison (ibid).

In this doctoral research a relativist paradigm was used to collect and analyse the perspectives of individuals regarding the performance of two housing methods for implementation in rural communities. Individuals with varying levels of housing experience, and which were from different backgrounds, were asked to contribute their personal perspectives in the housing assessment. The use of individual perspectives enabled all interested parties to participate in the evaluation process. The use of a relativist approach was advantageous when considering the spiritual and cultural performance of each housing method because many metrics in these dimensions are difficult to objectively measure, and because the relative assessments enabled intangible metrics to be evaluated alongside tangible performance metrics. A positivist
paradigm was used for the material testing of rammed earth and the seismic testing of rammed earth wall panels and assemblages.

3.2. A Kaupapa Māori Research Methodology

The research work for this doctoral thesis was conducted using a kaupapa Māori research methodology. A review of the literature showed that a kaupapa Māori methodology is defined and guided by the purpose of the research to benefit Māori, the acknowledgement of Māori values and knowledge, the use of an inclusive and reciprocal research process, and Māori benefit. In Kaupapa Māori research, both objective and subjective research approaches can be used, so long as the research is conducted in a way that acknowledges Māori protocol and is of benefit to Māori. Some guiding values of kaupapa Māori research that were seen regularly in the literature were Māori self-determination, benefit, control and reciprocity.

3.2.1. What is Kaupapa Māori Research?

“We know that there is a way of knowing, that is different from that which was taught to those colonised into the western way of thought. We know about a way that is born of time, connectedness, kinship, commitment, and participation.”

- Russell Bishop, 1996

Kaupapa Māori research is the Māori way of doing research. Before New Zealand was colonised by Europeans, Māori had their own methods of gathering, interpreting, establishing and protecting knowledge (Henry and Pene 2001). Māori knowledge has been passed down orally through many generations using mediums such as song, chant and axiom. The stories and lessons of the past are passed on in visual cues in places of significance such as whāriki (mats), tukutuku (ornamental panels often placed between carvings in a marae), whakairo (carvings) and kōwhaiwhai (paintings on the rafters of marae). Within the words and patterns important aspects of Māori history and culture are recorded. Following and respecting Māori protocols and practices is important when researching with Māori. The adherence and acknowledgement of Māori culture establishes aspects such as trust, openness and accountability between the people involved. The development of Kaupapa Māori research defined a way of research that was legitimate to Māori. It was a challenge to the idea that there was one universal way to conduct research that was best (Reid 1999). There are fundamental differences between Māori and post-industrial revolution Western thinking in how the world is perceived and valued and, the purpose of research.
The purpose of Kaupapa Māori research is different from the purpose of traditional research. Traditional research is conducted to increase knowledge through the collation of research observation that collectively can be used to define universal laws (Cram 1993). For Māori, the purpose of conducting research and developing knowledge is to benefit their community, to further their interests, to increase the mana (pride, identity) of their tribe, and to improve the ability of Māori to self-govern and control their own future. Māori expect the knowledge and outputs resulting from research to provide a benefit to all research participants involved (Reid 1999). Due to the significant differences in the purposes of research between Māori and Western perspectives, Māori have often been disillusioned by the outcomes of research projects conducted in the traditional Western way. There is a negative sentiment amongst Māori of research because past research conducted on Māori has rarely produced any direct benefit for Māori (Reid 1999). Past research involving Māori has described and identified the reasons for Māori underachievement or over-representation in areas such as crime, education, health, employment and incarceration but has not helped to improve or alleviate these issues for Māori (Smith 1992; Cram 1993). Outcomes such as community engagement with the research, individual empowerment or up skilling, and achieving social change, are desired research outcomes for Māori but these outcomes are often not the research objectives of researchers. Traditional research approaches are designed to primarily achieve the objectives of the researcher.

3.3. Reasons for Using a Kaupapa Māori Research Methodology

This doctoral research adopts a Kaupapa Māori research methodology. The research paradigm was better suited to the research context and to achieving the long-term goals of the housing research. The goals of the housing research were to:-

1. Recognise Māori sovereignty and right to self-govern and live self-sufficiently on their ancestral lands

2. Develop a sustainable housing solution

3. Encourage and support individuals from the local community to be actively involved in the research process and to enable the Ahipara whānau to implement an Uku dwelling on their ancestral land.
The use of a Kaupapa Māori research methodology in research involving Māori is advantageous from a legal perspective and is an acknowledgement of Māori sovereignty over their land and resources. In 1987 a document known as The Principles of the Treaty of Waitangi was written to clarify and define the intent of the treaty. The 6th principle identified was that Māori were to retain rangatiratanga (sovereignty) over their resources and taonga (property, goods and prized possessions). With respect to the rights of Māori under the Treaty of Waitangi, Justice Bisson determined that when the treaty was signed, the Māori chiefs were assured in good faith that every Māori individual would be guaranteed “the full and exclusive and undisturbed possession of their lands” (New Zealand Maori Council v Attorney-General 1987). This doctoral research was focused on developing a housing solution for implementation on Māori land, so it was appropriate to use a research methodology in which Māori could have a leading role.

3.3.1. Effectiveness of Solutions Developed Within a Māori Worldview

Solutions developed for Māori within a Māori worldview have been shown to be able to effectively meet the needs of Māori. The effectiveness of Māori solutions to Māori problems can be seen in initiative such as the “by Māori for Māori” health initiative and the kōhanga reo movement for Māori medium education.

The “by Māori for Māori” Māori health initiatives achieved positive improvement in Māori health metrics through the introduction of services such as mobile primary health providers who visited members of a community, by establishing large community networks, and by promoting healthier living practices (Kiro 2001). The initiative has resulted in the establishment of specialised Māori health service providers in the 1990s and gave Māori communities greater control and responsibility over the health services provided to Māori.

The kōhanga reo movement is led by Māori and has improved the achievement levels of Māori students at all levels of the education system. During the first decade of the initiative (1982-1990) many kōhanga reo were formed and operated by Māori communities with little financial assistance from the NZ Government. Kōhanga reo centres have now been established throughout the country and an estimated 60,000 children have since graduated from kōhanga reo (Te Kohanga Reo National Trust 2013). The success of the kōhanga reo movement and the support that it received from Māori also led to the establishment of Māori medium education at higher levels. The first kura kaupapa (Māori primary schools) were set up in 1986 (Smith 1992), and whare kura (high school) and whare wānanga (university)
followed soon after. These schools teach using a Māori language medium and imparted knowledge from a Māori ontological perspective.

Some non-Māori have criticized the Māori education initiative and similar Māori self-help solutions by calling them ‘separatist’, based on a ‘false reality’ or being ‘retrenchments to the past.’ Regardless of the criticism, the schools have been shown to clearly improve the academic performance of Māori students when compared to Māori who were enrolled in the mainstream education system (Smith 1992). Between 1998 and 2006, approximately 40% of Māori school leavers from whare kura left with an NCEA Level 2 qualification or higher, with the proportion being twice that of the national rate of Māori leavers (19%) (Alton-Lee 2008). Children who attended Māori schools were observed to be engaged and enthusiastic about learning and left the schools fluent in both Māori and English. They were able to fit well into both Māori and Western cultural settings. Lasting and positive outcomes have also been achieve for Māori by implementing health initiatives which are mobile, community-based, and holistic in their approach to achieving health and well-being.

3.4. Key Aspects of Māori Research

Several researchers have attempted to identify the essential aspects of Kaupapa Māori research. Ratima (2003) proposed five concepts which were central to Māori research: Interconnectedness, Māori identity, Māori control, collectivity and Māori potential. Bishop (2011) identified five areas of research which were of concern to Māori and which needed to be addressed in order to achieve legitimacy from a Māori perspective: Initiation, benefits, representation, legitimization, accountability. The key concepts described by the two researchers are listed in Table 5.

<table>
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<tr>
<td>Interconnectedness</td>
<td>Initiation</td>
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<tr>
<td>Identity</td>
<td>Benefits</td>
</tr>
<tr>
<td>Control</td>
<td>Representation</td>
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<tr>
<td>Collectivity</td>
<td>Legitimization</td>
</tr>
<tr>
<td>Māori potential</td>
<td>Accountability</td>
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Different researchers have described the essential aspects of Kaupapa Māori research. Although the descriptions represent different perspectives of what Kaupapa Māori research was and how it could be done, the perspectives were found to be consistent with other perspectives, and to be united by recurring themes and values such as inclusivity, reciprocity, control and Māori benefit. The key areas of kaupapa Māori research, as described by Bishop, were addressed in this doctoral research and are described in the following sections.

3.4.1. Initiation

Research initiation describes the process of determining the research focus, methods and questions. In Māori research, the research participants collectively determine the research questions, the benefits and outcomes that are sought, what work is to be done, and how the knowledge will be shared (Bishop 2011).

In the doctoral research process considerable time was spent at the outset to establish a relationship between researchers from the University of Auckland and Māori from the Ahipara community. The time spent to build relationships in the local community showed the commitment of the researchers to the wellbeing of the community. The time spend in the community also enabled those involved with the research to understand each other’s character and motivation to be involved with the research. The housing research direction and goals were determined collaboratively over a series of meetings. As a result of the meetings, three general research tasks were agreed upon: To gather data recording the perspectives of local individuals regarding housing methods, to conduct structural and seismic testing of flax-fibre reinforced rammed earth made using local sources of earth, and to implement the housing method using local resources and labourers.

3.4.2. Benefits

Kaupapa Māori research is conducted to benefit all research participants. Benefit to all research participants was ensured by using a collective research process and by choosing research methods that could represent Māori experiences, knowledge and values appropriately.

The desired benefits of the housing research to the community were to empower local individuals by helping them to develop research skills and gain trade skills over the course of the doctoral research and during the construction of a rammed earth dwelling. The physical construction of a house was desired, not just to achieve a tangible improvement in housing,
but to serve as a visible sign of improvement within the community. The implementation of the Uku house would prove that the housing method was practical to implement and was an achievable goal for Māori. These outputs were achieved alongside the goals to conduct quality research and to be able to publish and present the research findings in international journals and at conferences.

3.4.3. Representation

Representation is about how Māori experiences or views are recorded. Often the experiences of Māori have been represented in research by an authoritative expert or through the interpretation of researchers (Bishop 2011) rather than by using the responses of Māori individuals. Māori are capable of identifying the issues affecting them. Bishop & Berryman (2006) conducted a study of Māori experiences in education. The Māori students interviewed clearly identified that their teachers perceived and treated them differently to other students and explained how this negatively influenced their learning experience. In order to improve their learning experience the students identified and suggested several changes that their teachers could make. The students primarily desired to have more ability to express their self-determination in classroom relationships. Bishop & Berryman observed that Māori experiences were often presented in a way that was aligned with a negative view that pervaded traditional research findings and that this negative view could be alleviated by reducing researcher interpretation or generalizations of Māori responses.

In this doctoral research, the responses of Māori individuals from the local area were used to evaluate the suitability of housing methods for rural Māori communities. The use of ‘mauri’ to evaluate the performance of housing metrics was understood and well received by Māori and non-Māori survey participants alike.

3.4.4. Legitimization

Research legitimization defined what legitimate sources of knowledge were and how to conduct research in a way that would be legitimate to Māori. Māori knowledge is legitimized by the Māori community. In Kaupapa Māori the legitimacy of the Māori language, Māori knowledge, culture and values are assumed and accepted. Reid (1999) describes Kaupapa Māori research as research which places “Māori experience at the centre of the theoretical base.” An approach which produces authoritative research from a Māori perspectives is similar to the concept of epistemological validity presented by Denzin & Lincoln (1994). The
legitimacy of the research is largely defined by the processes followed when producing and sharing knowledge. One example is the importance of involving kaumatua (elders) in research. Due to the position of kaumatua in Māori society, it is important to have kaumatua in a mentoring or guiding role in the research (Henry and Pene 2001). Without the support of kaumatua in the research, the authority of the research findings is diminished. If cultural practices are not observed, the research does not have authority (Bishop 2011).

In terms of the legitimacy of research, there were some clear differences of opinion noted between Kaupapa Māori research and traditional research. Māori research has been seen to lack legitimacy because it does not adhere to the Western way of seeing the world (Smith 1992). Traditional research requirements include requirements for unbiased and objective observations, and to gather research data using methods which can be replicated by other researchers. Researchers should not have any personal conflicts of interest with the researched group. The latter requirement of good research practice, regarding conflicts of interest, makes it difficult for Māori to participate in research involving Māori issues and communities.

The concept of distance between the researcher and researched group is a problematic research requirement which is in conflict with the Māori custom of establishing whānaungatanga (the familial and relational links) between individuals. Whānaungatanga describes the sense of family connection and belonging between individuals and is based upon the rights and obligations of being a part of a wider family. The connection is not limited to Māori individuals and families but includes friendships and reciprocal relationships as well. At hui (meeting), time is set aside at the beginning for each person to share their identity and establish a connection with others at the hui. This connection of understanding between meeting participants needs to be established before knowledge can be shared or issues can be discussed. The process helps all those present at the meeting to understand the commitment of each individual to Māori, to each other and to the earth (Bishop 2011). The process also results in a meeting environment where there is a greater level of trust and accountability between meeting participants.

In this doctoral research time was taken to establish relationships and to recognise each person’s identity and intentions. A series of meetings were held in January 2009 between researchers from the University of Auckland and individuals from the Ahipara whānau before the decision was made to proceed with the housing research. Over the month of January
2009, discussions of the proposed research activities and outcomes of the work ensued after relational ties and a level of trust and commitment had been established between involved parties.

While the research relationship with individuals from the Ahipara whānau was established for the purpose of the housing research, spending time to strengthen relationships and to be a part of the community during the research was important. Regular face-to-face meetings were organised in Auckland and in Ahipara to maintain the relationship and to progress the research work. As a non-Māori, it was helpful that I took Māori language lessons because it helped me to better understand Māori culture, improved my ability to communicate with Māori individuals, and showed my respect of the Māori language and their culture. A long-term relationship has been established that will continue after the conclusion of this doctoral research.

3.4.5. Accountability

Accountability addresses the questions regarding who has control over the research processes, how the research findings are shared, and who is responsible for the consequences that arise from use of the research findings. Within traditional research there is the assumption that everyone should have access to all knowledge. Research findings are published in journals and books, and are shared at conferences. Māori have a more guarded approach to the sharing of knowledge. Knowledge is considered as something tapu (sacred) by Māori. Historically, specialized knowledge was entrusted to tohunga (experts, priests) to maintain and use for the benefit of the tribe (Cram 1993).

The use and protection of the results and data collected in this doctoral research was a common topic of discussion. Interest has been expressed by a number of groups, both locally and nationally, for access to the research outputs and to learn from the experiences of the Uku house construction project in Ahipara. Interested groups include individuals from other rural communities who desire to develop housing on their own land, groups with commercial interests, housing aid groups like Habitat for Humanity, Māori organisations, and government housing agencies. A charitable trust has been set up to protect and control how and with whom the Ahipara housing construction outputs and lessons are to be shared. One of the primary goals of the trust was to ensure that the developed Uku housing technology would be used to help other Māori communities to build affordable and appropriate housing solutions on Māori land in Te Tai Tokerau.
3.5. Who Can Do Māori Research?

Research conducted within a kaupapa Māori research paradigm should be conducted in a culturally sensitive manner. Because of this requirement, individuals who were familiar with Māori culture were more suitable to conduct Māori research. These individuals would be able to recognise meaningful aspects of the research, read non-verbal cultural cues, and could understand the culture of the people better than others who were unfamiliar with the culture (Merriam et al. 2001). In addition to possessing cultural awareness, researchers who were from the ethnic group studied had a level of authority to ask questions of the history and experiences of the cultural group which an outsider did not have (Swisher 1996).

In kaupapa Māori research, control of the research should remain with those who were the subject of the research or who would be influenced by the results. It is most appropriate for Māori to set the parameters of the research, but non-Māori can be invited to participate (Bishop 2011). It is not necessary for all researchers to be Māori. Bishop (2011) and Merriam et al. (2001) argued that selecting a researcher based on an individual’s cultural background was over-simplifying the issue and did not guarantee a more representative and authoritative result. The researchers identified that the most important consideration regarding eligibility and authority to conduct Māori research was that the researcher conducted the research in a culturally appropriate manner. Familiarity with the Māori language was also helpful (Cram 1993).

Smith (1990) proposed four models whereby non-Māori could conduct culturally appropriate research.

- Tiaki (mentor) model – where the research is guided by authoritative Māori
- Whāngai (adoption) model – researcher becomes a part of the whānau
- Power sharing model – where the community is sought by the researcher to develop the research in a meaningful way
- Empowering Outcomes model – The research is conducted to provide answers to questions that Māori want to know

As a non-Māori researcher, understanding who could do Māori research and why was important. The doctoral research approach adopted here has included aspects of all four models described by Smith (1990). The research has been guided by my main supervisor Dr. Kepa Morgan (Ngāti Pikiao, Te Arawa), and a power sharing model was used when the
research plan was developed alongside Māori from the Ahipara whānau. After the initial introduction period, I became a part of the family and was entrusted at times with the responsibility to look after their children and new-born baby, to help prepare food, clean the house, and participate in non-research related activities. The research topic of developing affordable and appropriate rammed earth housing for rural Māori communities also aligned with the empowering outcomes model because Māori were interested in research which developed suitable housing methods for implementation in rural Māori communities.

3.6. Research Methods

In this research, due to the diverse range of issues covered by the research questions and the intangible factors that need to be considered in order to find a solution for housing in a rural Māori community, a range of conventional and unconventional research methods were used to answer the four research questions listed in the Introduction chapter of the doctoral thesis.

The doctoral research was conducted in three parts:-

1. Conducting a holistic evaluation on rural Māori housing solutions in Te Tai Tokerau
2. Structural and seismic testing of flax-fibre reinforced, cement-stabilised, rammed earth
3. Implementation of a rammed earth house in Ahipara using locally available labour and resources.

While the second research question regarding material and seismic testing was suitably addressed using conventional engineering test methods and a positivist epistemology, the first and third research questions were more effectively addressed with the use of less conventional methods which were better able to assess intangible concepts and to record the experience and opinions of individuals from the Ahipara whānau.

In order to conduct a holistic evaluation of housing solutions for rural Māori communities in Te Tai Tokerau, two objectives were sought in the research method. The first objective was to evaluate potential Māori housing methods using the four dimensions of environment, culture, social and economy. The consideration of these four dimensions is a requirement listed in the Resource Management Act (RMA) (1991) for projects or actions which impact on the sustainable management of natural and physical resources and in particular, the use of
land, air and water. The second objective was to determine a result that was based on the perspectives all those involved in the housing process, and hence an inclusive research approach, was strived for. A survey was used to collect responses from a range of organizations and people groups over a wide geographical area using both face-to-face meetings and online surveys set up using the Survey Monkey website. To make the assessments more accessible to people of all backgrounds, the intrinsic Māori concept of mauri was used which is similar to the concept of well-being. Survey participants were asked to use the concept of mauri to assess the life supporting capacity of a resource or metric. A decision making framework known as the Mauri Model was used to analyze the data. The details of the survey and Mauri Model are provided in Section 3.6.1. The responses of individuals who lived in the local vicinity were considered equally with responses from those who had a technical understanding of how the housing methods would perform.

The use of the Mauri Model and individual responses to evaluate the suitability of local housing solutions was chosen because it was deemed to be an effective way to produce a holistic and representative assessment of local housing solutions for rural Māori. The use of mauri to evaluate the performance of, or impact upon, each performance metric enabled individuals from a wide range of backgrounds to participate in the decision making process. People with varying experiences and knowledge regarding different stages of the local housing process were able to participate. The inclusive approach used was perceived to be more effective than other data collection methods such as the use of quantitative assessments for each metric, cost based analysis, use of historical records and trends, interviewing housing professionals and experts, or gathering data from past housing surveys and case studies conducted in other regions. The use of data from these quantitative methods was likely to produce similar results to past research which has been shown to largely be ineffective in bringing about positive change in the local Māori community. Many of the cultural and social metrics would also be difficult to quantitatively assess such as the impact of housing on the role of Māori as kaitiaki (guardians) of their lands and the mana (pride) of living in a particular housing form. Also, the above quantitative data collection methods also often minimized the input and involvement of local Māori. The use of an inclusive survey and of the Mauri Model was well received by all participants and the method was able to be used to provide a clear endorsement to progress with the Uku rammed earth housing method.
3.6.1. The Mauri Model

The Mauri Model decision making framework (DMF) was developed by Dr. Kepa Morgan (2008) at the University of Auckland. The model was developed from a Māori worldview and used Māori ideas and concepts of sustainability to evaluate complex competing solutions in a holistically way. The Mauri Model was also designed to meet the legal requirement, specified in the RMA, to consider the four dimensions in decision making. A key difference of the Mauri Model from the more commonly used approach of impact assessments was the use of an indigenous concept of ‘mauri’ to derive metrics, rather than the use of technical and quantitative measurements. In the Mauri Model DMF, mauri was used to measure the wellbeing or life supporting capacity of each housing method for each metric.

To date, the Mauri Model has been used for several complex NZ situations and projects involving Māori. The cases include:-

- a process which was used to determine an acceptable water level for Lake Rotoiti;

- to identify and overcome key issues in the House of Tahu commercial development in Christchurch; and

- to assemble the perspectives among professional engineers of the effectiveness of different wastewater management systems.

The use of the Mauri Model provided an inclusive way to fairly account for each person’s perspective and provided an effective way to evaluate different solutions in a holistic manner. In each case, the use of the Mauri Model resulted in the identification of a solution which represented a fair compromise between the desires of all parties. Due to the transparent process of the Mauri Model DMF, a common outcome of using the method was a greater appreciation in participants of what was important to other parties and on a number of occasions, a realisation of how intrinsically unsustainable some status quo solutions and incremental improvements were (Morgan 2008). In 2004 the Mauri Model was used during the meetings of the SmartGrowth urban planning project for the Bay of Plenty. The use of the Mauri Model decision making framework evaluated an alternative waterless wastewater system alongside other more conventional solutions and showed that the alternative waterless system was the most sustainable option.
3.6.1.1. Process

The Mauri Model survey used in this doctoral research consisted of three parts:-

1. A pair-wise comparison of the four dimensions (Environment, Cultural, Social and Economic) to quantify worldviews,

2. An assessment of 12 performance indicators (three for each dimension),

3. A combination of the quantified worldviews and the raw performance assessments to provide a sensitivity assessment of the results.

A simplified variant of the Analytic Hierarchy Process (AHP) developed by Morgan (2008) was used to determine the biases of survey participants toward each of the four dimensions. The pair-wise comparisons were assigned a score between 3 and -3 for each pair, representing the relative importance between two dimensions. A score of 0 represented equal importance. Normally in AHP the reciprocal value is assigned to the corresponding pair however in the variant used, the negative equivalent whole number was used instead of the reciprocal value as shown in Table 6. This change was made to help survey participants significantly to fill out the pair wise comparisons correctly, kept the weighting methodology understandable to all participants, and allowed results to be checked easily by hand as fractional values were avoided.

An example is shown in Table 6 of one user’s survey response for the pair-wise comparison of the four dimensions. The participant considered the environmental dimension was more important than the economic dimension and assigned a score of 2 in the environmental row and economic column. Correspondingly the economic dimension was assigned a score of -2. These dimension comparisons were done for all dimension pairs. After the pair-wise comparisons were scored, the scores along the rows for each dimension were added up and a value of nine was added. The addition of nine was to eliminate potential negative sums and moved the potential range of total scores from between -9 and 9 to between 0 and 18. These totals were compared to determine the percentage weightings for each of the four dimensions.
Table 6 Example of a Pair-wise Comparison Survey Response using the Mauri Model

<table>
<thead>
<tr>
<th></th>
<th>Environmental</th>
<th>Cultural</th>
<th>Social</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>-</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cultural</td>
<td>0</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Social</td>
<td>-1</td>
<td>-1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Economic</td>
<td>-2</td>
<td>-2</td>
<td>-1</td>
<td>-</td>
</tr>
</tbody>
</table>


In the second part of the survey, performance indicators for each of the dimensions were assessed using the mauriometer shown below in Figure 5. The range of scores can range between ‘+2’ for mauri tū / ora (sustainable, fully restored) and ‘–2’ for mauri noho / mate (unsustainable, denigrated). Performance indicators are usually agreed upon by participants or stakeholders however in the housing survey they were pre-selected by the researcher.

![Figure 5 The Mauriometer (Morgan 2008)](image)

The 12 performance indicators used for the housing survey were:-

1. Environmental - Embodied Energy (whole life)
2. Environmental - Aesthetics and Acoustics
3. Environmental - Waste Generation / Recycling (during construction and disposal)
4. Cultural - Pride / Mana
5. Cultural - Self Sufficiency
6. Cultural - Kaitiakitanga (Guardianship of the Environment)
7. Social - Strengthens the Community (relationships and pride)
8. Social - Healthy Living Environment
9. Social - Fire / Insect / Decay Resistance
10. Economic - Affordability
11. Economic - Long-term Economic Performance
12. Economic - Availability of Local Builders and Resources

In the third part of the Mauri model process, a total score was determined for each housing method by applying the corresponding dimension weightings to each performance indicator score and determining the sum total of the weighted scores. Scores for each group were determined by averaging survey responses of individuals assigned to the group. Using the averaged survey responses and the dimension weightings, the performance indicator scores and final scores were determined for each housing method for each group.

3.6.1.2. Pilot Study

Before the final performance metrics had been chosen, a pilot study of the Mauri Model housing survey was conducted. For the initial survey, the 12 metrics below were chosen. The metrics were:

1. Embodied Energy
2. Aesthetics and Acoustics
3. Waste Generation / Recycling
4. Pride / Mana
5. Self Sufficiency
6. Kaitiakitanga (Guardianship of the Environment)
7. Suitable for Purpose (Housing)
8. Healthy Living Environment
10. Affordability
11. Long-term Economic Performance
12. Availability of Local Builders & Resources
Five key groups were identified for the survey and a person from each of the below groups was contacted to participate in the pilot study. Each of the participants gave their survey responses over the telephone.

1. Local earth builders / contractors
2. Environmentalist (Far North Environment Centre)
3. Rural Māori
4. Council (Far North District Council)
5. Government (Housing New Zealand Corporation)

In addition to filling out the survey, the pilot study participants were asked to comment on the suitability of the 12 metrics used, the suitability of the survey to record their views on house performance and any other pertinent thoughts.

The survey consisted of two parts. The first part recorded the relative importance of environmental, cultural, social and economic dimensions to the survey participant. Using statements like “Environment dimensions are Much More / More /Marginally More / Equal / Marginally Less / Less / Much Less important than Cultural dimensions” the relative importance of each participant was made clear and noted. In the second part of the survey, two housing types (rammed earth and light timber framed) were described to the participants. The participants were asked to rate the mauri of each of these housing solutions for all 12 metrics.

Based on data collected from the pilot study, the individual bias of participants from each group towards certain dimensions was determined and is shown in Table 7, the raw scores for the rammed earth and light timber framed housing methods are shown in Table 8 and Table 10 respectively, and the weighted scores for both housing methods are shown in Table 9 and Table 11.

<table>
<thead>
<tr>
<th>Table 7 Pair-wise Comparison Results of Each Survey Participant</th>
</tr>
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<tbody>
<tr>
<td>Earth Builder</td>
</tr>
<tr>
<td>Environmentalist FNEC</td>
</tr>
<tr>
<td>Rural Māori</td>
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<tr>
<td>Council FNDC</td>
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<tr>
<td>Government HNZC</td>
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The results obtained for the pilot study showed distinct differences between the perspectives of survey participants regarding the relative importance of the four dimensions in decision making and the performance of the two housing methods. The response from the
environmental group representative was the most biased and had the highest weighting for environmental factors and the lowest weighting for economic factors. The council representative filled out the survey to equally weight all four dimensions and so each received a weighting of 25%.

The five individuals surveyed had unique perspectives which were clearly shown in the results. The rammed earth house method was rated valued as sustainable (score greater than zero) in all survey responses whereas the light timber framed house method was rated sustainable by three (environmentalist, council and government representatives), and unsustainable by two (earth builder and rural Māori). The different perceptions for the light timber framed housing method and in particular the unsustainable perception given by rural Māori (-1.15) compared to the sustainable perception by council (0.92) were of particular interest. In a deeper analysis of where the discrepancy between the two responses was derived from, the data showed the council response perceiving light timber frame houses to have an overall sustainable and positive effect on the environmental and social dimensions whilst the rural Māori response perceived light timber framed houses to be environmentally unsustainable and detrimental to the social dimension. The application of weights to the raw results did not change the sustainability evaluation observations significantly but did increase and decrease the resulting sustainability scores derived from each response.

The pilot study showed that the different perspectives and biases of individuals could be adequately recorded using the Mauri model. The numerical analysis of the Mauri model was able to combine the housing evaluations of each group to provide a clear indication of perceived housing performance in the form of a numerical value.

As a result of feedback from the pilot study survey participants a few changes were made to the performance metrics in the survey and additional information was provided to survey participants regarding the two housing methods. The additional information took the form of a brief verbal description of each housing method accompanied by a photograph of a house built using each method. A copy of the survey form is appended in Appendix B.1.

The following changes were made to the performance indicators to provide clarity:-

- Embodied energy (defined as the manufacturing and transportation costs) was changed to a metric measuring whole life energy cost.
- The Aesthetics and Acoustics metric was split into two separate metrics
• A metric measuring the potential for owner input into the design process was added
• Waste Generation / Recycling was defined to be during the periods of construction and disposal only
• Suitable for purpose (Housing) and Healthy Living Environment were combined into one metric

A change was made to the groups surveyed. The earth builder group was not surveyed in the main survey because it was decided that they would have too much of a bias towards an earthen construction method. Members of Community Housing Aotearoa (CHA) were surveyed instead. CHA members were made up of housing professionals and community housing advocates that sought to improve the provision of affordable housing for local communities in New Zealand.

The pilot study showed that using mauri to evaluate the performance of housing was understandable and easy to use for all participants from the five groups approached. The use of mauri as a measure adequately captured the individual opinions of each individual. The results showed clear differences between individuals from each group.

3.6.1.3. Selection of Survey Participants

For the Mauri model housing survey, individuals were invited by their respective group leaders or employers to participate in the survey. Participation was voluntary and individuals were asked to provide their own opinions instead of the opinions of the group or organisation they were associated with. This was necessary to protect organisations (e.g. the Far North District Council and Housing New Zealand Corporation) which have a mandate to equally consider all four dimensions and because the publication of a housing method evaluation by these organisations could have a direct implication on their future housing initiatives. The request for individual opinions allowed employees of these organisations to participate and contribute their unique perspectives which were informed by their experiences and knowledge in different segments of the local housing provision process.

3.6.1.4. Data Collection and Recording

Surveys were conducted face-to-face whenever possible. This approach of collecting data was consistent with a Kaupapa Māori research approach and was required to incorporate a level of accountability to the research participants. Using locally held workshops and
meetings, individuals from the local council, environmental groups and the local area were surveyed. An online survey was made at the Survey Monkey website to collect the responses from individuals with whom organising a face-to-face meeting was not practical. Individuals from Housing New Zealand Corporation and Community Housing Aotearoa were surveyed online because they were located around the country and it was more convenient for them to submit their responses online. A description of the face-to-face and online survey process is provided below. The survey responses were categorised into groups with individual responses recorded anonymously.

**Face-to-face survey process**

1. A description of the survey and how the data would be used was explained to the participant
2. Participants were given the Participant Information Sheet to read (see Appendix B.2) and a consent form to sign (see Appendix B.3)
3. A survey form was then given out to the participants (see Appendix B.1)
4. The housing methods were described and instructions were given regarding how to complete the two parts of the survey
5. The completed surveys and signed consent forms were collected

**Online survey process**

1. Participants were sent an email explaining the housing survey and how the information would be used. A link was provided to the survey located on SurveyMonkey.com
2. The online survey had instructions on each page to guide users through the two survey sections. Their responses were stored in an online database upon submission

**3.6.1.5. Ethics and Research Approval**

Ethics approval was required to conduct the survey because the research involved human participants. Ethics approval was granted from the University of Auckland Human Participants Ethics Committee on November 12, 2009. A copy of the memorandum for Ethics Approval 2009 / 417, is appended in Appendix B.4.

Permission to survey Housing New Zealand Corporation staff required a research approval application to be submitted and granted. The research was approved on July 1, 2010 by the Research Access Committee chairperson to survey up to 10 Housing New Zealand Corporation staff.
3.6.1.6. Purpose, Limitations and Assumptions

The purpose of the survey was to establish the breadth of views regarding housing methods from stakeholders and end-users of rural Māori housing in Ahipara. The result was important because the standard of housing in the area was sub-standard and existing conventional housing methods were not accessible or appropriate for Māori living or wanting to live in the area. The results of the Mauri Model survey identified the strengths and weaknesses of each housing methods and provided some insight into how to make the housing methods more sustainable, accessible and appropriate for the people of Ahipara.

A limitation of the Mauri Model was that the survey data used qualitative measurements that cannot be verified. The results can not be confirmed through objective measurements and individual responses can contain strong biases based on personal experiences which are not representative of the norm. The effect of outlying responses is reduced as more responses are collected and used in the analysis.

As an inclusive framework, the acceptability and validity of the results are strengthened when individuals and groups with differing perspectives participate in the process. An advantage of the Mauri Model decision making framework is the tool’s ability to involve individuals and groups with different perspectives. The framework provides a way for all interested parties to have a role in the decision making process. For the inclusive decision making approach to work successfully, there is a requirement for those involved to recognise the value of holistic assessment and be open enough to proceed with the option with the highest mauri value or the option that represents the best compromise for all parties involved.

3.6.2. Structural Testing

For the material and seismic tests, the purpose of the tests was to establish the strength and seismic properties of Uku rammed earth, so that an Uku dwelling could be designed and built to NZ building standards.

From a seismic design perspective, the performance of a building in the following three groups of characteristics were important (IAEE 2004):

- The material properties – strength in compression, flexure and shear, material densities, and stiffness;
- Dynamic properties – natural frequencies, modes of vibration and damping; and
• Force-displacement characteristics – ductility, energy absorption and non-linear performance.

To test these properties, the use of traditional, established, structural test methods and analyses were used. The compression, flexure and shear tests, and the pseudo-static cyclic tests were conducted and analyzed using standard American and European test methods. Specific descriptions of the test methods used and test instrumentation have been provided in the chapters in which the results have been presented.

3.7. **Summary**

The purpose of the research was to improve the local housing situation in the rural community of Ahipara. The use of a kaupapa Māori research methodology was determined to be more appropriate for the housing research than a conventional research approach. Using this research paradigm, the research was conducted alongside Māori from the Ahipara whānau. In particular:

• Perspectives were gathered from groups involved in providing or who would be influenced by rural Māori housing decisions in Ahipara using the Mauri Model decision making framework;

• Conventional structural and seismic test methods were used to test the strength and seismic properties of Uku rammed earth wall panels;

• An Uku rammed earth house was designed and built by the Ahipara whānau on rural Māori land in Ahipara.
Chapter 4. MAURI MODEL SURVEY OF HOUSING METHODS

\textit{Mā whero, mā pango, ka őti ai te mahi}

\textit{With red and black the work will be complete}

\textit{This saying refers to co-operation between the chiefs (whero) and the workers (pango). If everyone does their part, the work will be done}

The outcomes of using the Mauri Model decision making framework for the decision making process of a community driven rural Māori housing project are presented in this chapter. The project was completed successfully with the construction of an Uku rammed earth dwelling by the Ahipara whanau in 2011. The Mauri Model (MM) decision making framework was described in the previous Chapter in Section 3.6.1.

4.1. Housing Methods Considered in the MM Survey

Two housing methods were identified to have potential as a practical housing method for implementation in rural Māori communities. The two solutions were:-

- Light timber-framed housing
- Uku - Flax-fibre reinforced rammed earth housing

4.1.1. Light Timber-framed Housing

In 2001, 95% of single unit dwellings in NZ were built using the light timber-framed method (Banks 2001). Light timber-framed construction remains the most common housing method in NZ, for single unit dwellings, due to NZ’s abundant timber resources, the familiarity of the building industry with the building method, and the availability of design tools, charts and building standards such as NZS 3604:2011 Timber-framed Buildings (Standards NZ 2011).

4.1.2. The Uku Housing Initiative

In 1996 the Uku housing research project was formed to investigate and develop an earth based housing method that would provide an accessible and appropriate housing method for implementation in Māori communities. The housing research was largely progressed by Māori and in consultation with representatives from a number of Māori tribes. The project was unique from other housing initiatives in that the research was conceived, conducted and controlled by Māori.
In 2004, two Uku dwellings (6 metres X 6 metres) were built in Māori communities to determine the social acceptability of the building concept (Morgan 2005). The Uku dwellings were well received by both communities. After confirming the positive social and cultural regard of Māori for Uku dwellings, the research proceeded with the construction of a two bedroom, 90 m² Uku house with another Māori whanau in Rotoiti. The Uku house was completed in 2009.

The Uku housing method has drawn significant interest from the Māori community because of its potential to provide an affordable housing alternative to light timber framed construction through the use of local labour and natural materials. The housing method was also perceived by Māori to better meet the housing needs and aspirations of Māori which included the use of buildings with a design life of six generations (150 years), control over the house design to better cater for the unique dynamics of the Māori lifestyle (large families and gatherings, cultural practices), housing which was less reliant on external expertise, housing which promoted self-sufficient living, the opportunity to use unskilled labour from the local community, and a method that was not overly dependent on large expensive machinery (Morgan 2005).

4.2. Conducting the MM Survey

From November 2009 to November 2010 the perspectives of individuals from groups who had an interest in local Māori housing solutions were collected. A housing survey based on the MM decision making framework was developed and given to individuals from the following groups and organisations:

- The Far North District Council (FNDC). Survey participants were employees working in the Policy and Planning, and Building Consent departments;
- Environmental groups based in the Far North District of NZ;
- Māori (aged 18+) who resided in the Far North District of NZ;
- Community Housing Aotearoa (CHA) – A group consisting of not-for-profit organisations that advocate housing solutions for low and modest income earners in NZ (http://communityhousing.org.nz/); and
Housing New Zealand Corporation (HNZC) – A Crown agent that is principal advisor to the NZ Government on housing issues. HNZC provides housing services for people in need. Survey participants were generally in corporate and advisor positions.

Individual responses were grouped into their respective groups and organisations to reflect their different position in and experience of the rural Māori housing process. Each individual’s perspective represented a unique, valid and valuable contribution to the housing assessment; Māori who grew up in the local community would respond using their first hand experience of rural Māori housing and evaluate from that perspective, while council workers would have a better understanding of aspects like the legal and economic implications, and national building requirements.

The majority of the surveys were conducted in person. This method of communicating, ‘kanohi ki te kanohi’ (face-to-face) was particularly important to engage Māori in the decision making process. Meeting in person helped to ensure survey participants had a clear understanding of how to complete the MM survey and to build trust. Where meeting in person was not practical, an online version of the survey was used. Responses from the HNZC and CHA groups were collected using the online survey while the rest of the surveys were conducted in a face-to-face setting. A total of 36 survey responses were collected.

4.3. Results

The survey responses were put into an Excel spreadsheet and were used to determine the bias of each group, calculate the raw scores of each group for each performance indicator, and combine the scores and weights to give a final weighted score of mauri for each housing method by each group. The results are presented below. In order to differentiate the MM’s weighting algorithm, the same results were processed using the Multi-Attribute Utility Theory (MAUT) method (a.k.a. Grid analysis). MAUT is one of the simplest forms of a Multiple Criteria Decision Analysis tool and was developed by Stuart Pugh at the University of Strathclyde in Glasgow, Scotland in 1976.

4.3.1. Dimension Weights

Dimension weights, determined using the MM, are shown in Table 12. The dimension weights, determined using the MAUT method, are presented in Table 13.
The dimension weights shown in Table 12 and Table 13 were determined using the same set of data. The MAUT method was observed to always associate a weight of 0% to at least one dimension. In the MAUT method, if one dimension was rated consistently less important than all of the other dimensions, the dimension was associated with a weight of 0%.

4.3.2. Un-weighted Raw Mauri Scores

The un-weighted raw total mauri scores for each housing method are shown in Table 14. The values listed were the sum of average mauri scores given for all 12 performance indicators by each group.
### Table 14 Mauri Model – Un-weighted Raw Scores for the Two Housing Methods

<table>
<thead>
<tr>
<th>Housing Type</th>
<th>Group</th>
<th>Un-weighted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber-Framed</td>
<td>FNDC</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Environmentalists</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Rural Māori in Ahipara</td>
<td>-0.76</td>
</tr>
<tr>
<td></td>
<td>CHA</td>
<td>-0.51</td>
</tr>
<tr>
<td></td>
<td>HNZC</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td><strong>AVERAGE</strong></td>
<td><strong>-0.23</strong></td>
</tr>
<tr>
<td>Uku</td>
<td>FNDC</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Environmentalists</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>Rural Māori in Ahipara</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>CHA</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>HNZC</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td><strong>AVERAGE</strong></td>
<td><strong>0.98</strong></td>
</tr>
</tbody>
</table>

A score above zero indicated a perception of positive mauri or sustainability whereas a negative score indicated the housing method was perceived to be unsustainable. The Uku housing method was perceived as sustainable by all groups, albeit to different degrees, whilst the timber-framed method received conflicting scores for sustainability. The average of the un-weighted scores over all five groups for the timber-framed method was negative which indicated that the method had a stronger perception of being unsustainable rather than being sustainable across all groups surveyed.

### 4.3.3. Weighted Scores

The weighted scores for each dimension are shown in Table 15 for the light timber-framed method and Table 16 for the Uku method. The weighted scores of the 12 performance indicators are shown in Table 17.
<table>
<thead>
<tr>
<th>Group</th>
<th>Environmental</th>
<th>Cultural</th>
<th>Social</th>
<th>Economic</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNDC</td>
<td>0.02</td>
<td>0.00</td>
<td>0.14</td>
<td>0.11</td>
<td>0.27</td>
</tr>
<tr>
<td>Environmentalists</td>
<td>-0.19</td>
<td>0.04</td>
<td>0.03</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Rural Māori in Ahipara</td>
<td>-0.30</td>
<td>-0.13</td>
<td>-0.14</td>
<td>-0.19</td>
<td>-0.76</td>
</tr>
<tr>
<td>CHA</td>
<td>-0.27</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.11</td>
<td>-0.50</td>
</tr>
<tr>
<td>HNZC</td>
<td>-0.17</td>
<td>-0.10</td>
<td>0.00</td>
<td>0.04</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>Environmental</th>
<th>Cultural</th>
<th>Social</th>
<th>Economic</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNDC</td>
<td>0.25</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.45</td>
</tr>
<tr>
<td>Environmentalists</td>
<td>0.50</td>
<td>0.44</td>
<td>0.24</td>
<td>0.24</td>
<td>1.42</td>
</tr>
<tr>
<td>Rural Māori in Ahipara</td>
<td>0.45</td>
<td>0.53</td>
<td>0.27</td>
<td>0.35</td>
<td>1.60</td>
</tr>
<tr>
<td>CHA</td>
<td>0.18</td>
<td>0.19</td>
<td>0.19</td>
<td>0.07</td>
<td>0.63</td>
</tr>
<tr>
<td>HNZC</td>
<td>0.31</td>
<td>0.13</td>
<td>0.23</td>
<td>0.07</td>
<td>0.75</td>
</tr>
</tbody>
</table>
### Table 17 Mauri Model – Weighted Scores of each Performance Indicator

<table>
<thead>
<tr>
<th>Performance indicators</th>
<th>Light timber-framed method</th>
<th>Uku method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FNDC</td>
<td>Env Group</td>
</tr>
<tr>
<td>ENV1 Embodied energy</td>
<td>0.00</td>
<td>-0.13</td>
</tr>
<tr>
<td>ENV2 Aesthetics and acoustics</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>ENV3 Waste generation / Recycling</td>
<td>-0.02</td>
<td>-0.13</td>
</tr>
<tr>
<td>CUL1 Pride / Mana</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>CUL2 Self-sufficiency</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>CUL3 Kaitiakitanga (guardianship of the environment)</td>
<td>-0.05</td>
<td>-0.04</td>
</tr>
<tr>
<td>SOC1 Strengthens the community</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>SOC2 Healthy living environment</td>
<td>0.06</td>
<td>-0.03</td>
</tr>
<tr>
<td>SOC3 Fire / Insect / Decay resistance</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>ECON1 Affordability</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>ECON2 Long-term economic performance</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>ECON3 Availability of local builders &amp; resources</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.27</strong></td>
<td><strong>0.01</strong></td>
</tr>
</tbody>
</table>

The score of 0.45 (shown in Table 16) by the Rural Māori in Ahipara group for the environmental mauri of an Uku house was the sum of the scores given by the individuals in that group regarding the three environmental performance indicators which are listed in Table 17. These were embodied energy (0.17), aesthetics and acoustics (0.12), and waste generation / recycling (0.16).

### 4.4. Discussion

#### 4.4.1. Impact of Individual Bias on Dimension Weights and Data Sensitivity

The pair-wise comparison of the four dimensions provided a mechanism for survey participants to influence weightings and acknowledge their own biases in the decision making...
process. The extent or degree to which the biases could preference one dimension over another was determined by the algorithms of the method.

Compared to the MAUT method the dimension weights, determined using the MM method, were shown to be conservative and fair. For the four dimensions (environmental, cultural, social and economic) the MM method produced weight ranges of 22-38%, 16-29%, 18-28% and 14-32% respectively (see Table 12) while the MAUT method produced ranges of 27-69%, 0-44%, 0-32% and 0-62% respectively (see Table 13). Dimension weight ranges averaged 14% for the MM and 45% for the MAUT method. The MM dimension weight ranges were on average 69% smaller than the MAUT method.

When using the MAUT method 0% weights were regularly assigned whereas it is much less likely to occur when using the MM. The lowest weight determined when using the MM in the housing survey for a dimension was 14%. The possibility of eliminating a dimension from the analysis was not perceived to be ideal in an inclusive decision making situation as the result would completely negate the scores given to indicators in that dimension. The result would have been divisive and would have been disrespectful to others who perceived that dimension to be an important consideration in assessing the sustainability of a rural Māori housing method.

The MM had a more conservative approach when calculating the dimension weightings and thus produced a fairer result. While the decision making framework enabled individual bias to influence the decision making process, the framework did not enable individual bias to overly favour a dimension or to disregard a dimension completely. By comparing the un-weighted raw total scores for each housing method (shown in Table 14) with the weighted total scores (in Table 15 and Table 16), it can be seen that the overall impact of individual bias on the overall maori score was minor. The largest effect of bias on the overall maori score for a housing method was a decrease of 0.12 on the mauriometer scale. The decrease was a result of the environmentalist group’s strong bias towards the environmental dimension which magnified the low scores given for the environmental performance indicators in the assessment of the timber framed method.

Because the modified dimension weights of the MM were restricted to a narrower range around the default weightings of 25% for each dimension, the survey results were more robust, than if the MAUT method was used, and data sensitivity was decreased. If a group or
individual response was added or removed from the original data set, the impact on the final results would be less than if a decision making framework like MAUT had been used.

4.4.2. Ranking the Options and Quantifying Their Sustainability

The MM was able to be used to rank the housing options by quantifying the sustainability of each performance indicator and determine a total mauri score for each housing option. In addition to providing a result which could be compared, using an assessment of mauri to evaluate the performance indicators provided a way to evaluate sustainability that both Māori and non-Māori participants could understand and use. Alternative methods evaluating the financial cost equivalent regarding the sustainability of an option or to evaluate the sustainability of an option relative to status quo or best practice would not be as meaningful or accessible to all of the survey participants. A positive mauri score correlated with a perceived sustainable performance and vice versa. The use of an intrinsic measure of sustainability also enabled a minimum level of sustainability to be set for decision making purposes and made possible a scenario where, if all options were unsustainable, that none of the options evaluated would be selected. Adopting a minimum score of +1 (mauri piki or an enhancing level of sustainability) at the beginning of a project would favour solutions that performed well in all dimensions. If a minimum mauri score of +1 was required, the housing method chosen would not just have to be better than the other options, it would have to receive a mauri score, across all four dimensions, which showed the option was sustainable. If a goal of a project is to produce a sustainable result and the best solution fails to meet the required level of sustainability, it is essential to have a result in which the project is guided to refine the original solutions or consider new ones, and to progress only when a suitably sustainable solution had been identified.

4.4.3. Strengths and Weaknesses Identified

The survey showed clearly the perceived strengths and weaknesses of each housing method with respect to sustainability. In Table 17, the performance indicator scores of each housing method are shown. These results were useful to help understand which performance indicators and dimensions contributed to or detracted from the final mauri score the most. The cultural dimensions of the Uku housing method were seen to be the largest contributor to the total mauri score whereas the environmental issues associated with the light timber framed housing method were shown to be the most detrimental dimension towards its total mauri score. From these results it was clear that the greatest sustainability improvements for
the light timber framed housing method could be achieved if the environmental concerns of the method were addressed; particularly the embodied energy and waste generation issues.

4.4.4. The Advantage of an Inclusive, Collective assessment in Evaluating Sustainability

An issue that arose when considering broad, holistic and non-technical concepts in the decision making process was that of assessment. How could the normative or intangible performance indicators for these dimensions be adequately assessed? The use of collective assessment in the community housing project was considered to be a fair and representative way to assess the sustainability of the housing methods, even more so than a detailed assessment from a professional. The assertion was made because collective assessment contained the perspectives of a diverse range of individuals, each whom possessed specialised knowledge with regard to the many different aspects of sustainability. An assessment from a professional was not likely to possess the expertise to appropriately evaluate a solution from all perspectives. An example from the housing survey was the performance indicator of kaitiakitanga (guardianship) for the cultural dimension. The best knowledge base from which to assess this performance indicator was from a person who was familiar with Māori values. Environmental groups similarly were in the best position to comment on the environmental dimensions, and local councils were likely to retain the best knowledge base and expertise with which to assess the wider economic impacts and implications of the housing methods. No individual or single group possessed all the pertinent knowledge needed to evaluate the housing solutions holistically. The assessment used for the MM housing survey incorporated knowledge from a larger collective knowledge base and thus was able to carry out a broad, holistic assessment in a fair and more representative way.

4.4.5. A Collaborative Process That Encouraged Participation and Co-operation

The MM was an inclusive method which was used to gather the perspectives of individuals with a diverse range of housing knowledge and experiences. Using the MM to determine the dimension weights and evaluate the sustainability of the housing methods, provided survey participants the opportunity to all participate and contribute to the decision making process. Any individual that wanted to participate in the survey could participate.

The transparency and simplicity of the MM data calculations also contributed to the acceptance of the survey by survey participants. The FNDC, HNZC and local Māori were initially hesitant to participate in the survey until they understood the mechanics of the Mauri
model, the purpose of the research, and the possible implications, before they approved the survey to be conducted with their staff and members. Due to the use of simple mathematical data manipulation in the MM, participants could determine or check the dimension weights and the mauri scores associated with their survey responses for each housing method on the spot, without the need for a calculator.

Through the use of the MM, individuals were able to present their perspectives on housing and have the responses incorporated into the decision making process in a fair and dignified way. Each perspective meaningfully contributed to the final solution in a transparent manner which could be easily checked by survey participants. Performance indicators, such as the environmental impact of a housing method’s aesthetics and acoustic properties, would be complicated to assess from a technical perspective but were able to be simply and meaningfully assessed by all survey participants using the concept of mauri. The use of mauri to measure the performance indicators was effective and well received by both Māori and non-Māori survey participants.

4.4.6. Practical to Conduct Early in a Project

The MM housing survey was simple enough to be conducted and analyzed at the early stages of the community housing project. Availability of the data early in the project was valuable because the most effective time to make changes or adjustments to the project was before any commitments had been made or work done. The MM survey provided an effective way to gather the housing knowledge available in the local community, and in people who worked in the housing field, and to use it to determine the sustainability of both housing methods across the four dimensions. The minimal time and resource requirements of the MM data collection process enabled the two housing alternatives to be assessed and to provide direction for the housing project direction before any major decisions and commitments had to be made. The MM method also enables all potential options to be assessed. Although the housing survey was used to evaluate two housing methods, it would have been possible to include more housing methods into the survey.

The MM housing survey was carried out without needing the survey participants to gather data or to possess any technical knowledge, or otherwise prepare beforehand. The performance indicators were evaluated intuitively using the concept of mauri while those who possessed specific knowledge relevant to any indicator could use that to inform their assessment.
The resource requirements to carry out the Mauri Model survey were minimal. The surveys that were carried out in person took approximately 10 minutes for participants to complete. For those that were not able to meet in person, an online version of the survey was made available to record their responses. The majority of the work required to conduct the surveys was in organising times and places to meet with individuals to complete the survey, and to obtain permission from organisations to conduct the survey with their members.

4.4.7. The Value of Gathering Individual Perspectives

For the MM housing survey, gathering the perspective of individuals who were from an organisation was easier than obtaining formal responses from organisations. From an early stage in the survey process it became apparent that it would be difficult to obtain survey responses from organisations involved in housing regarding the housing methods because their response could be interpreted as the organisations official stance regarding the housing method. The individual and personal perspectives of staff from these organisations however were able to provide a perspective that was valuable, because their survey responses would be different to that of local Māori and environmental groups. The different perspective was seen in the biases towards the four dimensions, and was assumed to be due to the different knowledge and experiences they had regarding the sustainability of implementing the two housing methods in rural Māori communities.

Morgan (2011) suggested that a balance between rigour and practicality was required in assessment processes in order to allow effective participation in the decision making process. He suggested that a reasoned judgement by a professional may be just as useful as the best predictive method or model. In the MM, each individual surveyed was treated equally and as a housing professional in their own right. For members of housing advocacy groups and government staff this was easily accepted but it was important that the local individuals, particularly local Māori who often did not have this status in decision making. The Māori surveyed were the recipients of the housing solutions and best understood the needs, issues and obstacles of Māori because they were the individuals who lived in the dwellings and who lived in the rural communities. The eagerness with which many Māori in the local community participated in the MM housing survey showed that there was a strong desire to be involved in the housing process and to address local housing issues. The MM housing survey concurred with a similar result to that observed in the reviewed literature of other community based sustainable development projects presented in Section 2.2.1; that
individuals in the local community were capable and willing to contribute towards sustainable development decisions in their local area if given the opportunity and adequate support.

The perspectives of individuals collected for the MM decision making framework provided a clear indication of the preferred housing method to develop. The Uku housing method was perceived to have a positive mauri and to be sustainable by all groups. The Uku method was unanimously preferred over the light timber-framed method as seen in Table 15 and Table 16. The positive mauri score given to the Uku method by all groups provided the Ahipara whanau the direction and confidence to progress with the implementation of the Uku housing method, knowing there was strong agreement, from a wide range of people and organisations involved in the rural Māori housing sector, regarding the sustainability of the Uku housing method.

4.4.8. Limitations of the MM

The MM decision making framework was used successfully in the housing project and provided valuable insight into the strengths and weaknesses of both housing methods. However some limitations of the MM were also observed.

The MM was a decision making framework that provided a holistic method to measure sustainability and to influence project decisions. The framework achieved this by combining the perspectives of a broad range of local individuals and stakeholders involved with local Māori housing solutions in Ahipara. The approach of the MM meant that the survey responses collected were not necessarily provided from a position of technical expertise. Personal and technical measurements of sustainability both provide useful information towards determining the sustainability of an option however some individuals or organisations involved in the decision making process may require the use of objective measures or question the credibility of approaches they are not familiar with.

In the community driven housing project, the MM decision making framework was sufficient on its own to guide the decision making process because of the nature of the project. For the construction of a single dwelling in the rural area, there was no legal requirement to undertake a specific consultation process with other individuals and stakeholders in the local community. The MM assessment was surplus to requirements from a legal perspective. For large projects that would normally require impact assessments to be carried out, the MM
should be used in conjunction with other methods rather than in place of them. The use of the MM provides valuable information regarding the sustainability of potential options but technical assessments of life-cycle impacts or cost-benefit analyses provide valuable information for decision making as well. Depending on the values of the decision makers, the data gathering approach of the MM assessment based on gathering individual perspectives may not be considered sufficient on its own or credible enough to be used for large projects. As noted by Selman (1998), the support of local authorities for alternative processes is vital if they are to be successfully implemented.

The Mauri Model limits the extent to which dimension weights can be influenced. Other decision making framework like MAUT have a much greater scope to influence the weights of one or two key dimensions. Although the trend in decision making has been towards broader and holistic assessment and consideration of the four dimensions, an equal consideration of the all dimensions may not always be preferred. Some projects do not aspire to be holistically sustainable but rather have a more specific purpose, such as for financial gain or the protection of an endangered species. Littig and Grießler (2005) noted that even with the acceptance and use of the ‘three pillar model’ where social economic and environmental goals were supposed to be equally considered, in practice positive social outcomes took a back seat to those of economic and environmental. The limited extent of the MM to influence the dimension weights may then be undesirable or perceived as unnecessarily restrictive by some. In this respect the MM was perceived to be particularly suited for situations where a holistically sustainable outcome was desired or where a compromise needed to be reached between groups with different perspectives, whilst not alienating any group in the process.

Consideration of the cultural considerations as a dimension of sustainable development has been a recent inclusion to decision making processes. Like the social dimension, cultural considerations will require time and experimentation to be effectively included in decision making processes. More so in this dimension than the others, the cultural dimension was identified to provide a space for beliefs, traditions and metaphysical concepts to be valued and included in decision making. Mana (pride and identity) and kaitiakitanga (guardianship over the environment) were examples of metrics used in the community driven housing project that attempted to measure the cultural aspects of sustainability. These concepts will likely be difficult to bring into mainstream decision processes in NZ, yet they represent an
important aspect of sustainable development that would improve the sustainability of
decisions made and are important sustainability considerations for Māori in particular.

4.5. Conclusions

For the community housing project conducted in Ahipara, the MM decision making
framework was used to gather the perspectives of individuals from groups with an interest in
rural Māori housing solutions in the Far North District of NZ. The survey responses were
used to evaluate the performance and sustainability of the light timber framed, and Uku
rammed earth, housing methods.

The MM decision making framework used the concept of ‘mauri’ to evaluate the housing
performance indicators. Use of the MM decision making framework and ‘mauri’ were well
received and able to be effectively used by both locals in the community and employees of
government agencies to evaluate the sustainability of the two housing methods. The MM was
used to record the perspectives of individuals with diverse perspectives on rural Māori
housing solutions in the four dimensions (environmental, cultural, social and economic) in a
way that was inclusive, transparent and fair.

The main weakness noted of the MM assessment was that the analysis and conclusions relied
on the perspectives of individuals which may not be accepted by some individuals or
organisation due to perception of credibility. The use of individual responses enabled housing
evaluations to be conducted with minimal resources and in a time efficient manner, and was
considered to be a meaningful and effective way to assess both tangible and intangible
metrics.

A key assumption of the MM was that the collective housing perspectives of local individuals
and individuals from housing organisations would produce an accurate and valid basis upon
which decisions could be made. For the community housing project in Ahipara, the results of
the MM provided clear guidance to proceed with the Uku method, and showed the method to
be perceived as sustainable by all groups. The successful application of the MM in this case
is also attributed to the strong support and participation received by the housing project from
local individuals and housing organisations.
Chapter 5. LITERATURE REVIEW OF FIBRE-REINFORCED SOILS

The structural and seismic research described from Chapter 5 to Chapter 9 fits into a larger research project to develop a flax-fibre reinforced rammed earth housing solution. A detailed literature review into fibre reinforced earth research has not been done, especially in the use of compacted earth as a structural wall material.

The research literature reviewed in this chapter provides the basis upon which the structural tests were conducted and provides an understanding of the mechanisms within fibre reinforced and cement stabilised earth to explain the failure mechanisms and strengths observed in later chapters.

5.1. The Benefits of Reinforcing Soil with Fibres

Fibre reinforcement of soil improves the strength properties and structural performance of the composite in a number of ways. In the research literature, fibre reinforcement of soil has resulted in increased tensile and compressive strength, soil cohesion, soil friction, ductility, energy absorption capacity and post-peak strengths of soil (Vidal 1966; Saxena and Lastrico 1978; Clough et al. 1981; Gray and Ohashi 1983; Consoli et al. 2002; Shukla et al. 2009). The beneficial effects resulting from reinforcing soil with fibre can also be observed in structures built by many past civilisations and in the natural world. Māori used flax-fibres to reinforce pā maioro (earth ramparts) that could withstand cannon fire (Belich 1988) and the use of fibre reinforced soil in the construction of earthen buildings is well known. The Bible records the Egyptians using straw in the production of unbaked mud bricks in the 15th century B.C. (Exodus 5:6-18). In the natural world, fibre-reinforcement of soil can be seen around the roots of plants and trees.

The main purpose of adding fibre reinforcement into soil is to resist applied tensile stresses and restrict soil deformation (Hejazi et al. 2012). The first modern scientific attempt to understand and develop fibre reinforced soil solutions is accredited to Vidal (1966) who examined the effect of inserting continuous oriented reinforcement into soil. The research conducted in soil reinforcement initially examined the effects of geo-synthetic material and galvanized steel rods and sheets. Research using fibre reinforced soil began in the 1980’s (Gray and Ohashi 1983).
There are two different methods of reinforcing soil with fibres. The first method features continuous oriented fibres in soil. Soil reinforced this was is known as systematically reinforced soil (Shukla et al. 2009) or reinforced earth (Vidal 1966). The second method features randomly distributed, discrete fibre reinforcement in soil (Hoare 1979; Gray and Ohashi 1983; Freitag 1986; Gray and Al-Refaei 1986). Advantages of using randomly distributed, discrete fibre reinforcement was that it permitted the use of fibre inclusions as an admixture during the process of mixing soil. The resulting soil composite had strength isotropy and the potential of planes of weakness developing parallel to the reinforcement was reduced (Yetimoglu and Salbas 2003; Shukla et al. 2009). If a local source of natural fibres was suitable and accessible, additional environmental and economic benefits could be realised as well.

5.2. Mohr-Coulomb Failure Envelope for Fibre-Reinforced Cohesionless Soils

![Mohr-Coulomb Failure Criterion for Fibre-reinforced Cohesionless Soils](Shukla et al. 2009)

A bi-linear failure envelope for a fibre reinforced cohesionless soil was developed for fibre reinforced soil (Shukla et al. 2009) and is shown in Figure 6. The model assumed a Mohr-Coulomb failure criterion. Consoli, Montardo et al. (2002) found that past research into the shear strength of unstabilised as well as cemented stabilised soils were adequately represented by assuming a Mohr-Coulomb failure criterion (shown below)

\[ \tau = \sigma \tan(\phi) + c' \]  

(1)

Where \( \tau \) = shear strength, \( \sigma \) = normal stress, \( \phi \) = angle of internal friction, \( c' \) = apparent cohesion.
The failure stress state of an unreinforced cohesionless soil in a triaxial test was represented by the Mohr’s circle marked (a) in Figure 6 with the stress state of a reinforced cohesionless soil in the Mohr’s circle marked (b). The effect of adding reinforcing fibres was represented as an increase in the confining stress ($\sigma_R$) on the cylinder compared to the unreinforced cylinder ($\sigma_3$). The reason for the increase in effective confining stress as a result of fibre reinforcement was due to the restricting effect of the fibres on the lateral deformation of the cylinder as vertical stresses were applied on the cylinder. Including fibre reinforcement in the soil and increasing the confining pressure on the cylinder had a similar effect of reducing lateral stresses and deformation. At the failure stress of the unreinforced cohesionless soil cylinder (a), a fibre reinforced cohesionless soil would not fail because the reinforced soil specimen had a lower shear stress as a result of the increased confining pressure derived from the reinforcing fibres.

5.2.1. Apparent Cohesion of Fibre Reinforced Soils

Experiments by Schlosser & Long (1974) showed that fibre reinforced cohesionless soils had an apparent cohesion ($c'$) similar to a cohesive soil. The Mohr’s circles (c) and (f) in Figure 6 represented the failure stress states of two fibre reinforced soil specimens. The improvement in the shear strength resulting from the fibre-reinforcement of the cohesionless soil was equivalent to the soil having an effective cohesion ($C_R$) value. No change to the gradient of the failure envelope of the fibre reinforced soils was observed. The orientation of fibre reinforced in soil had no effect on the coefficient of internal friction ($\phi$) (Gray and Ohashi 1983). Changes however in the surface, shape or roughness of fibre reinforcement was found to change the coefficient of internal friction of the composite (Ola 1989). The magnitude of the apparent cohesion ($c'$) that resulted from the addition of reinforcing fibres into the soil was found to be proportional to the orientation of the reinforcement to the direction of maximum strain or tension in the soil (Schlosser and Long 1974; McGown et al. 1978; Gray and Al-Refeai 1986; Ola 1989).

5.2.2. The Influence of the Orientation of Fibre Reinforcement on Shear Strength

The orientation of fibres in relation to the principle stress axis of tension in the soil determines the effectiveness of fibre reinforcement. Reinforcing fibres were shown to improve composite strength when oriented across regions of dilation (or tension) in sands but did not show any influence on strength when oriented across regions of compression.
(Michalowski and Čermák 2002). Depending on the orientation of the fibres relative to the
direction of principle tension in the soil, a proportion of the tension capacity of the fibre was
active to resist the dilative stress. Gray & Ohashi (1983) showed using a series of direct shear
test results that the shear performance of fibre reinforcement soil peaked at a fibre orientation
60° to the shear surface. This orientation was determined to be the direction of maximum
principal tensile strain in a direct shear test. Fibre reinforcement orientated at 90° to the shear
surface improved the shear strength characteristics of the soil but to a lesser extent than a
fibre orientation of 60°. Similar findings regarding the efficiency of improvement to shear
strength at the fibre reinforcement orientation angles of 60°, 90° and 120° to the shear surface
were observed by Ola (1989) who conducted shear box tests on lateritic soils.

The shear reinforcement of cohesionless soil using randomly oriented fibre reinforcement
was found to be equivalent to fibre reinforcement oriented at a 90° angle with respect to the
shear plane. Gray & Ohashi (1983) conducted shear box tests on a cohesionless soil
reinforced with randomly oriented fibres and fibres oriented 90° from the shear plane. They
found that the two fibre orientations had a similar performance in shear. Figure 7 shows the
shear strength characteristics of both reinforcing fibre orientations.

![Figure 7](image-url)

Figure 7 Shear Strength Characteristics of a Cohesionless Soil Reinforced with Randomly Orientated Fibres and Fibres Oriented 90 Degrees with respect to the Shear Plane (Gray and Ohashi 1983)
The correlation between the strengthening effect of random and oriented reinforcing fibres in soil enables the performance random fibres to be modelled through the adaption of existing models developed for orientated fibre reinforced soils. Due to the difficulty of modelling the effect of random fibre reinforced soil, a model did not exist. A number of models have been made for oriented fibre reinforced soils however such as the limit equilibrium of forces shear strength model developed by Gray & Ohashi (1983) which develops strength equations based on the idealized fibre-soil interaction shown in Figure 8.

![Figure 8](image-url)  
*Figure 8 Limit Equilibrium of Forces Fibre Reinforcement Model for Fibres Oriented Perpendicular to the Shear Surface (Gray and Ohashi 1983)*

### 5.2.3. Failure by Fibre Pull-out and Rupture

The two gradients that make up the bi-linear failure envelope (shown in Figure 6) represent the different soil-fibre interactions that occur when a soil specimen is subjected to a confining stress below a critical confining stress where specimens tend to fail by fibre pull-out, and above the critical confining stress, where the friction at the fibre-soil interface is sufficient to result in specimen failure by fibre rupture (Ranjan et al. 1994). The Mohr’s circles (e) and (g) in Figure 6 show the stress state of a reinforced cohesionless soil failing by the mechanism of fibre pull-out due to the specimens being subjected to a confining stress less than the critical confining stress.

Data gathered by Yang (1972) showed that the angle of internal friction ($\phi_i$) for fibre reinforced soil specimens that fail via fibre pull-out was larger than the angle of friction for fibre reinforced soil specimens that fail via fibre rupture. The friction angle of specimens that
failed via fibre pull out were influenced by the frictional forces generated between the fibre and soil while for specimens that failed via fibre rupture, the friction angle was more influenced by the tensile strength of the reinforcing fibre.

5.3. Extensible and Inextensible Fibre Reinforcement

The extensibility of reinforcing fibres influences extent of deformation that can occur in fibre reinforced soils before failure. Some of the earliest published research into soil reinforcement was conducted by Vidal (1966) and used relatively inextensible inclusions. These inclusions had a maximum tensile strain less than that of the soil and therefore resulted in composite failure by reinforcement rupture. Another group of researchers focused on reinforcing soil with relatively extensible soil reinforcement. Relatively extensible soil reinforcement was defined as reinforcement with a maximum tensile strain larger than that of the soil (McGown et al. 1978). Because the maximum tensile strain of the fibres is not reached, extensible reinforcement tends to fail by the mechanism of fibre pull-out. The key advantage of using extensible soil composites is a smaller loss of post peak composite strength and a more ductile composite failure mechanism compared to the use of relatively inextensible soil reinforcement (McGown et al. 1978).

The elastic modulus of ideally inextensible soil reinforcement is greater than 3000 times the elastic modulus of the soil (Gray and Ohashi 1983). Examples of inextensible reinforcing materials include metal strips and bars. Ideally extensible soil reinforcement has an elastic modulus less than 3000 times the elastic modulus of the soil. Examples include natural and synthetic fibres and geo-textiles. A generalised load-displacement plot of inextensible and extensible fibre reinforced in a cohesionless soil is shown in Figure 9.
5.4. Cement Stabilisation of Cohesionless Soils

Many soil stabilisation techniques that have been developed to improve the engineering properties of soils use cementing agents like lime and Portland cement. Cement stabilisation of soil improves material strength and durability. The formation of cement bonds between soil particles was found to increase the tensile strength, peak shear strength, soil stiffness and compressive strength (Clough et al. 1981). A disadvantage stabilising soil with cement however, was that it resulted in a composite that was more brittle. Cement bonds within soil were observed breaking at small strains and were completely broken at a strain of 1% for cemented sands (Wissa and Ladd 1964; Saxena and Lastrico 1978).

Cement stabilisation of soils is most effective above a cement content of 5%. The strength improvements observed in compression tests by Consoli et al. (2002) showed a greater strength increase per percent of cement added from specimens made with a cement content of 5% to 7% than a cement content of 3% to 5%. The higher effective strength gain at cement contents above 5% was because cement first binds to and reacts with the fines in the soil before bonding the soil particles together (Maher and Ho 1993). At cement contents less than 5%, there is not enough cement to bind the soil together. This explanation is also supported by the description of two types of soil-cement outlined by the Portland Cement Association (PCA 1979):-
• A cement-modified soil was a soil with less than 5% volume of cement and was described as a semi hardened mixture of soil where the cement added to the soil was enough to reduce soil plasticity, permeability and increase soil strength but was not enough to produce a coherent hard soil-cement. The stress-strain profile of cement-modified soil resembled that of unstabilised soil and an example is shown in Figure 11.

• Compacted soil-cement was a soil with a cement content of 5-14% and had an adequate amount of cement to both react with the soil particles and bind them together into a coherent hard soil-cement.

Cement stabilisation of sand has an insignificant effect on the friction angle of the composite. Clough et al. (1981) conducted 137 laboratory tests on, naturally-cemented sands found in the San Francisco area, uncemented sand, and artificially cemented sands (2% and 4% by weight) and found the cementation of sand, both artificial and natural, did not effect the friction angle of the sand. The same conclusion was reached by Consoli et al. (2002) who performed unconfined compression tests on 30 specimens with cement content between 3-7%. In experiments by Omine et al. (1996) however, the post failure frictional resistance of cement stabilised soils was observed to be significantly greater than unstabilised soils. The greater post failure frictional resistance was explained by the presence of larger soil particles formed by the cement bonds which remained after the soil had failed.

5.5. Cement Stabilized, Fibre Reinforced Soils

The simultaneous use of cement stabilisation and fibre reinforcement of soil improved the peak composite strength, post peak strength, and energy absorption properties of soil more than when either improvement method was used separately (Maher and Ho 1993; Omine et al. 1996; Consoli et al. 2002). When used separately, cement stabilisation of soil increased the compressive and shear strength of soil more than the fibre reinforcement of soil. The graph shown in Figure 10 by shows the strength contribution of cement stabilization and fibre reinforcement on unconfined compressive.
Figure 10 Effect of Fibre Content (FC) and Cement Content (CC) on Compressive Strength (Consoli et al. 2002)

From the literature reviewed, a table summarising the effect of cement stabilisation and fibre reinforcement effects was made and is shown in Table 18.

<table>
<thead>
<tr>
<th>Soil Characteristic</th>
<th>Cement stabilisation</th>
<th>Fibre reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Cohesion</td>
<td>++</td>
<td>0 to +</td>
</tr>
<tr>
<td>Internal friction</td>
<td>0 to +</td>
<td>+</td>
</tr>
<tr>
<td>Ductility</td>
<td>- -</td>
<td>+</td>
</tr>
<tr>
<td>Stiffness</td>
<td>++</td>
<td>0</td>
</tr>
<tr>
<td>Energy absorption</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Key: ‘++’ significant increase, ‘+’ increase, ‘0’ no effect, ‘-’ decrease, ‘- -’ significant decrease

5.6. Soil Ductility

Fibre reinforcement improves soil ductility. Ductility is defined as a measure of the ability of a structural system to deform beyond its elastic load-carrying capacity without collapse
(Williams 2004). One way used to indicate the ductility of a soil in the literature was by measuring brittleness using the brittleness index of a soil ($I_B$). The value is determined based on the ratio of the difference between the peak compression strength and the post-failure steady-state compressive strength to the steady-state compressive strength (Maher and Ho 1993). The brittleness index is defined by the equation

$$I_B = \frac{q_f}{q_{ult}} - 1$$

where $q_f = \text{compressive stress at failure}$, $q_{ult} = \text{steady-state compressive stress}$.

A high brittleness index indicates a brittle failure and a brittleness index close to or less than zero indicates a ductile failure.

The use of reinforcing fibres in cement stabilized soil decreases the brittleness index of the soil while the use of cement stabilisation increases the brittleness index of the soil. The stress-strain curve produced from a triaxial test of confined sand with and without reinforcing fibres shown in Figure 11. The sand with 7% cement reached a peak of 1200 kN/m$^2$ and had a residual strength of 380 kN/m$^2$ compared to a peak and residual strength of 200 kN/m$^2$ resulting from unstabilised sand. In this case, the brittleness index was 2.2 for the cement stabilised sand and zero for the unstabilised sand. Although the residual strength was higher for the cement stabilized sand than for the unstabilised sand, the cement stabilized sand was more brittle due to the decrease in strength after attaining peak strength.
The use of fibre reinforcement decreases the brittleness of a cement stabilised soil. Using the brittleness index Consoli et al. (2002) showed how the addition of fibre reinforcement to soil increased the post failure strength of the composite and resulted in a more ductile performance. The brittleness index of fibre reinforced and unreinforced sand specimens are shown in Figure 12. The graph showed that the brittleness index value was inversely proportional to fibre length.

5.7. Energy Absorption

The energy absorption capacity of soils were found to be improved by increasing cement content and fibre content (Consoli et al. 2002). The researchers calculated the area under the stress-strain curve for soil specimens with different cement contents, fibre lengths and applied confining pressures up to an axial strain of 10%. The results are plotted in Figure 13. The results showed that energy absorption was most improved when both cement stabilisation and fibre reinforcement were used together. Fibre reinforcement was not an effective way to increase energy absorption capacity when the soil had not been stabilised.
5.8. Issues Raised Regarding the Use of Natural Fibre Soil Reinforcement

Synthetic fibres have been researched and used more than natural fibres for soil reinforcement due to the inherent strength variability, reaction to moisture, and low durability of natural fibres. For engineering purposes, it is desirable that reinforcing fibres have performances which can be reproduced reliably and natural fibres are not as good as synthetic fibres in this respect. However, the cost and accessibility advantages of natural fibre soil reinforcement are an invaluable and practical resource for soil reinforcement in isolated and rural areas, and in developing nations.

5.8.1. Variability of the Physical Characteristics of Natural Fibres

The properties of natural fibres are highly variable. The properties of natural fibres vary depending on the position of the fibre in the plant, the age of the plant, the season or life stage of the plant (flowering, growth, death) at the point of harvesting, and the method used to extract the fibre (Ghavami et al. 1999; Rowell et al. 2000). Māori were known to harvested NZ flax at particular times of the year, to coincide with weather conditions and phase of plant growth, to obtain the best quality fibres. They also recognised that the method and care taken
in preparing the flax was important to ensure a high quality finished fibre was produced (Kanawa 2006).

5.8.2. Achieving a Homogeneous Mixture of Randomly Oriented Fibres

An issue raised by some researchers of fibre reinforce earths in the literature is the difficulty associated with mixing the reinforcing fibres into the soil matrix homogeneously. Fibre concentrations in the literature were typically were less than 1% of dry weight of soil and used lengths of less than 50 mm. Long fibre lengths were noted to easily tangle and mixing in the reinforcing fibres was described as a time consuming activity (Segetin et al. 2007; Hejazi et al. 2012).

Achieving a homogeneous mixture of fibres into large quantities of soil was an important consideration to ensure the soil mixture would be practical to use for the construction of full-sized rammed earth panels and a rammed earth dwelling. Two research projects examined methods of mixing large quantities of soil. Segetin et al. (2007) recommended a tumble mixing device after comparing a range of mixing methods, while Santoni & Webster (2001) demonstrated the successful use of a rotary hoe to mix large volumes of fibre and soil together for the construction of pavements suitable for aircraft and heavy traffic.

5.8.3. Fibre-soil Bond

One of the main purposes of fibre reinforcement of soil is to improve the tensile strength of the soil to resist the formation of shrinkage cracks and tensile forces. The bond of the fibre to the soil and friction forces resisting deformation between the fibre and soil are the mechanisms by which tensile strength is imparted to the soil composite. The strength of the fibre-soil bond was found to depend on soil cohesion, compression forces acting on the surface of the fibre, and the surface roughness of the fibre (Ghavami et al. 1999).

An issue identified by Ghavami et al. with the use of natural fibre reinforcement in soil was that the fibre dimensions varied with moisture content and temperature as shown in Figure 14. They observed when mixing natural fibres in wet soil, the fibres would absorb water and expand. The fibres also shrank in diameter as the soil composite dried, and left fine voids between the fibre and soil matrix, thus weakening the fibre-soil bond.
Segetin et al. (2007) coated NZ flax fibres with diluted enamel paint to reduce the water absorption characteristics of the natural fibre. Rammed earth beam specimens made with the treated fibres were tested in flexure and were found to have strengths that were lower than the specimens reinforced with uncoated NZ flax fibres. The researchers determined that the lower strengths were due to a lower content of fibres added to beam specimens made with coated fibres. A lower number of fibres were unintentionally added because the fibre contents were added by weight and the coated fibres weighed more than the uncoated fibres. The result was inconclusive.

5.8.4. Establishing the Durability of Fibre Reinforcement

The long-term durability of natural fibre reinforcement in rammed earth is not well known. Over time natural fibres will decay and little research has been done examining the durability of natural fibres in rammed earth walls. Coir fibres are reported to have an in-ground strength bearing life of 10 years and are considered to be one of the more durable natural fibres (Rowell et al. 2000; Hejazi et al. 2012). More research is required in this aspect of natural fibre soil reinforcement.

5.9. Natural Fibre Soil Reinforcement

Most regions in the world have a local and abundant source of natural fibres which can be used as soil reinforcement. The use of natural fibres, while often more variable than synthetic or manufactured reinforcement, has the advantage of being more accessible, affordable, and sustainable to use. Making use of locally available fibres can also promote self-sufficiency and support the development of local skills and industry. Four natural fibres, coir, sisal, barley straw and NZ flax, were identified as fibres suitable for soil reinforcement. The properties of the four natural fibres are detailed in Table 19. Some fibre property values
reported varied greatly between researchers. The variation observed was deduced to be a result of the inherent variability of natural fibres and of using different measuring methods. A summary of fibre content optimisation research for coir, sisal and barley straw is provided in Table 20.

Table 19 Properties of Natural Fibres Reported in Research Literature

<table>
<thead>
<tr>
<th>Researcher/s</th>
<th>Ultimate Tensile Fibre Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Fibre diameter (mm)</th>
<th>Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coir</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Chauhan et al. 2008)</td>
<td>100</td>
<td>2</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>(Hejazi et al. 2012)</td>
<td>250</td>
<td>4-5</td>
<td>0.01-0.02</td>
<td></td>
</tr>
<tr>
<td>(Ghavami et al. 1999)</td>
<td>150</td>
<td>3</td>
<td>0.13-0.56</td>
<td>26</td>
</tr>
<tr>
<td><strong>Sisal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Hejazi et al. 2012)</td>
<td>560</td>
<td>26-32</td>
<td>0.025-0.4</td>
<td></td>
</tr>
<tr>
<td>(Prabakar and Sridhar 2002)</td>
<td>286</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ghavami et al. 1999)</td>
<td>580</td>
<td>18</td>
<td>0.06-0.38</td>
<td>6</td>
</tr>
<tr>
<td><strong>Barley straw</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Bouhicha et al. 2005)</td>
<td></td>
<td></td>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td><strong>NZ flax</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Haab and Kingi 1998)</td>
<td></td>
<td></td>
<td>10-32</td>
<td></td>
</tr>
</tbody>
</table>

5.9.1. Coir

Coir fibres are extracted from the husk of a ripe coconut (*Cocos nucifera*). About 500,000 tonnes of coir are produced each year predominantly in India, Sri Lanka, Thailand, Vietnam, the Philippines and Indonesia. Coir fibres have been used to make ship ropes and fishing nets, due to the fibre’s high resistance to salt water, and for mats and sacking, due to a high abrasion resistance (FOA 2009). The unique characteristics of coir fibres include a high failure strain of 24% (Chauhan et al. 2008) and above average durability compared to other natural fibres due to a high lignin content (Rowell et al. 2000).

Chauhan et al. (2008) examined the effect of using coir reinforcement to improve the strength of subgrade soil to reduce the cost of building a road network. They tested fibres contents of 0.5%, 1.0%, 1.5% and 2% by weight of dry soil. Using unconfined compressive strength tests the researchers determined that the optimum fibre content was close to 0.75%. Ramesh, Krishna et al. (2010) researched a similar use of coir fibre reinforcement for ground improvement. Fibre reinforced soil specimens were made at fibre concentrations of 0.5%,
1%, 1.5%, 2%, 2.5% and 3% by weight of soil. The specimens were subjected to unconfined compression tests and a coir fibre content of 1% was found to be optimal for black cotton soil stabilized with 4% lime.

5.9.2. Sisal

Sisal fibres are extracted from the leaves of the sisal plant (*Agave sisalana*). Sisal is a plant native to Mexico but plantations producing sisal fibre are found in Brazil, Tanzania, Kenya, China, Cuba, Haiti, Madagascar and Mexico. Annual global production of sisal fibre is estimated to be 300,000 tonnes (FOA 2009). Sisal fibres are used for their strength properties and have been used to make load bearing ropes and floor mats (Giridhar et al. 1986). Sisal grows well in hot, dry climates which are often unsuitable for other crops.

Prabakar & Sridhar (2002) investigated the use of short sisal fibres to improve the strength properties of a silty clay. Sisal fibre contents of 0.25%, 0.5%, 0.75% and 1% by weight were used in their study. Unconfined compressive strength tests and undrained triaxial tests with confining pressures 69, 138 and 207 kPa were used to determine the cohesion and friction angle of the soil composite. Both the cohesion and friction angle peaked at a fibre content of 0.75%. Fibre lengths of 10, 15, 20 and 25 mm were used in the research and the results showed that fibre length had a significant effect on the friction angle of the soil composite. The optimal fibre length was found to be 20 mm.

5.9.3. Barley Straw

Straw is an agricultural by-product comprising of the dry stalks of cereal plants such as barley, rice, oats, wheat and rye. Straw is regularly used as animal feed and has many other uses. It is increasingly being used as an energy source for biomass power plants and bio-fuel production in recent times. Use of straw to reinforce earth bricks has been recorded since the time of the Egyptian Pharoahs in the Bible (Exodus 5:7-12) and it remains an important component in the manufacture of earth bricks and cob dwellings.

Bouhicha et al. (2005) researched the effect of barley straw reinforcement on earth blocks commonly used for house construction in Algeria. Four different soils found in Southern Algeria were reinforced with chopped barley straw in their research. Fibre concentrations of 0%, 1%, 1.5%, 2%, 2.5%, 3% and 3.5% were used in unconfined compressive strength tests and, from the compression test results of the four soils, a fibre concentration of 1.5% was shown to be optimal.
Table 20 Optimal Natural Fibre Concentrations Reported in the Research Literature

<table>
<thead>
<tr>
<th>Researcher/s</th>
<th>Optimal fibre content</th>
<th>Optimal fibre length</th>
<th>Soil</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coir (Chauhan et al. 2008)</td>
<td>0.75%</td>
<td>80 mm</td>
<td>Silty sand (70%) mixed with fly ash (30%)</td>
<td>UCS</td>
</tr>
<tr>
<td>(Ramesh et al. 2010)</td>
<td>1% by weight</td>
<td>Aspect ratio of 20</td>
<td>Black Cotton soil with 4% lime</td>
<td>UCS</td>
</tr>
<tr>
<td>Sisal (Prabakar and Sridhar 2002)</td>
<td>0.75%</td>
<td>20 mm</td>
<td>Silty soil</td>
<td>Undrained triaxial tests</td>
</tr>
<tr>
<td>Barley straw (Bouhicha et al. 2005)</td>
<td>1.5%</td>
<td>20-40 mm</td>
<td>4 soil types</td>
<td>UCS</td>
</tr>
</tbody>
</table>

KEY: UCS – Unconfined compressive strength test

5.10. NZ Flax (Harakeke)

NZ flax (*Phormium tenax*), known as harakeke, is a monocotyledon which belongs to the agave family. The NZ flax plant is not related to European flax but was named a flax because the fibres of the two plants were similar in appearance. NZ flax is a lily (Department of Conservation 2012). The plant thrives in the NZ environment and can be found growing in all parts of the country but grows best in swampy areas (Colenso 1891; Swarbrick 2009). NZ flax is indigenous to NZ and Norfolk Island (McLintock 1966).

5.10.1. Physical Properties of NZ Flax Fibre

Measuring the strength of NZ flax is difficult because the fibre has a non-uniform cross-section which varies along the length of the fibre. The cross-sectional shape of *Phormium tenax* also take a variety of irregular shapes with the two most common shapes being a horseshoe and a keyhole (de Rosa et al. 2010). Scanning electron microscopy performed on *Phormium tenax* fibres are shown below in Figure 15 and Figure 16.
In order to determine the tensile strength of *Phormium tenax* fibres, de Rosa et al. (2010) overcame the difficulties posed by the cross-sectional shape and variability along the length of the fibre by averaging the cross-sectional diameter at five random locations along each fibre using an optical microscope and calculated a mean fibre diameter assuming a circular cross-section. de Rosa et al. (ibid) tested 20 fibres at each fibre lengths 20, 30 and 40 mm. The tensile strengths were observed to decrease with increasing fibre diameter as well as with increasing length. The trend of lower strength in natural fibres with larger diameters was consistent with the low tensile strength observed in plants with large fibre such as stinging nettle, abaca and okra (Shibata et al. 2002; Bodros and Baley 2008; de Rosa et al. 2010). The decrease in tensile strength with increasing fibre length was also expected as natural fibres have flaws and longer lengths had a higher number of weak points at which tensile stresses would concentrate. The tensile strengths of *Phormium tenax* fibres measured by de Rosa et al. (2010) are shown in Table 21.
Table 21 Tensile Test Results on NZ Flax-fibres (de Rosa et al. 2010)

<table>
<thead>
<tr>
<th>Fibre length (mm)</th>
<th>No. of fibres tested</th>
<th>Tensile Strength (MPa)</th>
<th>Coefficient of Variance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>771</td>
<td>41.6</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>580</td>
<td>49.5</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>466</td>
<td>46.1</td>
</tr>
</tbody>
</table>

5.10.2. Cultural Significance of NZ Flax to Māori

NZ flax is a highly valued resource in Māori life and culture. It was common for Māori hapū (sub-tribe) to cultivate pā harakeke (plantations of NZ flax) of particular strains with desirable and superior qualities. Various parts of the plant were used for food and medicinal purposes, the leaves were used to make items like baskets and mats, and the fibres of the plant were used to make finer objects like clothing, deep sea fishing lines, footwear and rope (Colenso 1891; Swarbrick 2009). A 19th century missionary to New Zealand, William Colenso recorded the astonishment of Māori chiefs when they inquired about the vegetation of England and were told there was no harakeke there. He reports hearing on more than one occasion remarks like “How is it possible to live there without it?” and “I would not dwell in such a land as that” (Colenso 1891).

There are many Māori proverbs (whakataukī) which refer to the harakeke plant which show the plants value and significance to Māori. One is reproduced on the following page.
Ka whānau mai te pepi,
Ka takaia ki te harakeke.
Ka noho te harakeke, hei kakahu, hei rongoa,
Hei mea takaro,
Hei oranga mona a mate noa ia.

When a child is born,
He will be wrapped in the muka cloth made of flax.
The flax shall provide clothing, medicine,
toys for play and leisure,
and shall provide the means for living and survival health and wellbeing throughout his life’s journey.

5.10.3. Methods of NZ Flax Fibre Extraction

Before 1870 flax fibres were produced by Māori who would use a broken shell to scrape each leaf to extract the fibres (Colenso 1891). In the 1870’s, machines were developed to produce flax fibres faster and more reliably. Although the flax fibre produced by flax stripping machines were much coarser than hand stripped flax, one machine could produce 250 kg of fibre a day compared to 1 kg of fine hand stripped fibre per person (Jones 2003). Flax stripping technology continued to improve and a flax stripping machine designed in 1930 by E Sutton was able to strip 16 tonnes of flax leaves a day.

At present, there are no commercial manufacturers of flax fibre in NZ. Flax fibre was a principal export of NZ in the 19th century but the availability and accessibility of more cost-effective fibre sources, such as jute from India, and the development of the synthetic fibre industry, eventually led to the demise of the flax fibre industry. NZ’s last flax manufacturing mill closed in 1985 (Swarbrick 2009). The only operational flax machine remaining in NZ is located in the Foxton Flax Museum near Wellington.

Past Uku housing research project used flax leaves, harvested from a plantation in Rotorua, which were processed into fibres at the Foxton Flax Museum. A mobile flax stripper machine (Figure 17) was designed by Segetin, M. et al. in consultation with Māori flax weavers, and was built at the University of Auckland Engineering School in 2004.
The mobile flax stripper enabled flax leaves to be processing into fibres onsite and was used to manufacture the flax fibres used for this doctoral research. Flax leaves from a plantation in Ahipara were harvested and used for the construction of test specimens, test panels and the Uku dwelling in Ahipara. Customary Māori flax harvesting practices were followed which included, speaking karakia (prayers) before harvesting the plants, cutting the leaves at near vertical angle, and leaving the two inner sheathes unharmed. The extracted flax fibres were hung out to dry on a fence on rail as shown in Figure 18. The dried fibres were cut to the required lengths and stored in bulk bags until needed.
5.11. Review of NZ Flax-fibre Reinforced Rammed Earth Material Strength Tests

Six research projects were reviewed that tested material strength of NZ flax fibre and sisal fibre reinforced rammed earth. From the research projects, only the results of tests conducted on specimens with a fibre and cement content similar to the Uku mixtures used were reported in Table 22. Although several different variables were tested in each experimental program, cement content was found to be the most significant single variable to affect material strength and hence the results in Table 22 have been summarised according to cement content.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Compressive Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haab &amp; Kingi (1998)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(9% cement)</td>
<td></td>
<td>1.54 (16 beams)</td>
<td>&gt; 0.11 (1 panel)</td>
</tr>
<tr>
<td>(6% cement)</td>
<td></td>
<td>1.15 (2 panels)</td>
<td>&gt; 0.09 (1 panel)</td>
</tr>
<tr>
<td>Segetin et al (2005)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(8% cement)</td>
<td>1.56 (40 cubes)</td>
<td>0.30 (20 beams)</td>
<td></td>
</tr>
<tr>
<td>Walford (2005)</td>
<td>7.42 (128 cubes)</td>
<td>2.19 (16 beams)</td>
<td></td>
</tr>
<tr>
<td>Morgan &amp; Hoskins (2006)</td>
<td></td>
<td>2.8 (1 panel)</td>
<td>0.63 (3 panels)</td>
</tr>
<tr>
<td>Segetin et al (2007)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10% cement)</td>
<td>2.49 (14 cubes)</td>
<td>0.38 (7 beams)</td>
<td></td>
</tr>
<tr>
<td>Cheah &amp; da Silva (2007)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7.5% cement)</td>
<td>7.6 (33 cubes)</td>
<td>1.05 (7 beams)</td>
<td>0.73 (3 panels)</td>
</tr>
</tbody>
</table>

5.11.1. Haab & Kingi 1998

Haab & Kingi (1998) performed three point bending tests on 200 fibre reinforced, rammed soil-cement bricks. The bricks (300 x 140 x 100 mm) were made in a manual Cinvam ram press and were air dried for 28 days prior to testing. A range of cement contents (2-16% weight of dry soil), fibre contents of NZ flax and sisal (0.45-1.25%) and fibre lengths (20 mm – 100 mm) were tested. The jar test\(^1\) determined the soil used was comprised of 11% clay, 9% silt, 56% sand and 24% gravel.

---

\(^1\) The jar test refers to a field test that is used to give an indication of soil composition. It is conducted by suspending a soil in water inside the jar and measuring the sediment layers that form upon settlement. Measurements of the layer thicknesses indicate the proportion of clay, silt, sand and gravel in the soil.
The researchers determined the optimal mixture (for Cinva rammed bricks) to have a cement content of 9%, a fibre content of 0.75%, and a fibre length of 64 mm. The results showed negligible differences between the performance of NZ flax and sisal fibres. The data showed that specimens with higher fibre contents had higher ductility and lower material stiffness, but that the inclusion of fibres did not have a significant influence on the modulus of rupture (MoR) of the bricks. The flexural strength of the Cinva ram bricks were influenced predominantly by the cement content as shown in Figure 19.

![Figure 19 Flexural Strength was Proportional to Cement Content (Haab and Kingi 1998)](image)

Haab & Kingi (ibid) subsequently made two fibre-reinforced rammed earth panels (2.4 x 1.2 x 0.15 m) using a composition based on the optimized soil mixture determined from the Cinva rammed brick tests. The panels were made using a cement content of 9% and 6% respectively. Using the jar test, the soil used for the two panels was determined to have a soil composition of 7% clay, 7% silt, 34% sand and 52% gravel. Sisal fibres were cut to 65 mm and added to both wall panels at a content of 0.75% (by weight of dry soil). In both panels the earth was rammed around two vertical steel reinforcing bars which protruded from the concrete foundation and extended to half the height of the panels (1.2 m).

Lateral cyclic loads were applied at the top of each panel. In both cases the foundations failed before the earth panels, at 19 and 16 kN respectively. By assuming that the vertical steel reinforcement embedded within the panels did not affect the shear performance, and because no horizontal steel reinforcement was used or normal loads applied, the shear stresses attained in the panels were deduced using the equation below.

\[ f_{es} = \frac{V_n}{td} \]

where \( f_{es} \) = shear strength of earth, \( V_n \) = shear strength of the section, \( t \) = thickness, \( d \) = depth
The shear strengths attained in the panels before the test was stopped due to failure of the foundations were 0.11 and 0.09 MPa respectively. The results showed the wall panels had shear strength greater than the minimum shear strength value of 0.08 MPa for structural earth panels as specified in the NZS 4297:1998.

Flexural tests were performed on four smaller panels cut from the two tested panels. Average flexural strengths of 1.15 and 0.9 MPa were measured for the four panels made from the 9 and 6% cement content panels respectively. Sixteen bricks (300 x 150 x 100 mm) were cut out of the 9% and 6% cement content panels and tested. The bricks had an average flexural strength of 1.54 and 1.02 MPa respectively.

5.11.2. Segetin et al. 2005

Segetin et al. (2005) examined the effect of varying flax fibre length (40 mm and 60 mm) and content (0.4% and 0.6% by weight of dry soil) on rammed earth. Five beam specimens (600 x 150 x 150 mm) were made for each combination, along with two unreinforced control specimens, resulting in a total of 22 beam specimens. The test specimens were hand rammed in a heavy wooden mould using a 21 kg steel rammer with a 100 x 100 mm square head, and were made using soil with a cement content of 8%. Specimens were cured for 28 days before testing.

Four-point bending tests were used to determine the flexural strength of the beams following ASTM D1635-00 (ASTM 2006). From the remnants of the tested flax-fibre reinforced flexural beams, forty compression cube test specimens were made. The cubes were tested following ASTM D1634-00 (ASTM 2006). The average flexural and compressive strengths measured were 0.30 MPa and 1.56 MPa respectively.

The results of the tests showed that the different fibre contents and lengths did not have a significant effect on the flexural or compressive strength of the specimens. However, an increase in post failure non-linear flexural strength was observed as a result of reinforcing the specimens with flax-fibres. The large number of fibres observed to pull out of the flexural test specimens indicated that higher non-linear strengths would be possible if the bond between the fibre and earth was strengthened.
Walford (2005) examined the flexural and compressive characteristics of flax-fibre reinforced rammed earth panels when compacted vertically in layers, or horizontally in one or two layers (on-grade construction). A total of 8 panels were constructed. Four panels were rammed vertically (one was 200 x 1600 x 1600 mm and three were 150 x 1200 x1200 mm), and four panels were rammed on grade (one was 200 x 1600 x 1600 mm and three were 150 x 1200 x1200 mm). Three vertically rammed panels and four horizontally rammed panels were cut into 320 cube and 24 beam specimens. One vertically rammed panel (150 x 1200 x 1200 mm) was cut into 64 test cubes to measure the strength gain over time of the rammed earth. All the horizontally formed panels were compacted in one layer except the 200 mm thick panel which was compacted in two layers. The research conducted by Walford used the optimized mixture determined by Haab & Kingi (1998) for the Cinva rammed bricks (9% cement and 0.75% flax-fibre content). The strength gain over time results from the 64 cubes tested in compression showed that use of the 28 day strength was a conservative estimate of strength as shown in Figure 20. The strength gain over time data indicated that the compressive strength at 56 days was 50% greater than the strength at 28 days for the specimens tested.

The specimens from the vertically compacted panels had an average compressive and flexural strength of 7.42 MPa and 2.19 MPa respectively, whilst the specimens from the horizontally compacted panels had an average strength of 6.19 MPa and 1.36 MPa respectively. The
period of curing was not specified. The results showed that vertical construction resulted in a stronger material than on-grade construction, but that both methods produced structural grade rammed earth. For earth to be used as a structural material NZS 4298:1998 specifies that the material must have a compressive strength greater than 1.3 MPa, and a flexural strength greater than 0.25 MPa.

5.11.4. Morgan & Hoskins 2006

Research conducted by Morgan & Hoskins (2006) investigated the strength of thin flax-fibre reinforced rammed earth panels. Flexural and shear tests were performed on three 1200 x 1200 mm rammed earth panels. The panels were rammed on-grade in one layer, at thicknesses of 60, 80 and 100 mm. Racking shear tests were conducted on the panels and the shear strengths determined were 0.64, 0.7 and 0.56 MPa respectively. At a shear stress of 0.7 MPa the 80 mm thick panel failed via a crushing failure at the corners. The 60 mm and 100 mm thick panels failed in diagonal shear. The diagonal shear crack that formed in the 100 mm thick panel is shown in Figure 21. The panels were manufactured using the optimized mixture determined by Haab & Kingi (1998) of 9% cement and 0.75% flax-fibre content.

![Figure 21 Panel Tested in Shear (1200 x 1200 x 100 mm) (Morgan and Hoskins 2006)](image)

As the 80 mm panel had only failed at the corners of the panel, the panel was subjected to a 3 point bending test with a span of 760 mm. The flexural strength calculated was 2.8 MPa.
5.11.5. Segetin et al. 2007

Extending their previous research in 2005, Segetin et al. (2007) tested the effect of coating flax-fibres with enamel paint as a bonding agent. Beam specimens were made with flax-fibres that had been coated in enamel paint diluted with mineral turpentine. The coated flax-fibre reinforced beams were tested alongside uncoated flax-fibre reinforced beams. Fibre lengths of 70 mm and 85 mm, fibre contents of 0.6% and 0.8% (by weight of dry soil) and a cement content of 10% were used. The beam specimens (600 x 150 x 150 mm) were rammed in a heavy wooden mould in two equal layers. Specimens were tested after curing for 21 days.

The results showed that the uncoated flax-fibre specimens performed the best, followed by the coated fibre specimens, and then the unreinforced control specimens. The flexural and compressive strengths are summarised in Table 23. Ductility measurements of beam specimens were made by measuring the displacement of the loading crosshead from the beginning of loading until the displacement at which the flexural strength of the specimen dropped below 0.25 MPa (the minimum flexural strength specified in NZS 4298:1998). The unreinforced flexural specimens failed in a brittle manner upon first crack formation at displacements between 0.4-0.9 mm. The uncoated fibre-reinforced specimens attained peak flexural strength after first yield had occurred, during the non-linear part of the strength profile, and decreased below the 0.25 MPa level at displacements of 5-7 mm. The coated fibre specimens showed a large drop in strength at first crack and fell below the 0.25 MPa level at displacements of 1.3-2.4 mm. The test results are grouped by fibre coating in Table 23. The difference in strength in specimens reinforced with different fibre lengths or fibre concentrations was not significant with regard to the peak flexural strength measured.

<table>
<thead>
<tr>
<th>Number of beams tested</th>
<th>No fibres</th>
<th>Uncoated fibres</th>
<th>Coated fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Flexural Strength (MPa)</td>
<td>0.27</td>
<td>0.38</td>
<td>0.28</td>
</tr>
<tr>
<td>Ductility (mm)</td>
<td>0.4-0.9</td>
<td>5-7</td>
<td>1.3-2.4</td>
</tr>
<tr>
<td>Avg. Compressive Strength (MPa)</td>
<td>1.79</td>
<td>2.49</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The poor performance of the coated fibres was found to be a result of reduced fibre content in specimens with coated fibres. Fibres were added by weight and coated fibres weighed more than uncoated fibres. The coating of paint was found to account for 47% of the total mass of
the fibre content added and so it was deduced that the fibre contents in specimens with paint coated fibres were likely to have a fibre content equivalent to 0.32% and 0.43% by weight of dry soil.

All the non-coated fibre specimens (fibre content 0.6 and 0.8%) recorded higher flexural strengths in their non-linear region after first crack, whereas the paint coated fibres (fibre content 0.32 and 0.43%) did not. The result indicated that there was minimum flax-fibre content required before the flexural strength of a beam specimen could continue to increase after cracks had begun to form in the earth, and that this minimum level of fibre concentration was between 0.43 and 0.6%.

5.11.6. Cheah & da Silva 2007

Cheah & da Silva (2007) tested the compressive, flexural and shear strength, of flax-fibre reinforced rammed earth wall panels. Two 2400 x 1200 x 150 mm wall panels were built using soil sourced from a quarry located in Muriwai, NZ. A cement content of 7.5% (by weight of dry soil) and a flax-fibre content of 0.075% were used. From these two panels, three smaller square panels were made for shear testing, seven beams were made for flexural tests, and 33 cubes were made for compression tests.

Shear tests

Three 1200 x 1200 x 150 mm test panels were tested following ASTM E519-02 (ASTM 2000). The test setup is shown in Figure 22. Shear strengths of 0.72, 0.86 and 0.61 MPa (average 0.73 MPa) were recorded for the three panels.

![Figure 22 Diagonal Tension (Shear) Test Setup](image-url)
Bending tests

Seven beams (500 x 125 x 125 mm) were tested in four-point bending according to ASTM D1635-00 (ASTM 2006). The average flexural strength measured was 1.05 MPa. A cracked beam under load is shown in Figure 23.

![Figure 23 Four-point Bending Test (Cheah 2007)](image)

Compression tests

Thirty three compression cube specimens (125 mm each side) were dry cut from the two 2400 x 1200 x 150 mm wall panels. Twelve cube specimens were tested in compression in the x, y, and z, axes to examine the anisotropy of the material and the results are shown in Table 24. The 21 remaining specimens were tested in the vertical orientation and produced an average compressive strength of 7.7 MPa. The compression strengths measured were similar to the 12 specimens tested in the three orientations.

<table>
<thead>
<tr>
<th>Direction of testing</th>
<th>No. of specimens</th>
<th>Avg. Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>6</td>
<td>7.1</td>
</tr>
<tr>
<td>Horizontal – x</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Horizontal – y</td>
<td>3</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Chapter 6. MATERIAL STRENGTH TESTING OF FLAX-FIBRE REINFORCED RAMMED EARTH

The structural and seismic tests conducted in this doctoral study are presented over three chapters. Material tests of flax-fibre reinforced, cement stabilised, rammed earth (Uku) are presented in Chapter 6. Pseudo-static cyclic tests on Uku wall panels and an Uku wall assemblage are presented in Chapter 7 and Chapter 8 respectively. Shear test methods for rammed earth are compared in Chapter 9.

6.1. Seismic Demand in NZ

NZ is a seismically active country and all structures are required by the NZ Building Code (NZ Government 1992) to achieve a specified level of seismic performance. Seismic events in NZ result from the movement of the Pacific and Australian tectonic plates as shown in Figure 24.

In order to ensure the safe seismic design of structures, an equation is specified in the NZ Loadings Standard 1170.5 (Standards NZ 2004) to determine the elastic site hazard spectrum for horizontal loading $C(T)$

$$C(T) = C_h(T) \times Z \times R \times N(T, D)$$

Where $C_h(T) =$ spectral shape factor, $Z =$ hazard factor, $R =$ return period factor, $N(T, D) =$ near fault factor.

Seismological studies have been undertaken to create the seismic hazard maps, like the one shown in Figure 25 for the North Island. Figure 26 shows a simplified version of the seismic
hazard map. The hazard factors are determined in consideration of, the location of fault lines, the rate of plate movement, past seismic events, and the lay of existing landforms.

Figure 25 Hazard Factor Map of the North Island of NZ (Standards NZ 2004)
Using a combination of measurements and historical observations since 1960, an average of 363 earthquakes each year above magnitude 4.0 were determined to occur in NZ (GeoNet 2011). These records do not take into account the seismic events associated with the Christchurch earthquakes in 2010 and 2011. Average annual numbers and magnitudes of earthquakes in NZ for selected decades are shown in Table 25.

Table 25 Average Annual Number of Earthquakes in NZ

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0-4.9</td>
<td>100</td>
<td>205</td>
<td>388</td>
</tr>
<tr>
<td>5.0-5.9</td>
<td>20</td>
<td>17</td>
<td>30</td>
</tr>
<tr>
<td>6.0 +</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

6.2. Seismic Vulnerability of Earthen Structures

Earth as a structural material has a low tensile strength and is brittle. Due to the high mass of earth, large inertial forces can be developed in earthen structures during seismic events. The continual failure of hundreds of unreinforced earth buildings during seismic events such as
the 2003 Bam, Iran earthquake (Gharaati 2006), the 2001 El Salvador earthquakes, and the 2007 Pisco, Peru earthquake (Blondet and Aguilar 2007; Fierro et al. 2007), show that there is much work still required to improve the seismic design, and build quality, of earthen structures to withstand seismic events.

There are many examples of rammed earth structures that have exhibited a high level of seismic resistance. The earthen citadel Arg-e Bam (built 500 BC) endured many earthquakes before it was severely damaged during the 2003 Bam, Iran earthquake. During this earthquake the thinner upper walls collapsed onto the thicker walls below (Blondet and Aguilar 2007). The two storey Pompallier House in Russell, NZ (built 1841) has survived several earthquakes described as severe in the last 50 years and is currently in use as a museum (Jones 1996). The 7 storey rammed earth residential building in Weilburg, Germany (built 1828) was built in a low seismic zone and is still in use today (Minke 2006). The Potala Palace in Lhasa, Tibet (built 1690) also is regularly subjected to earthquakes. In August 2008, earthquakes of magnitude 6.4 and 5.1 occurred in Lhasa with epicentres located 50 and 60 miles from the palace respectively. These earthquakes destroyed hundreds of houses and killed nine people (USGS 2010) but the palace was undamaged. The Potala Palace remains a popular tourist destination today.

Many rammed earth structures have also not withstood seismic forces well. Reasons often are attributed to a lack of seismic design, poor construction quality, and inadequate building maintenance. The existence of many historic rammed earth structures in various states of disrepair show that proper design and regular maintenance is required to preserve the strength and durability of the material (Hughes 1983; Jaquin 2008). After the Bam, Iran earthquake, reconnaissance teams found that buildings of earth (as well as all other material types) collapsed because of poor material quality and workmanship (Gharaati 2006). In Bam, many seismically inadequate earthen buildings were found to have been built by homeowners who were disadvantaged and who did not have access to any other housing options. Failed structures in poor regions often reveal attempts to reduce the cost of construction by substituting or reducing the use of expensive construction materials such as cement and steel (ibid). Minke (2001) observed that cracks in earth panels commonly originated from the edge of window and door openings, around lintels of insufficient width, and at the top of wall panels in the absence of a ring beam. Without adequate design, perpendicular loads caused wall panel to fail out-of-plane. The provision of a ring beam, buttress or intermediate walls were recommended as ways to design wall panels to resist perpendicular loads. Parallel loads
could be resisted with good wall design such as having adequate wall widths between window and door openings, and from corners of the dwelling. Out-of-plane failures were considered the more dangerous failure method because they led to roof collapse.

Research into the seismic performance of rammed earth is needed so that suitable earthen building methods can be developed. Upon searching for relevant literature, there was a clear lack of published research on the seismic performance of rammed earth. Despite the regular loss of lives and collapse of buildings for centuries due to the failure of earth buildings, there remains a lack of accessible and appropriate seismically resistant building solutions. A survey of housing professionals by Zami & Lee (2011) found the lack of knowledge of stabilized earth construction methods by users, building professionals, and housing agencies, to be the most inhibitive barrier to the wider adoption of stabilized earthen solutions. Also due to a lack of research, existing earth building guidelines remain simplistic and inefficient. Without specific data, earth building guidelines necessarily used conservative approaches to design and have drawn significantly from other material guidelines such as from masonry standards (Standards NZ 1998; Jaquin 2008).

6.3. Material Tests

Material tests were conducted to characterise the compressive and flexural strengths of flax-fibre reinforced, cement stabilized, rammed earth. In total 75 cubes and 58 cylinders were tested in compression and 10 beams were tested in flexure.

Due to the impracticality of conducting flexural and shear tests on earthen materials, the NZ Earth Building Standard NZS 4297:1998 specifies empirical equations to determine flexural and shear strength based on compressive strength. The equations are reproduced below in equations (1) and (2),

\[
 f_{es} = 0.07 f_e 
\]

(1)
where \( f_{es} \) = the shear strength of earth and \( f_e \) = compressive strength of earth, and

\[
 f_{et} = 0.1 f_e 
\]

(2)
where \( f_{et} \) = the flexural strength of earth and \( f_e \) = compressive strength of earth.

The accuracy of the empirical strength relationships have been examined using the results of material strength tests conducted in this doctoral research and from the results of reviewed research of fibre reinforced, cement stabilised, rammed earth.
6.4. Muriwai Soil

Material test specimens were made using Muriwai soil. The composition of the soil is shown in Table 26.

<table>
<thead>
<tr>
<th></th>
<th>Muriwai soil (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>15.7</td>
</tr>
<tr>
<td>Sand</td>
<td>70.5</td>
</tr>
<tr>
<td>Silt</td>
<td>6.5</td>
</tr>
<tr>
<td>Clay</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Muriwai soil was sourced from the Sandstone Developments quarry located in Waimauku, Auckland. A soil stockpile from the quarry is shown in Figure 27. The soil was produced by grinding soft sandstone and passing the fragments through a 5 mm sieve. Rammed earth contractors in the region have used the Muriwai soil source successfully to build rammed earth houses in Auckland which include the dwellings built in the Earthsong Eco-Neighbourhood located in Ranui, West Auckland. A wet sieve analysis showed the Muriwai soil to have a high sand content (70.5%) and low clay content (7.3%) but was still suitable for rammed earth construction.

Houben & Guillaud (1994) have recommended soil plasticity limits for rammed earth buildings by collating the soil plasticity characteristics of historic rammed earth structures which have been performed well from a strength and durability perspective over their lifetimes. Their recommendation zone for rammed earth is reproduced in Figure 28 and includes soils with a Liquid Limit (LL) between 25-35% and a Plasticity Index (PI) between
0-15%. Soils with a PI up to 30% were acceptable if the soil had a high LL (up to 46%) as shown in Figure 28.

![Figure 28 Soil Plasticity Recommendations for Rammed Earth by Houben and Guillaud (1994)](image)

6.4.1. Manufacture of Specimens

For the material strength tests, specimens were cut out of existing rammed earth panels. The panels, from which test specimens were cut, were made using the Muriwai soil, had a cement content of 7.5% (by weight of dry soil), and a flax fibre content of 0.075%. Using full-sized panels and the undamaged portions of tested panels, cube and beam specimens were marked out. The specimens were then cut out of the panel using a diamond tipped chainsaw, circular saw, and table saw. Despite the specimens being subjected to considerable vibration and water as a result of using these cutting tools, the specimens retained their structural integrity. Some wet cut cubes are shown in Figure 29. Due to the thickness, weight, and strength of the rammed earth, it was necessary to use heavy duty wet cutting equipment and an overhead gantry to cut and manoeuvre the rammed earth panels. All extracted flexural specimens were 600×150×150 mm in dimension, and all extracted compression specimens were cut into 150 mm cubes.
The material tests conducted were grouped into three sets which are described below and detailed in Table 27:-

- Set 1 test specimens were cut from two 1.2 m square, 150 mm thick Uku panels tested in shear (used to produce 40 cubes, 1 beam) and nine 700 mm square, 150 mm thick Uku wallettes (600 x 600 x 150 mm) which had been used to conduct pull-out bar strength tests (used to produce 12 cubes). The 40 cubes from the shear test panels were tested horizontally (perpendicular to the direction of ramming) while the 12 cubes from the steel pull-out tests were tested vertically (parallel to the direction of ramming).

- Set 2 test specimens were cut from undamaged portions of the Uku wall assemblage that was subjected to pseudo-static cyclic loads which was reported in Chapter 8.

- Set 3 test specimens were cut from a 600 mm square, 150 mm thick Uku panel rammed at Rotoiti.

<table>
<thead>
<tr>
<th>Set</th>
<th>Soil used</th>
<th>Compression specimens</th>
<th>Flexural specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>Muriwai</td>
<td>52 cubes</td>
<td>1 beam</td>
</tr>
<tr>
<td>Set 2</td>
<td>Muriwai</td>
<td>20 cubes</td>
<td>6 beams</td>
</tr>
<tr>
<td>Set 3</td>
<td>Muriwai</td>
<td>4 cubes</td>
<td>3 beams</td>
</tr>
</tbody>
</table>
6.4.2. Test Methods

The compression tests were carried out following ASTM D1633-00 (ASTM 2007). The specimens were loaded at a rate of 15 MPa/min (250 kPa/s) using the concrete test machine shown in Figure 30. The test specimens were tested in a dry state as opposed to a saturated state specified in the test method. The test method ASTM D1633-00 was developed for soil-cement which could be used in a variety of applications where the stabilised soil could be below the water table or otherwise reach a saturated state. For cement stabilised rammed earth however, testing the specimens in a dry state was more appropriate. Rammed earth does not reach a saturated state in a properly designed and built earth dwelling. The dry testing of earth specimens is also supported in the NZ earth building standards.

![Figure 30 Concrete Test Machine used for Compression Tests](image)

Four point bending tests were carried out according to ASTM D1635-00 (ASTM 2006). The tests were performed using an Instron Universal Testing Machine (shown in Figure 31). Beam specimens were loaded at a rate of 0.02 mm/s.

The flexural strength (Modulus of Rupture) was calculated using the below equation

\[ R = \frac{PL}{bd^2} \]

where \( R \) = Modulus of Rupture, \( P \) = total load applied to the beam, \( L \) = span length, \( b \) = specimen width, \( d \) = specimen depth
Specimens in Sets 1 to 3 differed primarily in the way the panels, from which they were cut, were used. A consequence of making test specimens from Uku panels which had been used for previous tests and other purposes was a lack of control over specimen age at the time of testing. Test specimens were tested in an orientation perpendicular to the direction of ramming (horizontal) as specified in the test method ASTM D1633-00 as well as in the direction parallel to the direction of ramming (vertical). Details of the average compression and flexural tests result are shown in Table 28 and Table 29 respectively.

### Table 28 Average Compression Test Results of Sets 1 to 3

<table>
<thead>
<tr>
<th>Set</th>
<th>Label</th>
<th>n</th>
<th>Age (days)</th>
<th>Density (kg/m³)</th>
<th>Comp Strength (MPa)</th>
<th>Cement (%)</th>
<th>Flax-fibre (%)</th>
<th>Loading Direction</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>18</td>
<td>18</td>
<td>1700</td>
<td>4.4</td>
<td>7.5</td>
<td>0.075</td>
<td>Horizontal</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>S3A</td>
<td>8</td>
<td>594</td>
<td>1658</td>
<td>4.1</td>
<td>7.5</td>
<td>0.075</td>
<td>Horizontal</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>S3B</td>
<td>4</td>
<td>552</td>
<td>1801</td>
<td>8.1</td>
<td>7.5</td>
<td>0.075</td>
<td>Horizontal</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>S3C</td>
<td>10</td>
<td>594</td>
<td>1757</td>
<td>6.6</td>
<td>7.5</td>
<td>0.075</td>
<td>Horizontal</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>P1</td>
<td>12</td>
<td>342</td>
<td>1815</td>
<td>6.2</td>
<td>7.5</td>
<td>0.075</td>
<td>Vertical</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td>52</td>
<td></td>
<td></td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SM1</td>
<td>5</td>
<td>35</td>
<td>1675</td>
<td>3.7</td>
<td>7.5</td>
<td>0.075</td>
<td>Vertical</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>SM2</td>
<td>15</td>
<td>124</td>
<td>1719</td>
<td>4.6</td>
<td>7.5</td>
<td>0.075</td>
<td>Vertical</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td>20</td>
<td></td>
<td></td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>R1</td>
<td>4</td>
<td>236</td>
<td>1733</td>
<td>5.7</td>
<td>7.5</td>
<td>0.075</td>
<td>Vertical</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td>4</td>
<td></td>
<td></td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 29 Average Flexural Test Results of Sets 1 to 3

<table>
<thead>
<tr>
<th>Set</th>
<th>Label</th>
<th>n</th>
<th>Age (days)</th>
<th>Density (kg/m³)</th>
<th>Flexural Strength (MPa)</th>
<th>Cement (%)</th>
<th>Flax-fibre (%)</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S3</td>
<td>1</td>
<td>497</td>
<td>1817</td>
<td>1.05</td>
<td>7.5</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>SM</td>
<td>6</td>
<td>35</td>
<td>1723</td>
<td>0.62</td>
<td>7.5</td>
<td>0.075</td>
<td>45%</td>
</tr>
<tr>
<td>3</td>
<td>R1</td>
<td>3</td>
<td>257</td>
<td>1632</td>
<td>0.58</td>
<td>7.5</td>
<td>0.075</td>
<td>4%</td>
</tr>
</tbody>
</table>

| No. of specimens | 10 | AVG | 0.65 |

### 6.6. Discussion

#### 6.6.1. The Isotropy of Rammed Earth

The review of compression tests conducted by other researchers showed rammed earth specimens have been tested both perpendicular and parallel to the ramming direction. It seemed logical to test the material vertically, in a direction parallel to the direction of ramming, because gravity loads acted on rammed earth in that direction. Despite this, a loading direction perpendicular to ramming direction was described in the ASTM test methods for testing of soil-cement in compression and flexure. One perceived advantage of testing perpendicular to the direction of ramming was that the test specimens would be tested on the flat surfaces formed against the formwork during manufacture. The side of rammed earth beam and cube specimens formed during manufacture are often flat enough to not require further machining or to be capped with gypsum. From the compression test results of sets 1 to 3, the vertically tested specimens averaged 5.13 MPa and the horizontally tested specimens averaged 5.26 MPa. The difference measured between compression tests results in the two directions was insignificant and indicated the rammed earth behaved as an isotropic material. The results were consistent with the findings of Cheah & da Silva (2007) and Bui & Morel (2009). Bui & Morel tested the compressive strength of rammed earth in directions oriented perpendicular and parallel to the earth layers. They tested both large rammed earth specimens (200 x 200 x 400 mm) of similar size to in situ rammed panels and smaller equivalent compressed earth bricks (CEB) (95 x 95 x 294 mm). The results collected by Bui & Morel are shown in Table 30.
Using the assumption that rammed earth behaves as an isotropic material, the compression and flexural strength results were analyzed without differentiating between the directions in which specimens were loaded.

### 6.6.2. Compressive Strength Gain Over Time

The compressive strength of rammed earth as a function of time showed a positive linear correlation ($R^2 = 0.28$)\(^2\). The results are plotted in Figure 32. Specimen ages ranged from 35 to 594 days. The rate of strength gain over time observed in the compression results of the specimens in Sets 1 to 3 was clearly observed however the rate of strength increase was less than that observed by Walford (2005). The strength of the rammed earth specimens tested by Walford at an age of 56 days was 50% stronger than specimens tested at 28 days. Due to the lack of data regarding early strength gain characteristics of rammed earth, further comparisons of the material tests data with Walford’s observations cannot be made. It is possible that the rammed earth gains strength faster initially. Regardless of the early strength gain characteristics of rammed earth, the results showed that strength measurements of rammed earth taken at 28 days were conservative.

The strength results indicated that cement stabilised rammed earth continued to gain strength even after a year of curing. Compressive strength results were taken from specimens with ages up to 594 days and the strongest specimens were the oldest ones. It is known that cement based composites develop strength over time as the cement hydrates and cementitious bonds are formed. For concrete, it is common to measure the strength of concrete at 28 days, however this time period may be too short for rammed earth due to the lower water content of the material and the resulting slower rate of cement hydration. Jaquin et al. (2009) suggest rammed earth also increases in strength as the moisture content decreases due to internal

---

\(^2\) $R^2$ is the statistical coefficient of determination. The value of $R^2$ indicates how well the regression line fits the data. A value of 1 indicates a perfect fit while a value of 0 indicates a very poor fit.
suction forces which develop between soil particles. Walker et al. (2005) findings support the idea that rammed earth with a lower moisture content is stronger. They stated that the moist strength of rammed earth was likely to be less than half of the final ambient compressive strength. Reaching the final ambient moisture content in rammed earth can take years depending on the thickness of the panel and the drying conditions of the panel.

![Figure 32 Compressive Strength Gain over Time](image)

**6.6.3. Compressive Strength vs. Material Density**

The compressive strength of rammed earth was shown to correlate strongly to material density. A linear regression on the material test data produced a coefficient of determination ($R^2$) of 0.77. In Figure 33 the data points and line of best fit are shown.
Material density was shown to be an important attribute influencing material strength. The results showed that material density was closely related enough to compressive strength to be used to estimate the compressive strength of rammed earth. An equation to estimate the compressive strength of Muriwai rammed earth mix based on material density was derived and is shown below

\[ y = 0.0233x - 34.96 \]

where \( y \) = compressive strength (MPa), \( x \) = material density (kg/m\(^3\))

### 6.6.4. Flexural Strength in Relation to Specimen Age and Material Density

The flexural strength gain characteristics were similar to that observed for compressive strength. The two charts in Figure 34 and Figure 35 show the relationships of flexural strength to age and density. There were too few data points to make a conclusive statement about trends in the results.
6.6.5. Determination of Flexural Strength Based on Compressive Strength

NZS4297:1998 specifies 10% of the design compressive strength can be used as the design flexural strength. The empirical equation is useful and important because compression tests of rammed earth are not too difficult to conduct and often are the only strength characteristic measured in rammed earth construction projects.

The results of the material tests in this doctoral research showed that the empirical relationships between flexural and compressive strength included in NZS4297:1998
appropriate and conservatively predicted flexural strength. In the material tests, flexural strengths were measured between 10 and 19% of compressive strength. The research literature also contained similar results which showed that the flexural strength of rammed earth to be 14-30% of compressive strength. The average compressive and flexural strength values for test specimens in Sets 1 to 3 as well as the results of four rammed earth research projects are shown in Table 31.

<table>
<thead>
<tr>
<th>Set</th>
<th>Avg. comp strength (MPa)</th>
<th>Avg. flex strength (MPa)</th>
<th>Flex str. as a % of comp str.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>5.87</td>
<td>1.05</td>
<td>18%</td>
</tr>
<tr>
<td>Set 2</td>
<td>4.17</td>
<td>0.62</td>
<td>15%</td>
</tr>
<tr>
<td>Set 3</td>
<td>5.67</td>
<td>0.58</td>
<td>10%</td>
</tr>
<tr>
<td>Segetin et al. (2005)</td>
<td>1.56</td>
<td>0.30</td>
<td>19%</td>
</tr>
<tr>
<td>Walford (2005)</td>
<td>7.42</td>
<td>2.19</td>
<td>30%</td>
</tr>
<tr>
<td>Segetin et al. (2007)</td>
<td>2.49</td>
<td>0.38</td>
<td>15%</td>
</tr>
<tr>
<td>Cheah &amp; da Silva (2007)</td>
<td>7.60</td>
<td>1.05</td>
<td>14%</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>6.6.6.</strong></td>
<td></td>
<td><strong>17%</strong></td>
</tr>
</tbody>
</table>

6.6.6. Determination of Shear Strength Based on Compressive Strength

NZS4297:1998 also includes an empirical equation to establish a design shear strength using a value equal to 7% of the design compressive strength. Cheah & da Silva (2007) were the only researchers to reviewed the relationship between shear and compressive strength of rammed earth by testing both strength characteristics. The results of the three diagonal shear tests conducted are summarised in Table 32.

<table>
<thead>
<tr>
<th>Avg. comp strength (MPa)</th>
<th>Shear strength (MPa)</th>
<th>Shear str. as a % of comp str.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheah &amp; da Silva (2007)</td>
<td>7.60</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>9.6%</strong></td>
<td><strong>11.3%</strong></td>
</tr>
</tbody>
</table>

The results of the diagonal shear tests showed that the shear strength of rammed earth was between 8% and 11.3% of the average compressive strength. The NZS 4297:1998 equation to determine design shear strength was shown to be slightly conservative.
6.6.7. The Benefit of Flax Fibres in Cement Stabilized Rammed Earth

Research in the reviewed literature examining the effect of fibre reinforcement on rammed earth showed the inclusion of fibre reinforcement of earth improved the ductility and residual flexural strength but did not improve peak flexural strength. A similar result was observed in the material tests conducted.

![Strength Profile of Fibre Reinforced Composites](image)

*Figure 36 Strength Profile of Fibre Reinforced Composites (based on Filho et al. 1999)*

Filho et al. (1999) identified several common strength profiles that result depending on the fibre length and concentration in fibre-reinforced cement composites.

A material that fails at:-

- ‘A’ represents a brittle material.
- ‘B’ after reaching A shows an insufficient fibre content had been used
- ‘C’ after reaching A indicated failure by fibre pull-out. Early failure by fibre pull-out was often a result of insufficient fibre length
- ‘D’ after reaching A indicated a stable transfer of load to the fibres followed by fibre pull-out

The strength profiles observed in the 10 flax-fibre reinforced beams tested in this doctoral research were similar to the performance of ‘B’ Figure 36. The flexural strengths decreased suddenly upon yielding. The residual strengths resulting from the inclusion of flax fibre reinforcement were measured to be between 10-20% of the maximum flexural load attained.
It was clear that the 0.075% flax-fibre component in the tested beam specimens was too low to result in a full transfer of the flexural load from the rammed earth to the fibres and to attain a flexural strength profile of ‘D’. The flexural strength profiles of beam specimens in Sets 1 to 3 are shown in Figure 37, Figure 38 and Figure 39.
To quantify the post failure residual flexural strength of the flax-fibre reinforced rammed earth beams, the flexural strength values at a displacement 1 mm greater than the yield displacement were used. The average residual flexural strength measured from the flexural test results of Sets 1 to 3 was 0.09 MPa. There was little variation in the non-linear flexural strength in all three sets which showed that the fibres had been mixed well into the soil. A consistent strength was expected as all the beam specimens in Sets 1 to 3 had a flax-fibre content of 0.075% by weight of dry soil.

Residual strength values from flexural tests performed by Segetin et al. (2007) and Cheah & da Silva (2007) were measured to derive a relationship between concentration of flax-fibres and residual flexural strength. The residual strengths results taken from the two groups of researchers are shown alongside the doctoral research results in Table 33. The relationship between flax-fibre content and residual flexural strength is plotted in Figure 40. The graph showed that the residual flexural strength of rammed earth was linearly proportional to the concentration of flax-fibres.
Table 33 Residual Flexural Strengths from Material Tests

<table>
<thead>
<tr>
<th>Flax-fibre content (%)</th>
<th>Residual Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segetin et al. (2007)</td>
<td>0.80% 0.40</td>
</tr>
<tr>
<td></td>
<td>0.60% 0.39</td>
</tr>
<tr>
<td></td>
<td>0.43% 0.23</td>
</tr>
<tr>
<td></td>
<td>0.32% 0.19</td>
</tr>
<tr>
<td>Doctoral research</td>
<td>0.075% 0.09</td>
</tr>
<tr>
<td>Cheah &amp; da Silva (2007)</td>
<td>0.075% 0.08</td>
</tr>
</tbody>
</table>

Figure 40 Linear Extrapolation of Residual Flexural Strengths at Varying Flax-fibre Contents

Assuming a linear relationship between flax-fibre content and residual flexural strength, a minimum flax-fibre concentration of 0.43% would be required to achieve a residual flexural strength of 0.25 MPa. NZS4298:1998 specifies 0.25 MPa as the minimum flexural capacity of structural rammed earth. Rammed earth that can retain a structural level of flexural strength after initial failure would increase the safety of rammed earth buildings during seismic events, reduce the reliance on steel reinforcing bars to provide tensile capacity in wall panels, and enable higher ductility factors to be used in design.
6.7. Conclusions

Compression and flexural strength tests were conducted on flax-fibre reinforced, cement stabilized, rammed earth test specimens. All of the beam and cube test specimens were cut from full-sized panels and the undamaged portions of tested panels made using the Muriwai soil with a cement content of 7% and a flax-fibre content of 0.075%. The tests results established the flax-fibre reinforced rammed earth specimens had an average compressive strength of 5.2 MPa and an average flexural strength of 0.65 MPa.

The strength test results were also showed that the strength of rammed earth continued to increase long after the first 28 days. The oldest specimens tested, which had cured for 552 and 594 days, were the strongest. A strong correlation between material density and compressive strength was also seen in the results and an equation linking the two properties was derived for rammed earth made using the Muriwai mixture tested.

Comparisons of flexural and shear strengths as a percentage of compressive strength were made to examine the accuracy of empirical formulae specified in NZS4297:1998 that determined flexural and shear strengths of earth using the compressive strength value. The use of 10% of the compressive strength as the flexural strength was found to be appropriate and consistent with the test results, while the use of 7% of the compressive strength as the shear strength was found to be conservative with test results showing shear strengths equal to 8-11.3% of compressive strength.

The inclusion of flax-fibres into the soil mixture was found to increase the residual flexural strength of rammed earth but did not increase the peak flexural strength. The residual flexural strength was found to increase linearly with flax-fibre concentration and a fibre concentration of 0.43% was determined as the concentration at which a residual flexural strength of 0.25 MPa could be attained. The value of 0.25 MPa was significant as that was the minimum flexural strength for structural rammed earth specified in NZS4298:1998.
Chapter 7. PSEUDO-STATIC CYCLIC TESTING OF FLAX-FIBRE REINFORCED RAMMED EARTH PANELS IN THE LABORATORY AND ONSITE

Pseudo-static cyclic tests were conducted on six flax-fibre reinforced rammed earth panels. Two of the test panels were built and tested in a laboratory and the remaining four panels were built and tested at an outdoor site in Ahipara, NZ. Soil tests were conducted to determine an optimised earth mixture for rammed earth construction made from local earth sources, and two rammed earth construction workshops were held in order to train individuals how to build rammed earth wall panels. In an attempt to better simulate onsite construction practice, the test panels were built by individuals with little to no previous experience in rammed earth construction and were built using material sources available locally in the Ahipara.

The results of the panel tests were used to determine the structural ductility of the rammed earth panels and showed that the laboratory built rammed earth panels were stronger and less variable than panels built onsite. Observations are presented regarding the effects of involving individuals from the local community in the research and the issues identified during onsite construction and testing.

7.1. The Purpose of Constructing and Testing Wall Panels Onsite in Ahipara

The performance and viability of constructing rammed earth panels using individuals with no prior experience in rammed earth construction was of interest in this doctoral research. In order to observe the effects of constructing rammed earth panels in a local community setting, four test panels were constructed in Ahipara using the equipment and labour available in the rural community. The panels were cured in an exposed outdoor environment mimicking an onsite rammed earth construction setting.

The difference in strength of panels built onsite compared to those built in the laboratory was determined in this research. A common issue often observed during seismic events, in areas that use earthen construction forms, was that the buildings did not perform to the level assumed in design or measured in laboratory tests. Poorly constructed earthen dwellings have been identified in communities where homeowners construct their own dwellings and where there are limited options for housing. Inexperienced labourers and cost-saving construction
practices within such communities are recognised issues (Gharaati 2006). Reports by Ottazzi & Neumann (1982) and Neumann (1983) showed that the strength of locally formed adobe bricks was half the strength of bricks built with a high quality of workmanship. By constructing and testing rammed earth panels within the Ahipara community, the seismic performance of rammed earth panels, and the effects of constructing rammed earth structures using individuals from a local community, was better understood.

7.2. Soil Testing

Soil tests were carried out on various earth sources from the Ahipara area to determine an earth mixture suitable for rammed earth construction. Tests were performed on three earth sources and one sand resource. Okura, Onepu, and Pupepoto quarry were the earth sources. Okura was a rich red clayey earth available on the Ahipara research site (shown in Figure 41). Onepu was a yellow/orange clayey earth deposit taken from the side of a mountain in Ahipara. Pupepoto quarry earth was taken from a stockpile of the quarry’s overburden. The sand was taken from large sand hills near the research site.

Atterberg limits tests, wet sieve analyses and Alcock’s shrinkage tests were conducted on the three earth sources and mixtures of them. The Atterberg limits are used to measure the plasticity index, liquid limit and plastic limit of the earths, and the test results are shown in Table 34. Wet sieve analyses were used to determine the grain size profiles of the earth sources. Based on the Atterberg limits test and wet sieve analyses a mixture of one part Okura earth and one part sand was selected for further tests with flax fibres and cement. The earth mixture selected was referred to as “Okura sand”. The grain size profile of the Okura sand mixture is shown in Figure 42 and the specific composition of the earth mixture was detailed in Table 26.
A suitable earth mixture for rammed earth construction needs to have a low shrinkage value to prevent excessive crack formation as the wall dries out. A linear shrinkage of less than 0.05% is specified in NZS 4298:1998, which is equivalent to a shrinkage of 0.3 mm for a specimen length of 600 mm. Standards Australia (2002) and Keable (1996) specify more lenient shrinkage limits of 2.5% (15 mm) and 2% (12 mm) respectively. Selected results from the Alcock’s shrinkage tests are presented in Table 36. A value of one millimetre was selected as an acceptable level of linear shrinkage in the Alcock’s tests. This value was achieved with the Okura sand mixture when mixed with flax fibre concentrations of 0.15% and 0.3% by weight of dry soil.

<table>
<thead>
<tr>
<th></th>
<th>Liquid Limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plasticity Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okura</td>
<td>96.8</td>
<td>66.8</td>
<td>30</td>
</tr>
<tr>
<td>Onepu</td>
<td>99.5</td>
<td>65.8</td>
<td>33.7</td>
</tr>
<tr>
<td>Pukepoto Quarry</td>
<td>79.7</td>
<td>48.7</td>
<td>31</td>
</tr>
<tr>
<td>Okura Sand mixture</td>
<td>48.5</td>
<td>27.2</td>
<td>21.3</td>
</tr>
<tr>
<td>Muriwai</td>
<td>39</td>
<td>37.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Figure 42 Grain Size Profile of the Okura Sand Mixture

Table 35 Composition of the Okura Sand Mixture

<table>
<thead>
<tr>
<th>Okura sand mixture (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>2.7</td>
</tr>
<tr>
<td>Sand</td>
<td>62.1</td>
</tr>
<tr>
<td>Silt</td>
<td>12.6</td>
</tr>
<tr>
<td>Clay</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Table 36 Alcock’s Shrinkage Test Results

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Shrinkage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okura earth</td>
<td>27</td>
</tr>
<tr>
<td>Okura sand mixture</td>
<td>3</td>
</tr>
<tr>
<td>Okura sand mixture + 0.15% Flax</td>
<td>1</td>
</tr>
<tr>
<td>Okura sand mixture + 0.30% Flax</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
7.2.1. Material Strength Tests

Sixteen compression test cylinders were made using the Okura sand mixture. The normal Proctor compaction method (as specified in NZS 4402:1986) was used to form earthen cylinders with a consistent and known compactive effort. The dimensions of the earth cylinders were 105 mm in diameter and 115.4 mm in height. The cylinders were tested at 28, 56 and 81 days, and the results are shown in Table 37.

<table>
<thead>
<tr>
<th>Age of specimen</th>
<th>No. of specimens tested</th>
<th>Average compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>6</td>
<td>1.56</td>
</tr>
<tr>
<td>56</td>
<td>5</td>
<td>1.79</td>
</tr>
<tr>
<td>81</td>
<td>5</td>
<td>1.70</td>
</tr>
</tbody>
</table>

The statistical method specified in the NZ earth building standard NZS 4298:1998 section B4.2 was used to determine the characteristic compressive strength of the rammed earth from the test results. This method uses the three lowest results and the total number of specimens tested to determine the characteristic strength of earth using the following equation,

\[ f' = x_3^{1-\varepsilon} \times (x_2 x_1)^{\varepsilon/2} \]

Where \( f' \) = the characteristic strength of earth, \( x_3, x_2, x_1 = \) the three weakest test results with \( x_1 \) being the weakest, and \( \varepsilon = \) a constant whose value is dependent on the number of specimens tested and which is specified in NZS 4298:1998 section B4.2.

A characteristic strength of 1.26 MPa was determined for rammed earth specimens made with the Okura sand mixture. For the rammed earth test panels a design strength of 1.3 MPa was adopted. The compressive strength test results showed rammed earth made from the Okura sand earth mixture was of adequate strength with respect to the minimum compressive strength specifications given of 1.3 MPa in NZS4298:1998 and 1 MPa in Walker et al. (2005).

7.2.2. Optimisation of Cement and Flax Fibre Contents

The Okura sand mixture was combined with a range of cement contents (0%, 3% and 5% by weight of dry soil) and flax-fibres concentrations (0%, 0.15%, and 0.3% by weight of dry soil) to determine the optimal concentrations to use in the Okura sand mixture. The normal
Proctor compaction method was used to create 45 earthen compression test cylinders which comprised of five specimens for nine different admixture combinations. Finished cylinder dimensions were 115.4 mm high with a diameter of 105 mm.

Unlike the specimens tested previously as reported in Section 7.2.1 (which were tested in a dry state), these specimens were tested in a water saturated state in accordance with the instructions given in test method ASTM D1633-00 (ASTM 2007). The test procedure, which was developed for soil-cement, specifies that test specimens should be submerged in water for four hours prior to the test. Photos of the test specimens are shown in Figure 43, Figure 44, and Figure 45. The test results are summarised in Table 38 and a graph showing the relationship between compressive strength and cement content is shown in Figure 46. The specimens that were made without cement content partially disintegrated after being submerged in water for 4 hours and are shown in the first three rows in Figure 45. The cylinders with 3% and 5% cement content retained their form without any visible degradation.
Table 38 Compressive Strength (MPa) of Okura Sand Mixture Rammed Earth Specimens

<table>
<thead>
<tr>
<th>Flax fibre (%) by weight of dry soil</th>
<th>0.00</th>
<th>0.15</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (%) by weight of dry soil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.92</td>
<td>0.95</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>1.34</td>
<td>0.76</td>
<td>1.32</td>
</tr>
</tbody>
</table>
Some observations were drawn from these test results:

- The saturated cement stabilized test specimens were weaker than the dry unstabilized test specimens;

- Compressive strength increased with cement content and was unaffected by flax fibre contents; and

- The average strength of the specimens made with 5% cement and 0.15% flax fibre contents was an outlying result.

Jayasinghe & Kamaladasa (2007) conducted compressive strength tests on dry and saturated cement stabilised (6%) rammed earth panels. They observed that the compressive strength of saturated rammed earth specimens reduced to 46% (for a clayey earth) of an equivalent dry specimen. Using this observation an equivalent dry compressive strength of 2.5 MPa was predicted for the specimens made with 5% cement content.

A cement content of 6% was selected for the Okura sand rammed earth mixture. A graph showing the saturated compressive strength of the rammed earth specimens at different levels of cement is shown in Figure 46. The cement content was increased by 1% in the mixture selected in order to provide some redundancy because mixture variations were likely to occur when earth was mixed onsite. A flax fibre content of 0.15% was selected to reduce the shrinkage of the rammed earth. The lower fibre content of 0.15% was selected instead of
0.3% due to the difficulty of mixing higher flax concentrations into the rammed earth mixture.

The instruction in ASTM D1633-00 to saturate test specimens before testing was not ideal for ascertaining the strength of rammed earth in practice. The test method was developed for general soil cement applications which include examples like ground stabilisation where the composite is likely to become saturated or is located below the water table. Rammed earth in a structure however should not reach a saturated state. Design requirements for extended eaves and raised foundations are specified in the NZ Earth Building standards. Many unstabilised earth structures have been built in NZ and have performed well structurally in wet and snowy regions.

7.3. Wall Panel Construction

Six rammed earth wall panels were built using the Okura sand mixture. Two panels were built in the laboratory (AP1 & AP2) and four were built onsite in Ahipara (AP3, AP4, AP5 and AP6). All the panels were built to a height of 2000 mm and a thickness of 200 mm. AP4 was built as a corner wall which extended 1000 mm in the plane of loading and 500 mm in a perpendicular direction as shown in Figure 47. AP4 was analyzed as a 1000 mm wide wall panel with two deformed 12 mm diameter mild steel reinforcing bars, located on the left and right side of the panel. The test panel dimensions are summarised in Table 39.

<table>
<thead>
<tr>
<th>Test Panel</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP1</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>AP2</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>On-site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP3</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>AP4</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>AP5</td>
<td>1500</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>AP6</td>
<td>2000</td>
<td>2000</td>
<td>200</td>
</tr>
</tbody>
</table>
Each wall panel was built on a 400 mm deep, 300 mm wide reinforced concrete foundation beam with a 50 mm concrete nib cast in situ. Elevations of the 1000 mm, 1500 mm and 2000 mm wide test panels are shown in Figure 48, Figure 49 and Figure 50 respectively. Two vertical D12 steel reinforcing bars were placed in each panel at a distance of 150 mm from the sides of the wall panel. Due to a mistake in construction the reinforcing bar locations for panel AP6 differed. The as-built reinforcing bars locations for wall panel AP6 are shown in Figure 50. A reinforced concrete bond beam was cast on top of each wall panel.
Figure 49 Elevation of a 1500 mm Wide Test Panel – AP5

Figure 50 Elevation of a 2000 mm Wide Test Panel - AP6
7.3.1. Materials, Equipment, Labour, and Machinery

All materials required for construction of the test panels in Ahipara were sourced locally. Flax leaves were harvested from a plantation located on the Ahipara site. After drying for a period of four to five days the leaves were processed into flax fibres using a mobile flax stripping machine. The fibres were soaked in water, dried in the sun, and cut into lengths between 50-60 mm. The Okura sand mixture was processed and stockpiled onsite in Ahipara. Okura sand mixture was transported to Auckland for the laboratory construction of rammed earth panels.

Different methods and equipment were used to mix water, cement and flax fibres into the earth mixture. For the construction of full-sized test panels and the Ahipara dwelling, two different methods were used to mix the large volume of earth needed. In the laboratory, a compact loader equipped with a crowd action bucket was used (shown in Figure 51) and in Ahipara, a soil auger was used (shown in Figure 52). The compact loader mixed the material on two plywood sheets. In addition to the driver, labourers were required to add materials, sprinkle flax fibres, add water and move the earth mixture back into the centre of the plywood sheets. The second method, comprising of the soil auger, was connected to a tractor. As the auger rotated, the earth, sand, cement, flax-fibres and water components were added gradually. In selecting a method that was capable of mixing large volumes of flax-fibres, earth, cement and water, it was important that the method folded the earth and did not have vanes or tynes moving through the earth as this would strip out the flax-fibres. Both mixing methods allowed labourers to access the earth mixture to add more materials, sprinkle flax-fibres into the mixture, break up clumps of earth or flax, and to check the consistency and moisture content of the mixture. Adding water to bring the moisture content to the optimal level was done last as it made the earth mixture sticky and more difficult to mix. The earth was mixed until a homogenous mix was attained. Plywood sheets secured within custom made steel frames, and hand and pneumatic compaction tools were used to ram all the earthen panels made in this doctoral research.
7.3.2. Workforce Training and Selection of Workers

Individuals with little or no prior experience with the rammed earth method of construction were used to build the wall panels. The two laboratory based wall panels (AP1 and AP2) and three of the onsite wall panels in Ahipara (AP3, AP4 and AP5) were built during rammed earth workshops. Workshop participants comprised of individuals from the Ahipara area and university students. The first workshop was held in Auckland from the 1st-3rd July, 2009 and had approximately 15 participants. The second workshop was held in Ahipara from the 23rd-27th November, 2009 and was attended by over 100 people on some days. Workshop participants were taught how to build using the rammed earth method and initially built a small rammed earth panel. After this they built the test panels. Two photos from the workshop held in Ahipara are shown in Figure 53 and Figure 54. Test panel AP6 was built in Ahipara on the 8th of February, 2010 by a group of people who had attended the rammed earth workshop held in Ahipara.
The panels were designed according to NZS 4297:1998 for rammed earth subjected primarily to flexure. Standard equations used for reinforced concrete design were used to determine the flexural and shear capacities of each rammed earth panel. Flexural and shear capacities determined for each test panel are listed in Table 40 and Table 41 respectively. The calculations were based on an assumption of linear strain and that the yield stress of the steel reinforcing bars would be developed.
Table 40 Design Flexural Capacity of Wall Panels AP1 to AP6

<table>
<thead>
<tr>
<th></th>
<th>AP1/AP2/AP3/AP4 (push)</th>
<th>AP4 (pull)</th>
<th>AP5</th>
<th>AP6 (push)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of reinforcing bars</td>
<td>2/2/2/3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Reinf. bars yielding</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$f'_{e}$ (MPa)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$T$ (kN)</td>
<td>33.9</td>
<td>67.9</td>
<td>33.9</td>
<td>33.9</td>
</tr>
<tr>
<td>$a$ (mm)</td>
<td>153.5</td>
<td>307.0</td>
<td>153.5</td>
<td>153.5</td>
</tr>
<tr>
<td>$d$ (mm)</td>
<td>850</td>
<td>850</td>
<td>1350</td>
<td>1750</td>
</tr>
<tr>
<td>$jd$ (mm)</td>
<td>773.2</td>
<td>696.5</td>
<td>1273.2</td>
<td>1673.2</td>
</tr>
<tr>
<td>$M_n$ (kNm)</td>
<td>26.2</td>
<td>47.3</td>
<td>43.2</td>
<td>56.8</td>
</tr>
<tr>
<td>Height of loading (m)</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$F_n$ (kN)</td>
<td>12.5</td>
<td>22.5</td>
<td>20.6</td>
<td>27.0</td>
</tr>
<tr>
<td>$\phi F_n$ (kN)</td>
<td>10.0</td>
<td>18.0</td>
<td>16.5</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Table 41 Design Shear Capacity of Wall Panels AP1 to AP6

<table>
<thead>
<tr>
<th></th>
<th>AP1-AP4</th>
<th>AP5</th>
<th>AP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_{es}$ (kPa)</td>
<td>91</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>$t$ (mm)</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$d$ (mm)</td>
<td>800</td>
<td>1200</td>
<td>2000</td>
</tr>
<tr>
<td>$V_n$ (kN)</td>
<td>14.6</td>
<td>21.8</td>
<td>36.4</td>
</tr>
<tr>
<td>$\phi V_n$ (kN)</td>
<td>10.2</td>
<td>15.3</td>
<td>25.5</td>
</tr>
</tbody>
</table>

The value of $f'_{es}$ was determined using Eq. 4-1 in NZS 4297:1998

$$f'_{es} = 0.07 f_e$$

Where $f_e$ = the design compressive strength of earth.

7.5. Test Setup

Pseudo-static cyclic tests were conducted on each test panel. The test setup for the laboratory tests and the onsite tests differed slightly in the manner in which the lateral load was applied to the wall panel. The wall panels tested in the laboratory were loaded via a steel loading beam attached to the top of the earth wall panel concrete bond beam and was held in position
by being tightened against the vertical steel reinforcing bars as shown in Figure 55. A 50 ton jack was attached to the steel loading beam, and a large steel cantilevered reaction frame was used. Two braces were attached to the loading beam to restrain out-of-plane wall displacements.

Due to the lack of structural test facilities close to Ahipara, improvised solutions were devised to provide key test infrastructure onsite out of locally available machinery and equipment. Two improvised test setups were used for the onsite tests conducted in Ahipara. One of the test setups entailed the loading jack being attached between the bond beams of two rammed earth test panels as shown in Figure 56. Using this test setup wall panel AP3 was tested in conjunction with AP4. Following this, AP4, which had sustained some damage from the first test, was tested against AP5. The second test setup used a 12 ton excavator as a reaction frame. This setup was used to test wall panel AP6 and a photograph of the arrangement is shown in Figure 57. During each test conducted onsite, the bond beams of the wall panels were laterally braced to a truck or a tractor which had been parked parallel to the panel.
Figure 56 Test Setup of a Two Wall Panel Test Setup

Figure 57 Excavator used as a Reaction Frame for the Test of Wall Panel AP6
7.6. Results

In this section the lateral strengths and load displacement responses of the six wall panels are presented. A summary of test results for each wall panel is shown in Table 42. The laboratory test panels were stronger than the design indications and showed considerable non-linear load-displacement characteristics while the results of the four onsite test panels varied greatly. The first three wall panels tested onsite were much weaker than expected. The low panel strengths were attributed to the effects of the outdoor environment on the wall panel during the curing period. In particular, repeated wetting and drying of clay balls in the earth mixture left large voids in the wall surface. After implementing a few improvements to the construction method the fourth onsite panel, AP6, was built. The shape of the load displacement profile of AP6 was similar to the plots obtained for the laboratory tested panels. AP6 sustained a lateral load 10% below its design strength.

<table>
<thead>
<tr>
<th>Wall panel dimensions</th>
<th>Design Load (F₀)</th>
<th>Measured Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (d)</td>
<td>Width (mm)</td>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>AP1 34</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>AP2 36</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>AP3 49</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>AP4 47</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>AP5 49</td>
<td>1500</td>
<td>200</td>
</tr>
<tr>
<td>AP6 44</td>
<td>2000</td>
<td>200</td>
</tr>
</tbody>
</table>

* ‘+’ and ‘-’ denote values in the push and pull direction respectively. Bolded values indicate the predicted mechanism of failure.

7.6.1. Laboratory Test Panels - AP1 and AP2

On the 5th August, 2009, wall panel AP1 was tested after curing for 34 days. The panel failed in diagonal shear and sustained a maximum lateral load of 18.73 kN and 16.42 kN in the push and pull directions respectively. In both tests, the design loads were exceeded between 31% and 50%. During the test at a displacement of 2 mm some crushing of earth was observed at the bottom corners of the wall panel. As the magnitude of lateral displacements increased, fine horizontal flexural cracks formed between several rammed earth layers. A horizontal crack gradually developed across the full width of the panel in the lowest rammed earth layer.
At a displacement of 8 mm a diagonal shear crack developed during the push phase of the load cycle. The diagonal shear crack continued to widen over the remaining cycles. Near the end of the test, a vertical crack developed in the upper portion of the wall panel, which was aligned with the location of the steel reinforcing bar. The load displacement plot of wall panel AP1 is shown in Figure 58 and a photo of the wall panel at the conclusion of the test is shown in Figure 59.

![Figure 58 Load-displacement Plot of AP1](image_url)
Wall panel AP2 was tested on the 7th August, 2009 after curing for 36 days. The panel failed by a sliding shear failure at the base of the wall and sustained maximum loads of 16.95 and 16.73 kN in the push and pull directions respectively. Again the design loads were well exceeded during the test. Notably absent during this test was the development of fine flexural cracks between rammed earth layers that develop during the test of AP1 at lateral displacements around 2-3 mm. At a displacement of 8 mm the first sign of panel damage was observed in the form of a fine horizontal crack between the lowest two layers of rammed earth. The horizontal crack continued to increase in size during the test and the bottom layer of rammed earth was increasingly crushed and fragmented with each load cycle. The middle and top sections of the wall panel remained undamaged throughout the test. The wall panel began to tilt sideways as the bottom rammed earth layer was displaced as can be seen in Figure 60. The load displacement plot of AP2 is shown in Figure 61.
7.6.2. Onsite Test Panels - AP3, AP4, and AP5

The three panels AP3, AP4, and AP5 were built during the workshop held in Ahipara and were tested on the 12 and 13th of January, 2010. The panels failed at lateral loads which were
much lower than the design loads predicted. The quantitative results of these tests were not useful because of the poor quality of the wall panels. The process of forming and testing the panels however was valuable because the exercise showed clearly the detrimental effects of outdoor exposure on panel strength.

The first test was conducted between wall panels AP3 and AP4. The highest lateral load applied during this test was 2.57 kN and 1.99 kN in the push and pull directions respectively. Those loads were far below the design strengths of +/- 12.5 kN for AP3 and 12.5/-14.6 kN for AP4. The load-displacement plots for both wall panels are shown in Figure 62 and Figure 63. Wall panel AP3 had low stiffness and little strength. The shape of the load-displacement plot for AP4 indicate that the vertical steel reinforcement provided some lateral load resistance as the panel was cycled. AP4 was permanently displaced in the push direction over the course of the test.

![Load-displacement Plot of AP3](image-url)
The second test was conducted between wall panels AP4 and AP5. The results again showed very weak lateral load bearing strengths and low wall panel stiffnesses. The load-displacement plots of AP4 and AP5 are shown in Figure 64 and Figure 65. The lateral loads applied during the test were limited by the strength of AP4, which sustained a maximum lateral load of 1.76 kN and 2.31 kN in the push and pull directions respectively. The design loads for the panels AP4 and AP5 were 12.5/-14.6 kN and +/-20.6 kN respectively.
The main cause for the poor performance of the panels was attributed to the effects of outdoor exposure on the clay balls in the rammed earth material and the lack of clay in the mixture available to bind to other constituents in the rammed earth. During the preparation of the earth mixture, balls of clay up to 20 mm in diameter were formed. The clay balls were
identified initially in the laboratory built panels as the wall panels dried out and the clay balls shrunk. The resulting voids that formed in the wall panels are shown in Figure 66. The presence of clay balls and voids within the laboratory based panels did not seem to reduce panel strength. Both panels exceeded their design strengths by 30%-50%. For the onsite wall panels however, the negative effects on strength resulting from the clay balls in the mixture were much more significant. Cycles of hot and cold temperatures, and exposure to rain and wind eroded the surface of the wall panels and formed larger voids around the clay balls than what was observed in laboratory tests.

![Figure 66 Voids Developing Around Clay Balls in Wall Panel AP3](image)

A closer examination of the onsite wall panels showed that the surface of the rammed earth had become soft enough to dig out with a fingernail up a depth of about 10 mm in some places, such as at the interface between rammed earth layers. The lack of strength in the surfaces of the panels indicated a lack of binder in the earth mixture and a poor cohesion between the rammed earth particles. It is likely that the lack of binder in the mixture was a consequence of a large portion of the clay in the mixture binding to other clay particles instead of binding to the non-clay constituents. A photograph of wall panel AP5 after curing for a month in the outdoor environment is shown in Figure 67.
7.6.3. Onsite Test Panel - AP6

Wall panel AP6 was built on the 8th of February, 2010 by a group of people who had attended the workshop held in Ahipara. Changes were made to the rammed earth construction process used to build panel AP6 to reduce the effect of weathering on the panel and improve the quality of construction such as to:-

- Measure and add earth mixture constituents using fixed volume containers rather than by adding a number of shovel loads of earth, sand and cement.

- Sieve the earth mixture though a 10 mm mesh to break up the clay balls.

- Use one group of people to build the whole wall panel.

A large improvement was achieved in the strength and durability performance of wall panel AP6 compared to the previous three wall panels built onsite.

A 12 ton excavator was used as a reaction frame for the test of AP6. During an early stage of the test, the loading plate connecting the loading jack with the bond beam pulled out. As a result the wall panel was only subjected to load cycles in the push direction. The load-displacement plot of AP6 is shown in Figure 68. During the test the wall panel developed a
flexural crack at mid-height at a displacement of 2-3 mm. Beyond a displacement of 7 mm the top half of the panel laterally displaced over the bottom half of the wall panel along the crack which had formed at mid-height of the panel. The maximum lateral load sustained by the wall panel was 24.4 kN which was 9% less than the panel’s design load of 27.0 kN.

![Load-displacement Plot of Wall Panel AP6](image)

7.6.4. Structural Ductility of Wall Panels

The rammed earth panels made with the Ahipara earth mixture showed considerable non-linear strength during the cyclic wall panel tests. The structural ductility values determined for panels AP1, AP2 and AP6 ranged from 2.6 to 5.8 and are summarised in Table 43. Due to the poor performance of wall panels AP3, AP4 and AP5, these results were not analyzed. The yield displacements for the panels were determined using the reduced stiffness equivalent elasto-plastic yield definition and panels were deemed to have failed when the lateral capacity of the panel decreased below 80% of the maximum lateral load.
Table 43 Structural Ductility of Test Panels

<table>
<thead>
<tr>
<th>Wall panel</th>
<th>Yield displacement (mm)</th>
<th>Failure displacement (mm)</th>
<th>Structural ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1 (push)</td>
<td>6.0</td>
<td>15.6</td>
<td>2.6</td>
</tr>
<tr>
<td>AP1 (pull)</td>
<td>5.8</td>
<td>15.5</td>
<td>2.7</td>
</tr>
<tr>
<td>AP2 (push)</td>
<td>6.1</td>
<td>24.5</td>
<td>4.0</td>
</tr>
<tr>
<td>AP2 (pull)</td>
<td>4.5</td>
<td>26.1</td>
<td>5.8</td>
</tr>
<tr>
<td>AP6 (push)</td>
<td>5.4</td>
<td>25.7</td>
<td>4.8</td>
</tr>
</tbody>
</table>

7.7. Discussion

7.7.1. The Value of Constructing and Testing Panels Onsite

Constructing and testing rammed earth panels onsite achieved two useful outcomes. The first was that the process of testing onsite and the results of the tests allowed important observations to be made regarding the performance of rammed earth panels in a setting similar to that which would be experienced during the construction of a rammed earth dwelling. As a result of the onsite testing, the method of construction was refined and the impacts of outdoor exposure on the panels were better understood. The viability of using local labour and resources was also demonstrated.

Conducting the panel tests in the local community allowed many locals to participate in the research process. During this process people from the Ahipara community saw, experienced and understood how the rammed earth method was implemented and its potential to improve the local housing situation. The inclusiveness of the research approach increased the credibility and acceptance of the rammed earth housing concept because individuals from the community were able to handle the material and interact with the researchers. These intangible aspects of the onsite research were invaluable outcomes and helped to increase local interest and support for the research and housing method. The rammed earth housing concept was found to be well liked by individuals from the local community in Ahipara because it was a healthy and accessible housing solution. The use of earth to provide shelter for their whanau appealed to Māori because it used the same earth which had provided for their ancestors. Use of rammed earth housing was perceived as a more environmentally friendly method than light timber framed housing and was thus better aligned with the Māori worldview in which Māori are kaitiaki (guardians) over the land.
7.7.2. Evaluation of Test Setups used for Onsite Testing

In order to perform quasi-static cyclic wall panel tests in Ahipara it was necessary to improvise basic test infrastructure using locally available equipment and machinery. The use of a 12 ton excavator as a reaction frame was a suitable locally available substitute. The tracked base provided strong resistance to lateral movements and the weight of the excavator ensured that the machine did not overturn during the test. Additionally the manoeuvrability of the excavator’s boom helped to position the loading jack. The hydraulic system of the excavator kept the boom rigidly in place during the test. Trucks and tractors were suitable lateral bracing points for the wall panels.

The test setup where two wall panels were simultaneously loaded had several significant disadvantages. Tests conducted between two wall panels only tested the weaker panel to a point of failure because the load history of the weaker wall panel was applied to both panels. The rate of loading was also difficult to control due to the lateral movements of both wall panels during the test.

Onsite wall panels were built on oversized and long concrete foundations (400 mm deep, 300 mm wide and 8.5 metre long) to prevent overturning and lateral movement of the bases.

The Proctor test method is recommended as the method of manufacture for compression specimens during the construction of the wall panels due to the transportability of the equipment required and the consistent compactive effort applied to specimens made using the method.

7.7.3. Panel Failure Mechanisms and Design Assumptions

The load displacement performance and strength of a rammed earth panel was adequately predicted by assuming a flexural panel failure. The assumption of flexural panel failure was shown to be suitable regardless of whether the panel failed in flexure or shear. During the panel tests both flexural and shear panel failure mechanisms were observed. AP1 failed in diagonal shear, AP2 failed in sliding shear and AP6 failed in flexure. Despite the range of failure mechanisms observed, the load displacement profiles of the test panels invariably resembled a flexural failure response. The reason why panels that developed a shear failure mechanism still performed like a panel that failed in flexure was because the vertical reinforcing steel and concrete bond beam confined the rammed earth. The confinement kept the rammed earth in-plane, which were then able to resist further panel deformation. The
lateral load bearing strength of panels that had developed shear failure mechanisms reduced when the steel reinforcing began to yield. This was observed to occur at displacements between 6-10 mm.

The flexural strengths observed in the laboratory based panels showed that rammed earth can have a significant tensile strength capacity. In design, only the vertical steel reinforcement is considered to have tensile strength. The tensile strength of rammed earth is assumed to be nil and it is this assumption that is likely to be the reason why panels predicted to fail in flexure, failed in shear instead. Flexural panel failure was predicted for all the test panels except AP4. Out of the three panels analyzed (AP1, AP2 and AP6), two failed in shear and one failed in flexure. The lateral design loads and the measured loads sustained by the panels are summarized in Table 44. Panels AP1 and AP2 were predicted to fail in flexure but failed in shear at loads which exceeded both the design flexural strength and design shear strength. An analysis of the results showed that the shear strength predicted in design was reasonably accurate but that the flexural capacity of the wall panel was significantly underestimated. The actual flexural strengths of panels AP1 and AP2 were at least 50% and 35% greater than their design flexural strengths respectively. This result showed that the panels built and cured in the laboratory did have a significant tensile strength capacity.

The assumption that rammed earth has a nil tensile strength in design is conservative and appropriate. The tensile capacity of rammed earth did appear to be unreliable and significantly influenced by the moisture content of the material. In contrast to the flexural overstrength observed in panels AP1 and AP2, the onsite built panel AP6 failed in flexure at a lateral load that was 9% lower than the design flexural load for the panel. The comparison showed that the tensile strength of the rammed earth tested onsite was lower than the laboratory tested rammed earth. Rain on the onsite panels would have increased the moisture content of the panels and thus reduced the tensile capacity of the rammed earth. This conclusion is supported by the findings of Jaquin et al. (2009) who found suction between earth particles to be one of the main sources of strength in unsaturated rammed earth. They also showed that the magnitude of strength derived from suction forces was proportional to the moisture content of the rammed earth. The tensile capacity of rammed earth was shown to be highly variable and was too unreliable to use in design.
### Table 44 Design Predictions vs Actual Performance of Test Panels

<table>
<thead>
<tr>
<th>Wall Panel</th>
<th>Flexural failure load (kN)</th>
<th>Shear failure load (kN)</th>
<th>Actual failure load (kN)</th>
<th>Failure mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1</td>
<td>+/- 12.5</td>
<td>+/- 14.6</td>
<td>+18.73/-16.42</td>
<td>Diagonal shear</td>
</tr>
<tr>
<td>AP2</td>
<td>+/- 12.5</td>
<td>+/- 14.6</td>
<td>+16.95/-16.73</td>
<td>Sliding shear</td>
</tr>
<tr>
<td>AP6</td>
<td>+27.0</td>
<td>+36.4</td>
<td>+24.36</td>
<td>Flexural failure</td>
</tr>
</tbody>
</table>

‘+’ and ‘-’ denote values in the push and pull direction respectively

### 7.8. Conclusion

In this chapter the performance of laboratory built rammed earth panels were compared with panels built onsite in Ahipara, NZ.

Soil tests conducted on earth sources in Ahipara were used to determine an earth mixture suitable for rammed earth construction. The mixture chosen consisted of a 1:1 blend of a red clayey earth sourced from the Ahipara test site and a yellow sand resource available locally. Flax-fibre and cement additions of 0.15% and 6% cement respectively (by weight of dry soil) were selected for the rammed earth mixture.

An issue was identified in the panels built onsite when cured in an exposed outdoor environment. Clay balls in the rammed earth mixture were compacted into the panels and for the initial tests on the laboratory based panels; they did not seem to have any weakening effect. However, when the rammed earth panels were built using the same method and materials in an exposed outdoor environment, the panels were greatly weakened. Wall panels AP3, AP4 and AP5 which were built onsite had strengths which were much lower than their design strengths. Before the fourth onsite wall panel AP6 was built, improvements were made to the construction process to mitigate and reduce the issues observed in the previous panels built onsite. The most significant change was to sieve the earth mixture through a 10 mm mesh to break up the clay balls. Wall panel AP6 attained a lateral load that was 9% below the design load of the panel, which was a large improvement compared to the previous panels built onsite.

The load displacement plots showed that the rammed earth wall panels had a high level of ductility. Calculated structural ductility values ranged from 2.6 to 5.8. Even though some of the panels failed in shear, all of the panels showed considerable non-linear strength due to the
confinement of the rammed earth that was provided by the vertical steel reinforcement and concrete bond beam. Panels that failed in shear had similar load displacement plots and strengths to panels that failed in flexure. The test results indicate that the use of a structural ductility of 2.0 is justified for the rammed earth system and that a flexural failure assumption in design can be used to predict the strength of a wall panel.

Positive intangible outcomes resulted from conducting the research onsite in the community, which were invaluable to the research project. By making the research accessible to people from the community in Ahipara, interest in the housing method was generated and acceptance of the rammed earth housing solution was shown. Through the onsite tests, strength issues arising from the exposure of panels to the outdoor environment were identified and were largely able to be mitigated through improvements to the construction process.
Chapter 8. PSEUDO-STATIC CYCLIC TESTING OF A FLAX-FIBRE REINFORCED RAMMED EARTH ASSEMBLAGE WITH OPENINGS

A pseudo-static cyclic test was conducted on an Uku wall assemblage consisting of three wall panels, a door opening, and a window opening, to examine the seismic performance of the wall system as a whole. The primary objective of this test was to investigate the non-linear performance and ductile capacity of the Uku wall assemblage. Another point of interest was to observe how the performance of each structural element interacted with and influenced other structural elements; in particular, the influence of half-height panels positioned next to full-height panels, the effect of the reinforced bond beam cast over the three full-height panels, and the strength behaviour of three wall panels acting simultaneously.

The design of the wall assemblage was based on wall line B of the Rotoiti Uku dwelling. Due to a lack of seismic data regarding the performance of Uku wall panels and assemblages when the building was designed, conservative seismic design parameters were used to determine the structural capacity for the dwelling (shown in Figure 69). The calculations submitted to and consented by the Rotorua District Council used a structural ductility factor ($\mu$) of 1.0 and a Structural Performance Factor ($S_P$) of 0.9. The Rotoiti dwelling was designed to be strong enough to resist seismic loads elastically. A better understanding of the inelastic or non-linear capacity of Uku will enable future structures to be designed more efficiently and to lower loads.

Prior to the doctoral research, material tests had been conducted to establish the compressive, flexural and shear strengths of the Uku material used in Rotoiti. The test results are summarized below in Table 45. These strength values were used to predict the lateral load capacity of the wall assemblage and the failure mechanisms of each wall panel.
Table 45 Summary of Uku Material Test Results (Cheah 2007)

<table>
<thead>
<tr>
<th></th>
<th>Average Strength (MPa)</th>
<th>Coefficient of Variance</th>
<th>Design Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>7.60</td>
<td>23.7%</td>
<td>4.60</td>
</tr>
<tr>
<td>Flexural</td>
<td>0.35</td>
<td>28.9%</td>
<td>0.18</td>
</tr>
<tr>
<td>Shear</td>
<td>0.73</td>
<td>17.0%</td>
<td>0.52</td>
</tr>
</tbody>
</table>

8.1. Construction, Instrumentation and Bracing of the Test Assemblage

The dimensions of wall line B and the wall assemblage built in the laboratory are shown in Figure 71 and Figure 72 respectively.

Wall line B was 6.2 m long in total and featured a 2.4 m ranch slider, a 1.2 m wide window opening which extended to the concrete bond beam, and three 150 mm thick earthen wall panels (with panel widths of 0.8, 0.7 and 1.1 m respectively). The test assemblage dimensions were modified due to laboratory construction constraints. Panels in the test assemblage had widths of 0.9, 1.1 and 1.1 m respectively. The 2.4 m opening for the door was reduced to 1 m due to space constraints in the laboratory. Mimicking the detail used onsite, the rammed earth
panels were built on top of a 50 mm high nib wall which had been poured on the reinforced concrete slab foundation to provide a shear key between the concrete slab foundation and the rammed earth panel. The concrete nib defined the width of the wall panels and made setting up the formwork easier. A reinforced concrete bond beam, 150 mm X 200 mm in cross section, was cast in situ on top of the rammed earth panels using permanent macrocarpa formwork. The rammed earth was compacted around vertical D12 steel reinforcing bars which spanned continuously from the reinforced concrete foundation into the reinforced concrete bond beam. The earth panels were referred to as EP1, EP2 and EP3 as shown in Figure 71.

The test assemblage was built by the same construction team that built the Rotoiti Uku dwelling. Each of the three wall panels were built in the same sequence as was used for the Rotoiti house construction and one panel was completed per day. The concrete bond beam was cast in situ on the earthen wall panels on the following day the day after the third panel had been rammed. The wall was left to cure for a 28 day period, during which the wall was instrumented with 61 displacement gauges.

Two lateral struts were attached to the concrete bond beam; one at the position of the load jack and one between EP1 and EP2 above the door opening. Two vertical struts were placed at both ends of the wall and were hand tightened against the top of the bond beam. The vertical struts simulated the vertical restraint provided by perpendicular earth wall lines at both ends of wall line B in the Rotoiti Uku dwelling. Teflon sliding plates were placed on the interface between the vertical restraints and the bond beam to prevent the vertical restraints from interfering with lateral wall movements along the axis of loading.

**8.2. Pre-test Wall Analysis**

The Uku wall assemblage was analyzed using SAP. An assumption was made that the walls would fail initially in flexure. Flexural panel failure was predicted based on panel analysis using the compressive, flexural and shear strengths shown in Table 45. The Uku wall system was modelled as a frame with columns at the centre lines of each wall panel, and a rigid beam along the centreline of the bond beam. The effective heights of each column were determined for each loading direction. In situations where a full-height panel was pushed against the half-height panel, an effective length 300 mm longer than the remaining unimpeded height was used.
Due to the asymmetrical geometry of wall line B, two bracing line models were created for loading in both directions as shown below in Figure 72. These models were used to determine the number of vertical steel bars that needed to be cast into each wall panel to meet the seismic capacity requirements according to *NZS 4229:1999 Concrete Masonry Buildings Not Requiring Specific Engineering Design*. The predicted wall failure mechanism was a mixed flexure-shear mode. Flexural cracks were predicted to form initially and progressively curve towards the centre of the panel as shear failure began to dominate.

**Figure 72 SAP Models of Wall Line B in Both Directions**

### 8.3. Pseudo-static Cyclic Wall Test

After the wall panels had cured for 28 days, the Uku wall assemblage was subjected to a quasi-static test. The wall exhibited considerable non-linear strength, but contrary to the predictions of flexural failure, each of the three panels failed via diagonal shear and sliding shear mechanisms. The maximum lateral load sustained by the test wall was 53 kN in the push direction and 59 kN in the pull direction. The maximum loads attained were less than the calculated ultimate lateral loads, in both directions, of 62.8 kN when pushing (84%) and 61.0 kN when pulling (97%) as shown in Table 46.

**Table 46 Summary of the Wall Test Results**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Maximum Displacement (mm)</th>
<th>Maximum Lateral Load (kN)</th>
<th>Predicted Lateral Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push (+ve)</td>
<td>25.7</td>
<td>52.8</td>
<td>62.8</td>
</tr>
<tr>
<td>Pull (-ve)</td>
<td>-24.8</td>
<td>-58.7</td>
<td>61.0</td>
</tr>
</tbody>
</table>

### 8.3.1. Load History

The load history used a displacement control that was based on interstory drift. At a wall height of 2.4 m, an interstorey drift of 1% was equivalent to a displacement of 24 mm. A drift-based load control was used because the yield displacement of the test assemblage was
not able to be accurately predicted. Due to the low ductility of the earth panels, initial cycles at low percentages and increments of interstorey drift were used. The wall was cycled twice per magnitude in accordance with the Park (1989) loading history. The cycles began with one cycle at 1/32 of a degree (0.75 mm) and increased gradually to an interstorey drift of 1.25% (30 mm). The load history of the cyclic test is shown in Figure 73.

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Drift</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.031%</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>0.125%</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>0.186%</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>0.250%</td>
<td>6.0</td>
</tr>
<tr>
<td>2</td>
<td>0.313%</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>0.375%</td>
<td>9.0</td>
</tr>
<tr>
<td>2</td>
<td>0.438%</td>
<td>10.5</td>
</tr>
<tr>
<td>2</td>
<td>0.500%</td>
<td>12.0</td>
</tr>
<tr>
<td>2</td>
<td>0.625%</td>
<td>15.0</td>
</tr>
<tr>
<td>2</td>
<td>0.750%</td>
<td>18.0</td>
</tr>
<tr>
<td>2</td>
<td>0.875%</td>
<td>21.0</td>
</tr>
<tr>
<td>2</td>
<td>1.000%</td>
<td>24.0</td>
</tr>
<tr>
<td>2</td>
<td>1.125%</td>
<td>27.0</td>
</tr>
<tr>
<td>2</td>
<td>1.250%</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Figure 73 Load History of the Uku Wall Test

8.4. Results and Observations

8.4.1. Load-displacement Plot

The load-displacement plot recorded during the wall test is shown in Figure 74. The test assemblaged was deemed to have failed when a load cycle failed to reach 80% of the peak lateral load previously attained and is indicated in Figure 74 by the red dot in both directions. The shape of the plot before wall failure was similar in shape to the hysteresis loops observed
in seismic tests of plywood sheathed timber shear walls (controlled by slip of sheathing nails) (Dean et al. 1986). The horizontal dotted lines indicate the predicted ultimate lateral load \((F_u)\) of the wall assemblage.

The structural ductility of the test assemblage was determined to be 1.5 in the push direction and 2.8 in the pull direction as shown in Table 47. The yield displacement was determined using the reduced stiffness equivalent elasto-plastic yield definition (Park 1989) and the displacement at failure was taken as the point at which the load bearing capacity of the assemblage reduced to less than 80\% of the maximum load attained previously.

<table>
<thead>
<tr>
<th>Loading direction</th>
<th>Yield displacement (mm)</th>
<th>Failure displacement (mm)</th>
<th>Structural ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push</td>
<td>14.9</td>
<td>22.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Pull</td>
<td>8.8</td>
<td>24.3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

8.4.2. Description of Wall Panel Failures

The wall system exhibited several failure mechanisms during the test. At a lateral displacement of 6 mm, a fine crack formed at the corner of the window and at the control joint between EP2 and EP3. The nib wall on which EP1 was built detached from the concrete foundation beam and rocked with EP1, with measured vertical displacements up to 2 mm. The top half of EP2 failed first with a 6 mm wide diagonal shear crack developing at a lateral displacement of -7 mm. A large shear crack developed on the opposing diagonal as the load was reversed. At a lateral displacement of 11 mm, it was possible to see through the cracks in EP2. Up until a displacement of 21 mm, EP1 showed minimal damage and was observably rocking on the concrete foundation beam. A sliding shear mechanism had developed between the concrete bond beam and the top of EP3 from an early stage in the test. EP2 continued to develop new shear and flexural cracks, and existing cracks widened. At a lateral displacement of 21 mm EP1 developed a large diagonal shear crack; by this point EP2 was severely cracked. Small shear cracks developed in EP3 as lateral displacements increased past 30 mm. Figure 75, Figure 76 and Figure 77 shows photos of EP1, EP2 and EP3 respectively at the end of the test.
8.4.3. Material Tests

Compression and flexural strength tests were conducted on specimens extracted from the un-cracked wall panels remaining at the conclusion of the test. The tests were guided by ASTM D1633-00 Standard Test Methods for Compressive Strength of Moulded Soil-Cement Cylinders and ASTM D1635-00 Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam in Third Span Loading. The results are presented below in Table 48.

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimens tested</th>
<th>Age (d)</th>
<th>Average Strength (MPa)</th>
<th>Strength Range (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>5</td>
<td>35</td>
<td>3.70</td>
<td>1.61 – 6.98</td>
</tr>
<tr>
<td>Flexure</td>
<td>6</td>
<td>35</td>
<td>0.21</td>
<td>0.10 – 0.39</td>
</tr>
</tbody>
</table>

8.5. Discussion

8.5.1. The Effect of the Flax Fibres

The fibres were observed to hold cracked earth panels together. Even after large cracks had developed, the presence of flax-fibres in the panel acted as a link holding detached blocks of earth in place and preventing them from falling out of plane. Flexural tests that were conducted on 600 mm beams extracted from un-cracked areas of the earth wall revealed a
post crack flexural strength of approximately 28 kPa which reduced in strength as displacements increased. Without the fibres, the beams would have collapsed as soon as a crack had developed in the specimen.

8.5.2. Low Material Test Results

The average compressive and flexural strengths measured from dry-cut Uku samples were 7.6 MPa and 0.35 MPa respectively. These specimens had been cured for 117 days. Post-test compressive and flexural tests extracted from un-cracked panels of the test assemblage revealed significantly lower average strengths. The specimens were wet-cut from the test wall and cut to required test dimensions using a diamond-tipped chainsaw. Use of a chainsaw was required due to the thickness and orientation of the wall panels after the test. The results of 35 day compression and flexural tests averaged at 3.7 MPa and 0.21 MPa respectively. The reduction in material strengths were attributed primarily to the use of a wet extraction method and to the difference in specimen age to a lesser extent. Using the strength gain over time relationship determined in Section 6.6.2, a strength gain of 9% or 0.3 MPa would be expected if a 35 day old specimen was cured for 117 days instead. The remaining decrease of 3.6 MPa in compressive strength was determined to be a result of using a wet and rough cutting method to extract specimens from the test assemblage.

8.5.3. Non-ductile Shear Failure of the Wall Panels

All three wall panels exhibited non-ductile failure mechanisms. EP1 rocked initially and then failed in diagonal shear, EP2 failed in diagonal shear, and the top layer of EP3 de-bonded from the 4 D12 vertical steel reinforcing bars connecting the earthen panel to the bond beam and exhibited a sliding shear mechanism of failure.

The sliding shear mechanism that developed between EP3 and the bond beam was suspected to have arisen as a result of pouring the concrete bond beam too soon after the panel had been constructed. Post-test observations of EP3 revealed a softer layer of earth at the top of the panel which could be indented using a fingernail. The colour of the top most rammed earth layer was also noted to be paler than the rest of the wall panel. At the time the concrete bond beam was poured, the panel had been curing for less than 24 hours and was likely to have absorbed additional water as the concrete bond beam was cast in situ on top of the panel within permanent timber formwork. The same problem was not expected to occur in the Rotoiti Uku house because there was a period of weeks between the construction of the wall
panels and the in situ casting of the concrete bond beam. EP3 represented 37% of the total effective wall width. Judging from the observations of the wall panel, EP3 was likely to have not contributed significantly to the strength performance of the wall assemblage during the test.

8.5.4. Non-linear Strength of the Wall Assemblage

Although all three wall-panels failed in a non-ductile manner, the overall wall system showed an appreciable level of non-linear capacity. The non-linear strength observed was partly due to each wall panel having a different stiffness but the increasing level of non-linear strength after first yield indicated that the failed wall panels retained an appreciable level of strength post-failure. Due to the difficulty in assessing the loads carried by each individual panel, the non-linear performance of individual panels could not be accurately identified.

8.5.5. Structural Ductility of Uku Wall Assemblage

The results of the wall test showed that the wall assemblage had considerable non-linear strength despite the individual panels failing via shear mechanisms usually associated with brittle failure. The non-linear characteristics of the wall assemblage were not due to the yielding of the vertical steel reinforcing bars as predicted but rather the sliding, rocking and crushing of the earth panels. Based on the structural ductility factors of 1.5 and 2.8 observed in the push and pull directions, a structural ductility value of 1.25 was considered reasonable for use in design. The use of the value 1.25 in design is supported by the structural ductility results determined for the wall panel tests reported in 0 which were between 2.6 to 5.8. The assumption of an elastic structure with a structural ductility of $\mu = 1$ for the Rotoiti Uku dwelling was shown to be conservative.

8.6. Conclusion

The test of the Uku wall assemblage did not attain the predicted ultimate lateral loads. The wall test reached 84% in the positive direction (push) and 97% in negative direction (pull). Contrary to predictions derived from material strength test results that all three wall panels would fail initially in flexure, the three wall panels failed via shear mechanisms of rocking, diagonal shear and sliding shear.
Despite the individual panels failing via shear mechanisms, the test assemblage exhibited significant non-linear capacity. The use of a structural ductility factor of $\mu = 1.25$ was supported by the results of the wall assemblage test.
Chapter 9. EVALUATING SHEAR TEST METHODS FOR STABILIZED RAMMED EARTH

Despite the re-emergence of rammed earth construction in recent decades it remains a specialist and novel building method in most developed nations. One aspect hindering a more widespread use of rammed earth construction, particularly in areas subject to seismic risk, is the method of characterising the shear strength of rammed earth. Rammed earth walls are built in situ as monolithic structures so test specimens have to be specifically manufactured. Issues with laboratory testing of rammed earth include: reproducing in situ compactive efforts and ramming methods; selection of specimen size, format and testing arrangements; choice of sample sizes; difficulties performing non-standard tests; and the costs of testing.

Due to a lack of a specific shear test for rammed earth, test methods have either followed geotechnical or masonry testing procedures. The research in this chapter compares the performance of shear test methods. Two different methods were used to evaluate the shear strength of rammed earth; the triaxial test (geotechnical), and the triplet test (masonry). Results are presented and recommendations for design and future work are given.

9.1. Shear Strength of Rammed Earth

Determining the shear strength of rammed earth is essential if an efficient and safe rammed earth structure is to be built. Geotechnical and masonry evaluations have both been used by researchers. In the literature reviewed, the Mohr-Coulomb failure criterion (shown below) was used to characterise the shear strength of rammed earth.

\[ \tau = \sigma \tan(\phi) + c' \]

Where \( \tau = \) shear strength, \( \sigma = \) normal stress, \( \phi = \) angle of internal friction, \( c' = \) apparent cohesion

The apparent cohesion is an indicative measure of the shear strength when no normal stress is applied to the material. The strength is derived from a range of sources including negative pore pressures (suction) between soil particles and cementation. The tangent of the angle of internal friction \( \phi \) represents the rate at which the shear capacity of the material increases when a normal stress is applied.
9.1.1. Experimental Studies Using Geotechnical Testing Methods

Standard geotechnical shear tests such as the triaxial test and the shear box test have been used. Jaquin et al. (2009) used triaxial tests to better understand the source of shear strength in rammed earth and looked particularly at the contribution of matric suction. This suction results from the adsorption and capillary effects in a soil matrix and induces water to flow from a wetter soil (lower matric suction) to a drier one (higher matric suction) in an unsaturated soil. Their results showed that as pore water pressures decreased, matric suction and hence the apparent cohesion and shear strength increased.

Bouhicha et al. (2005) used the shear box test method to evaluate the strength of compacted earth reinforced with barley straw. Their work was part of a wider study of the physical and mechanical properties of fibre reinforced compressed earth blocks. Their test results are presented in Figure 78 and showed that a 1.5% and 3.5% (by weight of soil) addition of straw increased the apparent cohesion by up to 50% (from 330 kPa to 493 kPa) but decreased the angle of internal friction.

9.1.2. Experimental Studies Using Masonry Shear Test Methods

Unreinforced brick masonry is structurally comparable to rammed earth and has similar failure mechanisms e.g. diagonal shear failure and sliding shear failure along mortar joints (Magenes and Calvi 1997; Venkatarama Reddy and Prasanna Kumar 2010). These shear failure modes were observed in a series of full-size rammed earth wall tests at The University of Auckland which were subjected to cyclic horizontal loads (Cheah et al. 2008).
The current European Standard for determining the shear strength of masonry (henceforth referred to as the triplet test) is designed to determine the shear strength along the horizontal bed joints. ASTM E519-02 (ASTM 2000) is an alternative shear test that uses 1.2 metre square test specimens. The larger test specimen represents the behaviour of a rammed earth wall panel more accurately but requires the use of specialised laboratory facilities and experience in order to conduct the test and thus has a limited practical application. The equation used in ASTM E519-02 to determine the shear stress is shown below.

\[
S_s = \frac{0.707P}{A_n}
\]

Where \(S_s\) = shear stress, \(P\) = applied load, \(A_n\) = mean solid cross sectional area in the x and y axes of the specimen.

Cheah and da Silva (2007) used the ASTM method to evaluate the shear strength of cement stabilised rammed earth specimens reinforced with NZ flax fibres. Three 150 mm thick specimens (1200 mm X 1200 mm) were tested in compression diagonally. Each specimen failed in tension along the diagonal. The shear stresses and strains were calculated using formulae provided in the ASTM E519-02 standard. The compressive loads applied to the specimens were correlated to shear stresses of 612, 716 and 860 kPa (mean 729 kPa) (Cheah 2007). A photo of the test setup is shown in Figure 79.

![Figure 79 Diagonal Shear Test of Cement Stabilised Rammed Earth (Cheah 2007)](image)

The reported shear strengths in the research reviewed were of a similar magnitude. There was also a logical strength difference between the apparent cohesion values measured for compacted earth (330 kPa to 493 kPa) to the shear stress results of the ASTM diagonal shear tests on cement stabilised rammed earth specimens (ranging from 612 kPa to 860 kPa). It is
clear from the research reviewed that rammed earth has an appreciable amount of shear strength that can be used in the design of structures. This is not recognised in many earth building standards at present.

9.1.3. Design Guidance for the Shear Strength of Rammed Earth

The shear strength sections in national earth building design standards from Australia, NZ, USA, and Zimbabwe were reviewed. The NZ and Australian standards cover cement stabilised (and unstabilised) rammed earth design and the routine practice of using cement stabilised rammed earth in the USA suggest the same of the New Mexico Code (Walker and Maniatidis 2003).

The New Zealand Earth Building standard NZS4297 allows a design shear strength of 0.08 MPa to be used for standard grade construction and provides an empirical formula that allows specifically engineered earth structures to use a shear strength equal to 7% of the design compressive strength (Standards NZ 1998).

Bulletin 5, produced by CSIRO Australia, allows a design shear strength of $10 + 10d$ kPa to be used, where $d$ is the depth below the top of the wall in metres (Middleton 1987). This guide makes an allowance for the increased shear strength available when a normal stress is applied to the earth. The allowance of 10 kPa per metre depth of rammed earth correlates to an angle of internal friction of 27 degrees. This was determined by calculating the normal stress exerted by one cubic metre of rammed earth (assuming a material density of 2000 kg/m$^3$) and thus calculating the angle which would result in a shear strength increase of 10 kPa using the Mohr-Coulomb failure criterion.

In many earth building standards design shear strengths are not addressed or allowed in design without further evidence, such as testing. These standards typically have design requirements based on the compressive strength of the earth material and the slenderness of the walls. Such standards however are not appropriate for use in seismic areas such as New Zealand. The Zimbabwe Earth Building standards (Standards Association of Zimbabwe 2001) and the New Mexico Adobe and Rammed Earth Building Code (General Construction Bureau. 1991) are two examples.
9.2. Experimental Materials

In this research stabilised rammed earth specimens were reinforced with natural fibres; sisal and NZ flax. These two natural plant fibres were chosen due to their material properties and accessibility in local communities. The soil used was blended into a composition suitable for rammed earth construction and is detailed in Section 9.2.2.

9.2.1. Natural Plant Fibres

The inclusion of natural fibres in cement based composites can increase material toughness and strength through energy absorbing mechanisms like fibre debonding and pull-out, and by transferring loads across cracks (Filho et al. 1999). Galan-Marín et al. (2010) found that reinforcing soil with 0.25-0.5% of sheep wool (by weight) and alginate (a soil stabiliser derived from algae) prevented the formation of visible shrinkage cracks during the drying process and changed the failure mode from a sudden failure to one which continued to deform after the ultimate load had been reached.

In this research hard plant fibres sisal (*Agave sisalana*) and NZ flax (*Phormium tenax*) were used due to their good load bearing properties. The fibres were cut to lengths between 50 and 60 mm and were added into the rammed earth mixture in concentrations of 0.05% and 0.1% (by dry soil weight). From seven different researchers the tensile fibre strength and Young’s modulus of sisal was established to be between 298 – 577 MPa and 9 – 19 GPa respectively (Filho et al. 1999; Silva et al. 2008). Research on NZ flax fibres indicated a similar tensile strength range between 371 – 588 MPa (Harris and Woodcock-Sharp 2000; Ochi 2006). King and Vincent (1996) proposed a Young’s modulus of 31.4 GPa for the fibre.

9.2.2. Soil Selection and Preparation

Selecting a suitable soil for rammed earth construction was essential. Recommended soil constituent limits for rammed earth recommended by Walker et al. (2005) were 45-80% sand and gravels, 10-30% silts and 5-20% clay.

Wet sieve analyses and hydrometer tests were used to determine the grain size distribution of local fine (brick) clay and coarse (sand and gravel) sources. A 1 fine: 1 coarse mixture was selected. The composition of the blended soil was 13% clay, 19% silt, 50% sand and 18% gravel. The soil was mixed with cement in a 13:1 soil to cement ratio (7.7% cement by dry
weight of soil) which was selected based on past mix optimisation research (Haab and Kingi 1998).

A modified Proctor compaction test was conducted and determined that the optimal water content (O.W.C.) of the soil mix was 7.5%. Due to the addition of cement and the use of a lower custom compactive effort in test specimens (explained in Section 9.2.3), a water content of 10% was selected. The NZ earth building standards allow a water content within 3% of the O.W.C. to be used (Standards NZ 1998).

9.2.3. Soil Compaction

A custom compactive effort was used in this research for the manufacture of specimens. This arbitrary value was deemed to represent the compactive effort attained in a rammed earth wall more closely than a standard Proctor or modified Proctor compactive effort. The NZ earth building standards define that a sufficient compaction of rammed earth has been reached when the surface ‘rings’ when dropping a 6.5 kg hand rammer 300 mm on to the wall material (Standards NZ 1998). The standard Proctor compaction achieves a lower compaction than that achieved in rammed earth wall construction (Maniatidis 2005) and this is supported by Lilley and Robinson’s (1995) research which measured the O.W.C. of standard Proctor specimens and simulated onsite rammed earth specimens. A custom compactive effort of 1560 kJ/m$^3$ was used for this research (260% of a standard Proctor and 58% of a modified Proctor). This value was chosen based on the researcher’s judgement of when the formwork began to resonate. For a given compactive effort and water content there is a maximum bulk density than can be achieved in a soil. When this is attained any further compactive energy travels through the compacted soil to the formwork where it is dissipated by creating vibrations. The compaction details and compactive efforts of the different methods are listed in Table 49. The layer thicknesses were chosen so that all test specimens consisted of three rammed earth layers approximately 70 mm thick with layer interfaces at 1/3 and 2/3 of the specimen height. The dry densities of the triaxial and triplet specimens ranged between 2040 kg/m$^3$ and 2150 kg/m$^3$. 
Table 49 Compactive Effort of Proctor Compaction Methods used for Test Specimens

<table>
<thead>
<tr>
<th>Type of Compaction</th>
<th>No. of blows per layer</th>
<th>Height of blows (mm)</th>
<th>No. of layers</th>
<th>Weight of Rammer (kg)</th>
<th>Compactive Effort (kJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Proctor</td>
<td>27</td>
<td>300</td>
<td>3</td>
<td>2.5</td>
<td>600</td>
</tr>
<tr>
<td>Modified Proctor</td>
<td>27</td>
<td>450</td>
<td>5</td>
<td>4.5</td>
<td>2700</td>
</tr>
<tr>
<td>Custom Triaxial</td>
<td>26</td>
<td>450</td>
<td>3</td>
<td>4.5</td>
<td>1560</td>
</tr>
<tr>
<td>Custom Triplet</td>
<td>88</td>
<td>450</td>
<td>3</td>
<td>4.5</td>
<td>1560</td>
</tr>
</tbody>
</table>

9.3. Method

The shear strength of the rammed earth specimens was determined using the triplet test and the triaxial test.

9.3.1. The Triaxial Test

The triaxial test was conducted according to BS1377-8 – Part 8 (BSI 1990). 13 cylindrical specimens with a 2:1 aspect ratio (200 X 100 mm) were rammed in three layers using an automated mechanical rammer at the University of Bath. Four specimens were made with no fibre reinforcement and three specimens were made for each fibre content; 0.05% sisal fibre, 0.1% sisal fibre and 0.1% NZ flax fibre. Specimens were stored in a curing room held at 20 degrees and at a relative humidity of 62.5% for 21 days. The specimens were then capped on the top and bottom face and stored in the curing room for further 7 days. Specimens were tested at 28 days using a triaxial test at confining pressures of 0, 100 and 200 kPa. The confining pressures were chosen to cover the range of normal stresses that could be experienced in the walls of a one or two level structure. Compressed air was used to provide the confining pressures. Specimens from each of the different fibre contents were tested at the three confining pressures. A loading rate of 0.5mm/min was used.

9.3.2. The Triplet Test

The triplet test was conducted according to EN 1052-3 (BSI 2002). 28 stabilised rammed earth triplet specimens were made in total. Three sets of nine were rammed; one set with no fibre, another with 0.05% sisal fibre and the last with 0.1% sisal fibre. One triplet specimen was made with 0.1% NZ flax fibre. The dimensions of each triplet were 100 mm (W), 200 mm (L) and 200 mm (H). Each triplet was rammed in 3 layers approximately 70 mm thick after compaction. The triplet specimens were stored in a curing room held at 20 degrees and at a relative humidity of 62.5%.
Nine triplet specimens from each fibre combination set were tested under three normal stresses of 0.1 MPa, 0.3 MPa and 0.5 MPa as specified in the test method. The single NZ Flax fibre reinforced triplet was tested under a normal stress of 0.3 MPa. The lateral load was applied using a hand driven jack at a rate between 10-20 kN/min.

The triplet specimens were tested at ages between three and four weeks, and were capped with dental plaster 4 days before testing. The triplet test results did not show any appreciable difference in strength between three and four weeks old specimens. An assumption was made that the strength of the rammed earth specimens was related to the water content at time of test. The water content of six rammed earth specimens rammed for the modified Proctor test was monitored for 40 days. After two weeks, the water content of all six specimens was below 4% as seen in Figure 80. From the graph it can be seen that after two weeks in the curing room there was little further change in the water content. The graph also shows that the four specimens with initial water content higher than the O.W.C. (7.5%) reached equilibrium water content of 3.5% whereas the two specimens with an initial water content of 7% and 6% levelled out at a lower water content around 2.4%.

Figure 80 Water Content over time of Stabilised Rammed Earth Specimens with Differing Initial Water Contents

9.4. Results

The shear strengths determined from the tests are reported with apparent cohesion values (c’) and the angles of internal friction (φ). The results for the triplet tests are displayed in Table 50 and the results of the triaxial test in Table 51.
During the triplet tests the normal stresses applied on the specimens were kept at the set level during the test by the StrainSmart Control software. The shearing force applied was recorded by the software and the maximum value was used to determine the failure shear stress of the specimen using the below equation.

\[ \tau = \frac{F_s}{(2 \times A_n)} \]

Where \( \tau \) = shear stress, \( F_s \) = shearing force, \( A_n \) = mean cross sectional area of the two rammed earth layer interfaces

Three specimens were tested for each fibre content and normal stress combination. Each test result presented in Table 50 represents the mean result of the three specimens tested for each combination. Only one triplet specimen was tested for the subset D1(F).

The shear stress results were plotted against normal stress and a linear regression on the data allowed the apparent cohesion and angle of internal friction to be determined.

### Table 50 Shear Strength Results of the Triplet Shear Test

<table>
<thead>
<tr>
<th>Specimen Subset*</th>
<th>Age at Test (d)</th>
<th>Fibre (%)</th>
<th>Normal Stress (kPa)</th>
<th>Shear Stress (kPa)</th>
<th>Apparent Cohesion (c') (kPa)</th>
<th>Angle of Internal Friction (( \phi ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-3</td>
<td>27</td>
<td>0</td>
<td>107</td>
<td>453</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>A4-6</td>
<td>26</td>
<td>0</td>
<td>311</td>
<td>609</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7-9</td>
<td>21</td>
<td>0</td>
<td>522</td>
<td>857</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1-3(S)</td>
<td>20</td>
<td>0.05</td>
<td>108</td>
<td>435</td>
<td>286</td>
<td>53</td>
</tr>
<tr>
<td>B4-6(S)</td>
<td>20</td>
<td>0.05</td>
<td>318</td>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B7-9(S)</td>
<td>20</td>
<td>0.05</td>
<td>525</td>
<td>991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1-3(S)</td>
<td>23</td>
<td>0.1</td>
<td>109</td>
<td>465</td>
<td>383</td>
<td>45</td>
</tr>
<tr>
<td>C4-6(S)</td>
<td>21</td>
<td>0.1</td>
<td>383</td>
<td>744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7-9(S)</td>
<td>20</td>
<td>0.1</td>
<td>524</td>
<td>876</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1(F)</td>
<td>19</td>
<td>0.1</td>
<td>318</td>
<td>745</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*S denotes a sisal fibre addition; F denotes a NZ Flax fibre addition

During the triaxial test, the axial load, axial displacement and pore water pressures were recorded and the maximum axial load was used to determine the deviator stress. The deviator stress reported in Table 51 was adjusted to take into account the weight of the loading ram and effect of the confining pressure on the loading ram. Mohr’s circles were plotted from the test results and the least-squares method was used to fit a linear line that was tangential to the Mohr’s circles. The apparent cohesion and angle of internal friction values were determined from this line. The correlation coefficient shows how closely the line derived by the least
squares method met the requirement to be tangential to all of the Mohr’s circles. A value close to 1 indicates a good fit.

Table 51 Shear Strength Results of the Triaxial Shear Test

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Age at Test (d)</th>
<th>Fibre (%)</th>
<th>Confining Pressure ($\sigma_{3f}$) (kPa)</th>
<th>Deviator Stress ($\sigma_{d}$) (kPa)</th>
<th>Principle Stress at Failure ($\sigma_{1f}$) (kPa)</th>
<th>Apparent Cohesion ($c'$) (kPa)</th>
<th>Angle of Internal Friction ($\phi$)</th>
<th>Correlation Coefficient ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>27</td>
<td>0</td>
<td>0</td>
<td>3709</td>
<td>3709</td>
<td>724</td>
<td>48</td>
<td>0.993</td>
</tr>
<tr>
<td>M2</td>
<td>28</td>
<td>0</td>
<td>108</td>
<td>4447</td>
<td>4555</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>28</td>
<td>0</td>
<td>200</td>
<td>4895</td>
<td>5095</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>28</td>
<td>0</td>
<td>0</td>
<td>3804</td>
<td>3804</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N1S</td>
<td>28</td>
<td>0.05</td>
<td>0</td>
<td>3816</td>
<td>3816</td>
<td>758</td>
<td>47</td>
<td>1</td>
</tr>
<tr>
<td>N2(S)**</td>
<td>28</td>
<td>0.05</td>
<td>100</td>
<td>3491</td>
<td>3591</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N3(S)</td>
<td>28</td>
<td>0.05</td>
<td>200</td>
<td>4883</td>
<td>5083</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1(S)</td>
<td>27</td>
<td>0.1</td>
<td>0</td>
<td>3632</td>
<td>3632</td>
<td>554</td>
<td>56</td>
<td>0.998</td>
</tr>
<tr>
<td>O2(S)</td>
<td>27</td>
<td>0.1</td>
<td>100</td>
<td>4717</td>
<td>4817</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O3(S)</td>
<td>27</td>
<td>0.1</td>
<td>0</td>
<td>3901</td>
<td>3901</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1(F)</td>
<td>27</td>
<td>0.1</td>
<td>100</td>
<td>4729</td>
<td>4829</td>
<td>648</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>P2(F)</td>
<td>27</td>
<td>0.1</td>
<td>200</td>
<td>5520</td>
<td>5720</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3(F)</td>
<td>27</td>
<td>0.1</td>
<td>0</td>
<td>3816</td>
<td>3816</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S denotes a sisal fibre addition; F denotes a NZ Flax fibre addition

** Specimen N2(S) was omitted from analysis due to uneven bearing issues on the top face during the triaxial shear test

The triplet tests failed along the planes between the rammed earth layers and the triaxial samples failed along diagonal planes as shown in Figure 81 and Figure 82.
9.5. Discussion and Analysis

9.5.1. Lower Apparent Cohesion Measured Using the Triplet Test Method Compared with the Triaxial Test

The apparent cohesion measured using the triplet test ranged between 286 – 380 kPa (mean 332 kPa) whereas the apparent cohesion measured using the triaxial test was approximately double; between 554 – 758 kPa (mean 671 kPa). The apparent cohesion is an indicative measure of the stresses within the material that resist shear. For one or two level rammed earth structures, the normal stresses acting on the walls are small and the shear strength value of the material is derived predominantly from the apparent cohesion.

The difference in the measured apparent cohesion is not surprising although the reasons for the two-fold strength increase using the triaxial test is important to understand. The triplet test forced the specimens to fail at the planes between the rammed earth layers. The interface is weaker than the rammed earth layer because of several reasons. As the soil is compacted in layers, the top of the layer receives more compaction than the bottom and bonds less effectively to the subsequent layer above. During the time between ramming subsequent layers some loss of moisture (and where cement is added partial curing) will also occur. The fibres added to the triplet specimens did not extend between rammed earth layers and would not have contributed to the shearing resistance measured. The triaxial tests which failed diagonally through several rammed earth layers would have benefited from the fibres. The triaxial specimens showed no evidence of failing along the weak planes between rammed earth layers. The slight intersection of the diagonal failure planes with the base in a few of the
triaxial specimens indicate that an aspect ratio larger than 2:1 would provide a more accurate test of the material’s shear strength.

The difference in apparent cohesion results arises because the triplet test measures the shear strength at the interface between rammed earth layers whereas the triaxial test measures the shear strength of the material through several rammed earth layers. The larger apparent cohesion measured using the triaxial test method was attributed to the diagonal orientation of the failure plane through several rammed earth layers. This failure plane has greater frictional forces and tighter particle interlock than one located between rammed earth layers.

As a layered material the shear strength capacity of rammed earth will vary depending on the orientation of the applied load and this is clearly seen in the results. The tests have shown that rammed earth has a lower shear capacity along the horizontal plane between the layers than through the rammed earth layers. Despite the weaker shear strengths measured on the horizontal plane between rammed earth layers, a diagonal shear failure was deemed more likely to occur due to the placement and geometry of structural rammed earth walls in practice. Structural rammed earth walls typically range between 0.7 to 4 metres in length and are often built adjacent to other structural walls which would restrict horizontal movement in a layer. It is unlikely that a sliding shear failure would occur before a diagonal shear failure and thus the triaxial test provides a better measure than the triplet test of the shear strength capacity of a rammed earth wall.

9.5.2. Friction Angles and Earth Building Standard Allowances

CSIRO Bulletin 5 was the only standard found that allowed design shear strengths to increase in proportion to applied normal stresses. The angle of friction assumed in that standard was calculated to be 27 degrees. In this research the angle of friction measured for the cement stabilised rammed earth test specimens ranged between 45 – 56 degrees. This result was measured consistently in both test methods. For stabilised rammed earth structures subjected to high normal stresses, this result implies a significant increase in shear strength capacity. Apart from CSIRO Bulletin 5, no method is provided in any other earth building standard to use this shear strength component in the structural design of an earth structure.

9.5.3. Comparison of Test Results with Design Guidance for Shear Strength

Shear strength is an important design parameter for rammed earth buildings in seismic regions. The two earth building standards reviewed that allowed design shear strengths for
rammed earth to be used in design were the New Zealand Earth Building Standards and CSIRO Bulletin 5.

Using the method provided in NZS4297, a 95th percentile design compressive strength of 2.8 MPa was established for the stabilised rammed earth used in this research. Results were corrected for specimen aspect ratios (2:1) and sample size (5). Based on the NZ earth building standard NZS4297, a design shear strength of 200 kPa (with testing) was calculated for a structure with specific design and 80 kPa (without testing) for standard grade construction. The mean apparent cohesion values determined from the triplet and triaxial shear tests were 331 kPa and 671 kPa respectively with the latter result being argued as the more representative value for the material.

The tests conducted have shown that stabilised rammed earth walls have greater shear strength than is currently allowed for in design by existing earth building standards.

9.5.4. Recommended Method for Characterising the Shear Strength of Stabilised Rammed Earth

The recommendation from this research is to use the triaxial test method to establish the shear strength of stabilised rammed earth. Test specimens should be rammed to an aspect ratio of at least 2:1 and use a compactive effort equivalent to a standard Proctor compaction test. Using the standard Proctor compaction avoids the complications and issues that may arise from using custom compactive efforts or compactive efforts based on the formwork ‘ringing’. The use of a standard Proctor compactive effort is lower than that typically achieved in rammed earth and thus errs on the conservative side.

For situations where only the compressive strength of stabilised rammed earth is known, a conservative estimate of shear strength can be made by using a design shear strength equal to 7% of the design compressive strength. This is currently permitted in the NZ Earth Building Standards (Standards NZ 1998) for a specifically designed structure.

The triplet test was not recommended as a shear test method for rammed earth because:

- Manufacture and preparation of triplet test specimens required a lot of time and effort. Custom formwork was also required.

- The triplet specimens weighed 10.5 kg on average. This was not as convenient or safe to transport and test as the triaxial specimens (<4 kg).
Locating a laboratory that has the capability and expertise to conduct a triplet test is potentially more difficult and expensive than a triaxial test.

The test measures the shear strength of the interface between rammed earth layers but due to the limited horizontal deformation potential in practice, rammed earth walls are more likely to fail diagonally through several rammed earth layers.

9.6. Conclusions

Stabilisedrammed earth construction is growing in use around the world. Although rammed earth technology has been used since historic times until now, there is still a lot of uncertainty in the area of determining and understanding the shear performance of rammed earth. A better understanding of the shear strength of rammed earth and how to characterise it will allow less conservative guidelines to be specified and more widespread use of the building method.

This research has used the triplet test (masonry) and the triaxial test (geotechnical) to establish the shear strength of a stabilisedrammed earth material reinforced with sisal and NZ flax fibres. The main findings were that the apparent cohesion of the cement stabilised rammed earth had a mean of 671 kPa when using the triaxial test and 332 kPa when using the triplet test. The difference in test results was due to the way the triplet test forced a shear failure to occur along the weak interface between rammed earth layers whereas the triaxial test specimens failed along a stronger diagonal shear plane. Although the triplet test will provide a more conservative design, the triaxial test better represents the diagonal shear failure which is the predominant shear failure mode for rammed earth walls in practice.

A review of existing building standards for rammed earth construction showed that only the NZ Earth Building standards and CSIRO Bulletin 5 had specified an allowable design shear stress for rammed earth. The standards allowed design shear strengths of 80 kPa and 10 kPa respectively. A value of 210 kPa would be allowed by the NZ earth building standards for a specifically designed rammed earth structure using the soil mix used in this research.

A recommendation is given to use the triaxial test as a shear test method for rammed earth using specimens with an aspect ratio of at least 2:1 that are made using the same compactive effort as a standard Proctor compaction test.
The use of a lower bound design shear strength for stabilised rammed earth equal to 7% of the design compressive strength, as specified in the NZ Earth Building Standard NZS4297, has been shown to be conservative and the use of this lower limit is supported by the results of this research.
Chapter 10. IMPLEMENTATION OF THE AHIPARA WHAREUKU

This chapter records the process of implementing a flax-fibre reinforced rammed earth housing solution within the Ahipara community. The chapter is presented in sections which correspond with distinct stages of the implementation process. Although the different stages often overlapped, the chapter has been written to provide a roughly chronological account of the process.

The experiences, lessons learnt and observations made are recorded in order to document the key steps in the implementation process. Details of the tasks that needed to be completed, the obstacles encountered and how they were overcome, and the costs of the project, are provided to assist others aspiring to implement a rammed earth housing solution in a rural Māori community.

This research was conducted under the auspices of a Memorandum of Understanding (MOU) with the Unaiki Mare Trust, in partnership with members of the trust and their relatives, all of whom are henceforth referred to as Ahipara whānau.

Ahipara is located near the northern tip of the North Island of New Zealand as is shown in Figure 83, 327 km from Auckland by road, approximately 4 ½ hours travel by motor vehicle.

Figure 83 Map Showing the Shortest Road Route between Auckland and Ahipara
10.1. Introduction from the Ahipara Whanau

Whangatauatia is the mountain
Karirikura is the sea
Wairoa is the river
Whaaro Te Oneroa a Tohe is the foreshore
Tinana is the canoe
Tumoana is the people
Te Rarawa is the tribe

This is the chief introduction for this area
Breath of life!

- This is the pepeha (customary introduction) of Rueben Taipari Porter (Te Rarawa), a research partner from the Ahipara whanau

My maunga (mountain) Rangituhituhi that protects my back from the harsh west wind and the cold southerlies has been doing so for over 20 generations of sustainable occupation by my ancestors.

My river Ngā Karoro has been washing the bones of our deceased in our valleys since the times when the clans of Te Rokeka occupied this valley. Ngā Karoro has been supplying us with tuna (eels) and wai māori (drinking water) below our papa kāinga (original home) since my great grandmother Kararaina was a child and generations before.

My sweet water spring from the puna (well) where the black winged gulls nest, has been providing me with drinking water all my life and will carry on this task for my children when I am passed.

My whenua (lands) has provided me with kai Māori (food) of all varieties from our kūmara (sweet potato) and peruperu (potato), our taputini (sweet potato variety), our reka marauroa, our urenika (Māori potato) our maika, our taro. The fruit trees my nana Puni Mare planted over 50 years ago still provide today,

The sea Karirikura, adjacent to my whenua, is important enough to me to name my daughter after to maintain that link for her to remind her where she comes from in this world.

My whenua connects me to my foreshore and long beach and its sustenance of tuatua, tipa (scallops), kūtai (mussels) and toheroa. The journey that our ancestor Tohe made along our takutaimoana (foreshore) Te Oneroa a Tohe and through my whenua on his way to Hokianga connects me to the 5 tribes of Muriwhenua (North Cape)
That connection is maintained by the constant acknowledgement of the spirits that pass my valley on their final journey along Te Ara wairua (pathway of the spirits) to Te Rerenga wairua (Cape Reinga) where they leap into Rarohenga (the underworld) and return home to their final resting place of our ancestors to Hawaiki.

All of my memories of my life centre around this whenua. My relationships all stem from here with my Elders, my parents, my siblings, my cousins and my wider whanau. My best friends all connect to me through their lands that surround me and their whakapapa that connects them to me. My children are all connected to them through our whakapapa and our whenua...

All those who are important to me, descend from these lands.

They encompass all that is valuable and precious to me.

My whenua, my whanau and my whare are inseparable when describing what my future hopes are for my whanau... and now my whenua has provided my with a home through the knowledge shared with us in the project called Whareuku.

This project called Whareuku will help us to maintain Ahikaaroa, our sustainable occupation of our whenua for another 20 generations and we can maintain a stable whanau because of that noho. Ahikaaroa is the term for long term occupation and this is the destiny of my mokopuna (grand children) and their descendants.

To have a place to belong to and be responsible of, is the greatest legacy that I can possibly leave them

Mana whenua, mana tangata, mana atua (Power from the land, people and God).

10.1.1. The Significance of the Uku Housing Research to the Ahipara Whanau

The concept of a structure made from an organic substance such as the whenua, that will give protection and shelter to our hapu and our mokopuna is an ideal that sits well with us. Many people have been responsible for our whenua for over 20 generations and until recently it has remained in good condition under our care. For a structure to be built on the whenua, made from the very whenua that it resides on, with the potential to be a structure to provide for the next five generations is the essence of what Māori would call true prosperity.
Whareuku is to my hapū (sub-tribe) in Ahipara, more than just a dwelling, a house or even a home. It is a concept of hope for a future of security and serenity for our mokopuna, in this ever changing and challenging landscape we once called Mother Earth, Terra madre and Papa-tū-ā-nuku (Earth mother). Whareuku is a hope for true prosperity.

Whareuku captures the essence of whanaungatanga, kaitiakitanga and kotahitanga.

- **Whanaungatanga**: The bonding and nurturing of a community by supporting and sheltering its members through many of life’s experiences.

- **Kaitiakitanga**: the holistic responsibility of guardianship of the land, the people and the essence of nature spirit that is the creation of life.

- **Kotahitanga**: to aspire together as one source, to improve a member’s community for the benefit of their community and tomorrow’s community.

Whareuku uses these principles to build a structure of strength and calm to provide an ideal environment in which to raise the next generation of kaitiaki in.

### 10.2. Establishing Relationships

At the beginning of the housing project, it was important to meet potential research partners kanohi ki te kanohi (face-to-face). The Māori practice of kanohi kitea (presenting yourself to people face to face) was important for the initial meetings because all of those involved were meeting for the first time and did not know each other. Adhering to this practice enabled a good partnership and relationship to be established between the university researchers and Māori individuals from the Ahipara community.

On 27th December 2008, researchers from the university travelled to the Far North District to meet with people and groups who were potential partners for the rural Māori housing research. The meetings were held with different parties over four days.

The university researchers met with a representative of the Ahipara whānau, the eventual research partners, who had organised a meeting at Te Kohunga beach, Ahipara. The meeting began with introductions. The representative from the Ahipara whānau shared his connection to the land and how his tribe, Te Rarawa, came to settle in the area. He established his genealogical link to the land all the way back to his ancestors who migrated to Aotearoa (New Zealand) on the Te Rarawa waka (canoe).
Over the next four months, further trips were made to meet people who were to be involved in the Ahipara research project. Earth samples were gathered from a number of potential local sources for testing as shown in Figure 84 and Figure 85, and flax leaves were harvested from an onsite flax plantation for testing purposes as well (Figure 86).

![Figure 84 Bellingham’s Quarry Overburden (left)](image1)

![Figure 85 Earth from the Proposed Site of House Construction (right)](image2)

![Figure 86 Harvesting Leaves from a Flax Plantation Located on the Proposed Housing Site in Ahipara](image3)

In July 2009, a rammed earth construction workshop was held at the University of Auckland for members from the Ahipara community to observe and learn how to building rammed earth panels. Two rammed earth panels were constructed over the three day workshop. During the workshop participants mixed, transported and rammed the earth mixture, and practiced setting up and taking down the formwork for each panel (Figure 87). The workshop was an opportunity to gain experience ramming earth panels and to build relationships with researchers from the university. The laboratory setting also reduced the risks associated with
a new construction experiment, where greater control of equipment requirements, material variability, and personnel safety was possible.

Figure 87 Preparing the Formwork during the Rammed Earth Workshop held at the University of Auckland July 2009

In the same month, a day trip was organised for individuals from Ahipara and students from the university to visit two sites where flax-fibre reinforced rammed structures had been built previously. The first dwelling visited was located at Te Kura Kaupapa Māori o Piripono, Otara (Figure 88 & Figure 89) and the second at Waimango Papakainga, Tikapa Moana (near the Firth of Thames).

Figure 88 North View of the Rammed Earth Dwelling at Te Kura Kaupapa Māori o Piripono, Otara, Auckland (left)

Figure 89 Rammed Earth Dwelling at Te Kura Kaupapa Māori o Piripono, Otara, Auckland (right)
A memorandum of understanding was signed between the Unaiki Mare Whānau Memorial Trust from Ahipara and the Uku – Sustainable Earth Fibre Housing Project research team based at the University of Auckland in July 2009.

10.3. Engaging with the Local Community

The rammed earth housing research was a large undertaking and required the support of the community in order to succeed. In addition to building relationships with individuals from the Ahipara whānau, it was important to engage on a larger scale with the community of Ahipara. The Māori right to self-determination also meant it was appropriate to use an inclusive, community-friendly, research approach to develop and implement a housing solution for Māori. Two ways in which the local community were invited to participate in the research were by attending a rammed earth building workshop held in Ahipara and by volunteering to participate in the Mauri model survey to evaluate the performance of two housing methods for their community. The workshop was conducted over five days (23rd-27 November, 2009), and was attended by local families, kaumatua (elders), youths and tradesmen, both Māori and non-Māori. A group from the local school Te Rangi Aniwaniwa performed a haka (an impromptu choreographed dance performance) as a way of showing their support for the research. Photos showing the construction of rammed earth panels are shown in Figure 92 and Figure 93. Methods used to mix earth during the workshop are shown in Figure 94 and Figure 95.
Sixteen Māori individuals from the local community participated in the Mauri Model surveys. This was a way Māori could influence the decision making process of the research and share their knowledge and experience with regard to the performance of the two housing methods surveyed.

The support gained from the inclusion and participation of local Māori in the research gave the research legitimacy. To illustrate this point, when the Mauri Model survey of housing perspectives was being conducted with some locals, a kaumatua came and interrupted the meeting to challenge the authority of the researcher (who he noted was not from the area or of Māori decent), to collect information from Māori and to implement a housing solution for Māori. Because of the efforts made previously to partner with Māori from the Ahipara community and to conduct research in a culturally inclusive manner, local Māori present were able to explain to the kaumatua that this research was legitimate and was not conducted to exploit Māori but rather to benefit them. If the research had not been conducted in a way
that was culturally appropriate and legitimate, the challenge from the kaumatua would have been credible and could have negatively affected the research.

The project had a high profile within the community which resulted in local businesses providing reduced rates for building materials and services, and also resulted in many opportunities to share the research with others. Many individuals from Māori communities around the country came to see the research, to support the house construction, and to acquire information regarding how to develop self-sufficient housing on their own lands. The housing research was publicized in newspapers (as shown in Figure 96), radio interviews were conducted and broadcast on local and national radio stations, and the research was televised on a number of occasions.

10.4. Choosing the House Location

The Ahipara whānau already had an idea where they wanted to build the rammed earth house. Nearly a decade earlier they had built a simple seat on the spot so that they could visit the location, sit there and visualize living there. The view of the land from that site is shown in Figure 97.
The location was chosen for a number of reasons. First, the location was chosen because it was in the centre of the land block. From that point, the occupants could keep watch over all of their property. As a kaitiaki (guardian) of the land it was important for the Ahipara whānau to be able to see what was happening on it. It was mentioned that their ancestors used to live in that area but over the last century, as their more immediate ancestors integrated into the Western way of living, the whānau had moved to live at the side of their property that was adjacent to the main road. Living here made it easier to get to work, and to access services and shops at the local town centre. The whānau ceased to live off their land and to maintain the property. Up until 10 years ago when some of the Ahipara whānau returned to live on the land, the land was unproductive and covered with gorse. Another reason for the location was that it was closer to the family urupā (cemetery).

The location was suitable for a rammed earth house. The site was located on top of a small rise, was not susceptible to flooding, and had natural drainage. Due to the elevation and the lack of obstructions the site received unimpeded sunlight exposure. The top of the rise had a flat area that was large enough to build a house with a rectangular floor plan with a longer axis in the east-west direction. Dwellings built using this orientation maximize exposure to the sun.

There were other desirable and functional advantages of the site chosen. The site had ample flat space toward the north side of the building location which was consequently used as a children’s play area and outdoor gathering space. A large hill on the Southern aspect also shelters the dwelling from prevailing winds. Water from a nearby natural spring towards the south is used to provide drinking and general water needs.
10.5. House Design

The house design process took into account a range of considerations. Most importantly, the design was guided by the Ahipara whānau, to meet their specific lifestyle requirements and wants. Other design considerations arising from an understanding of Māori cultural norms and traditions, and design details that would improve the performance and constructability of a rammed earth dwelling were also taken into account. Design decisions for the house were made holistically to improve the performance of the house. The benefits of each decision are outlined in the tables below in the environment, social, cultural and economic dimensions. The benefits of using a rammed earth housing design are listed in Table 52.

<table>
<thead>
<tr>
<th>Environmental</th>
<th>Social</th>
<th>Cultural</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low embodied energy</td>
<td>Healthier air quality due to minimal chemicals in rammed earth wall panels</td>
<td>More sustainable way of living on the land</td>
<td>Low maintenance cost</td>
</tr>
<tr>
<td>Minimal need for heating during winter and cooling during summer</td>
<td>Healthier air quality due to earth wall ability to naturally regulate internal moisture levels, thus preventing condensation and issues resulting from dampness</td>
<td>Promotes self-sufficient living through the use of construction methods that non-technically skilled whānau can use</td>
<td>Many rammed earth buildings have lasted centuries</td>
</tr>
<tr>
<td>Minimize use of products with chemicals in wall construction</td>
<td>Identity of whānau and community integrated into the house because they built it</td>
<td>Damage to rammed earth walls can be repaired using earth, water and cement</td>
<td></td>
</tr>
<tr>
<td>Longer design life means house does not need to be demolished and rebuilt every 50 or so years</td>
<td></td>
<td></td>
<td>More than 90% of materials (earth, flax) required were already owned by the whānau</td>
</tr>
</tbody>
</table>

In addition to meeting the needs of the immediate Ahipara whānau as a family with young children, the dwelling needed to be used to facilitate their role in the community. The Ahipara whānau often host gatherings and meetings at their home, and have visitors and extended family coming to visit throughout the year. The kitchen, dining and lounge areas needed to be able to comfortably host groups of up to 50 people and to temporarily accommodate visitors staying overnight. To accommodate these needs, the house was designed with a large kitchen area, and a large lounge area that could be used as a sleeping area.
Specific desires of the Ahipara whānau were to use natural and local building materials. In particular they wanted to avoid the use of treated timber. The Ahipara whānau also wanted the house to be operated solely off a locally generated power source and to have an environmentally friendly onsite wastewater disposal system. A low level of privacy within the house was acceptable as well. The members of the Ahipara whānau had grown up in small or traditional wharenui (meeting house) styled buildings with little to no privacy, but had also lived in conventional dwellings with separate bedrooms. They concluded that it was healthier for a family to grow up with less privacy noting that when there was little privacy in the home, everyone had to learn to get along with one another. There was nowhere to hide or a room to escape to. Everyone had to learn to compromise, share and accept one another’s differences. An open communal living environment was achieved by designing the building similar to a wharenui and by eliminating any internal doors within the building (except the bathroom). The benefits of the lifestyle requirements and desires of the Ahipara whānau are detailed in Table 53.
Māori values and culture that influenced the house design are summarized in Table 54. Māori associate tapu (sacred or prohibited) and noa (profane or common) attributes with various household activities and require the separation of these activities. For example, food
preparation is tapu whilst washing and bathing is noa. As a result the kitchen should not be connected to the bathroom, toilet or laundry areas (Hoskins et al. 2002). Other cultural considerations include the requirement to have a large porch or veranda area in front of the house to facilitate the greeting of visitors before entering the house and to have visitors arrive in clear view of the house occupants to the front of the house.

<table>
<thead>
<tr>
<th>Room arrangement</th>
<th>Environmental</th>
<th>Social</th>
<th>Cultural</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children are easily visible</td>
<td>Children can see parents from most places in the house</td>
<td>Common/profane tasks (noa) not connected to rooms where sacred tasks (tapu) are performed. E.g. Food preparation (tapu) separated from washing (noa)</td>
<td>Efficient use of floor space due to removal of hallways</td>
</tr>
<tr>
<td>Large porch/verandah area</td>
<td>Useful for large house gatherings</td>
<td></td>
<td>Easy access to outdoor environment. Useful for hosting and welcoming visitors and meetings</td>
<td></td>
</tr>
<tr>
<td>Elevated land</td>
<td>Unobstructed exposure to sun throughout the day for light and indoor heating</td>
<td>Good view of land, countryside, ocean and nearby towns</td>
<td>Clear view of the pathway to the house so that visitors arriving can be seen in advance</td>
<td>Natural drainage, no risk of flooding</td>
</tr>
</tbody>
</table>

The house also incorporated good housing design principles which improved the thermal performance of the house and made the design, construction and performance of the house more efficient. The house was built to have a large area of the house with openings facing towards the north to enable natural sunlight to enter and warm the house. The majority of window and door openings were placed on the northern side of the building. Minimal openings were placed on the southern walls which received no sun exposure. Exposure to natural sunlight or sources of heat is especially important during the winter in rammed earth structures because the material can absorb the heat and release it over many hours into the night thus keeping the house warmer without the need for artificial heating. The doors and windows of the Ahipara dwelling were double glazed to improve the insulative properties of the dwelling. A sloped exposed rafter ceiling was used to improve air circulation within the house. A simple rectangular, single storey, and roughly symmetrical floor plan, was adopted to improve the seismic performance of the house, and the rammed earth wall panel locations were chosen to make the house more efficient to build. The benefits of these design decisions are summarised in Table 55.
Table 55 Environmental, Structural and Rammed Earth Design Influences

<table>
<thead>
<tr>
<th>Environmental</th>
<th>Social</th>
<th>Cultural</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td>Reduces heat loss</td>
<td>Helps to maintain a healthy indoor temperature</td>
<td>More sustainable way of living on the land.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reducing energy consumption</td>
</tr>
<tr>
<td>Lots of north facing openings &amp; less south facing openings</td>
<td>Maximize natural heat gain and lessen building heat loss</td>
<td>Healthier due to use of natural ambient heat to keep house warm</td>
<td>More sustainable way of living on the land.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximising solar energy to heat house</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lessen cost to keep house warm during winter</td>
</tr>
<tr>
<td>Rectangular, single storey, symmetrical</td>
<td>Less building material waste. House was built using modular panels and formwork</td>
<td>Accessible for elders, safe for children</td>
<td>Efficient and simple structural and seismic design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower construction cost due to simple, single storey design</td>
</tr>
<tr>
<td>Use of a sloped timber diaphragm with exposed rafter ceiling</td>
<td>Healthier indoor air quality as a result of better air circulation</td>
<td>Similar form to a wharenui</td>
<td>Roof is structural and can resist torsional forces</td>
</tr>
<tr>
<td></td>
<td>Perception of space due to high roof height</td>
<td></td>
<td>High roof height is more comfortable for formal meetings</td>
</tr>
</tbody>
</table>

10.6. Soil Testing

Earth samples were taken from a number of potential sources to identify a suitable local source of earth to use for construction of the rammed earth dwelling. Earth was first taken from the site at which the house was to be built. A karakia (prayer) was spoken before the ground was broken. Earth samples were gathered from four locations around Ahipara for further analysis at the university geomechanics laboratory. Jar tests were performed on each of the four soils initially to gain a rough indication of each soil’s composition. The jar tests conducted are shown below in Figure 98.

Figure 98 Jar Tests of Earth from Four Potential Local Earth Deposits for the Ahipara House Construction
Identifying local sources of earth suitable for the house construction was important because a large amount of earth was required for the house construction. The decision directly impacts on the durability and strength of the final rammed earth product and the cost of construction.

At the university, soil tests were conducted on the earth samples and on mixtures of the earth samples. Each test and the properties the tests are used to measure are described in the following sections.

**10.6.1. Wet Sieve Analysis and Hydrometer Test**

The wet sieve analysis and hydrometer tests were carried out to determine the particle size distribution of each earth sample. The wet sieve analysis determined the distribution and proportion of gravel and sand particles, and the proportion of fines in the earth samples. The hydrometer test was needed to determine the gradation and proportions of silt and clay particles. For rammed earth construction the clay proportion of the earth mixture is particularly important because clay particles have a large influence on the performance of the rammed earth product. Clay is a natural binder within the rammed earth mixture and thus influences material strength, permeability and durability. The binding ability of clay is reduced by the addition of cement and vice versa, so an appropriate balance of both constituents is required to ensure the mixture has adequate binding ability. There is a general agreement in rammed earth building literature regarding appropriate gradations of earth for rammed earth construction. The soil gradation plot of an earth deposit from Sandstone Developments Quarry located in Muriwai, Auckland, and the upper and lower limits for rammed earth construction used in this research, are shown in Figure 99.

A blank soil gradation template has been provided in Appendix C.1 as a resource which can be used to determine the suitability of an earth mixture for rammed earth construction from a soil particle gradation aspect.
10.6.2. Atterberg Limits Test

The Atterberg Limits test was used to measure the plasticity properties of the fine-grained earth sources as shown in Figure 100. The results of the test reveal the Plasticity Index, Liquid Limit and Plastic Limit of the earth. Houben & Guillaud (1994) surveyed many historic rammed earth structures and found that the most durable structures were made with earth mixtures that had soil plasticity properties within specific ranges. A selection criterion for a suitable rammed earth mixture for the research project was that the earth mixture had to have plasticity properties similar to that found in durable historic rammed earth structures.
10.6.3. Alcock’s Test

Shrinkage tests were conducted on the earth samples, and mixtures of them. Earth mixtures were compacted into 600 mm long moulds and were left to dry for 28 days at room temperature. The amount of length-wise shrinkage was measured to determine the shrinkage of the earth mixture. The NZ Earth Building standards have stringent shrinkage limits of $\leq 0.05\%$ for rammed earth (Table 2.1 in Standards NZ 1998) so selecting an earth mixture with low shrinkage characteristics was one of the critical considerations. A photo of the Okura and Muriwai earth samples after the 28 day Alcock’s test is shown in Figure 101.
Using the results from the previous four tests, a 1:1 earth mixture of Okura earth and sand was selected. The selected earth mixture was referred to as “Okura sand.”

10.6.4. Compression tests

Using the Okura sand mixture, rammed earth compression cylinders were made and tested according to the American Standard Test Method D1633-00(2007) *Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders*. The tests were conducted to identify an optimum percentage of flax fibres and cement to add into the earth mixture and to ensure a compressive strength of 1.3 MPa was exceeded by rammed earth specimens made using the mixture selected. A custom mould and rammer was made to manufacture the test specimens and is shown in Figure 102. The rammed earth cylinders manufactured are shown in Figure 103.

The final rammed earth composition selected for the Ahipara dwelling comprised of the Okura sand earth mixture with an addition of 6% cement and 0.15% flax fibres (by weight of dry soil).

10.7. Wall Panel Tests

Tests were conducted on full-size wall panels built in a test laboratory in Auckland, and onsite in Ahipara, to evaluate the seismic capacity of rammed earth made using the Okura sand mixture. Two panels were built and tested at the University of Auckland Civil
Engineering Test Hall. Five panels were built on-site in Ahipara but only four were tested due to issues encountered when building and testing onsite in Ahipara.

10.7.1. Laboratory Panel Construction and Testing

In June 2009 concrete foundations were poured (Figure 104) in preparation for the construction of the rammed earth panels. Six cubic metres of Okura sand were transported in bulk bags to the university. Flax leaves were also harvested from Ahipara (Figure 105) and were transported to Auckland where they were processed into flax fibres (Figure 106) using a mobile flax stripper (Figure 107) which was designed and built for the housing research.

The rammed earth formwork and equipment was also transported to the university and a bobcat tractor was hired to mix and transport the earth during construction. The formwork used is shown in Figure 108.
In July 2009, a construction team consisting of students from the university and members of the Ahipara whānau (Figure 109) were taught the process of building rammed earth panels. The group proceeded to build the first two rammed earth panels using the Okura Sand mixture. The rammed earth panels were capped with a layer of concrete the day after the second rammed earth panel had been completed. A photo of the second rammed earth panel with a concrete cap is shown in Figure 110.

The wall panels were left for 28 days to cure. The panels were instrumented with equipment to measure displacements and applied loads in preparation for the wall panel test as shown in Figure 111. During the wall tests, the panels were loaded laterally at the top of the panel and...
were cycled fully back and forth twice at each displacement level. The wall panels were cycled using increasingly large displacements until panel failure was attained. Failure was defined as the point when the maximum load the wall was able to resist had decreased to 80% of the highest load attained in previous load cycles. A failed panel is shown in Figure 112.

Both panels resisted loads that were approximately 50% stronger than the predicted strength capacities. A summary of the predicted and actual loads are shown in Table 56.

<table>
<thead>
<tr>
<th></th>
<th>Predicted Lateral Load (kN)</th>
<th>Lateral Load sustained (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ve direction</td>
<td>-ve direction</td>
</tr>
<tr>
<td>Wall Panel 1</td>
<td>12.5</td>
<td>-12.5</td>
</tr>
<tr>
<td>Wall Panel 2</td>
<td>12.5</td>
<td>-12.5</td>
</tr>
</tbody>
</table>

The design predictions assumed the rammed earth in the panels had no tensile capacity and that only the steel reinforcing bars would resist tensile forces generated in the panel. The results showed that the rammed earth contributed up to half the tensile strength provided by the steel reinforcing. The similar strength results observed in both panel tests showed that the stronger-than-expected wall panel performance was reliable and could be repeated.
10.7.2. Onsite Panel Construction and Testing in Ahipara

In November 2009, three full-size wall panels were built on-site in Ahipara by locals. The walls were built on 300 mm wide, 400 mm deep reinforced concrete foundations and were reinforced with D12 vertical steel bars. A 1.2 metre wide panel, a 2.0 metre wide panel and a corner panel featuring a wall opening were built and are shown in Figure 113. A photo of the walls six weeks later, just before the first onsite wall panel tests were conducted, is shown in Figure 114.

Figure 113 The First Three Rammed Earth Walls Built Onsite in Ahipara at 27 November 2009

Figure 114 First Three Rammed Earth Walls Built Onsite in Ahipara at 11 January 2010
The test results showed the wall panels underperformed significantly. As can be seen in Table 57, the three panels attained strengths 9% - 21% of their design loads. The under performance of the wall panels was not consistent with the superior performance observed in the two wall tests conducted in the laboratory. The low strength of the onsite wall panel tests were the result of the combination of both poor construction techniques and natural curing conditions that were less than optimal. Poor construction technique left the wall panels susceptible to damage during the first few days of curing. Although it is preferable to leave the wall panels within their formwork overnight, a well built wall panel can be exposed straight after construction, but not to extreme heat or rain. In the event that a less than optimal construction of an earth panel has occurred, the provision of a covered, temperate, and moist curing environment during the first few days was found to be acceptable. The controlled and protected curing period enabled the weak and permeable panel to strengthen without incurring damage from the environment and compensated for poor construction technique from a strength and durability perspective. Panels built consequently were protected from strong sunshine and heavy rain exposure during the first few days of curing by covering panels with a tarpaulin sheet. Following these three onsite tests, a fourth onsite test panel was built and tested using the improvements identified below. The fourth onsite test attained 90% of predicted wall panel capacity.

<table>
<thead>
<tr>
<th>Table 57 Predicted vs Actual Lateral Loads for Rammed Earth Panels Tested Onsite in Ahipara</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Lateral Load (kN)</td>
</tr>
<tr>
<td>+ve direction</td>
</tr>
<tr>
<td>Onsite Wall Panel 1-1</td>
</tr>
<tr>
<td>Onsite Wall Panel 1-2</td>
</tr>
<tr>
<td>Onsite Wall Panel 1-3</td>
</tr>
<tr>
<td>Onsite Wall Panel 2-1</td>
</tr>
</tbody>
</table>

Four reasons were identified for the poor result in the first three panels built onsite.

1. Workmanship

The wall panels were built by members in the community attending a construction workshop. All of the people building the panels were ramming for the first time and the lack of adequate compaction and consistency was apparent after the panels had been left to cure outdoors for a
few weeks. Even during the construction of an earth panel, different construction teams were substituted in to give as many people as possible an opportunity to experience building an earth panel. In retrospect, the use of many inexperienced people significantly decreased the quality of the panels.

The importance of experience was shown to be important to ram a good quality panel. During the project it became very clear that it took time and practice for an individual to become proficient with tasks like manoeuvring the pneumatic rammer and to be able to consistently discern when an ideal level of compaction in the earth had been achieved. The results of the workshop showed that clear verbal instruction and descriptions without experience were not sufficient to ensure consistently good workmanship.

For the construction of subsequent rammed earth test panels and the panels in the Ahipara dwelling, a group of eight individuals were selected. Even within the group selected, certain individuals were assigned specific roles such as being in charge of operating the pneumatic rammer, and mixing the earth, sand, cement and flax, together to achieve the required mix. Each individual became adept at their specific tasks and the quality of panel construction improved as a result.

2. Material mixing procedure

The finished surface of the three rammed earth panels built onsite had a dusty finish. The result indicated a lack of binder in the earth mixture, and that the earth mixture had too much sand and not enough clay. During the workshop many people helped to shovel sand and earth together in a specific ratio. It is likely that the volume of a shovel load of material differed based on the persons involved. In addition to this, the dampness of the clay rich soil and the mixing methods resulted in the clay sticking to other bits of clay and forming balls of clay up to 30 mm in diameter. These balls decreased the surface area of clay available to bind to other constituents in the earth mixture. The lack of clay in the earth mixture binding to other constituents would have decreased the strength of the material. Apart from cement, clay was the only other binder in the rammed earth mixture used.

To improve the mixing process, fixed volume containers were used to measure out the quantities of sand, earth and cement for each mixture. The clay rich earth was raked through a 10 mm mesh made from an old bed frame to break up the clay balls. These improvements
reduced the dusty finish observed in the initial walls and improved wall panel strength observed in subsequent construction.

3. Onsite test method

The test setup used for onsite tests did not work as planned and reduced the rate of loading and maximum loads that could be applied to the panels. In an ideal test setup, the loading jack is attached to a stiff reaction frame or a strong wall. This enables the jack to push in one direction without moving in the other. Onsite in Ahipara there was no existing wall panel testing infrastructure that was suitable or accessible to the researchers in the locality so an improvised test setup was devised and used. Due to the high stiffness observed in the panel tests conducted in the laboratory, it was envisioned that longer and stiffer rammed earth panels could be used as reactions frames for testing of thinner wall panels. If the wall panels had performed similarly to the laboratory based panels, the stronger panels would have sustained only minor damage whilst the weaker panel would have yielded. The test setup envisaged would test two panels at the same time but only one panel would yield and fail, and the other would ideally remain undamaged. Unfortunately, the onsite wall panels were weaker and less stiff than expected. During the two onsite tests conducted, both the weaker and stronger panels yielded. The load applied during each test was limited by the capacity of the stronger panel. The yielding of both panels also meant that the loading jack was displacing and pushing in both directions and thus the rate of loading was difficult to measure and control.

A 12 ton excavator was used as a standalone reaction frame to test the fourth onsite wall panel. The excavator was driven into position and left running during the test to keep the hydraulics pressurised. A steel component was manufactured to connect the loading jack to the excavator boom. The test using the excavator as a reaction frame worked as planned and the displacements applied to the fourth onsite wall test panel were able to be controlled accurately. A photo of the improved test setup is shown in Figure 115.
The connection of the excavator to the loading jack to the earth wall is shown in Figure 118. A custom pin was designed and manufactured to connect the 50 ton loading jack to the excavator because the pinhole size for the quick hitch coupler (50 mm) and the loading jack (30 mm) were different. The pin consisted of two parts as shown in Figure 116 and Figure 117:

- A 300 mm long steel pin shaft at a diameter of 45 mm reducing to a diameter of 30 mm at 85 mm from one end

- A 100 mm long steel cylinder with an outer diameter of 45 mm and an inner diameter of 30 mm

The pin shaft was inserted through the pinhole on one side of the quick hitch, through the 30 mm eye of the hydraulic jack, and through the pinhole on the other side of the quick hitch.
The steel cylinder was slid onto the end of the pin shaft so that the other side of the pin fitted snugly within the quick hitch pinhole.

The use of an excavator as a reaction frame for onsite panel testing worked as designed and is recommended for future onsite tests of rammed earth wall panels. Excavator size and bracing requirement were determined by ascertaining the expected moments generated from the test setup (based on predicted lateral load and height of loading).

Two engineering calculations were required to ensure the excavator could be used as a reaction frame. They were:-

- To check that the custom made steel pin would not fail in shear. The 50 ton loading jack could exert a shear force of 500 kN while the pin could withstand a shear force of 488 kN. The shear capacity of the pin which was sufficient because the test setup involving the strongest rammed earth test panel would result in a maximum shear force of 27 kN being applied to the pin.

- To check the excavator would not overturn during the test. The maximum moment that was predicted to be exerted by the loading jack on the excavator was 54 kNm (27 kN applied at a height of 2 metres). Assuming the centre of mass to be located
between the excavator tracks, a moment arm of 1.4 metres existed in both directions from the pivot points, which were the tumblers at ends of both excavator tracks. The 12 ton excavator thus had a moment resisting capacity of 168 kNm in both directions. Up to 84 kN could be applied to the rammed earth walls, in either directions, before the excavator would begin to overturn. The predicted lateral load capacity of the strongest rammed earth panel to be tested was 27 kN so there was thus no risk of the excavator overturning.

4. Exposure to the natural elements

Exposure of the wall panels to the natural elements during the curing period was detrimental to the final strength of rammed earth. The walls were rammed during the peak of summer and so were subject to high temperatures which dried out the surface of the panels before they could cure properly. The walls also were subject to heavy rain and strong winds which formed fine cracks in the panels. Constant wetting and drying had a negative effect on the clay balls in the rammed earth mixture that was not observed in the laboratory test panels. The shrinkage and expansion of the clay balls near the surface of the panels created voids in the earth near to the surface. In some cases, the voids became large enough for the clay balls to fall out of the wall panel completely.

When a panel has just been rammed, the cement in the panel still requires time to hydrate and bond with the surrounding earth mixture. Wet concrete mixtures usually require a period between 7 and 28 days to reach 80% of its final strength. In rammed earth it takes longer for the cement to cure because the earth mixture has lower water content.

Instead of formwork being removed after the panel had been rammed, consequently rammed earth panels were left in the formwork overnight. Cover was arranged to protect the panel surface from strong direct sunlight or heavy rain over the first 24 hours after construction as the wall panel was most susceptible to damage during this period. The improvement in durability and strength as a result of the increased protection of the wall panels can be observed in the wall panels of the Ahipara dwelling. The rammed earth panels on the west and south sides of the house which have been constantly exposed to strong prevailing winds and driving rain for more than three years have resisted significant pitting and erosion.

Without the onsite tests, the effect of the environment on the earth panels and other issues would not have been addressed in a timely manner. Recognising these effects in test panels
and having time to solve the issues before house construction began were an invaluable outcome of the onsite wall panel tests.

If a wall panel showed signs of being susceptible to extreme climatic conditions during curing, then the panel was protected from dramatic wetting and drying phases for at least the first 2-3 days. Wrapping a tarpaulin cover around a wall panel would achieve this.

**10.8. Resource Gathering and Machinery Preparation**

The resources and processes used to build the house were guided by what was available locally. For the Ahipara project, the majority of the labour, materials, machinery and expertise needed were sourced from within the Ahipara whānau and local area. The trait of rammed earth construction, to be adapted to use locally available materials, promotes self-sufficiency and gave the constructed house a local identity. The ability of the whānau to identify where elements within the house were sourced from and who built it gave those elements special value and whakapapa (ancestry/lineage). To give an idea of what was sourced locally, the materials and services used are described in the below sections. Key materials that had to be sourced outside of the local community included:

- **Window and door glazing** – Mangonui Aluminium, a distributor of Fletcher Aluminium – a window and door fabricator based in Auckland
- **Steel reinforcing and Coloursteel roofing** – Glenbrook, south of Auckland
- **Cement from Golden Bay Cement** – Portland, near Whangarei
- **Petrol for machines and vehicles**

A map of the locations where these materials were manufactured in relation to Ahipara is provided in Figure 119.
10.8.1. Professional Services

Professional architectural and engineering services were required for this project. The architectural drawings were drawn by a family friend and favourable rates were charged for architectural reviews by a Māori architect from Te Tai Tokerau. A copy of the final Architectural Drawings for the Ahipara dwelling is appended in Appendix D. The majority of the engineering work and calculations were provided by the researcher. They included:

- Soil tests – to select a good earth mixture for rammed earth
- Material property and strength tests – to determine shrinkage, and strength properties of rammed earth made from Ahipara earth sources
- Wall panel tests – to determine wall behaviour and appropriate design assumptions for rammed earth panels made from Ahipara earth sources
- Soil bearing tests – to verify the bearing capacity of the ground on site
- Structural calculations for the Ahipara house – to ensure the strength of the building is satisfactory and that the structure has enough capacity to withstand strong seismic and wind events. A copy of the main structural calculations for the Ahipara dwelling is appended in Appendix C.2.
• Specific design for timber ridge beams and the concrete ring beam in the house – specific design enabled the use of longer spans and more efficient sections. Required to ensure beams meet serviceability limits (so they do not sag and bend) and ultimate limits (so they do not fail during major seismic or wind events).

• Specific design of exposed rafter timber diaphragm roof – to efficiently use existing timber available, and to ensure the roof rafters and purlins are spaced according to the NZ timber code.

• Thermal evaluation of the wall panels and house - calculating R-values of each element in the house and modelling the thermal performance of the dwelling. Using thermal performance data, gathered from past rammed earth research and the earth building community, to ensure a healthy indoor temperature will be attained.

• Conducting a high pressure spray durability test – to verify the built wall panels were as durable as assumed

• Liaising in general with local council and other architects and engineers involved with the housing project

• Being an on-site engineer supervising the project – to ensure the excavation work, concrete foundations, rammed earth work, bond beam, and roof structure, were carried out as per the drawings and to an acceptable standard.

It is important to note that if whānau are used to provide professional services, they need to be registered with a formal professional body such as the Institution of Professional Engineering New Zealand (IPENZ) or the New Zealand Institute of Architects (NZIA) in order to be able to provide a producer statement for the work so that it is acceptable to a Building Consent Authority (BCA). The use of registered professionals ensures engineering and architectural details meet building code requirements, and only registered professionals can sign producer statements for these works. Producer statements are used by BCAs as grounds to issue a Building Consent or a Code of Compliance Certificate.

10.8.2. Construction Materials

The earth, sand and flax required to construct the rammed earth walls were all sourced from the build site or nearby. Although the finished rammed wall panels have considerable value,
the financial cost for acquiring the materials constituents was very low. The main financial cost in acquiring resources was for petrol to excavate and transport the materials to site. A stockpile of macrocarpa timber which had been stored for years by a local individual was bought at a good rate and was used to provide the timber for nearly all timber elements in the building. Being aware of the unique resources available in the local area and being able to adapt the house design to use it saved the project thousands of dollars.

10.8.3. Vehicles and Machinery
Tractors, trucks and a range of vehicles and machines were required during the project. Within the Ahipara community, a lot of these could be borrowed or rented at preferential rates. A large air compressor to drive the pneumatic ram was borrowed from a friend for the duration of the project. A soil auger used previously to build a rammed earth house was gifted to the project. The auger was repaired by the Ahipara whānau and was adapted to mix the earth more vigorously. The availability of the auger replaced the need to hire a bobcat compact loader or rotary hoe.

10.8.4. Labour
The biggest cost in a rammed earth project is labour. All of the labour used to build the house came from the Ahipara whānau and local youths who were unemployed. Under the Community Max government scheme to up skill youths on the benefit, local youths were paid a subsidised wage to build the Ahipara dwelling. There were also a large number of tradesmen within the Māori community who contributed their skills to the project. People were needed to help fix machinery, to lay concrete, to do carpentry work, install the windows and doors, put on the roof, do the plumbing and electrical work, fit out the bathrooms and kitchens and make cabinetry for the house. All these services were able to be sourced from within the Ahipara whānau.

10.8.5. Local Business Support
Many businesses in the local area, such as the local quarry, cement company, window and door supplier, and building suppliers gave preferential rates for the project because of the project’s profile within the community. It was initially thought that the project would be met with resistance by commercial businesses because the majority of the labour, services and resources required for construction were sourced locally and within Ahipara whānau but the businesses that were approached were found to be supportive of the housing initiative. The
general sentiment seems to be that they were glad that some development was occurring locally on Māori land and recognised the positive flow on effect to the local economy if more Māori developed their land.

10.9. Building Consent Process

The building consent process took 12 months. The application was submitted in April 2010 and building consent was granted in April 2011. The delays in obtaining building consent arose from the use of an alternative housing method which resulted in the Far North District Council requesting a number of peer reviews to be conducted of the architectural design and engineering aspects. Some of the issues raised by council required additional testing to be conducted and solutions to be devised.

The two letters received from FNDC, and the two responses to them, are provided in Appendix C.3 to Appendix C.6

10.9.1. Project Information Memorandum (PIM)

In January 2010, an application for a PIM was made to the FNDC as a precursor to submitting a building consent. Although it was not essential to apply for a PIM, it was done so that FNDC staff could let the Ahipara whānau know what documents and information they would need to include in the building consent for the housing project. A PIM also was requested as it would reduce the time the building consent would take to be processed. Proactively, the FNDC sent a team of four staff to visit the Ahipara whānau to better understand the scope and intentions of the project and to give advice regarding the building consent process. The FNDC staff explained that they were glad that this project, developing housing on rural Māori land, was planned and that they wanted to see this project succeed. Due to past conflicts between Māori and the local council regarding development on Māori land, the council identified the Ahipara housing project as an opportunity to provide a successful precedent for rural Māori land development.

10.9.2. Building Consent Application

On 15th April, 2010, the building consent application was submitted to council. The application included a TP58 for the proposed onsite wastewater system, architectural drawings, engineering calculations and a Producer Statement 1 (PS1). In order to get these documents, experts and professionals were engaged.
The value of the building determined the value of levies and taxes to be charged. The Ahipara building was given a value of $50,000 by the Ahipara whānau at an estimated value of $450/m² in the building consent application. The average cost of building small dwellings in the area was $1,787/m² (Department of Building and Housing 2013). The low cost of construction was possible because the building method used materials (e.g. earth, flax, sand) that were already owned by the Ahipara whānau, and because labour and tradesman work could be sourced from within the Ahipara whānau. The development contribution cost for the project was also negotiated to a lesser amount because the house was not connected to the power grid, or municipal water networks.

10.9.3. First Letter from FNDC

On the 4th May, 2010, the FNDC sent a letter requesting more information. Evidence was requested to support the assumptions made in the engineering calculation. One assumption was that the rammed earth structure would perform similarly to a concrete masonry structure. The response to the FNDC letter detailed the tests that had been conducted on the rammed earth material and on full-size panels showing that the behaviour of the rammed earth panels was similar to concrete masonry. Additional engineering calculations were provided to show that certain concrete and timber beam elements in the house had been engineered to meet building requirements.

The lack of building details in the submitted building consent documents were pointed out. To address these points, the requested details for various connections and fittings were added to the architectural drawings.

A query was also raised regarding the thermal performance of the building. Past thermal testing and research conducted on a similar rammed earth dwelling in Rotoiti was provided to show that rammed earth building method performed better than equivalent fully insulated light timber framed dwellings. The thermal resistivity of flax-fibre reinforced rammed earth was measured and used to determine the R-value of the earth walls in the house.

The experience of the Ahipara whānau living in the building over the 2013 winter showed that the indoor temperature remained within a range comfortable enough for the family to live in, with three children aged between 0 and 3, without the need for a heater. The mornings were noted to be cold during winter but warmed up quickly once the sun rose or as breakfast was prepared as a result of the heat generated from the gas stove boiling water or cooking
breakfast. During the winter, the building remained warm into the night due to the high thermal mass and north facing design of the structure. During the summer the indoor temperatures were reported to remain comfortable during the peak of summer without the use of any cooling device.

Because the building project used an Alternative Solution wall system, the FNDC requested an independent engineer to review the design and issue a Producer Statement 2 (PS2) for the project. The designs were shown to a chartered engineer from the engineering department. He affirmed that the wall system would perform adequately and issued a PS2 for the project.

Due to delays in obtaining building consent and practical issues delaying the project further, some building work on the project commenced before building consent was obtained from the FNDC. By the time of the responses to FNDC had been compiled and delivered, the concrete foundation work had been completed and some rammed earth wall panels had been built. The FNDC was aware that some construction work had taken place already and requested the project engineer to sign a Producer Statement 4 (PS4) to confirm the building work completed so far had been reviewed and was acceptable. The work was reviewed by the engineer and a PS4 was obtained for the work completed.

Responses to the queries raised in the first letter from FNDC were submitted to council on the 17th June, 2010.

10.9.4. Second Letter from FNDC

On 28th June, 2010, a second letter from the FNDC was received with another set of queries regarding the building consent application.

The FNDC did not accept the engineering peer review provided in the response because the engineer who issued the PS2 worked at the same university as the researchers and thus was not considered independent. An independent review was requested. An engineering consultant was hired to review the engineering plans and a high pressured spray test was conducted on site to verify the durability of the rammed earth wall panels. The engineer was satisfied with the calculations and test results and issued a PS2 for the project.

Queries were raised regarding E2 External Moisture and H1 Energy Efficiency aspects of the house design. The detailing proposed around the window fixtures and the rammed earth wall panels were not accepted. An architectural peer review of the design was requested. A design
firm was engaged to review the external moisture performance of the building and provide a suitable window detail. The energy efficiency issues with regard to thermal insulation were also reviewed by the firm, and a PS1 was issued for the updated design.

As requested by the FNDC, a report was written which documented the building work that had been completed thus far while further construction on site ceased.

Responses to the queries raised in the second letter from FNDC were submitted to council on 8\textsuperscript{th} April, 2011.

10.9.5. Building Consent Granted

On the 11\textsuperscript{th} of April 2011 FNDC notified the Ahipara whānau that Building Consent had been granted for the project.

10.9.6. Review of Building Consent Process

In total the engineering aspects were peer reviewed twice and the architectural aspects once. The additional peer reviews were required because of the unfamiliarity of the rammed earth construction method, structural design method, thermal performance data, and standardised architectural details.

Many architectural details used in the project were not standard because alternative details were considered more suitable for purpose or because there were no standard architectural details for rammed earth buildings. In the architectural plans, building details for other structural materials and custom designed solutions were used. It would have been difficult for FNDC staff to verify the suitability of these custom solutions so it was not unreasonable that they requested an independent architectural peer review.

There were similar concerns raised regarding the engineering calculations for the rammed earth walls and the validity of assumptions made. The ability for the researchers to physically test the material was a great advantage to overcome these concerns.

The building consent documents were refined over the 12 month period. The resulting set of drawings and engineering calculations will be a useful resource for future rammed earth projects. The dialogue between the Ahipara whānau and the FNDC during the building consent process revealed both technical and cultural issues, and provided a precedent for how to overcome each one of them.
As the FNDC becomes more familiar with rammed earth dwellings and better guidance is made available to Māori individuals and communities regarding how to design rammed earth buildings, it is envisaged that obtaining a building consent for future housing projects will not require any additional peer reviews and can be processed in a much shorter timeframe.

**10.10. Timeline of Construction**

**10.10.1. Excavation and Foundation Work**

On 6\textsuperscript{th} March, 2010, the excavation of the site began (Figure 120). A 6.5 ton excavator was hired and an experienced concreter and machine operator from the Ahipara whānau was hired to do the excavation work.

![Excavation of the Ahipara House Site](image)

By 25\textsuperscript{th} March, the trenches for the foundation beam reinforcing steel had been dug out as shown in Figure 121. A graded aggregate was placed in the trenches to level out the ground and bring the trench depth to 300 mm below ground level. Sheets of damp proof course (DPC) and reinforcing cages were laid in the trenches as shown in Figure 121 and Figure 122. The formwork for the concrete foundation beam was built and included the formwork for a 50 mm high concrete nib on top of the foundation beam.
On 29th March, 10 m$^3$ of concrete was poured to form the concrete foundation beams. The finished result is shown in Figure 123 and Figure 124. The concrete pour was generally acceptable but some areas required remedial work. On the west side of the building, sections of the formwork bowed in and out due to inadequate formwork stiffness. The concrete nibs which bowed out to a width greater than 200 mm were cut back to the required width using a concrete saw. Cement grout was used to widen nibs to 200 mm at a few points.

The vertical reinforcing bars were positioned in the formwork as the concrete was being poured. All the vertical reinforcing bars, except one, were placed in the right positions. The positions of the bars after the concrete pour can be seen in Figure 125. The reinforcing bar that was placed in the wrong position was removed. A 12 mm hole was drilled in the correct location for the reinforcing bar and a replacement was grouted into the hole.
Three small concrete foundation slabs were consequently poured; one in the kitchen (Figure 126), another for the patio area adjacent to the lounge (Figure 127) and the third, for the bathroom (Figure 128). The formwork, reinforcing mesh and DPC for the concrete slabs were placed on 7th April, and the concrete slabs were poured the day after using hand mixed concrete.
10.10.2. Wall Construction

On 23rd April, the formwork for the first rammed earth wall panel set up (Figure 129) and the panel was built (Figure 130). There were a few issues with machinery breakdown but they were repaired without much delay. The construction crew consisted of seven people. Two people were assigned to ramming the earth, three to adding the rammed earth constituents into the auger, one person added water to the mixture and checked the quality of the rammed earth mixture, and one person transported containers of mixed earth from the auger to the people ramming earth into the formwork.

Starting from the 23rd of April, the wall panels were built at a constant pace of around four panels per week. The quality of wall panels built improved as the experience of the construction team increased.
The wall panels were built in the order shown in Table 58.

Table 58 Order of Wall Panel Construction for the Ahipara Dwelling

<table>
<thead>
<tr>
<th>Date</th>
<th>Wall Line ID</th>
<th>Date</th>
<th>Wall Line ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 April 2010</td>
<td>B2</td>
<td>21 May 2010</td>
<td>A5 (window)</td>
</tr>
<tr>
<td>27 April 2010</td>
<td>C2</td>
<td>25 May 2010</td>
<td>A4 (window)</td>
</tr>
<tr>
<td>29 April 2010</td>
<td>B3</td>
<td>27 May 2010</td>
<td>B1</td>
</tr>
<tr>
<td>30 April 2010</td>
<td>P5</td>
<td>3 June 2010</td>
<td>P2</td>
</tr>
<tr>
<td>4 May 2010</td>
<td>C3</td>
<td>4 June 2010</td>
<td>D6 (window)</td>
</tr>
<tr>
<td>5 May 2010</td>
<td>D2</td>
<td>4 June 2010</td>
<td>M2</td>
</tr>
<tr>
<td>6 May 2010</td>
<td>P7</td>
<td>7 June 2010</td>
<td>P1</td>
</tr>
<tr>
<td>6 May 2010</td>
<td>D1</td>
<td>9 June 2010</td>
<td>M1</td>
</tr>
<tr>
<td>7 May 2010</td>
<td>D3</td>
<td>10 June 2010</td>
<td>P6</td>
</tr>
<tr>
<td>10 May 2010</td>
<td>A2</td>
<td>11 June 2010</td>
<td>N1</td>
</tr>
<tr>
<td>11 May 2010</td>
<td>A1</td>
<td>14 June 2010</td>
<td>M3</td>
</tr>
<tr>
<td>12 May 2010</td>
<td>A3</td>
<td>16 June 2010</td>
<td>N2</td>
</tr>
<tr>
<td>14 May 2010</td>
<td>C1</td>
<td>17 June 2010</td>
<td>D4 (window)</td>
</tr>
<tr>
<td>18 May 2010</td>
<td>P4</td>
<td>17 June 2010</td>
<td>D5 (window)</td>
</tr>
<tr>
<td>20 May 2010</td>
<td>P3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The order of panel construction was split into two groups. The first group of panels were those which would be built as standalone panels. These panels are highlighted red in Figure 131 and Table 58. Standalone panels were the easiest panel arrangement to set up formwork for and ram. The panels highlighted blue in Figure 131 and Table 58 could only be built after the adjoining red standalone panels had been built and left to cure for at least five days. The final wall panel was rammed on 17th June.
Photos showing how the panel construction onsite are shown from Figure 132 to Figure 138.
Figure 134 Formwork Set Up to Build an Adjoining Wall Panel (B1) on Wall Line B (left)

Figure 135 Panels on Wall Line A completed (right)

Figure 136 Ahipara Construction Site at 26 May, 2010

Figure 137 Ahipara Construction Site at 4 June, 2010
10.10.2.1. Anomalies during Panel Construction

On 18\textsuperscript{th} May, due to failing light, construction of wall panel P4 was stopped around 150 mm from the finished height of the wall panel. The last 150 mm was rammed the next day. To date there has been no observable issue arising along this cold joint.

On 28\textsuperscript{th} May, due to equipment failure, only half of the N1 wall panel was completed during the day. As this was a Friday, the wall panel was not completed until Monday. On 1\textsuperscript{st} June the half constructed panel was knocked down and rebuilt.

10.10.3. Concrete Bond Beam

The reinforced concrete bond beam was poured on 2\textsuperscript{nd} July, and is shown in Figure 139 and Figure 140. In the week preceding, permanent macrocarpa timber formwork (Figure 141) and steel reinforcing (Figure 142) was assembled and put in place. The macrocarpa timber was sourced from a lumberjack in the local area and is shown in Figure 143.
Figure 139 Ahipara Construction Site at 22 July, 2010

Figure 140 Concrete Bond Beam Poured Within Permanent Macrocarpa Formwork (left)

Figure 141 Permanent Macrocarpa Formwork Assembled on Top of the Rammed Earth Panels (right)

Figure 142 Steel Reinforcing Cages Made for the Concrete Bond Beam (left)

Figure 143 Macrocarpa Timber Sourced from Peria, Northland (right)
10.10.4. Pitched Timber Diaphragm Roof Construction

In August 2010, three carpenters from the Ahipara whānau built the roof structure of the dwelling. The finished roof is shown in Figure 144. The roof featured a pitched roof diaphragm with exposed rafters as shown in Figure 145. The structural diaphragm provided by the roof design, and the concrete bond beam, were designed to resist torsional forces within the building and in the roof structure.

![Figure 144 Roof Installed on the Ahipara Dwelling in August 2010 (left)]

![Figure 145 Macrocarpa Cladding, Rafters and Ridge Beam Installed (right)]

10.10.5. Windows and Door Fixtures

The windows and doors were installed in July 2011. The fixtures were all double glazed and were custom made to fit the window and door spaces around the building. In retrospect, money could have been saved if the openings were built to standard window and door sizes. Bi-fold doors were used for the kitchen (Figure 146 left hand side) and sliding doors for the lounge (Figure 146 right hand side) and bedroom. The two windows installed in the kitchen and dining room are shown in Figure 147.

![Figure 146 Double Glazed Doors to the Kitchen and Lounge (left)]
The windows and doors placed on the south side of the building (Figure 148) were smaller to reduce heat loss from the building.

10.10.6. Other Building Features

In August 2013 a wood stove fireplace with a flue was installed into the lounge area. The fireplace was added to heat the house during the winter when day time sun exposure was not enough to heat the house.

Four solar panels were installed on the south side of the building and are shown in Figure 149. The solar power set up provided less power than expected. At present the solar panels generate enough electricity to provide basic lighting, pump water and run a laptop. The system will be improved so that a washing machine and fridge can be run onsite.
The Autoflow onsite waste water disposal system was used for the Ahipara dwelling and is shown in Figure 150. The system comprises of three tanks and has been working well. The system is gravity fed as the tanks are positioned downhill from the house. Periodically, the solid waste that accumulates inside the tanks needs to be emptied.

Using leftover macrocarpa timber, the cabinets, closets and cupboards in the house were built as shown in Figure 151 and Figure 152.
GIB Aqualine was used to line some areas in the bathroom where constant water exposure was expected as shown in Figure 153. Exposing rammed earth to moist air or water is not an issue as long as there is a way for the rammed earth to dry out (e.g. through sun exposure or air circulation). A gas califont was installed to provide hot water.

In July 2013, the house was instrumented with 20 thermal sensors. These buttons record measurements of temperature and relative humidity at 20 minute intervals. Thermal data will be gathered over the next 2-3 years and used to assess the performance of the building.

10.11. Cost of Construction

During the implementation of the Ahipara building, records were kept to document the cost of house construction. A summary of the costs incurred at each stage of the project is shown in Table 59. A more detailed breakdown of the costs is provided in Appendix C.7. The costs
listed were paid during the Ahipara project but the project also received considerable in-kind and voluntary support as well. These cost savings and contributions to the project are not accounted for in the table below.

Table 59 Cost of Ahipara House Construction

<table>
<thead>
<tr>
<th>Stage of construction</th>
<th>Cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Machine hire</td>
<td>$3000</td>
<td></td>
</tr>
<tr>
<td>• Labour</td>
<td>$2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5000</td>
</tr>
<tr>
<td>Concrete foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Concrete</td>
<td>$13000</td>
<td></td>
</tr>
<tr>
<td>• Materials</td>
<td>$7000</td>
<td></td>
</tr>
<tr>
<td>• Labour</td>
<td>$5000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$25000</td>
</tr>
<tr>
<td>Rammed earth walls and bond beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Machine hire and maintenance</td>
<td>$4000</td>
<td></td>
</tr>
<tr>
<td>• Materials and consumables</td>
<td>$6000</td>
<td></td>
</tr>
<tr>
<td>• Labour</td>
<td>$28500</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$38500</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Materials (insulation, aluminium sheets)</td>
<td>$5000</td>
<td></td>
</tr>
<tr>
<td>• Timber</td>
<td>$15000</td>
<td></td>
</tr>
<tr>
<td>• Labour</td>
<td>$5000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$25000</td>
</tr>
<tr>
<td>Window and door fittings</td>
<td>$18000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$18000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$111500</td>
</tr>
</tbody>
</table>

The cost of building in the area, as estimated by the Department of Building and Housing (DBH) for small houses (<145m²) in Ahipara was $1787 (including kitchen and bathrooms) (Ministry of Business Innovation and Employment 2013). The Ahipara dwelling has a floor area of 101 m². The cost of building the structural elements and closing in the Ahipara rammed earth house was $1104/m².

The pie chart shown in Figure 154 shows the construction costs divided into labour, materials and machinery. The material and machinery costs were for resources that were not available or could not be acquired from within the Ahipara whānau and had to be purchased. The labour component of the construction however was sourced solely from within the Ahipara whānau. The labour costs include wages paid for both physical labour for the building of rammed earth walls and tradesman work. Although the majority of labourers from the
Ahipara whānau were paid during the construction, the project costs showed there was considerable sweat equity capital that could have been contributed in lieu of a financial outlay from the Ahipara whānau.

As the process was the first time a rammed earth dwelling was implemented by the Ahipara whānau, there were many lessons learnt. Costs can be reduced now that a local method of construction has been developed and inefficiencies during construction have been identified. The cost of the concrete foundation for the Ahipara dwelling was inflated due to a decision during construction to change from a rammed earth floor to concrete, and issues with the quality of the concrete floor that was laid. The cost reported for the concrete floor included the cost of the remedial work. These issues are estimated to have inflated the cost of building project by $5000-10000. Future rammed earth houses built were also envisaged to save costs by designing the house to incorporate window and doors of standard dimensions.

During the project, $7,200 was spent on engaging professionals for services such as surveying, architectural reviews and engineering work, and for paying costs associated with submitting and processing a building consent with local council. Due to local council waiving some costs and professional services providing preferential rates, the actual costs for professional services and local council are likely to be around $10,000 to $12,000.
Brief details and costs for selected non-structural aspects of the house are provided below in Table 60. The current solar panel system generates enough electricity to power a fridge continuously, a washing machine, basic lighting systems and electrical components such as the water pump, a television, modem and laptop.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panel system</td>
<td>$20,000</td>
<td>10 panels and associated wiring and control unit</td>
</tr>
<tr>
<td>Onsite Wastewater treatment</td>
<td>$10,000</td>
<td>Autoflow system. Sponsored by JR Mackenzie.</td>
</tr>
<tr>
<td>Fireplace</td>
<td>$3,000</td>
<td>Including installation costs</td>
</tr>
<tr>
<td>Bathroom</td>
<td>$2,500</td>
<td>Shower, toilet and basin. Labour provided free.</td>
</tr>
<tr>
<td>Kitchen</td>
<td>$1,500</td>
<td>Including water pump, sink and waterproofing</td>
</tr>
<tr>
<td>Water tank and fittings</td>
<td>$2,500</td>
<td></td>
</tr>
<tr>
<td>Outdoor detached laundry</td>
<td>$2,000</td>
<td></td>
</tr>
<tr>
<td>Cabinetry</td>
<td>$5,000</td>
<td>Materials and labour</td>
</tr>
</tbody>
</table>

10.12. Sources of Funding

The implementation of the Ahipara dwelling was fully funded by the Ahipara whānau. At the outset of the project there were minimal savings for funding the project. The required funds were acquired during the project and by taking out a $20,000 personal loan. The Ahipara whānau received greater support from funding bodies after they had begun the project, engaged with the local community, showed that they were committed to the kaupapa, and demonstrated their plans to build a house were viable. Te Puni Kokiri (TPK), a government organisation with a mandate to promote Māori education and development, funded a $72,000 position for a project manager for the Ahipara housing project, with additional requirements to hold wananga (forums and educational seminars) during the project to share the knowledge acquired during the project with other Māori, and to document the process. An additional $20,000 top-up was added to the contract nearer to the end of the project. JR Mackenzie, a philanthropic organisation, donated $10,000 for the onsite wastewater system. Many individuals contributed equipment, machinery and time during the project. Voluntary contributions, donations and discounts received during the project from many individuals, businesses and organisations have been estimated to have reduced the project costs by at least $10,000.
10.13. Recommendations

The implementation of the Ahipara rammed earth dwelling has been an invaluable process to undertake. By going through the process of researching the rammed earth system implementing the structure, many practical and cultural challenges were experienced and overcome.

In particular, some recommendations that have resulted from the implementation process include:-

- To put more thought into design decisions and how they benefit all four dimensions of environment, social, cultural and economic.

- To conduct soil testing to determine a suitable earth mixture for rammed earth. The particle gradation of a earth mixture used for rammed earth construction should fall within the boundaries set out in the plot provided in Appendix 10.6.

- That the use of registered professional services is important and unavoidable in order to gain building consent. It also ensures the building will be safe and healthy to live in, and durable.

- It is important to set aside time to train a specific team of people for rammed earth construction.

- It is advisable to practice using the rammed earth method by making a few rammed earth panels before building panels for a dwelling.

- If a weak wall panel is identified (by susceptibility to erosion as a result of exposure to the weather), panel durability and strength can be retained if the panel is covered with a tarpaulin. Identifying and covering weak wall panels during the first 1-3 days is critical because the rammed earth is also most vulnerable to damage during this period.

10.14. Summary

The housing research was carried out with the goal of conducting research that had integrity in both the Māori world and the Western world. The process of working with the Ahipara whānau to create a research plan, to conduct structural tests in the laboratory and onsite, and
to implement the dwelling locally, ensured that the research was conducted in a way that benefitted Māori and had credibility with the Ahipara whānau. The skills gained by local individuals, the housing precedent set by implementing the dwelling, and the addition of a tangible and visible asset within the community, were invaluable benefits received by the community as a result of participating and contributing to the research project. The provision of time, expertise and money to the research by the Ahipara whānau has been reciprocated through these outputs. The Ahipara whānau also supported academic research goals and accommodated the research needs by providing local resources and personnel at no cost, so that material and structural tests could be conducted in accordance with standardised test methods. The results of the research have since been published in one journal and have been presented at national and international conferences. The ongoing commitment of the Ahipara whānau to support research can be seen through their desire to partner in further rammed earth experiments. The whānau have allowed the university researchers to instrument the Ahipara dwelling with thermal monitoring devices and will work with researchers to collect the data over the next 2-3 years.

The outputs of the research, culminating in the implementation of the rammed earth dwelling, have achieved both Māori and Western objectives of research. The research outcomes have validated the use of a kaupapa Māori research methodology to conduct research which has integrity in both worlds and which has consequently resulted in the development of a housing solution which has credibility in both worlds.
Chapter 11. CONCLUSIONS

The purpose of this doctoral research was to develop and implement the Uku rammed earth housing method in Te Tai Tokerau using local resources and labour. The housing research was achieved by using a Kaupapa Māori research methodology and working in partnership with a Māori whānau from Ahipara. The doctoral research focused on the following three activities:-

1. Facilitation of an inclusive, community-wide, decision making process in which two potential rural housing solutions for Ahipara were evaluated based on their intrinsic sustainability in the dimensions of environmental, social, cultural and economic. Perspectives of individuals and organisations that were involved or affected by local housing solutions in Ahipara were gathered by adapting the Mauri Model decision making framework to evaluate housing methods.

2. Soil tests, material strength tests and cyclic tests on full-sized rammed earth panels, made by local labourers using local materials, were conducted. Research establishing the strength of rammed earth, and in particular seismic performance of rammed earth panels were scarce in reviews of existing research literature. Even more scarce were published structural research which examined methods to predict the performance oframmed earth that were stabilized with cement or reinforced with natural fibres. The structural and seismic tests conducted during the doctoral research have shown consistent mechanisms of shear failure in full-sized panels and considerable non-linear strength during cyclic loading. The results were used for the engineering design of the Ahipara Uku dwelling and established a structural ductility factor of $\mu = 1.25$ was justified for the design of Uku rammed earth structures.

3. The implementation of an Uku rammed earth house in Ahipara brought together the results of the Mauri Model assessments and the rammed earth strength and seismic testing data. The implementation produced a tangible and visible output within the community and an immediate housing benefit for the Ahipara whānau. The exercise resulted in the development of a practical and local precedent for how to implement a rammed earth housing method on rural Māori land.
11.1. Use of a Kaupapa Māori Research Methodology

A kaupapa Māori research methodology was used for the doctoral research. The use of the methodology showed the value and viability of using a research approach which acknowledged Māori values and knowledge, to research, develop and implement a rural housing solution on Māori land. The use of a kaupapa Māori research methodology helped the process of establishing a research partnership with the Ahipara whānau, and the methodology aligned the guiding values and protocol of the doctoral research with the existing values, practices and expectations present in the Ahipara whānau. Initiatives such as the use of an inclusive decision making tool, local workshops, and local labour for test specimen construction, made the research process accessible to Māori from the Ahipara whānau, to other individuals from the local community, and to other Māori housing stakeholders. The research outputs, such as the recording of structural test data, the precedent of building a rammed earth house on rural Māori land, and the construction of an Uku rammed earth dwelling in Ahipara, benefitted the range of individuals who contributed to the research and will be of use to Māori planning to implement the housing method on their ancestral lands in the future.

11.2. Mauri Model Assessment of Rural Housing Methods

The Mauri Model decision making framework was modified to be used in the context of evaluating rural Māori housing methods. The Mauri Model has been used in other NZ and international contexts which involve complex situations with multiple variables to evaluate, but had not been used to evaluate Māori housing prior to this doctoral research.

The use of the Māori concept of ‘mauri’ as a measure of sustainability for each of the housing metrics was unique and different from conventional housing assessments. Mauri was used to measure the intrinsic sustainability of a metric as opposed to an assessment based on monetary or relative measures. The use of ‘mauri’ as a measure of sustainability was well received by the individuals and organisations who participated in the housing surveys. Māori especially were appreciative because they were familiar with the concept of mauri and the Mauri Model survey enabled them to use the concept to holistically evaluate the sustainability of housing performance metrics and contribute to the decision making process.

The use of the Mauri Model decision making framework also produced a clear result favouring the Uku rammed earth housing method over the light timber framed method. In
addition to providing a comparative assessment, the results of the Mauri Model surveys provided sustainability performance data for each method in each of the four mauri dimensions of environment, social, cultural and economic, which enabled the sustainable and unsustainable performance ratings of each housing method to be determined.

Due to the simplicity of the mathematical manipulations applied to the data, queries regarding result processing could be checked independently by survey participants without the need for a computer. Also, the Mauri Model framework enabled each individual to meaningfully contribute to the assessment of each housing method in a dignified and fair way.

### 11.3. Rammed Earth Material Strength Tests and Full-sized Panel Tests

Material strength tests on rammed earth specimens and pseudo-static cyclic tests on full-sized rammed earth panels were conducted. The structural and seismic testing established the compressive and flexural strength of rammed earth made using local Ahipara earth sources (Chapter 6), and the seismic performance of full-size rammed earth panels (Chapter 7) and a rammed earth wall assemblage (Chapter 8) when subjected to cyclic loads.

At the outset of the material testing research, a number of soil tests were conducted to determine a suitable rammed earth mixture using earth sources from Ahipara. An earth mixture, referred to as Okura Sand, was selected. Material strength tests results were used to establish that the rammed earth mixture should include a cement content and flax-fibre content of 6% and 0.15% (by dry weight of soil) respectively, and to quantify the compressive, flexural and shear strength of the rammed earth composite. The rammed earth compression test results indicated that rammed earth made using the Okura Sand mixture had an average dry compressive strength of 2.5 MPa, which was greater than the minimum compressive strength for structural rammed earth of 1.3 MPa as specified in the earth building standard NZS 4298.

Six full-size rammed earth panels, and a rammed earth assemblage comprising of 3 panels, were built and subjected to pseudo-static cyclic tests. Two panels and the 3-panel assemblage were built in the civil engineering test hall laboratory, and four panels were built onsite in Ahipara. The labour force used to build the panels comprised of individuals from the Ahipara whānau and university students, all of whom were trained during the doctoral research period to build using rammed earth.
Structural analysis based on design strength parameters established from the material test results showed that the full-sized panels would fail in flexure. Contrary to these predictions, both of the standalone panels built in the laboratory, and all three panels in the rammed earth assemblage, failed via various sliding shear and diagonal shear failure mechanisms. Two of the three standalone panels successfully tested onsite in Ahipara also failed in shear, whilst the third test panel failed in flexure. The results of tests conducted on full-sized panels showed clearly that the strength of a rammed earth panel, comprising of rammed earth reinforced with vertical steel bars, built on a reinforced concrete foundation and with a reinforced concrete bond beam, could be more accurately predicted by:-

- Recognising the tensile strength of rammed earth in panel design. The design approach used assumed that the rammed earth had no tensile capacity and that the tensile capacity of an Uku earth panel was solely derived from the steel reinforcing bars. The assumption that the rammed earth did not contribute to the tensile capacity of the wall panel resulted in an overly conservative prediction of flexural strength. The two laboratory built panels, AP1 and AP2, were predicted to fail in flexure but both instead failed in shear in both push and pull directions at lateral loads that were 30-50% higher than predicted.

- Using a suitably heavy excavator as a reaction frame. For onsite testing of rammed earth panels, in the absence of an accessible local structural testing facility, using an excavator was found to be a practical and effective local solution.

11.3.1. Structural Ductility

A structural ductility factor of 1.25 was shown to be justified in the design of Uku rammed earth walls. Based on the non-linear load-displacement profiles measured during the testing of full-sized panels and the test of the 3-panel assemblage, the test results consistently exhibited considerable non-linear capacity. The performance of the laboratory panels (AP1, AP2) and the onsite panel (AP6) was equivalent to structural ductility factors of between 2.6 and 5.8, and structural ductility factors of 1.5 and 2.1 was determined for the 3-panel Uku wall assemblage in the push and pull directions.

11.3.2. Shear Test Method for Rammed Earth

The shear strength of rammed earth was found to be the most critical strength parameter yet no standardised shear test methods exist for rammed earth. Shear tests on rammed earth
reported in the research literature used a variety of shear tests developed for other materials such as the shear box and triaxial test used predominantly for soil tests, triplet tests for unreinforced masonry, and diagonal shear tests for masonry and fibre reinforced composites. The triaxial and triplet test methods were identified as two shear test methods that would be practical to conduct on rammed earth specimens for rammed earth research or construction projects, with the triaxial test method found to be the more accurate test method of the two. The main advantages of the triaxial test method over the triplet test method were the greater availability of test equipment and expertise for triaxial testing because the test method was a common soil test method, and because diagonal shear failure planes were induced during the triaxial test. In contrast, the triplet test induced shear failure between rammed earth layers. Although both shear failure mechanisms were observed in panel tests during the doctoral research, diagonal shear failure across multiple layers of rammed earth was the more commonly observed shear failure mechanism. A modified triaxial method test method (described in Chapter 9) has been recommended which adjusts the triaxial test to be more suitable for the shear strength evaluation of rammed earth.

11.4. Implementation of an Uku Rammed Earth dwelling in Ahipara

Implementation of the Ahipara dwelling has provided practical insights into some common housing development obstacles. The process of house implementation was documented beginning with the need to establish relationships and identity, and progressed through the stages of building design, soil testing, material testing, obtaining building consent, training the labour force, and physical construction. The report detailing the implementation of the Ahipara rammed earth dwelling (Chapter 10) will be a document which will help other researchers better understand the process of researching using a Kaupapa Māori research methodology and provides a precedent to people aspiring to develop housing on Māori land regarding how to overcome housing obstacles and implement Uku rammed earth housing in a collaborative and inclusive way.

The cost of building the Ahipara Uku dwelling was $111,500. The costs were divided into different stages of construction as shown in Table 61.
The costs of construction were also divided into labour, machinery, and material costs. Labour costs accounted for 36% of the total cost of construction. The emphasis on the cost of labour was recorded because the majority of labour required during the construction of a rammed earth dwelling can often be provided from within a Māori community or whānau. The contribution of labour from the end-users could be used as an effective contribution towards the financial down payment requirement for a mortgage using the concept of sweat equity. In New Zealand banks and financial institutions require an upfront financial deposit for a mortgage of up to 20% of the total value of a mortgage. Saving enough money to apply for a mortgage is a large obstacle to housing for many Māori whānau. For the construction of the Ahipara Uku dwelling, all of the labourers and tradesmen who worked on the house were from the Ahipara whānau. The Ahipara project was able to be funded by the whānau and there they did not need to apply for a mortgage, but the potential for using the sweat equity concept as an effective down payment for a mortgage when using a rammed earth construction method is evident.

**11.5. Future Research**

The doctoral research focused on the development and application of research predominantly in the areas of Kaupapa Māori research, holistic and sustainable decision making, and structural testing of fibre-reinforced rammed earth. Over the course of the research specific topics have been identified which would be valuable to research further.

The following topics have been identified for further research:-

- Use of the Mauri Model for assessment in other Māori communities or in other indigenous and Pacific communities. The research would ascertain local perspectives

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**Table 61 Costs of Each Stage of Construction for the Ahipara Uku dwelling**

<table>
<thead>
<tr>
<th>Stage of Construction</th>
<th>Value ($ in NZD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td>5,000</td>
</tr>
<tr>
<td>Concrete foundation</td>
<td>25,000</td>
</tr>
<tr>
<td>Rammed earth wall and bond beam</td>
<td>38,500</td>
</tr>
<tr>
<td>Roof</td>
<td>25,000</td>
</tr>
<tr>
<td>Window and door fittings</td>
<td>18,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$111,500</strong></td>
</tr>
</tbody>
</table>
regarding the holistic sustainability of local housing methods and provide a practical way to include alternative housing methods in the decision making process. The results would enable the holistic sustainability performance of existing housing methods and alternative housing methods to be evaluated and compared. The data would also identify the weaknesses and strengths of existing housing methods, and could be a way to facilitate inclusive discussion between many housing stakeholders with differing views and interests regarding local housing solutions.

- The viability of using or adapting Uku rammed earth to other communities. The research could be done from both a resource perspective, and social acceptability and constructability perspectives. The resource perspective would evaluate local earth and fibre sources in other localities and develop rammed earth test specimens made with locally available resources. The social acceptability and constructability research could examine the perspectives of the target end user to evaluate their regard of rammed earth housing and to evaluate the ability of the end users to build using a labour intensive method such as rammed earth.

- More research regarding the flax-fibre reinforcement of rammed earth is required. In the doctoral research a range of flexural strengths for flax-fibre reinforced rammed earth were measured ranging from 0.09 MPa (minimum stable flexural strength measured after failure) to 1.05 MPa (peak flexural strength). In all flexural tests conducted during the doctoral research there was a considerable and sudden drop in flexural strength after reaching the peak flexural strength. Past researchers involved in the Uku housing research were able to attain higher flexural strengths (0.9 MPa – 2.8 MPa) and achieve a more gradual decline in flexural strength after attaining peak flexural strength. The higher strengths reported by past researchers involved in past research in connection with the Uku housing project used flax-fibre concentration of 0.75% (by dry soil weight). During the doctoral research however, the maximum attainable fibre concentration was 0.3% and even at this concentration of flax-fibres, with the fibres carefully mixed in by hand, the fibres tangled into balls and matted together within the earth mixture. Such procedures to mix fibres homogenously into the earth would be impractical when mixing the volume of earth required during the construction of a rammed earth dwelling. Research into practical large scale methods of mixing a higher concentration of flax-fibres homogenously into a rammed earth mixture could greatly improve the non-linear flexural strength of Uku rammed earth.
The improved flexural performance would have a significant effect on the performance of Uku rammed earth panels and if strong enough, could make the current inclusion of vertical steel reinforcement within Uku rammed earth wall panels redundant.

- Seismic tests on full-sized Uku rammed earth panels in both laboratory and onsite settings would be valuable to examine in more detail the structural ductility of panels and assemblages. The results would enable more efficient seismic design and reduce the use of conservative design values and assumptions.

- Diagonal shear tests conducted on both unreinforced rammed earth panels and rammed earth panels reinforced with vertical steel, a reinforced concrete bond beam, and foundation beam, would help to identify the effects of the vertical steel and reinforced concrete elements on the performance of a rammed earth panel. The indication of flexural failure based on material test results and the observation of shear failure in full-sized, steel reinforced, rammed earth panel tests indicate that the presence of additional structural elements within a rammed earth panel has a significant effect on the structural performance of the panel. A better understanding of intra-panel stresses during lateral load cycles would enable a more accurate, specific structural design approach to be developed for an Uku rammed earth panel.

11.6. Concluding Remarks

Using a kaupapa Māori research methodology over a conventional methodology to research, develop, and implement a housing solution on rural Māori land empowered the Ahipara whanau to provide housing for their own people, and showed respect for Māori by acknowledging their traditions, values and indigenous knowledge. All of the procedural additions (such as meeting face to face and establishing relationships and identity before discussing the research) and values (such as sharing project control with local Māori when setting research goals and conducting the research, and creating outputs and goals so that each and every research participant would gain something of value from the research) gave the research integrity and resulted in the research receiving strong support from local Māori as well as non-Māori and organisations involved with the housing research. The positive reception and impact of the research on Māori can be seen in the implementation of three
more Uku dwellings by the Ahipara whānau and in the interest expressed by several other Māori whānau to implement Uku houses on their ancestral lands.

The use of a kaupapa Māori research methodology enabled the Uku housing research group and the Ahipara whānau to work together and made it possible to research and implement the Uku housing concept locally. Without the knowledge and guidance provided from the Uku research team, the Ahipara whānau would not have been able to overcome the technical and legal obstacles associated with building a rammed earth house on Māori land and the housing project would have had little credibility amongst their whānau and in the community. However, without the acceptance, endorsement and physical support of the Ahipara whānau, the Uku housing research team would have been unable to use any of the material or resources available within the community for the research, or build a prototype rammed earth dwelling on rural Māori land.

The successful application of a kaupapa Māori research approach to rural Māori housing research, and the specific precedents of local decision making, structural testing, and implementation, show the use of a kaupapa Māori methodology as well as the use of a flax-fibre reinforced rammed earth housing solution to be applicable, viable, and effective in a present-day New Zealand context.

Use of a Kaupapa Māori research methodology resulted in the successful implementation of Uku housing. The implementation of an Uku dwelling improved the standard of living for the Ahipara whānau by providing a good quality house for their whānau to live in. The positive response of those from the local community of Ahipara, and especially local Māori, to the use of a Kaupapa Māori research approach and the use of a culturally informed and inclusive house implementation process, showed that the approaches and processes used during the research could be beneficially applied by other Māori groups and Māori housing providers seeking to develop on Māori land throughout New Zealand. As many indigenous people groups have similar cultural values and aspirations to Māori, there is the potential for the housing research methodology used, and perhaps the Uku housing method too, to be adapted to recognise the cultural processes and values of other people groups, and to provide holistic and appropriate housing solutions for them as well.

*Me whakatika te matatika ki roto i te tikanga kia tika ai.*

*If the approach used adheres to the code of ethics of Māori cultural values, the result will be equitable and enduring for Māori.*
ACKNOWLEDGEMENTS

Although the PhD has been a personal pursuit of mine, it has only been with the help of many others that I have been able to begin the journey, and to overcome struggles along the way.

First I acknowledge my Lord Jesus Christ, for showing me unconditional love, forgiveness, and acceptance. I recognise that the opportunity and ability I have been given to undertake doctoral studies was an undeserved gift, and understand that with the gift comes the responsibility I have to use what I’ve learnt and gained to serve others humbly and to be a blessing.

*Fear of the LORD is the foundation of true wisdom. All who obey his commandments will grow in wisdom. Praise him forever!*

*Psalm 111:10 (NLT)*

Much thanks is given to my main supervisor Dr. Te Kipa Kepa Brian Morgan. Not only are you an engineer and thinker ahead of your time, but you have been able to guide me, a difficult soul, to bring out the best in me. Without your support and vision, the research wouldn’t exist and I would not have completed the PhD. Thank you for mentoring and encouraging me, and for your friendship.

My thanks are also given to my co-supervisor Professor Jason M. Ingham for his guidance and commitment to me in my research. Your feedback has always been clear, given in a very timely manner, and available to me whenever I asked. I could not ask for better. Thank you. Your help and support has been invaluable to me and the quality of my research.

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I think also of those from the department and university who have spent considerable time, and often helped beyond what was expected of them, to support me to complete the doctoral research. These include advisors Hugh Morris, Professor Pete Walker, Dr Andrew Heath, administrative staff Mags Woo, Pervin Sontoke and Santha Pollayah, and laboratory
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OVERVIEW OF A CEMENT-STABILISED FLAX-FIBRE REINFORCED RAMMED EARTH (UKU) BUILDING SYSTEM FOR NEW ZEALAND INDIGENOUS COMMUNITIES

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Keywords: earth building, design guide, Uku, sustainable housing, Maori, indigenous, rammed earth

Summary
This paper outlines research that has been undertaken to create an accessible, low-cost, sustainable earth building solution for Māori (the indigenous people of New Zealand) living in rural communities. Many individuals and families in rural Māori communities live in overcrowded dwellings with a low, inadequate standard of living. Reasons for the poor housing condition that exists can be attributed to legal issues regarding Māori land and land ownership, the urbanization of Māori, and the financial cost of constructing on isolated, undeveloped Māori land.

In July 2003, a four year research grant was awarded to develop a low-cost flax-fibre reinforced rammed earth housing concept into a commercially viable building technology. An important measure of the value of the research was the ability of rural Māori communities to be able to use the outputs of the research directly. Consequently a community reference group was created comprising of representatives from potential Māori user groups/areas. During the research, an optimized Uku soil mix was determined comprising of 8% cement and 0.075% flax fibres. Material tests have also been conducted to determine the lower 5% compressive, flexural and shear design strengths of the material. The construction process was optimized throughout the research with the development of such devices as a mobile flax stripper and a custom-made formwork system. Improvements in construction methodology were also implemented.

The research concluded in April 2008, with the construction of a full-size Uku house on the foreshore of Lake Rototai. This research has resulted in the development of a technology that rural Māori communities can immediately benefit from and has created a platform for future research and development of the Uku building system.

1. Introduction
Māori are the indigenous people of New Zealand and migrated to New Zealand as early as 800 AD from Polynesia (Howe 2007). StatisticsNZ (2001) has indicated that there are approximately 84,000 Māori currently residing in rural areas of New Zealand (2.3% of the national population). Slightly more than 5% of the total land area in New Zealand remains in the control of Māori, but many rural Māori communities are unable to fully utilize ‘Māori land’ owned by their hapu (sub-tribe) to provide adequate housing and living conditions for their members. A report published by Housing New Zealand (2005) showed that a disproportionately high and unacceptable number of individuals living in rural Māori communities reside in overcrowded, substandard dwellings. The New Zealand Housing Research Centre (NZHRC) has identified obstacles (Forrest 2007) that are obstructing the provision of quality and affordable housing developments on rural Māori land.

Aid in the form of local government housing funds, accommodation benefits and boosting of state housing around New Zealand have had limited success in increasing the standard of living for rural Māori (Forrest 2007). Uku, a flax-reinforced soil-cement construction technology (Segedin et al. 2006) is a practical housing solution that is being researched at the University of Auckland to address this issue. The difficulties and limitations that rural Māori communities encounter when building on Māori land and how the Uku building system has been developed to manage and overcome these barriers are addressed.
1.1 Māori Housing Obstacles

Obstacles preventing the adequate provision of housing to members of rural Māori communities can be grouped into 3 areas: financial barriers, legal issues and the urbanization of Māori.

‘Māori land’ is subject to specific laws in New Zealand (Te Tutukutanga Whānui Māori Act 1991). One example is the inability to alienate the land from Māori. This has created lending issues because Māori land cannot be used by financial institutions as a security. The majority of Māori land is located in rural areas. A photo of Māori land under the guardianship of the Waimaungo Papakainga Trust is shown in Figure 1. Papakainga refers to land used for housing a hapu or whanau (extended family). In many areas, especially coastal, plots of Māori land are remote and in a nearly natural undeveloped state. This is desirable because the land is, for the most part, untouched by human activity, but disadvantageous because it often elevates the access costs and the overall cost of developing building infrastructure on Māori land to an insurmountable level. Machinery and building resources are expensive to access, transport, and use, not just because of the distance, but because of other reasons including inadequate road infrastructure and lack of access to amenities and utility networks (e.g. telecommunications, water and electricity). Financial barriers are one of the main obstacles hindering rural Māori communities from utilizing their land to provide adequate housing for members of their community.

![Figure 1 Photograph of Māori land owned by the Waimaungo Papakainga Trust (Morgan 2005)](image)

The Māori population is urbanizing rapidly. Many Māori, particularly young unmarried Māori, have relocated into urban areas in order to secure work, earn money and live a more modern lifestyle. Before the Second World War more than 80% of Māori lived in rural areas. Today 64% of Māori live in urban areas (Meredith 2007). As a result, many rural Māori communities are depopulated and lack a younger workforce. This has increased the cost of building on Māori land because technically-trained skilled labour has to be sourced from surrounding regions to fill shortages that have developed in the local workforce.

Legally, Māori land is owned by the local Māori hapu with historic ties to the land. Māori land is collectively owned, often by over a thousand people spanning several generations. Managing building developments on Māori land is further complicated by the relocation of many owners into urban centres. These distant owners often have weak ties to their ancestral lands and lack the knowledge of genealogical links that are vital to understand in order to make progress towards a meaningful outcome (e.g. building a house).

1.2 Background of the Uku Project

The Uku research aims to develop a cement-stabilized, flax-fibre reinforced, rammed earth building system to provide a method of domestic house construction that overcomes the legal and financial obstacles preventing rural Māori communities from utilizing their ancestral lands to provide adequate dwellings and good standards of living for their members (Morgan 2005). The name given to the building system ‘Uku’ is the Māori language translation for earth. In 1996 the Waikato Area Research Unit undertook research investigating the viability of a rammed earth housing solution for rural Māori communities. Two rammed earth panels were constructed and tested, and revealed the potential to develop a low-cost earthen housing solution for Māori. The construction workshops with Uku (2003-2005) developed the earth housing concept further by building two simple rammed earth dwellings on Māori land. The first dwelling was constructed on a rural Māori papakainga located on the foreshore of the Firth of Thames (Waimaungo Papakainga) shown in Figure 2. The second dwelling was built on urban Māori land in Otara, Auckland City (Kohe Te Rahuitanga). In June 2003, the Foundation for Research, Science and Technology (FRST) awarded a 4 year grant to develop Uku, an accessible low-cost rammed earth housing solution for rural Māori communities. A major output of this research was the construction of the full-size Uku house in Rotokuri.
1.3 Advantages of Building with Earth

Houben and Ouillaud (1994) estimated that a third of the world’s population lives in earthen structures, with the majority residing in the developing world. For many millennia earthen structures have been the most common building solution in the world and it is still true of earthen structures today. The reasons why earthen construction has remained so widely used are due to:

- Material availability – In the majority of areas where human settlements are established, there is a nearby source of soil that can be used for earthen construction.
- Low-cost – Earthen material is abundant and easily extractable. It requires minimal material processing and is locally sourced.
- Easy to work – Earthen dwellings can be built using simple hand tools.
- Simple and intuitive – Earth buildings can be built without design guides and technical training.
- Strength – Earth has adequate strength for use as a structural material.
- High thermal mass – Earthen materials are capable of absorbing a large amount of heat energy. During hot days the earth keeps the building cool. During the night the heat is slowly released, keeping the building warmer.
- Durable – Earthen structures have long-term permanence. Many well designed and constructed earth heritage structures are still in use centuries later, like the Potala Palace, Tibet and the Great Wall of China (Jaquin et al. 2000).
- Low toxicity – Earthen structures generally do not require significant processing and mixing with chemical additives. Earthen structures are naturally past and fire resistant. As a result the material is generally non-toxic or of low toxicity (North 2008).

1.4 Seismic Design Requirements of Earth Building in NZ

Morgan (2005) outlined how earth building in New Zealand started with Māori construction of pa (strategic military settlements) and pit houses. Earth building usage as a method of housing increased during the European settlement of New Zealand (Walker et al. 2003). However, following the magnitude 7.6 Marlborough earthquake in 1848 (Grapes et al. 1968) and the magnitude 8.2 Wairarapa earthquake in 1855 (in which many earthen structures were badly cracked or completely destroyed) (GNS Science 2007), earthen construction quickly fell out of favour. Only recently, since 1980, has the earth building industry in New Zealand experienced a significant revival as interest in sustainable construction methods and environmentally friendly buildings has increased.

New Zealand is located at the active boundary of the Australian and Pacific tectonic plates (The New Zealand Landforms 2007). GNS Science, a government owned research institute, records 100 to 150 national earthquakes annually that are large enough to be felt (GNS Science 2007). The majority of earth building knowledge transferred to New Zealand has come from countries where seismic design was not a relevant design consideration. Due to the lack of national research and knowledge of the seismic performance of earth buildings, the majority of earthen designs, particularly before 1968 (when the New Zealand Earth Building Standards were released), had to be certified by a Registered Professional Engineer.

Figure 2  Photograph of Te Akuware - a simple rammed earth dwelling built on rural Māori land owned by the Waimanga Papakainga Trust (Morgan 2005)
In 1998 three earth standards were released in New Zealand by Standards NZ- 
- NZS 4297 Engineering Design of Earth Buildings 
- NZS 4296 Materials and Workmanship for Earth Buildings 
- NZS 4206 Earth Buildings Not Requiring Specific Design 

The earth standards have simplified the process for gaining building consents for earthen structures in New Zealand but still require the input of professional engineering expertise for non-specific design compliance to certify the suitability of the soil and the construction approach. The lack of professional engineers in Māori communities is an obstacle preventing Māori communities from accessing earthen construction technologies. The Uku project addresses this issue by creating a design guide that provides rural Māori communities with the tools and knowledge to uptake the Uku technology as well as by reducing the need for external input into the design and construction of dwellings built on Māori land. The design guide is a tool that provides greater accessibility to rural Māori communities to build safe structures using the Uku building system.

2 Unique Elements of the Uku Building System 

The Uku building system has been conceptualized with the idea of creating a system that is an accessible and sustainable housing solution for rural Māori communities as well as a technology that can be transferred and used independently by the rural Māori community.

2.1 Māori Community Reference Group 

The Uku research was conducted with input from a Māori community reference group (MCRG) comprised of representatives from Māori communities and organizations who were potential end users. An important measure of the research value resided in the ability of the target end users to directly apply the research to provide for their own housing needs. By meeting with potential end users throughout the research the Uku technology was developed to better utilize the resources available to Māori communities and to address their specific needs and issues. Working with the MCRG provided a way for the representatives of the Māori groups to gain an understanding and affinity with the Uku project, and relay the research to the people in their community. Relationships have been formed with tribal groups from Taitokerau (Northland), Tairawhiti (East Coast) and Waianiki (Bay of Plenty) shown in Figure 3.

![Figure 3 Diagram showing Taitokerau, Waianiki and Tairawhiti iwi (tribe) locations (Te Puni Kokiri 2008)](image)

2.2 Sweat Equity Financing 

A financing concept that uses sweat equity as a mechanism to make the Uku building system more affordable has been incorporated into the building process. The sweat equity concept uses labour and time, invested by the owner (and family) during the construction process, attaches a monetary value to their involvement and uses the monetary value of their work as part of the down payment for the house. The Uku system is able to utilize unskilled labour and as a result, labour contributions are not limited to residents who have undertaken formal technical training. Morgan (2005) documents the success in past trials using volunteer labour and/or residents from the local Māori community during construction to provide the majority of the labour required during construction of the wall elements of a building.

2.3 Use of Local, Low-energy, Renewable Resources 

The use of local resources (labour and building materials) was maximized where possible. For the dwelling built at Waimango, local soils were tested and a suitable soil source located 0.5 km away from site was chosen. The soil required a 30% sand addition (sourced 10 km away) in order to reduce the soil shrinkage to within the limits imposed in the earth standard NZS 4208 (Standards NZ 1008).
The soil located on site proved troublesome to use for construction. In total the soil took five weeks to extract, transport and mix in preparation for use in the Uku walls. The additional sand required to reduce shrinkage was mixed into the soil at a local quarry. Using local soils increased the labour and time required for construction. After the Waimango project, earth extracted from a soil quarry was preferred because it required less labour and time, and provided a more consistent soil composition. The soils on the urban site in Otara were not suitable due to a high organic content. For the Otara dwelling, soil was sourced from the Lyons quarry located at Woodhill and the Stevensons Quarry at Wairau.

Flax leaves were processed into flax fibres using a mobile flax stripper that was developed as part of the Uku project. The fibres used for construction were manufactured from leaves harvested at a flax plantation at Te Hapua, near the Rototiti Uku house.

It is important to acknowledge that not all the materials used in the Uku building system were locally sourced, low-energy, renewable materials. New Zealand is a very seismically active country and in order to satisfy the seismic demand requirement using the Uku wall panels, vertical D12 reinforcing bars were installed in all structural Uku wall panels at approximately 500 mm centres (e.g. 1200 mm long wall panels have three D12 vertical reinforcing bars). The introduction of steel reinforcing bars was a desired result but was necessary to satisfy the moment demands on the wall panels. Further testing of the Uku wall system, when subjected to seismic loading, will reveal whether a less conservative ductile design is appropriate. Until this is demonstrated the wall design will assume an elastic system response without a significant displacement or ductile capacity. The Uku mix contains an 8% (by weight) addition of Golden Bay Ordinary Portland Cement which has a high embodied energy. The addition of cement was considered necessary to provide resistance against moisture and advantageous as it improved the strength of the Uku material.

2.4 Machinery and Equipment Requirements

The soil, flax fibre, and rammed can be mixed and rammed using only hand tools and hand rammers. However access to a large supply of low-cost labour is needed to make this system commercially viable. Mixing, transporting and ramming the Uku mix is a highly labour intensive task. In practice a pneumatic rammer (and air compressor) has been used in conjunction with a hand rammer to compact the Uku soil. Similarly when mixing the soil in order to minimize labour requirements and decrease the mixing time, a compact loader (and driver) is hired to mix the soil onsite and transport it to the ramming location. The Uku building system requires a minimum of four people on site (including the compact loader driver). Measurements of site-task durations show that, by using the machinery and mechanical devices mentioned above, the shuttering system can be dismantled and erected in 1.5 hours and the ramming process can be completed in less than 3.5 hours.

The use of a pneumatic rammer and a compact loader during construction was not originally envisioned as a part of the Uku construction system. These additions require fuel and machinery/mechanical components that are less accessible to isolated rural areas and greatly increase the energy input during house construction. However due to the practical advantages of constructing buildings in a short period of time and the cost savings achieved by reducing labour requirements, it was decided to use machinery and mechanical equipment during construction where it would make the construction of an Uku dwelling easier to build and more affordable to the owner.

2.5 Design Guide

One of the objectives of the Uku project was to create a design guide that allowed rural Māori communities to make use of Uku technology without needing professional engineering expertise during the design, consenting and construction stages. A design guide was authored that currently is able to show how to verify the structural aspects of the dwelling. The current design guide was used successfully for the Uku house built at Rototiti. The building consent was issued in November 2007. The design guide is undergoing refinement and will continue to be developed to improve aspects such as the seismic and thermal design methodology (as the performance of the Uku wall system is better understood) and other aspects like defining practical/empirical preliminary soil tests and being translated into the Māori language.

3 Uku Research Objectives

The primary objectives of the FRST funded Uku research project were to:
- Develop the technology for the earth fibre composite material;
- Optimize end-user adoption of the technology and trial the results;
- Build full scale trials and develop a commercialization strategy.

The FRST funded Uku research was completed in April 2008. A summary of each stage is covered below.
3.1 Developing the Technology

The research has optimized the Uku (flax/cement/soil) mix composition initially proposed by Haab (1969). The present Uku mix (by weight proportions) consists of 9% cement and 0.075% flax fibres (cut to 60–70 mm lengths), mixed with soil at a moisture content of approximately 22%. Haab (1969) proposed a 0.76% flax component but the Uku research found a 0.075% flax proportion was more practical on a large scale because it reduced clumping of the flax and made it easier to mix the fibres homogeneously into the soil. The flax content reduction also decreased the labour requirement for separating and cutting the fibres to length.

Testing of the Uku material was conducted following standard test procedures defined by the American Society for Testing and Materials (ASTM). A summary of the results is shown below in Table 1. NZS 4296 specifies that rammed earth material that is used in construction needs to exceed 1.5 MPa in compression and 0.25 MPa in flexure. The measured compressive strength of the Uku material easily satisfied the requirements with an average of 7.3 MPa and a lower 5% characteristic design strength of 4.8 MPa. In flexure the material also passed with an average strength of 0.36 MPa. Although the design strength in flexure was below 0.25 MPa (0.10 MPa), all seven test beams failed above 0.25 MPa. The low flexural design strength was due to the spread of the results and the low number of flexural samples tested.

<table>
<thead>
<tr>
<th>Material Test</th>
<th>Average Strength [MPa] (x̄)</th>
<th>Coefficient of Variance [%] (σ/x̄)</th>
<th>Design Strength [MPa] (x̄ – 1.65σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>7.6</td>
<td>23.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Flexural</td>
<td>0.35</td>
<td>23.0</td>
<td>0.10</td>
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<tr>
<td>Shear</td>
<td>0.73</td>
<td>17</td>
<td>0.52</td>
</tr>
</tbody>
</table>

3.2 Optimizing End-user Adoption

In order to optimize end-user adoption of the technology, aspects of the construction process were refined as constructability issues were identified. In addition to this a design guide was developed. Following traditional Māori methods, the flax fibres were initially extracted by hand but this proved to be too slow and labour intensive. Consequently the process was moved to the Foxton Museum flax threshing machine. Working in collaboration with various weavers, a mobile trailer-mounted prototype flax stripping machine was designed and constructed at the University of Auckland. This machine now provides the flax fibre used during Uku construction. Another optimized aspect was the shuttering system used to restrain the formwork against the high lateral loads developed when ramming the earth. The formwork system developed by David Easton (a prominent rammed earth expert residing in California, USA) was adopted initially. Using this system the 300 mm wall panels at Waimango took three working days to ram each, including time to set up the formwork. The development of a modular formwork system (used for the Otara dwelling) decreased the wall panel build time to 10 hours. Reducing the wall thickness to 150 mm in combination with the modular formwork further decreased the wall build time to 5 hours (used for Rotokiti house). The modular formwork system developed is shown in Figure 4 and allowed wall panels up to 2.2 metres in length to be constructed per setup. The Otara dwelling and Rotokiti house construction progressed at one wall panel per working day.

Figure 4  Photograph of the modular Uku formwork system developed by the research team
3.3 Full Scale Trials

Construction of the Rototiti Uku house (60 m²) in April 2008 satisfied the FRST requirement to build a full scale house using the Uku building system. The plan for the Uku house is shown in Figure 5. Another house with the same floor plan was built 100 metres away from the Uku house using conventional timber frame construction. Both dwellings were built on a reinforced concrete floor and with an exposed rafter timber diaphragm roof. The timber house will be used as a reference point to evaluate the thermal performance of the Uku house. A photograph of the Uku dwelling in Rototiti under construction in March 2008 is shown in Figure 6. Both houses feature two bedrooms, a lounge, kitchen, laundry, toilet and carport. The construction inputs of both structures have been recorded and a detailed comparative analysis of the embodied energy and environmental impact of the timber and Uku construction methods will be evaluated. Each dwelling will be equipped with 15 thermal sensing buttons located on the interior and exterior of the walls. A memorandum of understanding (MOU) has been signed between the Uku research team and the occupants of the two houses to allow the dwellings to be monitored for two years.

Figure 5 Plan View of the Uku dwelling.

Figure 6 Uku dwelling in Rototiti under construction.

4 Conclusion

In New Zealand there is an issue with providing adequate housing and standards of living for individuals and families living in rural Māori communities. Issues of land ownership, the cost of construction on Māori land and the urbanization of the Māori population have created obstacles to land development that result in overcrowded and sub-standard living conditions for many residents living in these areas.

The Uku research has been conducted with the purpose of creating a low-cost, sustainable building system that is accessible to rural Māori communities. The Uku technology was developed to take advantage of local resources and materials and address issues preventing the adequate provision of housing on Māori land. To ensure that the developed technology was practical and usable by rural Māori communities, the research progressed with input from a community reference group. An important measure of the research project’s value was the ability of rural Māori communities to directly apply the outputs of the research.

As a result of the FRST funded research, an optimal Uku soil mix has been determined (8% cement, 0.375% flax and soil) and the construction process has been improved through the optimization of the building process and the introduction of machinery and mechanical devices where appropriate. The completed construction (in April 2008) of an Uku house on the foreshore of Lake Rototiti using local labour and materials has demonstrated that the proposed solution is constructable and practical.

The Uku building system incorporates a minimal proportion of high embodied energy and/or manufactured materials (cement and steel reinforcement). These additions were required to satisfy the NZ Earth Building Standards and provide adequate seismic capacity in the structure. The use of machinery (compact loader) and mechanical devices (pneumatic rammer and air compressor) was necessary because it improved the constructability of the house and reduced labour costs. Although these devices and materials detract from the original vision of developing a sustainable, low-energy construction system that uses local resources, tools and materials exclusively, compromises were necessary in order to create a practical building system that could benefit the rural Māori community end user.

The FRST funded research has been completed and a usable building system has been created. Aspects of the Uku building system can be refined; there is always scope for improvement and optimization. However, the research has successfully provided a working baseline technology, upon which further research can be conducted and which rural Māori communities can begin to use, to benefit their members now.
5 Acknowledgements

Funding for this project was provided by the New Zealand Foundation for Research, Science and Technology. The provision of building materials by Golden Bay Cement and Pacific Steel was much appreciated. Laura Devoichi and Rohann DaSilva are thanked for being great fellow researchers to work alongside. Brian Morgan, the main contractor, has been very kind to, and accommodating of, the research team on-site. Hugh Morris has provided a wealth of earthen research knowledges and resources. Thanks also to Colin Nicholas for keeping the Robit house construction in order. Laboratory technicians Hank Mooy, Tony Daligan, Mark Byram, Noel Parinpanayagam and Jeff Melder readily gave their time, support and advice throughout the project. The Uku research is richer and more useful because of their involvement

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UKU: Concept to Construction Using Flax-Fibre Reinforced Stabilised Rammed Earth

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Abstract: Uku is a low-cost flax fibre-reinforced stabilized rammed earth walled housing system that has been designed for the rural Māori communities of New Zealand. In the year 2008, the first Uku house was built using local labour from the rural Māori community and is currently occupied by a local Māori family. Māori are the indigenous people of Aotearoa New Zealand. This paper will present the development of Uku from a low-cost, natural material concept, into a 90 m², two bedroom house located on the Southern shore of Lake Rototui, NZ.

Financial, geographical and legal obstacles to rural Māori land development, and the use of existing conventional housing solutions to overcome these obstacles has provided a sub-optimal housing outcome in terms of accessibility and appropriateness for rural Māori and their culture. At present a disproportionately high number of rural Māori live in sub-standard and overcrowded living situations.

The Uku research began in 1996 to develop an accessible, affordable and appropriate housing system for rural Māori. The Uku housing system has been developed to utilize locally available material resources, to be able to employ local community based labour and to equip rural Māori communities with the resources and knowledge to build their own houses independently using the Uku method.

The completed construction of the first Uku house has shown the cost of building Uku walls to be greater than equivalent timber framed walls. The construction of the Uku house was successfully completed and as more Uku houses are built, the affordability and constructability of Uku houses will improve. The Uku method’s consideration of Māori culture and social values, the use of traditional and local resources, and the potential for Māori to provide their own housing, continues to attract increasing interest from Māori communities around New Zealand.

Keywords: Rammed earth house, Uku, Flax fibre, natural fibre composite, rural housing

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1 Introduction

This report describes the process through which a flax-fibre reinforced rammed earth housing method was developed, from a fibre earth composite material, into a 90 m² two bedroom house on rural Māori land at Haunungi '10a2b Papakainga'; located on the Southern shore of Lake Rototoi, New Zealand. The housing method was named 'Uku', one of the Māori words for earth. The Uku housing method was developed to address the difficulties and obstacles encountered when building with conventional housing methods on Māori land for the local Māori community. The Uku method increases the use of local resources, acknowledges Māori culture and traditions, and empowers the local community to provide their own housing solutions. A breakdown of the Rototoi Uku house costs are detailed in Section 4.

1.1 The Māori people

Māori are the indigenous people of Aotearoa New Zealand (NZ) and migrated to NZ as early as 800 AD from Polynesia (Howe 2007). StatisticsNZ (2006) has indicated that there are approximately 96,000 Māori currently residing in rural areas of NZ (2.5% of the national population). Slightly more than 5% of the total land area in NZ remains in the control of Māori, but many rural Māori communities are unable to fully utilize ‘Māori land’ owned by their hapu (sub-tribe) to provide adequate housing and living conditions for their members.

1.2 Rural Māori Housing Obstacles

![Figure 1: Photo of Māori land owned by the Waimango Papakainga Trust (Morgan 2005)](image)

A report published by Housing New Zealand (2005) showed that a disproportionately high and unacceptable number of individuals living in rural Māori communities reside in overcrowded, substandard dwellings. Obstacles preventing the adequate provision of housing to members of rural Māori communities can be grouped into 3 areas: financial barriers, legal issues and the urbanization of Māori.

The majority of Māori land is remote which elevates the cost of development. A photo of Māori land under the guardianship of the Waimango Papakainga Trust is shown in Figure 1. In many areas, especially coastal, plots of Māori land are geographically isolated and in a natural undeveloped state. This is desirable because the land is, for the most part, untouched by human activity, but disadvantageous because it elevates the access costs and the overall cost of developing building infrastructure on Māori land to an insurmountable level. Machinery and building resources are expensive to access,
transport, and use, not just because of the distance, but because of other reasons including inadequate road infrastructure and a lack of access to amenities and utility networks (e.g. telecommunications, water and electricity). Given the extensive land loss in the past, further land alienation to generate the capital necessary for development is a highly contentious issue and not possible under the contemporary legislation for Māori land. Financial barriers are one of the main obstacles hindering rural Māori communities from utilizing their land to provide adequate housing for members of their community (Forrest 2007).

Legally, Māori land is owned by the local Māori hapu with historic ties to the land and is subject to specific laws in New Zealand (Te Ture Whenua Māori Act 1993). Māori land is collectively owned, often by over a thousand people spanning several generations and is inalienable. Lending agencies in New Zealand have been reluctant to deal with the complex and multiply owned nature of Māori land (Federation of Māori Authorities 2009). Managing building developments on Māori land is further hindered by the relocation of many owners into urban centres. These distant owners often have weak ties to their ancestral lands and lack the knowledge of genealogical links that are vital to understand in order to make progress towards a meaningful outcome (e.g. building a house).

The Māori population urbanized rapidly during the 1950's and 60's as a result of the Town and Country Planning Act (1953) that only allowed a single family that farmed each block of rural land to live on it. More recently rural Māori communities have been impacted by a second wave of urbanisation caused by the mechanisation of farming work that has reduced the number of jobs available in rural areas. Many Māori, particularly young unmarried Māori, have relocated into urban areas in order to secure work, earn money and live a more modern lifestyle. Before the Second World War more than 80% of Māori lived in rural areas. Today 84% of Māori live in urban areas (Meredith 2007). As a result, many rural Māori communities are depopulated and have a depleted local labour force. This has increased the cost of building on Māori land because technically-trained skilled labour has to be sourced from surrounding regions to fill shortages that have developed in the local workforce.

1.3 Māori Community Reference Group (MCRG)

A MCRG comprising of representatives from Māori communities and organizations was formed in 2003. Through a series of hui (meetings) five key attributes for a rural Māori housing method were identified (Morgan 2005). The development of the Uku housing method was guided by these key attributes:

1. Designs that required a minimum of input by professional engineers
2. A design-life of six generations or 150 years
3. Construction technology that can be adopted by a non-technical workforce
4. Construction technology not overly dependent on large complex machinery
5. Low cost easily transferable construction technology

2 The Uku Housing Method

A fibre-reinforced earthen construction method was chosen because it promoted the use of locally available resources. Soil, sand, flax fibres, and labour resources can be sourced from within most rural Māori communities. Earth as a housing material possesses several inherent advantages (e.g. long-term permanence of earthen structures, high thermal mass for indoor temperature regulation, and natural resistance to fire and insects). A mobile flax decortication device built in 2004 has provided the ability to process flax
sources in close proximity to the building site.

Most of the labour required to build Uku walls can be provided by non-technically trained labour. During the construction of the Rotoiti Uku house two unemployed 18 year old boys from the local whanau (extended family) were employed and trained onsite by the local accredited builder building the house. Employing and training the local workforce in this manner expands the available local expertise, benefits the local economy and strengthens relationships within the community.

Cultural needs and expectations can be better met by empowering Māori to provide their own housing. Māori have tikanga (practices) regarding many aspects of housing. All three Uku buildings that have been built so far have been named and blessed. Rules exist regarding the positioning of rooms in a house, the kitchen cannot be linked to a bedroom or a bathroom, and large living areas are needed to accommodate family gatherings. The identity of Māori is strongly associated with their ancestral lands. Using earth and flax resources from their ancestral lands to provide shelter for their family is a form of cultural revival, an acknowledgement of the indigenous knowledge possessed by their ancestors and a source of pride to the owners.

Structurally the building system comprises of three parts as shown in Figure 2:
1. A reinforced concrete slab with deeper footings beneath the walls
2. Cement-stabilized, flax-fibre reinforced rammed earth walls panels with a concrete ring beam cast insitu on top of the panels connecting them together
3. A Pacific gull-wing plywood diaphragm roof on exposed rafters

Figure 2: North face of the Rotoiti Uku house

3 Project Timeline

Figure 3: Diagram showing the development of the Uku method
The research has progressed through a number of stages as shown in Figure 3.

3.1 Conceptualization and Development

In 1996, a Māori research organisation secured seed funding to investigate the use of flax-fibre reinforced earth for housing. The Forest Research Institute was subcontracted to assist with the development and testing of the fibre reinforced earthen composite.

By 1997, recipe optimisation research for flax-fibre reinforced cement-stabilized cinva rammed bricks had been completed by Haab and Kingi (1988). The optimised mix consisted of 9% cement and 0.75% flax fibres (by weight) cut to lengths of 64 mm. Sisal fibres and the wet and dry treatment of fibres prior to soil compaction were also tested and revealed no significant influence on the material performance of the bricks.

The optimized mix was used to build a monolithic Uku wall panel 150 mm thick, 1.2 m wide and 2.4 m high in 1998. The wall panel was tested in a test apparatus for triple skin plywood shear walls. During the test, the apparatus failed before the wall panel and no strength value was obtained. Even without a final numerical result, the test showed the potential of using Uku as a structural building material.

3.2 Technology Transfer

A Māori Community Reference Group (MCRG) was established in 2003. After several hui (meetings), key desirable attributes of a housing method for rural Māori communities were specified. A Māori research organisation, Nga Pae O Te Maramatanga, funded the construction of two, 6 metre X 6 metre, single room Uku dwellings in 2004 to test the practical implementation and social acceptance of the Uku structures. The first Uku dwelling was built on rural Māori land on Waimango Papakāanga (65 km southeast of Auckland, NZ). An onsite soil source (blended with local sand) was used but proved to be very time consuming and labour intensive. The second dwelling was built on urban Māori land in Otara, Auckland, and used soil from Lyons Quarry located in Waimauku, Auckland (Morgan 2005). The two dwellings demonstrated the positive social acceptance of Uku in the Māori community. The two dwellings were initially designated as a garage for a lawn mower and a laundry room but were changed by the owners into a music room and a meeting house / sleeping area respectively.

3.3 Implementation

In June 2004 the Foundation for Research, Science and Technology (FRST) awarded a research grant to develop the Uku method. The research had three parts:

1. To develop the technology for the earth fibre composite material
2. To optimise end-user adoption of the technology
3. To build full-scale trials

In 2004 a mobile flax deortication device was designed (shown in Figure 4). The machine enabled the fast and mobile processing of flax leaves into flax fibres (shown in Figure 5).
Various structural tests were carried out to determine the compressive, flexural and shear strength of the Uku material through the Ngati Pikiao Project Earth Building Composites Using Indigenous Fibres (2004), SCION Research (2005) and at the University of Auckland (2007, results shown below in Table 1).

<table>
<thead>
<tr>
<th>Method of Test</th>
<th>No. of Samples Tested</th>
<th>Average Strength</th>
<th>95% Design Strength</th>
<th>Coefficient of Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compress.</td>
<td>33 Cubes</td>
<td>7.6 MPa</td>
<td>4.6 MPa</td>
<td>23.7%</td>
</tr>
<tr>
<td>Flexural</td>
<td>8 Beams</td>
<td>0.35 MPa</td>
<td>0.18 MPa</td>
<td>28.9%</td>
</tr>
<tr>
<td>Shear</td>
<td>3 Panels</td>
<td>0.73 MPa</td>
<td>0.52 MPa</td>
<td>17.0%</td>
</tr>
</tbody>
</table>

Thermal data was collected over the summer of 2005 on the Otara Uku dwelling and was input into a thermal simulation software package to predict the thermal performance of Uku walls over a range of wall thicknesses.

In 2007 the Rotoiti house design was drafted by architects, DesignTribe. The structural design calculations were done at the University of Auckland (da Silva 2007) and the building consent was approved in November the same year by the Rotorua District Council. The FRST funded Uku project concluded in March 2008 with the construction of a 2 bedroom house with an indoor floor area of 90 m² on the Southern shore of Lake Rotoiti.

4 Rotoiti Uku House Financial Analysis

During the construction of the Rotoiti Uku house, a builder’s journal was kept for each working day. Each entry recorded the weather conditions, workers present, hours worked, and the work done. The journal allowed the labour and machine hours to be measured, and the rate of progress to be monitored. The total cost of construction including the foundation, walls, roof and fittings (windows, doors and a skylight) was $84,900.

The construction of the concrete slab foundation and the timber roof were subcontracted out at $14,000 and $21,000 respectively. The window, door and skylight fittings (all double glazed) cost $16,500. The financial details presented focus on the cost of building the Uku walls as they are the main variation from current conventional building practice. The Uku walls cost $33,400 and are broken down into labour, machinery and material cost components in Table 2 below. A timber framed wall equivalent was estimated at a cost of $19,900 (Rawlinson & Co. 2008).
The labour consisted predominantly of four local workers; a skilled builder, two non-technically trained young adults and the house owner. Under the guidance and training of the experienced builder, the other members of the team were able to provide the majority of labour required during the construction of the Uku house.

Three pieces of machinery were used when building the Uku walls:
1. A compact loader (Bobcat shown in Figure 6) – to mix, transport and lift the soil
2. An air compressor (shown in Figure 7) – to operate the backfill tamper
3. A backfill tamper (shown in Figure 7) – to compact the soil in the formwork

![Figure 6: Compact Loader mixing soil](image1)

![Figure 7: Air Compressor and Backfill Tamper](image2)

The use of machinery enabled the construction of a 2.4 metre high Uku wall (up to 2.2 metres long) to be built within an 8-hour working day with a workforce of four people. By reducing the number of people on-site and the amount of work required, time was saved, costs were reduced and a safer working environment was created. The costs realised during the Rototiti house construction are listed below in Table 2.

**Table 2: Costs incurred during construction of the Rototiti Uku House**

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>No.</th>
<th>$/unit</th>
<th>Cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Labour</strong></td>
<td>hrs</td>
<td>904</td>
<td>15.00</td>
<td>13560</td>
<td></td>
</tr>
<tr>
<td><strong>Machinery</strong></td>
<td>hrs</td>
<td>86</td>
<td>115.00</td>
<td>9890</td>
<td></td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bobcat &amp; Compressor</td>
<td>hrs</td>
<td>86</td>
<td>115.00</td>
<td>9890</td>
<td></td>
</tr>
<tr>
<td>Bond beam (shutters, concrete)</td>
<td>m</td>
<td>58</td>
<td>42.50</td>
<td>2465</td>
<td></td>
</tr>
<tr>
<td>Reinforcing steel &amp; Fasteners</td>
<td></td>
<td></td>
<td></td>
<td>1276</td>
<td></td>
</tr>
<tr>
<td>Shadow clad timber walls</td>
<td>m2</td>
<td>12</td>
<td>201.00</td>
<td>2412</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>m3</td>
<td>21</td>
<td>45.00</td>
<td>945</td>
<td></td>
</tr>
<tr>
<td>Soil Transportation</td>
<td>km</td>
<td>3</td>
<td>310.00</td>
<td>930</td>
<td></td>
</tr>
<tr>
<td>Cement (40 kg bag)</td>
<td>each</td>
<td>77</td>
<td>10.00</td>
<td>1306</td>
<td></td>
</tr>
<tr>
<td>Flax</td>
<td>kg</td>
<td>21</td>
<td>25.00</td>
<td>525</td>
<td>9939</td>
</tr>
<tr>
<td><strong>Subcontracted Work</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td></td>
<td></td>
<td></td>
<td>14000</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td></td>
<td></td>
<td>21000</td>
<td></td>
</tr>
<tr>
<td>Fixtures (windows, doors, skylight)</td>
<td></td>
<td></td>
<td>16500</td>
<td>16500</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$84989</td>
</tr>
</tbody>
</table>

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5 Discussions of Costs

5.1 Rototoi Project Soil Costs

The soil costs incurred during the project are particular to the Rototoi Uku construction. The earth material used for the house was sourced from Lyons Quarry, Auckland (310 km from site). Five suitable soil sources were identified from local quarries, however due to resource consent conditions for the quarries, none of the local soil sources identified could be used. As a result, the Lyon Quarry soil source (used for past Uku walls built at the University of Auckland) was used. Future Uku buildings will use local soil sources.

5.2 Optimisation of the Building Process

During the construction period, ways to optimise the construction process and save costs were identified. The Rototoi house was built using one set of formwork and four labourers. Wall construction progressed at one Uku panel a day. There is the capacity to build 2 to 3 wall panels at a time (each day). The air compressor used is able to support three backfill tampers simultaneously (only one was used). Similarly, one compact loader bucket contains enough soil material for 2 to 3 layers of rammed earth but only one panel was rammed at a time. Further improvements could be achieved by improving the structural detailing and floor plan design of the house. Only one Uku wall panel can be built per day per set of formwork (due to curing). A 200 mm long wall and a 2000 mm long wall effectively require the same amount of time to build. Future Uku houses will be designed to make better use of the modular wall lengths available.

5.3 Sweat Equity

The upfront cost required to secure a loan to finance the construction of a house is an obstacle that brings many ideas of home ownership in rural Māori communities to an end. The Uku method provides a way for the owner/s to provide a larger deposit on a house loan by incorporating the value of labour provided during construction and the value of materials provided from the land. For the Rototoi Uku house, the cost of labour, earth material and flax fibres was $16,000 (19% of the total house cost). Using the sweat equity concept the owner/s would be able to supplement their initial monetary deposit for the loan with the non-monetary owner provided costs that would otherwise be incurred for the house. Once an agreement has been established with a lending agency regarding home loans with a sweat equity component, many more rural Māori communities will be able to secure a house loan and become house owners.

6.0 Conclusion

The construction of the first Uku house (2 bedrooms, 90 m²) on the Southern shore of Lake Rototoi in 2008 is a key milestone in the development of the Uku method. The Rototoi house has demonstrated that the Uku method can be built using local resources and labour. The method continues to be developed toward the goal to achieve the key objectives of a rural Māori housing solution that were identified at the beginning of the research process by a Māori Community Reference Group.

The Rototoi house cost $84,900 to build (39% attributable to the Uku walls). During construction, methods of optimizing the construction process were identified such as incorporating the modular construction system dimensions when designing the floor plan and to make use of the existing capacity to build more than one wall panel at a time.

As more Uku houses are built, the method will continue to improve. In turn this will result in a more affordable building method and a better housing situation for rural Māori.
7.0 References


Appendix A.3 Newspaper and Magazine coverage of Uku in July 2009

Earth housing a new low-cost option

A Uku house will be built in Northland as part of a University of Auckland engineering research project into sustainable, low-cost housing options for rural Maori.

Civil Engineering PhD student John Cheah is working with the Ahipara community to develop the Uku house by the end of 2010. Uku, Maori for earth, is a building method which involves mixing earth and flax with cement to build quality, affordable housing.

“The research follows the principles of papakainga development. It aims to equip rural Maori communities with the knowledge to use their own earth and labour to build desirable housing,” Mr Cheah says.

“Rural Maori are an important and significant component of the New Zealand population who have a lower average quality of health and accommodation due to issues with housing. This research seeks to address this imbalance.”

Mr Cheah says Uku technology is ideal for rural Maori communities where land is owned by the local hapu, rather than individuals, and when financial barriers may prevent them from developing that land.

The earth and flax for the Ahipara Uku house will be sourced from within Ahipara, and the community will work together to build the house to New Zealand building and council standards, including the New Zealand earth building standards.

Ahipara residents attended a workshop at the University’s Faculty of Engineering this month where they learnt how to prepare the flax, how to mix it with earth and cement, and how to compact it into walls.

Mr Cheah also verified the suitability of Ahipara earth and flex for Uku housing, and conducted seismic tests on the finished walls as part of his research. Another workshop will be held at Ahipara in November when four practice walls will be built on site.

Ahipara resident Rueben Taipari Porter, from Te Rarawa iwi, is leading the project in his home town, and is building the first Uku house in Northland for his hapu.

He will support the building of additional Uku houses in his community once Mr Cheah’s research project ends. Mr Porter, whose whanau stretches back 20 generations in Ahipara, says he has an obligation to provide better conditions for his descendants.

“Improving the standard of living for my people is an important factor in my leading this alternative concept. I am very grateful to the University and the Engineering Faculty for their support,” he says.

Mr Cheah hopes his study will help validate the performance and viability of Uku housing so it can be adopted by more communities. The results will be compiled into a design guide, which will be available in English and Te Reo Maori.

The University’s Faculty of Engineering has been involved in the construction of three previous Uku dwellings — at Haumingi papakainga on Lake Potoiti, Te Kura Takawaenga O Piripono in Orara, and Waimango papakainga on Tikapa Moana (Firth of Thames).

Mr Cheah’s three year project is funded by a Top Achiever Doctoral Scholarship, awarded to New Zealand’s top scholars by the Government.

Previous Uku research at the University has been supported by the Foundation for Research Science and Technology, and Nga Pae o Te Maramatanga.

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09 373 7599 ext 849539*

Figure 155 Building Today - Magazine - July 2009, page 13
EARTH HOUSING COULD BE WAY FORWARD FOR RURAL MAORI

Building an “uku” house – using earth, flax and cement – is part of a University of Auckland engineering research project into sustainable, low-cost housing options for rural Maori. Civil engineering PhD student John Cheah is working with the Ahipara community in Northland to develop the uku house by the end of 2010. Uku, Maori for earth, is a building method which involves mixing earth and flax with cement to build quality, affordable housing. Cheah says uku technology is ideal for rural Maori communities where land is owned by the local hapu rather than individuals, and when financial barriers may prevent them from developing that land. The earth and flax for the houses will be sourced from within Ahipara, and the community will work together to build the house to New Zealand building and council standards. Ahipara residents recently attended a workshop at the faculty of engineering in July to learn the techniques needed. The faculty has been involved in building three previous uku dwellings at Lake Rotori, Otara, and Tikapa Moana (Firth of Thames). Cheah’s three-year project is funded by a Top Achiever Doctoral Scholarship, awarded to New Zealand’s top scholars by the government.

Figure 156 NZ Education Review - Magazine - 17 July 2009, page 5
Rural Maori may benefit from earthen technology

Earth housing could be the way forward for rural Maori.

An ukuru house will be built in Northland as part of an Auckland University engineering research project into sustainable, low-cost housing options for rural Maori.

Civil engineering PhD student John Cheah is working with the Ahipara community to develop the ukuru house by the end of 2010.

Uku, Maori for earth, is a building method which involves mixing earth and flax with cement to build quality, affordable housing.

“The research follows the principles of papa-kaitangata development.

“It aims to equip rural Maori communities with the knowledge to utilise their own earth and labour to build desirable housing,” John says.

“Rural Maori are an important and significant component of the New Zealand population who have a lower average quality of health and accommodation because of issues with housing. This research seeks to address this imbalance.”

John says ukuru technology is ideal for rural Maori communities where land is owned by the local hapu, rather than individuals, and when financial barriers may prevent them from developing that land.

The earth and flax for the Ahipara ukuru house will be sourced from within Ahipara, and the community will work together to build the house to New Zealand building and council standards, including the New Zealand earth building standards.

Ahipara residents attended a workshop at the university’s faculty of engineering in July where they learnt how to prepare the flax, how to mix it with earth and cement, and how to compress it into walls.

John also verified the suitability of Ahipara earth and flax for ukuru housing, and conducted seismic tests on the finished walls as part of his research. Another workshop will be held at Ahipara in November when four practice walls will be built on site.

Ahipara resident Rueben Taipari Porter, from Te Rarawa iwi, is leading the project in his home town and is building the first ukuru house in Northland for his hapu.

He will support the building of more ukuru houses in his community when John’s research project ends. Rueben, whose whanau stretch back 20 generations in Ahipara, says he has an obligation to provide better conditions for his descendants.

“Improving the standard of living for my people is an important factor in my leading this alternative concept.”

“I am very grateful to the university and the engineering faculty for their support,” Rueben says.

John hopes his study will help validate the performance and viability of ukuru housing so it can be adopted by more communities.

The results will be compiled into a design guide, which will be available in English and Maori.

The university’s faculty of engineering has been involved in the construction of three previous ukuru dwellings, at Haumanga papa-kaitangata on Lake Rotiti, Te Kura Takawaenga O Piripono in Otara, and Waimango papa-kaitangata on Tikapa Moana (the Firth of Thames).

John’s three-year project is funded by a top achiever doctoral scholarship, awarded to New Zealand’s top scholars by the government.

Previous ukuru research at the university has been supported by the Foundation for Research Science and Technology, and Ngai Pae o Te Maramatanga.
An uku house for Ahipara

An uku (earth) house is to be built at Ahipara as part of a University of Auckland engineering research project into sustainable, low-cost housing options for rural Maori.

Civil engineering PhD student John Cheah is working with the Ahipara community to erect the house by the end of next year.

Mr Cheah said the research project would follow the principles of papakainga development, the aim being to equip rural Maori communities with the knowledge to use their own earth and labour to build desirable homes.

"Rural Maori are an important and significant component of the New Zealand population who have a lower average quality of health and accommodation due to issues with housing," he said.

"This research seeks to address this imbalance."

He described uku technology (involving a mixture of earth, flax and cement) as ideal for rural Maori communities where land was owned by the hapu rather than individuals, and where financial barriers might prevent the development of that land.

The earth and flax for the house would be sourced within Ahipara, and "Improving the standard of living for my people is an important factor in my leading this alternative concept."

Rueben Porter

the community would work together to build the house to national and council standards, including New Zealand earth building standards.

Earlier this month Ahipara residents attended a workshop at the university's engineering facility, where they learned how to prepare the flax, how to mix it with earth and cement, and how to compact it into walls.

Mr Cheah also verified the suitability of Ahipara earth and flax for building, and had conducted seismic tests on finished walls as part of his research.

Another workshop will take place at Ahipara in November, when four practice walls will be built on-site.

For his hapu

Ahipara resident Rueben Porter will lead the project in his home town, and will build the first uku house in Northland for his hapu.

And he will support the building of more once Mr Cheah's research project is completed.

Mr Porter, who says his whanau have lived at Ahipara for 20 generations, said he had an obligation to provide better living conditions for his descendants.

"Improving the standard of living for my people is an important factor in my leading this alternative concept," he said.

"I am grateful to the university and the engineering facility for their support."

Meanwhile, Mr Cheah hoped his study would help validate the performance and viability of uku housing so it could be adopted by more communities. The results would be compiled into a design guide, which would be available in English and te reo Maori.

The university's faculty of engineering has already been involved in the construction of three uku dwellings, at Haumangi papakainga (Lake Rotoiti), in Otara, and Tikapa Moana (the Firth of Thames).
Clay, flax house for Maori

A house made from clay and flax will be built in Northland to help address the housing imbalance for rural Maori.

University of Auckland engineering student John Cheah is working with the Ahipara community to build the “uku” house by the end of 2010.

Rural Maori had a lower-than-average quality of health due to housing and this was a way to address that imbalance, he said.

Uku, Maori for earth, is a building method which involves mixing earth and flax with cement to build quality, affordable housing.

The technology was ideal for rural Maori communities where land was owned by the local hapu, rather than individuals, and when financial barriers might prevent development, Mr Cheah said.

Earth and flax for the Ahipara uku house will be sourced from within Ahipara, and the community will work together to build the house to New Zealand building and council standards, as well as national earth building standards.

Ahipara resident Rueben Porter is leading the project and is building the first uku house for his hapu. He will support the building of additional uku houses in his community once Mr Cheah’s research project ends.

Mr Cheah hopes his study will help validate the performance and viability of uku housing so it can be adopted by more communities.

— APN

'Uku' house will be built of clay and flax

y André Huenber

A house made from clay and flax will be built at Ahipara to help address the housing imbalance for rural Maori.

University of Auckland engineering student John Cheah is working with the Far North community to build the “uku” house by the end of 2010.

Rural Maori had a lower-than-average quality of health due to housing and this was a way to address that imbalance, he said.

Uku, Maori for earth, is a building method which involves mixing earth and flax with cement to build quality, affordable housing.

The technology was ideal for rural Maori communities where land was owned by the local hapu, rather than individuals, and when financial barriers might prevent development, Mr Cheah said.

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Ahipara resident Rueben Porter is leading the project and is building the first uku house for his hapu. He will support the building of additional uku houses in his community once Mr Cheah’s research project ends. Mr Porter said he had an obligation to provide better conditions for his descendants.

Mr Cheah hopes his study will help validate the performance and viability of uku housing so it can be adopted by more communities.

The results will be compiled into a design guide in English and Maori.

HOME HELP: John Cheah is building uku housing.
Living in the arms of Mother Earth

Research aims to teach rural Maori to use soil, flax and their own labour to build houses

by Yvonne Tahana
Maori affairs reporter

Increasing the demand for homes made from a repackaging of papatuanuku, the earth, is what a low-cost housing project in the Far North hopes to achieve.

Auckland University’s Engineering School has been leading research into the performance of uku housing — a building method which involves mixing earth, flax and cement to use as a base material.

But civil engineering PhD student John Cheah, who is working with the Ahipara community to develop a house by the end of 2010, one of only a handful this decade, says it is an idea that rural Maori have yet to be sold on.

Researchers have identified that group as a significant component of the population who have a lower-than-average quality of health because of housing issues.

“A lot of them like it, they don’t have the idea of earth as poor or undesirable, but they need some more evidence that they’re quality. They want to visit a friend who has an earth house, they want to go touch it,” Mr Cheah said.

The research aims to “equip rural Maori communities with the knowledge to use their own earth and labour to build desirable housing”.

In a three-year study Mr Cheah will look at the performance and viability of uku housing so it can be adopted by more communities.

Proving the theory that the uku mixture will help keep homes warm in winter and cool in summer will be high on that agenda.

“There’s a lot of heat energy around in winter — it’s just about capturing it. You also want to design it so the walls are shaded during the summer because the sun is higher in the sky, you want it heating the roof and reflecting and only getting part of your walls.”

The results of the study, which builds on previous work by the university, will be compiled into a guide available in English and Te Reo.

A two-bedroom uku home built at Lake Rototiti cost $85,000 but Mr Cheah expected significant cost savings on this as resources would be sourced locally from communally owned land and labour costs kept to a minimum. While a kitset might be cheaper in the long run, the saved heating costs associated with the uku home would hopefully make the newer choice more attractive.

SEEING IS BELIEVING: Most people want evidence of the quality of an uku house.
### Survey of Perspectives on rural Māori housing methods

#### Pair wise comparisons

<table>
<thead>
<tr>
<th>Māori Well-being</th>
<th>Ecosystem Environment</th>
<th>Hapū Cultural</th>
<th>Community Social</th>
<th>Whanau Economic</th>
<th>Total</th>
<th>+9</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecosystem Environment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(-3) Much Less Imp, (-2) Less Imp, (-1) Marginally Less Imp, (0) No Difference,

<table>
<thead>
<tr>
<th>Metric</th>
<th>UKU Wall Concept</th>
<th>Timber Framed Wall Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco1</td>
<td>Embodied Energy (whole life)</td>
<td></td>
</tr>
<tr>
<td>Eco2</td>
<td>Visual and sound advantages</td>
<td></td>
</tr>
<tr>
<td>Eco3</td>
<td>Waste Generation / Recycling (during construction and disposal)</td>
<td></td>
</tr>
<tr>
<td>Cult1</td>
<td>Pride / Mana</td>
<td></td>
</tr>
<tr>
<td>Cult2</td>
<td>Self Sufficiency</td>
<td></td>
</tr>
<tr>
<td>Cult3</td>
<td>Kaitiakitanga (Guardianship of the Environment)</td>
<td></td>
</tr>
<tr>
<td>Com1</td>
<td>Strengthens the community (relationships and pride)</td>
<td></td>
</tr>
<tr>
<td>Com2</td>
<td>Healthy Living Environment</td>
<td></td>
</tr>
<tr>
<td>Com3</td>
<td>Fire / Insect / Decay Resistance</td>
<td></td>
</tr>
<tr>
<td>Econ1</td>
<td>Affordability</td>
<td></td>
</tr>
<tr>
<td>Econ2</td>
<td>Long-term Economic Performance</td>
<td></td>
</tr>
<tr>
<td>Econ3</td>
<td>Availability of Local Builders &amp; Resources</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(-2) Demigrated, (-1) Diminishing, (0) Maintaining, (+1) Enhancing, (+2) Fully Restored
(2) Mauri nobo / mate, (1) Mauri heke, (0) Maintaining, (+1) Mauri piki, (+2) Mauri tu / ora
Uku wall Concept (Flax-fibre reinforced, cement-stabilized, rammed Earth)

Conventional timber framed wall Concept
Appendix B.2 Mauri Model Housing Survey – Participant Information Sheet

PARTICIPANT INFORMATION SHEET
Project title: Development of a flax-fibre Reinforced Rammed Earth Housing method (UKU) for Rural Maori Communities
Name(s) of Researcher: Jing Siong (John) Cheah

Researcher Introduction
My name is Jing Siong (John) Cheah. I was born in Kuala Lumpur, Malaysia and immigrated with my family to New Zealand when I was 2 years old. I grew up in Tamaki makau rau (Auckland). Presently I am a Civil and Environmental Engineering doctoral student at the University of Auckland researching a flax-fibre reinforced earthen housing method called UKU for rural Maori communities.

Invitation
You have been selected to participate in this survey because you belong to a group or organisation that is involved with the provision of housing on rural Maori communities. Your participation is voluntary. The survey will take approximately 20 minutes to complete. Participants can receive a summary of survey results.

Survey Rationale
There are currently no decision making frameworks in mainstream use that achieve the effective integration of cultural effects from the perspective of Tangata Whenua. A decision making tool called the Mauri model is being trialled to evaluate rural Maori housing methods. The Mauri model uses the concept of Mauri or Wellbeing to quantitatively assess the performance of each housing method.

Project Procedures
Participants will be guided through a 2 page survey where they will assign weights to the economic, social, cultural and environmental aspects and assign scores to 12 metrics regarding the performance of the listed housing methods as housing solutions for rural Maori communities.

Survey Results Use, Disposal and Anonymity
The results will be used to identify the advantages and disadvantages of a timber framed house and a flax-fibre reinforced rammed earth house in order to find areas of mutual agreement and areas of contrast with regard to the economic, environmental, social and cultural aspects. All results will be anonymous and cannot be traced back to you. Results will be stored for 6 years in a secure place, after which they will be securely disposed of. As the surveys are anonymous, the data cannot be withdrawn once it is submitted.

Contact Details
Researcher Jing Siong (John) Cheah
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Head of Department: Dr. Bruce Melville
Department of Civil and Environmental Engineering
The University of Auckland Private bag 92019 Auckland
Phone: 09 373-7599 extn. 88165 Email: b_melville@auckland.ac.nz

"For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Office of the Vice Chancellor, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 extn. 83711." APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 11 NOVEMBER 2009 for 3 years. Reference Number 2009/417
Appendix B.3 Mauri Model Housing Survey – Consent Form

CONSENT FORM

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Development of a Flax-fibre Reinforced Rammed Earth Housing method (UKU) for Rural Maoi Communities

Name(s) of Researcher(s): Jing Sioung (John) Cheah

I have read the Participant Information Sheet, have understood the nature of the research and why I have been selected. I have had the opportunity to ask questions and have them answered to my satisfaction.

• I agree to take part in this research.
• I understand the survey will take approximately 30 minutes to complete
• I wish / do not wish to receive the summary of findings.

If you wish to receive a summary of findings, please provide a mailing address or email address:

____________________________________________________

• I understand that data will be kept for 6 years, after which they will be destroyed.
• I understand that I cannot withdraw my results once I have submitted the survey because the surveys are anonymous.
• I understand the results will be reported in a way that does not identify me as the source.

Name ________________________________

Signature ___________________________ Date __________________

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 11 NOVEMBER 2009 FOR 3 YEARS REFERENCE NUMBER 2009 / 417
Consent Forms giving the dates of approval and the reference number before you send them out to your participants.

5. Please send a copy of this approval letter to the Manager - Funding Processes at Research Office if you have obtained any funding.
Appendix C.1 Soil Particle Gradation Plot with Rammed Earth Limits
(blank)
Appendix C.2 Structural Calculations for the Ahipara Whareuku
Structural Design Calculations

Client: Rueben Porter
Architect: Heremana Hepa
Location: Ngakoroa Road, Ahipara, Tai Tokerau, New Zealand

Kepa Morgan was the Principal Investigator of a research project considering cement stabilised harakeke reinforced rammed earth walls (UKU) as a structural material for use in rural Māori communities. This research project was funded by the Foundation for Research Science & Technology and concluded in 2009. The Ahipara Whareuku is the continuation of this research and is to be the forth case prototype structure for this research project. The calculations presented herein form the basis of a seismic design guide for cement stabilised flax- fibre reinforced rammed earth buildings. Since the project initiated, a machine to strip the flax-fibre has been made and a series of tests have been performed to determine optimum fibre length, fibre quantity, cement quantity, soil types and mixing methods (Segetin, Jayaraman et al. 2006). Tests have been performed to determine soil compressive and tensile strength, soil shear strength and bar pullout strength as reported by Segetin et al. (Segetin, Jayaraman et al. 2006) and Cheah & da Silva (Cheah and da Silva 2007).

Compressive and seismic tests have been conducted on the specific soil mix proposed for the Ahipara Whareuku and are documented in the appendix. The optimal proportions of the constituent materials used to manufacture UKU panels are:

Uku / Clay-Soil: 30 litres (on-site)
One / Sand: 18 litres
Muka / Flax Fibres: 30 g between 60-70 mm in length
Cement: 4 litres
Wai / Water content: 20%

Consequently, the design procedure detailed here is only valid for construction that uses the mix composition specified above.

The data used in the calculations presented herein to determine wall capacity were based on seismic experiments conducted by Cheah & da Silva (Cheah and da Silva 2007) and compressive and seismic tests conducted on the Ahipara soil mix in 2009.
Table 1 - Design parameters from Table 3.2 of NZS 4230:2004

<table>
<thead>
<tr>
<th>Design philosophy</th>
<th>Service performance</th>
<th>Structural ductility factor $\mu$</th>
<th>Minimum performance factor $S_p$</th>
<th>Required detailing</th>
<th>Method of design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic structure</td>
<td>Perfect elastic and inelastic behaviour</td>
<td>1.00</td>
<td>1.0</td>
<td>Solid framed or partially framed on all sides</td>
<td>Design must meet additional ultimate strength requirements. Design shall be in accordance with 8.7.2</td>
</tr>
<tr>
<td>Normal ductile structure</td>
<td>Design to avoid collapse on elastic range</td>
<td>1.25</td>
<td>1.0</td>
<td>Solid framed or partially framed on all sides</td>
<td>Design must meet additional ultimate strength requirements. Design shall be in accordance with 8.7.2</td>
</tr>
<tr>
<td>Limited ductile structure</td>
<td>Elastic behaviour of energy dissipation through specified behaviour</td>
<td>1.25</td>
<td>0.5</td>
<td>Solid framed or partially framed on all sides</td>
<td>Design must meet additional ultimate strength requirements. Design shall be in accordance with 8.7.2</td>
</tr>
<tr>
<td>Seismic structure</td>
<td>Dissipation of energy by ductile behaviour in specified locations</td>
<td>1.00</td>
<td>0.5</td>
<td>Solid framed</td>
<td>Design must meet additional ultimate strength requirements. Design shall be in accordance with 8.7.2</td>
</tr>
</tbody>
</table>

NOTE: The $S_p$ is for the ultimate limit state condition and for the serviceability limit state, see 8.5.23.

Table 1 depicts the available seismic design parameters, and the table has been reproduced from NZS 4230:2004. A nominally ductile structure has been adopted $\mu = 1.25$, with $S_p = 0.9$. Past seismic tests of UKU wall panels have all shown a consistent non-linear capacity (Cheah, Morgan et al. 2008; Feisenfeld 2008). The hysteresis loops of two wall tests are shown below. Five full size wall tests have been conducted in total and all have exhibited non-linear strength. On the basis of these tests the performance of the UKU house as a nominally ductile structure has been assumed.

Figure 1 - Load Displacement Curve of a Cyclic Test of an UKU Wall Panel Without Shear Reinforcement (Feisenfeld 2008)
Figure 2 – Load Displacement Curve of a 5.5 metre long UKU Wall System (Cheah, Morgan et al. 2008)

Due to the similarity in the performance and characteristics of cement stabilized rammed earth to concrete masonry, NZS4229:1999 Concrete Masonry Buildings Not Requiring Specific Engineering Design (Standards NZ 1999), will be used as a base for the bracing calculations.

At an Ultimate Limit State (ULS) design level earthquake (μ = 1.25), past tests have shown that there will be minor flexural cracks forming between some of the rammed earth wall layers. Hairline shear cracks developing from the flexural cracks will also have formed. The performance requirement for a structure after a ULS design level earthquake is to retain its load bearing strength. The formation of cracks in past wall panel tests at the ULS design level of ductility has not reduced the structural strength of the wall panels (Cheah, Morgan et al. 2008; Fehsenfeld 2008).
Structural Demand

NZS 4229:1999 shall be used to calculate the wind and seismic lateral forces that act on the structure. This is because the UKU structure being considered falls within the scope of section 1 of NZS 4229:1999 by having a single storey with a total floor area less than 600 m². In addition, the material densities and reinforcement layouts of concrete masonry and Uku are similar. This calculation sheet is intended to be the prototype and template for the final design procedure. The floor plan of the Ahipara Whareulu is shown below in Figure 3.

Wind Actions

Height to apex = 3.76 m
Wall height = 2.2 (UKU) + 0.24 (bond beam) = 2.44 m
Roof height = 0.94 + 0.29 (rafter) + 0.09 (purlin) = 1.32 m

From Table 4.2 of NZS 4229:1999:
Across Ridge wind demand = 63.7 BU/m
Along Ridge wind demand = 80.1 BU/m
(Note: 20 BU = 1 kN)
Wall length perpendicular to Across Ridge direction = 15.8 m (From Fig. 1)
Well length perpendicular to Along Ridge direction – 7.0 m (From Fig 1)
(Ref Figure 4.2 pg 41 NZS 4229)
Across Ridge wind demand = 63.7 x 15.8 = 1006.5 BU = 50.3 kN
Along Ridge wind demand = 80.1 x 7.0 = 560 BU = 28.0 kN

**Seismic Actions**

From Table 4.1 of NZS 4229:1999, Kaitaia is in earthquake zone C
From Table 4.3 of NZS 4229:1999, Assuming UKU walls are equivalent to solid filled 20 series masonry units with light roof
Seismic demand = 10 x 1.4 = 14.0 BU/m²
Floor area = 7.0 x 15.8 = 110.6 m²
Seismic Demand = 14.0 x 110.6 = 1548.4 BU = 77.4 kN

77.4 kN > 50.3 kN, therefore seismic actions are critical.

From NZS 4229:1999 A3.2.1, density of masonry used = 2200 kg/m³.
From NZS 4229:1999 A3.1.4, μ = 2 and S_p = 0.57.
20 series masonry is 190 mm wide.

The density of the Ahipara Sand rammed earth walls is 1850 kg/m³. (Refer to Appendix A)
The rammed earth walls will be built 200 mm wide.
Structural Ductility Factor, μ = 1.25
Structural Performance Factor S_p = 0.9

Factored load, \( F = \frac{77.4}{\mu} \times \frac{2}{1.25} \times \frac{1850}{2200} \times \frac{t_e}{190} \times \frac{S_p}{0.67} = 147.2 \text{ kN} \)
Torsional Analysis

![Diagram of Wall Line](image)

**Design basis and assumptions:**
- Longer walls are stiffer and attract a larger proportion of force (proportional to the square of their length).
- Accidental eccentricity of 0.1B shall be accounted for.
- Walls located further away from the centre of mass (CoM) shall attract more force due to moment than walls closer to the CoM.
- Walls less than 0.7 m shall provide no bracing capacity.
- Walls located under window openings shall provide no bracing capacity.

X-Y datum is located in the centre of the North-Eastern corner of the Ahipara UKU House as shown in Figure 4. The acting full height wall lengths are listed in Table 2.
### Table 3 - Full-height Wall Lengths in the Ahipara Whareuku House

<table>
<thead>
<tr>
<th>Wall</th>
<th>Length (m)</th>
<th>Wall</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1</td>
<td>M1</td>
<td>1.3</td>
</tr>
<tr>
<td>A2</td>
<td>2.2</td>
<td>M2</td>
<td>1.1</td>
</tr>
<tr>
<td>A3</td>
<td>1</td>
<td>M3</td>
<td>1.7</td>
</tr>
<tr>
<td>B1</td>
<td>1.6</td>
<td>N1</td>
<td>1</td>
</tr>
<tr>
<td>B2</td>
<td>1.7</td>
<td>N2</td>
<td>1.1</td>
</tr>
<tr>
<td>B3</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>2</td>
<td>P1</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>1.9</td>
<td>P2</td>
<td>2</td>
</tr>
<tr>
<td>C3</td>
<td>1.5</td>
<td>P3</td>
<td>0.9</td>
</tr>
<tr>
<td>D1</td>
<td>0.3</td>
<td>P4</td>
<td>2.2</td>
</tr>
<tr>
<td>D2</td>
<td>1.7</td>
<td>P5</td>
<td>1.5</td>
</tr>
<tr>
<td>D3</td>
<td>1.4</td>
<td>P6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

ΣX: 18.6  
Centroid X: 8.03  

ΣY: 18.1  
Centroid Y: 4.70
Demand in X direction

L_e is the effective structural length of walls (L_e = L^2 if L > 0.7 and L_e = 0 if L < 0.7),

\[ \Sigma L_{ex} = 31.38 \text{ m} \]

B = 15.8 m, (where B = the X dimension of the house), \hspace{1cm} 0.1B = 1.58 \text{ m}

Moment due to accidental eccentricity, \[ M_e = 1.58 \times 147.2 = 232.6 \text{ kNm} \]

Force per linear metre due to moment shall be taken as \[ \frac{M_e}{\Sigma L_{wi}d_{ii}} \]

Where \[ L_{wi} = \text{The square of the structural length of wall 'i' in the X and Y directions.} \]

Assume the stiffness of a wall increases proportionately to the square of the wall length.

(E.g. An 2 metre long wall would attract 4 times the load of a 1 metre long wall.)

\[ d_{ii} = \text{distance of wall 'i' to the Centre of Mass (CoM) in the perpendicular direction.} \]

Table 4 - Effective Lengths of Wall Lines in the Ahipara Whareuku house

<table>
<thead>
<tr>
<th>Wall Line</th>
<th>Effective Length ((L_{wi})) (m)</th>
<th>Perpendicular Distances to CoM ((d_{ii})) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.84</td>
<td>8.03</td>
</tr>
<tr>
<td>B</td>
<td>9.02</td>
<td>2.83</td>
</tr>
<tr>
<td>C</td>
<td>9.86</td>
<td>3.37</td>
</tr>
<tr>
<td>D</td>
<td>5.66</td>
<td>7.57</td>
</tr>
<tr>
<td>Total</td>
<td>31.38</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Line</th>
<th>Effective Length ((L_{wi})) (m)</th>
<th>Perpendicular Distances to Wall Lines ((d_{ij})) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>5.79</td>
<td>4.7</td>
</tr>
<tr>
<td>N</td>
<td>2.21</td>
<td>2.7</td>
</tr>
<tr>
<td>P</td>
<td>21.35</td>
<td>2.1</td>
</tr>
<tr>
<td>Total</td>
<td>29.35</td>
<td></td>
</tr>
</tbody>
</table>

For the X direction,

\[ \frac{M_e}{\Sigma L_{wi}d_{ii}} = \frac{232.6}{6.84 \times 8.03 + 9.02 \times 2.83 + 9.86 \times 3.37 + 5.66 \times 7.57} = 1.49 \text{ kN/ m} \]
Looking at line A,

Total Effective Length = 6.84 m

Direct force attracted shall be determined from:

\[ F \times \frac{L}{L_s} = 147.2 \times \frac{6.84}{31.38} = 32.1 \text{ kN} \]

Force attracted due to moment = 1.49 x 6.84 = 10.2 kN
Total demand on wall line A = 32.1 + 10.2 = 42.3 kN

Similarly demands for the rest of the lines in the X direction are shown in,

<table>
<thead>
<tr>
<th>Wall Line</th>
<th>Force Attracted (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42.15</td>
</tr>
<tr>
<td>B</td>
<td>55.41</td>
</tr>
<tr>
<td>C</td>
<td>60.90</td>
</tr>
<tr>
<td>D</td>
<td>34.96</td>
</tr>
<tr>
<td>Total</td>
<td>193.43</td>
</tr>
</tbody>
</table>
Demand in Y direction

\[ \sum L_\sigma = 29.35 \text{m} \]

\[ B = 7.0 \text{ m, } 0.1B = 0.7 \text{ m} \]

Moment due to accidental eccentricity, \( M_e = 0.7 \times 147.2 = 103.0 \text{kNm} \)

Force per linear metre due to moment in the Y direction,

\[ \frac{M_e}{\sum L_\sigma d_\sigma} = \frac{103.0}{5.79 \times 4.7 + 2.21 \times 2.7 + 21.35 \times 2.1} = 1.32 \text{kN/m} \]

Looking at line M,

Total Effective Length = 5.79 m

Direct force attracted:

\[ F \times \frac{L_o}{\sum L_o} = 147.2 \times \frac{5.79}{29.35} = 29.0 \text{kN} \]

Force attracted due to moment = 1.32 \times 5.79 = 7.6 \text{kN}

Total demand on wall line M = 29.0 + 7.6 = 36.6 \text{kN}

Similarly, the demands for the rest of the walls in the Y direction are shown in Table 6.

<table>
<thead>
<tr>
<th>Wall Line</th>
<th>Force Attracted (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>36.69</td>
</tr>
<tr>
<td>N</td>
<td>14.00</td>
</tr>
<tr>
<td>P</td>
<td>135.29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>185.98</strong></td>
</tr>
</tbody>
</table>
Ahipara UKU Wall Moment Capacity

The material design values for the Uku panels are as follows:

- $f_t = 300$ MPa
- $f_e = 1.43$ MPa (refer to Appendix A)
- Bar edge distance = 150 mm

From NZS 4297:1998, “[Reinforced] Members subjected primarily to flexure shall be designed as beams…” Using concrete theory, a rectangular compression stress block shall be assumed with $\alpha = 0.85$ and $\beta = 0.85$, as per NZS 3101:2006 (Standards NZ 2006).

**Assumptions**
- The self weight of roof and wall panel provides no axial load onto the panel
- Compression steel is not considered
- Maximum compressive strain of the earth is 0.003

Looking at a panel that is 1.0 m long with 2-D16 at 700 centres

Guess that one tensile bar is yielding,

- $I = \frac{d^4}{64} \times 300 = 60319$ N
- $d = \frac{0.85 \times 1.43 \times 200}{248} = 292$ mm
- $\varepsilon_c = 0.003 \times \frac{d - c}{c} = 0.003 \times \frac{850 - 292}{292} = 0.0057$
- $\varepsilon_y = \frac{\sigma_y}{E} = \frac{300}{200000} = 0.0015$

Since $\varepsilon_y > \varepsilon_c$, the tensile bar is yielding and the initial guess is correct.

- $jd = d - \frac{a}{2} = \frac{248}{2} = 725$ mm
- $M_c = T \times jd = \frac{60319 \times 726 \times 10^{-4}}{2} = 43.8$ kNm
- $\Phi M_n = 0.8 \times 43.8 = 35.0$ kNm

Repeating this for each wall length produces the below table.

**Table 8 - Flexural Strength of UKU Wall Panels**

<table>
<thead>
<tr>
<th>Wall Length (L, mm)</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dM_c$ (kNm)</td>
<td>29.55</td>
<td>25.38</td>
<td>30.20</td>
<td>35.03</td>
<td>39.86</td>
<td>44.68</td>
<td>49.51</td>
<td>54.33</td>
</tr>
<tr>
<td>Wall Length (L, mm)</td>
<td>1500</td>
<td>1600</td>
<td>1700</td>
<td>1800</td>
<td>1900</td>
<td>2000</td>
<td>2100</td>
<td>2200</td>
</tr>
<tr>
<td>$dM_c$ (kNm)</td>
<td>59.16</td>
<td>63.98</td>
<td>68.81</td>
<td>73.63</td>
<td>78.46</td>
<td>83.29</td>
<td>88.11</td>
<td>93.94</td>
</tr>
</tbody>
</table>
Ahipara UKU Wall Moment Capacity Check

Assumptions
- A wall height of 2.3 m (2.2 m wall height + 0.2 m mid height of bond beam)
- Walls acting as cantilevers

<table>
<thead>
<tr>
<th>Line</th>
<th>Structural Length (m)</th>
<th>Flexural Capacity (kN/m)</th>
<th>Total Demand (kN)</th>
<th>$\phi M_{lt} &gt; M^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line A</td>
<td>4.2</td>
<td>163.19</td>
<td>97.17</td>
<td>OK</td>
</tr>
<tr>
<td>Line B</td>
<td>5.2</td>
<td>211.49</td>
<td>128.14</td>
<td>OK</td>
</tr>
<tr>
<td>Line C</td>
<td>5.4</td>
<td>221.15</td>
<td>140.08</td>
<td>OK</td>
</tr>
<tr>
<td>Line D</td>
<td>4.1</td>
<td>153.53</td>
<td>80.41</td>
<td>OK</td>
</tr>
<tr>
<td>Line M</td>
<td>4.1</td>
<td>158.36</td>
<td>84.39</td>
<td>OK</td>
</tr>
<tr>
<td>Line N</td>
<td>2.1</td>
<td>74.98</td>
<td>32.21</td>
<td>OK</td>
</tr>
<tr>
<td>Line P</td>
<td>11.9</td>
<td>482.20</td>
<td>311.17</td>
<td>OK</td>
</tr>
</tbody>
</table>
Ahipara UKU Wall Shear Capacity

From NZS 4297:1998 Cl 7.2, Design of earth walls for shear and torsion shall be in accordance with established principles for reinforced concrete, as set out in NZS 3101, section 9 modified by the requirements of this section. (Standards NZ 1998)

\[ V = f'_{p,t} t d + A_{p,t} f_s d + k_s f_t t d \]  
(NZS 4297:1998 Eq 7-6)

- \( f_{p,t} = 100.1 \text{ kPa} \) (refer to Appendix A)
- \( t \) = wall thickness
- \( d = L_4 \)
- \( k_s = 0.3 \) (Shear Factor from Bond Beam connection (ref 7.3.1.2 pg 41 NZS4297))
- \( f_t = 5.57 \text{ kPa} \) (Axial Load from Bond Beam)

Since there is no shear steel reinforcement in the panels, \( A_p = 0 \). The shear strength capacity comes from the shear capacity of the earth alone with an axial load applied on the wall panel from the bond beam.

Looking at a panel that has an effective length of 1.0 m, with no steel shear reinforcement
Shear strength, \( V_s = f'_{p,t} t d + k_s f_t t d = 100.1 \times 10^4 \times 0.2 \times 1 + 0.3 \times 5.57 \times 10^4 \times 0.2 \times 1 = 20.35 \text{ kN} \)

\[ \phi \sigma_s = 0.7 \] (NZS 4297:1998 Cl 5.3.1.3)
\[ \phi V_s = 0.7 \times 20.35 = 14.25 \text{ kN} \]

Repeating this for each wall length produces the below table.

**Table 10 - Shear Strength of UKU Wall Panels**

<table>
<thead>
<tr>
<th>Wall Length (L mm)</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi V_s (kN) )</td>
<td>9.57</td>
<td>11.40</td>
<td>12.82</td>
<td>14.25</td>
<td>15.67</td>
<td>17.10</td>
<td>18.52</td>
<td>19.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wall Length (L mm)</th>
<th>1500</th>
<th>1600</th>
<th>1700</th>
<th>1800</th>
<th>1900</th>
<th>2000</th>
<th>2100</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi V_s (kN) )</td>
<td>21.37</td>
<td>22.80</td>
<td>24.22</td>
<td>25.65</td>
<td>27.07</td>
<td>28.50</td>
<td>29.92</td>
<td>31.35</td>
</tr>
</tbody>
</table>
**Ahipara UKU Wall Shear Capacity Check**

- The shear capacity of a wall panel is reduced to 80% if the effective wall panel height is less than the wall panel width.
- The effect of half height wall panels on the effective height of adjacent wall panels has been taken into account.
- The shear performance of the wall panels when subjected to a clockwise torsional force is worse than under an anticlockwise torsional force and is shown below in Table 11.
- The shear demand on each wall has been distributed according to the square of the wall panel lengths because the longer a wall panel is, the stiffer it is and the more force it attracts.

### Table 12 - Summary of Shear Capacity and Demand for Wall Panels in the X Direction

<table>
<thead>
<tr>
<th>Wall</th>
<th>Effective Length (m)</th>
<th>Shear Capacity (kN/m)</th>
<th>Total Demand (kN/m)</th>
<th>$\phi W &gt; V^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.8</td>
<td>11.40</td>
<td>6.18</td>
<td>OK</td>
</tr>
<tr>
<td>A2</td>
<td>2.2</td>
<td>31.35</td>
<td>29.90</td>
<td>OK</td>
</tr>
<tr>
<td>A3</td>
<td>1</td>
<td>14.25</td>
<td>6.18</td>
<td>OK</td>
</tr>
<tr>
<td>B1</td>
<td>1.44</td>
<td>20.52</td>
<td>20.01</td>
<td>OK</td>
</tr>
<tr>
<td>B2</td>
<td>1.36</td>
<td>19.38</td>
<td>17.85</td>
<td>OK</td>
</tr>
<tr>
<td>B3</td>
<td>1.36</td>
<td>19.38</td>
<td>17.85</td>
<td>OK</td>
</tr>
<tr>
<td>C1</td>
<td>2</td>
<td>28.50</td>
<td>14.18</td>
<td>OK</td>
</tr>
<tr>
<td>C2</td>
<td>1.52</td>
<td>21.56</td>
<td>12.80</td>
<td>OK</td>
</tr>
<tr>
<td>C3</td>
<td>1.2</td>
<td>17.10</td>
<td>7.98</td>
<td>OK</td>
</tr>
<tr>
<td>D1</td>
<td>0.9</td>
<td>12.82</td>
<td>5.00</td>
<td>OK</td>
</tr>
<tr>
<td>D2</td>
<td>1.7</td>
<td>34.22</td>
<td>17.85</td>
<td>OK</td>
</tr>
<tr>
<td>D3</td>
<td>1.12</td>
<td>15.36</td>
<td>12.11</td>
<td>OK</td>
</tr>
</tbody>
</table>

### Table 13 - Summary of Shear Capacity and Demand for Wall Panels in the Y Direction

<table>
<thead>
<tr>
<th>Wall</th>
<th>Effective Length (m)</th>
<th>Shear Capacity (kN/m)</th>
<th>Total Demand (kN/m)</th>
<th>$\phi W &gt; V^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1.04</td>
<td>14.32</td>
<td>10.71</td>
<td>OK</td>
</tr>
<tr>
<td>M2</td>
<td>0.88</td>
<td>12.94</td>
<td>7.67</td>
<td>OK</td>
</tr>
<tr>
<td>M3</td>
<td>1.36</td>
<td>19.38</td>
<td>18.31</td>
<td>OK</td>
</tr>
<tr>
<td>N1</td>
<td>0.8</td>
<td>11.40</td>
<td>6.34</td>
<td>OK</td>
</tr>
<tr>
<td>N2</td>
<td>0.88</td>
<td>12.54</td>
<td>7.67</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>28.50</td>
<td>25.35</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>P1</td>
<td>2</td>
<td>28.50</td>
<td>25.35</td>
<td>OK</td>
</tr>
<tr>
<td>P2</td>
<td>2</td>
<td>10.26</td>
<td>5.13</td>
<td>OK</td>
</tr>
<tr>
<td>P3</td>
<td>2.2</td>
<td>31.35</td>
<td>30.67</td>
<td>OK</td>
</tr>
<tr>
<td>P4</td>
<td>1.2</td>
<td>17.10</td>
<td>14.26</td>
<td>OK</td>
</tr>
<tr>
<td>P5</td>
<td>1.36</td>
<td>19.38</td>
<td>18.31</td>
<td>OK</td>
</tr>
<tr>
<td>P6</td>
<td>1.28</td>
<td>18.24</td>
<td>16.22</td>
<td>OK</td>
</tr>
</tbody>
</table>

**Table 14 - Summary of Shear Capacity and Demand of each Wall Line**

<table>
<thead>
<tr>
<th>Line</th>
<th>Structural Lengths (m)</th>
<th>Shear Capacity (kN)</th>
<th>Total Demand (kN)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line A</td>
<td>4</td>
<td>56.39</td>
<td>42.25</td>
<td>OK</td>
</tr>
<tr>
<td>Line B</td>
<td>4.16</td>
<td>59.27</td>
<td>55.71</td>
<td>OK</td>
</tr>
<tr>
<td>Line C</td>
<td>4.72</td>
<td>67.25</td>
<td>60.90</td>
<td>OK</td>
</tr>
<tr>
<td>Line D</td>
<td>3.72</td>
<td>53.00</td>
<td>34.96</td>
<td>OK</td>
</tr>
<tr>
<td>Line M</td>
<td>3.28</td>
<td>46.73</td>
<td>36.69</td>
<td>OK</td>
</tr>
<tr>
<td>Line N</td>
<td>1.68</td>
<td>23.94</td>
<td>14.00</td>
<td>OK</td>
</tr>
<tr>
<td>Line P</td>
<td>10.76</td>
<td>153.31</td>
<td>135.29</td>
<td>OK</td>
</tr>
</tbody>
</table>
Bond Beam Design

The assumed bond beam cross-section is displayed in Fig. 5.

For low earthquake zones NZS 4299 requires a 200 x 100 concrete bond beam with 2/D12 and R6 ties at 400 centres. (See Table 7.1 NZS 4299) (Standards NZ 1998)

The proposed concrete bond beam is a 200 x 200 section with 4/D12 and R6 ties at 400 centres which is greater than the requirements.
Wall Reinforcing Bar Diagrams

Figure 7 to Figure 13 show the vertical reinforcement that is required for each wall line.

Wall Line A

Vertical B/E W/d Reinforcing Steel
All vertical steel to be 100 mm from the edge of the wall panel
All vertical reinforcing steel to have a 500 mm lag cast into the concrete foundation

Figure 7 - Vertical Reinforcing Locations for Wall Line A
Wall Line B

Figure 8 - Vertical Reinforcing Locations for Wall Line B

Wall Line C

Figure 9 - Vertical Reinforcing Locations for Wall Line C

Wall Line D

Figure 10 - Vertical Reinforcing Locations for Wall Line D
APPENDIX A - Characteristic Strengths of Earth

On the 25th August 2009, 10 UKU compression cubes, made from the Ahipara soil deposit (mixed 1:1 with sand). The samples were tested in compression at the University of Auckland Civil Materials laboratory. The results are summarised in table 15 below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [kg/m³]</th>
<th>Compressive Strength (MPa)</th>
<th>Corrected Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1H1</td>
<td>1817</td>
<td>3.17</td>
<td>2.03</td>
</tr>
<tr>
<td>E1H2</td>
<td>1928</td>
<td>2.66</td>
<td>1.70</td>
</tr>
<tr>
<td>E1H3</td>
<td>1852</td>
<td>2.86</td>
<td>1.83</td>
</tr>
<tr>
<td>E1H4</td>
<td>1884</td>
<td>2.93</td>
<td>1.88</td>
</tr>
<tr>
<td>E1V1</td>
<td>1814</td>
<td>2.17</td>
<td>1.73</td>
</tr>
<tr>
<td>E2H1B</td>
<td>1796</td>
<td>2.96</td>
<td>1.90</td>
</tr>
<tr>
<td>E2H2B</td>
<td>1828</td>
<td>2.41</td>
<td>1.54</td>
</tr>
<tr>
<td>E2H3B</td>
<td>1836</td>
<td>2.65</td>
<td>1.69</td>
</tr>
<tr>
<td>E2H4T</td>
<td>1923</td>
<td>3.38</td>
<td>2.16</td>
</tr>
<tr>
<td>E2H5T</td>
<td>1872</td>
<td>3.34</td>
<td>2.14</td>
</tr>
<tr>
<td>1855</td>
<td>2.87</td>
<td>1.86</td>
<td></td>
</tr>
</tbody>
</table>

Design Compressive Strength

Section 84.2 of NZ4298 (Standards NZ 1998) is used to determine the characteristic value for compression

\[ f'_{c} = x_2^{2/3} \times (x_3 - x_1)^{1/3} \]

Where \( x_1 \), \( x_2 \) and \( x_3 \) are the 3rd lowest, 2nd lowest and lowest strengths measured respectively.

For a sample size of 10, \( t = 0.35 \) (See Section 84.2 NZS 4298)

\[ f'_{c} = 1.7^{2/3} \times (1.69 \times 1.54)^{1/3} = 1.43 \text{ MPa} \]

Design Shear Strength

The shear strength of earth shall be given by the equation

\[ f_{λ} = 0.07 f'_{s} \] (Cl 4.5.4. NZS 4297)

\[ f_{λ} = 0.1 \text{ MPa} \]

The steel in the earth wall is assumed to have no shear strength.
References


Appendix C.3 First Letter from FNDC

4 May 2010

Reuben Abel Porter
20A Ngakorua Road
RD 1
Kaitaia 0481

Att: Heeni Porter

Dear Sir / Madam

RE: 1 Bedroom Dwelling and Effluent Disposal System, 30A-30B Ngakorua Road, Anipara 0481

Thank you for lodging your building application with the Far North District Council.

Initial vetting of your application has highlighted the need for further information to be provided to enable the process of issuing your consent to continue. The time period for processing your application has been suspended under Section 46 (2) of The Building Act 2004, however this will be resumed as soon as the necessary information as listed below is received.

Building Aspect

1) Page 3 of the engineers calculations indicates that the bracing is considered comparable to NZS4222; yet the strength of a reinforced rammed earth structure is unlikely to be similar to Masonry. The comparison to rammed earth also appears to be slightly off line as the proposed wall is 200mm wide and rammed earth buildings in both NZS4299 and NZS4297 are a minimum of 280mm. Additionally there are other items that appear to require engineering input/comment or the provision of research information.
   - Please provide engineer details for the balance of the structure including foundations, slab, ridge beam and connections (part timber wall/portal earth leaves a pivot point), roof bracing (bracing shown as connecting to external eave corners) etc.
   - Provide the research information indicated in the engineer calculations and include details of testing for compliant insulation of wall.
   - This building project uses an “Alternative Solution” wall system and thus, please provide an independent engineer’s design peer review. The engineer is to provide comment on the PS1 and code clauses covered by the PS1.
   - Please provide H1 (insulation) calculations but please note that it is not possible to obtain an R value of 3.2 in a purlin cavity of 30mm and still have a gap of 25mm between the roof underlay and the insulation.
• Engineer is required to sign all relevant architectural plans and provide comment on the fact that the floor plan and no carport structures have changed from the engineer’s design.

2) Please provide revised plan details for the following:
• Detail protection of exposed ridge beam ends (Macoreapa timber is not suitable for exposure to the weather). If the ridge beam does not extend out as detailed on drawing 8 then the roof wave cantilever exceeds NZS3604 and thus engineering is required. If the ridge beam does extend out then the balance of the wave will still require engineering.
• Detail wave gutter flashing as thus building is in a very high wind zone.
• Detail compatible fixing of shower wall lining batten to earth wall.
• Provide full building specifications.
• Detail sill floor flashing noting that the raised nib under the detail may hinder adequate flashing.
• The window sill flashing detail appears to rely on a sealant flashing that does not appear to reasonably comply with NZ/AS1 sill flashing details for rammed earth not with BRANZ guide to flashing of masonry blocks and thus provide an appropriate detail.

3) Engineer is required to supply PS4 for building work that has already been undertaken – noting that this work does not form part of this consent.

It would assist considerably if you would include your consent number FC-2010-1254/0 when responding. Please provide 2 copies of your information, (3 copies if Commercial). If submitting plans, one copy at normal scale size (2 if Commercial) and one copy must be A3 size. This will ensure the information provided is included with your application and that processing continues with the minimum of delay.

Note: If engineer certified plans are required please ensure any changes / variations / modifications are endorsed.

Signed on behalf of Far North District Council by
Mark Chisell
BUILDING OFFICER
Fax No. 08 407 6419
Appendix C.4 Response to the First Letter from FNDC

Building Aspects that need addressing in the Building Consent for the Ahipara Whareuku

BC-2010-1254/0

Point 1.1 - Assumption that the bracing of a reinforced rammed earth structure is similar in performance to NZS4229 Concrete Masonry Buildings.

We have conducted 5 full size wall panel tests and a number of component level tests in shear, flexure and compression that have shown similar material characteristics and performance to that of concrete masonry – in particular the low flexural strength and the high compressive strength of the materials.

In each of the 5 wall panel tests, flexural cracks between rammed earth layers were the first failure mechanism to be observed with shear failure following at greater loads and displacements. The performance of the wall panel tests’ are listed below alongside the design flexural and shear loads of each test.

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
<th>Reinforcing</th>
<th>Design Load (kN)</th>
<th>Load Attained (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flexure</td>
<td>Shear</td>
</tr>
<tr>
<td>11 Jul '08</td>
<td>5.5m long UKU wall with 3 wall panels. 150mm thick.</td>
<td>9 D12 vert. rebars</td>
<td>+/- 53.2, 60.6</td>
<td>+/- 120</td>
</tr>
<tr>
<td>20 Sep '08</td>
<td>1.0(W)x2.4(h)x0.15(t) 2 D12 vert. rebars 150 mm from end faces</td>
<td>+/- 14.9</td>
<td>+/- 29.6</td>
<td>14.1</td>
</tr>
<tr>
<td>5 Aug '09</td>
<td>1.0(W)x2.0(h)x0.2(t) 2 D12 vert. rebars 150 mm from end faces</td>
<td>+/- 13.0</td>
<td>+/- 16.0</td>
<td>18.7</td>
</tr>
<tr>
<td>7 Aug '09</td>
<td>1.0(W)x2.0(h)x0.2(t) 2 D12 vert. rebars 150 mm from end faces</td>
<td>+/- 13.0</td>
<td>+/- 16.0</td>
<td>16.9</td>
</tr>
<tr>
<td>13 Apr '10</td>
<td>2.0(W)x2.0(h)x0.2(t) 2 D12 vert. rebars 500 and 1750 mm from left</td>
<td>+/- 28.5</td>
<td>+/- 40.0</td>
<td>24.4</td>
</tr>
</tbody>
</table>

In the first four tests the UKU wall panels managed to reach a load very close to or exceeding the design flexural strength. The one test wall that did not reach a load close to the design flexural strength was the Ahipara Wall Panel 3 test. The load attained was only 86% of the design flexural load. The lower strength was attributed to the use of reused reinforcing bars. In that particular test panel the reinforcing bars were straightened as much as possible but retained some bends. This
created difficulties ramming the earth around the steel reinforcing. The reinforcing bars used in the house will be new and straight lengths.

The five UKU wall panel tests have shown a non-linear load bearing capacity which is characteristic of a ductile material rather than a brittle material which exhibits a linear elastic load bearing capacity. The hysteresis plot of each test is shown below.

Figure 1 – Load Displacement Curve of a 5.5 metre long UKU Wall Panel System (Cheah, Morgan et al. 2005)

Figure 2 – Load Displacement Curve of Rotoiti UKU Wall Panel 1 (Felsenfeld 2005)
Figure 3 - Load Displacement Curve of Ahipara UKU Wall Panel 1

Figure 4 - Load Displacement Curve of Ahipara UKU Wall Panel 2
Figure 5 - Load Displacement Curve of Ahipara UKU Wall Panel 3

Ahipara Wall Panel 3 was a uni-directional test. As a result of this the rest position of the wall displaced horizontally as the test proceeded.

The UKU wall was equated to a 200 series solid filled masonry wall. In terms of material density the UKU wall (1850 kg/m³) is 350 kg/m³ lighter than the solid filled masonry (2200 kg/m³). The width of 200 series is 190 mm and the Ahipara UKU wall is 200 mm. Corrections to account for these differences have been taken into account in the structural calculation for the Ahipara Whareku.

Whereas most reinforced concrete masonry structural designs use a structural ductility factor of 2 and a structural performance factor of 0.67, the UKU structural design has used a structural ductility factor of 1.25 and a structural performance factor of 0.9. Given the observed performance of past UKU test walls the value adopted for the design is conservative. Furthermore, NZS4297 specifies a structural performance factor of 0.67 to be used for the design of earth structures (Standards NZ 1998) however we have chosen to design to the more stringent value of 0.9.

Because of the material similarities between the UKU material and concrete masonry, the past material and seismic tests we have performed on UKU wall panels, and the conservative approach that has been taken in the structural calculations regarding the Ahipara Whareku, the University of Auckland UKU research team is confident that the design methodology specified in NZS 4229 can be adapted and used for houses built using the UKU material.

Point 1.2 – The issue of walls thinner than 280 mm as specified in NZS 4297 and NZS 4299

The wall thickness influences two main attributes of the house; structural strength and thermal performance. Discussion with Hugh Morris, one of the authors of the Earth Building Standards, has revealed that the choice of wall thickness specified in the Earth Building standards was mainly governed by the thermal performance of earth walls. 300 mm thick earth walled buildings are commonly and successfully used overseas, particularly in Australia and the USA. New Zealand has a temperate climate and in the North Island of New Zealand the mean daily temperatures through each season lie within the range of 4 degC to 25 degC. Due to lack of local research into the performance of earth structures in NZ a general minimum thickness has been specified and a minimum wall thickness of 280 mm has been adopted. Due to the more temperate climate of New Zealand there is the potential to use thinner wall panels and the UKU research team is continually monitoring the UKU dwellings and recording their performance.

As part of the UKU research we have built two houses in Rotorua to evaluate the thermal performance of houses with flax fibre reinforced earth walls (UKU) to standard timber framed wall construction. Both houses have a similar floor plan and are located in the same area. 24 thermal monitoring buttons have been placed at both houses and have been logging the internal and external temperatures and the relative humidity in each room since November 2008. The data logging is still continuing today.

The timber framed house was a NZ Building Code compliant design and an assessment using the ALF 3.2 Calculation tool reveals that the house passes with a BPI Score of 1.29 against a BPI Target of 1.55. The UKU house was issued a conditional consent pending the thermal performance of the house after 2 years of monitoring.

The first journal paper detailing the measured thermal performance of both the timber framed house and the UKU house has been accepted for publication this year. In terms of meeting the 15°C benchmark as a minimum indoor temperature for housing (specified by the World Health Organisation (WHO) and inferred in the NZ Building Code), the average temperature in the UKU living room was 1.2°C below this in the winter season. The winter indoor temperature peaked at 9.0°C and averaged 14.8°C. The summer indoor temperature peaked at 32.66°C and averaged 21.78°C. In comparison the timber framed house that complied with the NZ Building Code performed slightly worse. The timber framed house reached a higher peak (33.16°C) and average temperature (23.8°C) in the summer and a lower peak (6.00°C) and average (13.36°C) temperature in the winter. The research results were not surprising because of the high thermal mass of the UKU house which has an averaging effect on fluctuating room temperatures. It should be noted also that the external temperatures peaked at -1 degC in the winter of 2009 and that this was recorded at both houses.

The Ahipara Wharekau features walls that are 50 mm thicker than at the Rotorua UKU house and Ahipara is classified in Climate Zone 1 whereas Rotorua is classified as Climate Zone 2. Due to the positive performance of the Rotorua UKU house compared to a code compliant timber framed house, the thicker 200 mm walls of the Ahipara house (compared to the Rotorua UKU house) and the more temperate climate in Ahipara, the reduction of wall thickness from the recommended 280 mm in the NZ Earth Building Standards to the 200 mm proposed for the Ahipara Wharekau will likely meet the thermal performance requirements specified by the WHO and inferred by the NZ Building Code.
Point 1.3 – Engineering Details for the balance of the structure

Reinforced Concrete Foundation Beams – The foundation is a 300 mm (width) X 450 mm (depth) strip footing that follows the profile of the earth walls. The footing is reinforced by 4/012 bars with R6 stirrups at 400 mm centres. The reinforced concrete foundation beams are designed following the standard footing design specified in NZS4299 Earth Buildings Not Requiring Specific Design for footings in areas with an earthquake zone factor of < 0.5.

Reinforced Concrete Foundation Slabs – standard design, 100 mm thick, 17.5 MPa with 665 reinforcing mesh.

Ridge beam design – see attached calculations

Connections – has been discussed with Mark Christiansen. Timber gable will be anchored into the concrete bond beam at 500 centres and the roof bracing will be connected over the top of the earth walls.

Point 1.4 – Provide research information indicated in the engineer calculations

The key results of past seismic testing of UKU Wall Panels have been provided in point 1. These were used to select the structural ductility and structural performance factors.

The material testing on samples made from the Ahpara soil mix is shown below. 10 samples were made and tested in compression. These samples allowed the determination of the material density and compressive strength. With a sample size of 10 and the compressive strengths results shown below a design compressive strength of 1.43 MPa was calculated.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (kg/m³)</th>
<th>Load (kN)</th>
<th>Compressive Strength (MPa)</th>
<th>Corrected Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1H1</td>
<td>1867</td>
<td>210.357</td>
<td>3.17</td>
<td>2.03</td>
</tr>
<tr>
<td>E1H2</td>
<td>1908</td>
<td>167.265</td>
<td>2.66</td>
<td>1.70</td>
</tr>
<tr>
<td>E1H3</td>
<td>1852</td>
<td>184.459</td>
<td>2.86</td>
<td>1.93</td>
</tr>
<tr>
<td>E1H4</td>
<td>1884</td>
<td>193.657</td>
<td>2.53</td>
<td>1.88</td>
</tr>
<tr>
<td>E1V1</td>
<td>1814</td>
<td>114.794</td>
<td>2.37</td>
<td>1.73</td>
</tr>
<tr>
<td>E2H1B</td>
<td>1796</td>
<td>202.36</td>
<td>2.56</td>
<td>1.90</td>
</tr>
<tr>
<td>E2H2B</td>
<td>1828</td>
<td>167.375</td>
<td>2.41</td>
<td>1.54</td>
</tr>
<tr>
<td>E2H3B</td>
<td>1856</td>
<td>172.69</td>
<td>2.65</td>
<td>1.69</td>
</tr>
<tr>
<td>E2H4T</td>
<td>1923</td>
<td>223.279</td>
<td>3.38</td>
<td>2.16</td>
</tr>
<tr>
<td>E2H5T</td>
<td>1872</td>
<td>233.074</td>
<td>3.34</td>
<td>2.14</td>
</tr>
</tbody>
</table>

Point 1.5 – Provide an independent peer review of the engineer’s design

The engineer’s design has been peer reviewed. See the PS2.
**Point 1.6 – H1 calculations**

ALF3.2 has been used to evaluate the timber framed house in Rotoiti which meets the NZ Building Code requirements. The timber framed house passed. The UKU house in Rotoiti has to date performed better thermally than the timber framed house both in the summer and in the winter. The Ahipara Whareuku will be built with thicker walls and in a more temperate zone. Based on our observations, the house will meet the performance requirements from a thermal perspective.

The purlin cavity has been increased to 150 mm.

**Point 1.7 – Engineers comment on architectural designs**

The architectural plans have been signed.

There is no carport structure in the current design and the engineer’s design is based on the current set of architectural plans.

**Point 2.1 – Exposed ridge beam**

The ridge beam cantilevers out as detailed on drawing 6. Purlins have been enlarged to 150K50. Ridge beam ends have been detailed.

**Point 2.2 – Eave gutter flashing**

Standard detail.

**Point 2.3 – Shower wall lining fixing to earth wall**

Has been detailed.

**Point 2.4 – Full Building Specifications**

Attached.
Point 2.5 – Sill floor flashing

The below will be added to architectural drawings in the next revision.
Point 2.5 – Window sill flashing

The window sill detail proposed is a rammed earth window sill. An experienced rammed earth technician who has built over 10 rammed earth houses and complexes both in Australia and New Zealand will be advising on the specific detailing of the earthen window sills.

Point 2.6 – Other points

E3 Internal moisture

The R value of the Ahuriri Earth Wall is 0.53 using the formula given in NZS4297 3.5.2. This is less than the minimum value specified in E3.

The Earth Building Association of New Zealand surveyed around 60 earthen houses with unpainted earth walls in New Zealand and none of the houses has condensation issues. This survey tended to support the idea that unpainted earth walls do not suffer from condensation regardless of their R value.

Earth has a natural moisture absorbing qualities and internal moisture is rarely a problem in unpainted earth walls. The internal walls of the Ahuriri Wharekura will remain unpainted.

Veranda
A 2 metre wide veranda has been planned after the house construction has been completed. This is pertinent because it impacts on durability and potential moisture issues. Although it is not in the current set of drawings it will be designed and built within 2 years of the completion of the house at the latest. The engineer’s representative, Jing Siiong Cheah, will continue to visit the structure and family over the next 2 years at least to monitor the house thermally and make observations on the performance of the house and to ensure the veranda will be built.

**External moisture barrier**

To provide additional moisture protection to the walls and to improve durability we are experimenting with applying a breathable water barrier to the exterior surface of the rammed earth walls. The product is Equus WB2. Equus is a water-based mixture of silicone based chemicals which reduces the capillary absorption of the material it is applied to without clogging them.

See [http://www.equus.co.nz/content/datasheet-pdf/wb2.pdf](http://www.equus.co.nz/content/datasheet-pdf/wb2.pdf)

**Point 3 – PS4**
The PS4 is attached.

The PS4 covers the construction of the reinforced concrete ring beam foundation, the material selection and construction of the fibre reinforced cement stabilised rammed earth walls.

The project has had a CM4 level of observation performed by the engineer’s representative Jing Siiong Cheah BEng(Civil), to ensure the foundations and walls have been built according to the design and specifications provided on drawings title 01-12 and specifications 01-21.
Appendix C.5 Second Letter from FNDC

26 June 2010

Reuben Abel Porter
30A Ngakaroa Road
RD 1
Kaitaia 0481

At: Heeni Porter

Dear Sir / Madam

RE: 1 Bedroom Dwelling and Effluent Disposal System, 30A-30B Ngakaroa Road, Ahipara 0481

A technical check of the required information you have supplied has highlighted the need for further information to be provided to enable the process of issuing your consent to continue.

The time period for processing your application has been suspended under Section 46 (2) of The Building Act 2004, however this will be resumed as soon as the necessary information as listed below is received.

Building Aspect

1) The insulation information provided appears to indicate that the building will not meet the requirements of H1 and E3 and thus please provide a peer review from a suitably independently qualified expert who can reasonably assess the details provided. The change to a 150x45 purlin will still not allow the installation of a 170mm insulation batt with allowance for a 25mm gap between the roof underlay and the top of the batt.

2) The provision of a peer review by a fellow staff member of the University of Auckland is not considered independent and the PS2 provided excludes code clause B2. Thus please provide an "independent" peer review from a suitably qualified insured expert and include both code clauses B1 and B2.

3) Please provide an independent E2 peer review and PS1 from an appropriately qualified and insured architect and ensure that this peer review does not provide comment in relation to the "future" verandah as this does not form part of the Consent and thus cannot be considered in this Building Consent Application.

4) It is Council’s understanding that this building has proceeded without a building consent. Please detail how far the building has progressed and stop building until the consent has been issued. Please provide this information and a new building consent for the balance of the work and apply for COA as per the provision of actions required by the Council notice issued on the property BC-2010-1591.
It would assist considerably if you would include your consent number BC-2010-1254/0 when responding. Please provide 2 copies of your information, (0 copies if Commercial). If submitting plans, one copy at normal scale size (2 if Commercial) and one copy must be A3 size. This will ensure the information provided is included with your application and that processing continues with the minimum of delay.

Note: If Engineer certified plans are required, please ensure any changes / variations / modifications are endorsed.

Signed on behalf of Far North District Council by
Mark Christansen
BUILDING OFFICER
Fax No. 09 407 0419
Response to FNDC

8 April 2011

Building Consent Number: BC-2010-1254/0

Att: Mark Christiansen

This document explains how each point raised in the letter sent on the 23 June 2010 has been addressed. The letter listed 4 issues with the building consent submission.

1) The insulation information provided appears to indicate that the building will not meet the requirements of H1 and E3 and thus please provide a peer review from a suitably independently qualified expert who can reasonably assess the details provided. The change to a 150x45 purlin will still not allow the installation of a 170mm insulation batt with allowance for a 25mm gap between the roof underlay and the top of the batt.

Does the building design meet H1 Energy Efficiency requirements?

This is an important question and is one of the key aspects of the house design the research group will monitor for two years after completion as was done for the Rotoiti UKU house.

Using thermal record logs taken from the UKU house and a light timber framed house built in Rotoiti, a case is presented that the Ahipara UKU house will be able to provide an adequate indoor temperature in an energy efficient manner.

The Rotoiti houses

An UKU house and a standard light timber framed house were built in Rotoiti in 2000. The relative humidity and indoor temperatures were recorded from December 2000 until August 2003. During this period measurements were logged at 20 minute intervals at 23 points around the interior and exterior of both houses using MAXIM iButton Devices. The two dwellings had a near identical floor plan and were built approximately 150 meters apart.

The Rotoiti house was the first UKU house and the third UKU dwelling that has been built. It has 150 mm thick flax fibre reinforced earth walls, a light timber roof clad with 0.4 mm Corrugate Colorcote ZR8 and was built on a concrete slab foundation. The timber framed house was similarly built but with timber framed walls in place of the earth walls. Double glazing was used for windows and sliding doors in both dwellings. The area is on the Southern shore of Lake Rotoiti and is classified as Climate Zone 2.
The thermal results of the two houses are shown below.

<table>
<thead>
<tr>
<th>Season</th>
<th>Period</th>
<th>Location</th>
<th>Rotoiti UKU house</th>
<th>Rotoiti Timber Framed House</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Summer</td>
<td>(Dec08- Feb09)</td>
<td>Lounge</td>
<td>17.0</td>
<td>32.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bedroom</td>
<td>17.4</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outdoor</td>
<td>8.1</td>
<td>33.4</td>
</tr>
<tr>
<td>Autumn</td>
<td>(Mar09- May09)</td>
<td>Lounge</td>
<td>11.3</td>
<td>27.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bedroom</td>
<td>10.6</td>
<td>27.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outdoor</td>
<td>0.9</td>
<td>28.9</td>
</tr>
<tr>
<td>Winter</td>
<td>(June09- Aug09)</td>
<td>Lounge</td>
<td>9.0</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bedroom</td>
<td>8.8</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outdoor</td>
<td>-0.9</td>
<td>18.7</td>
</tr>
</tbody>
</table>

The results show the minimum and maximum temperatures recorded over three seasons for each house.

BRANZ recommends indoor temperatures of a dwelling range between 18 and 24 °C. The World Health Organisation recommends a minimum temperature of 16 °C. The results show that during the summer and autumn period, the average house temperatures of both houses were within or close to the recommended limits. During the winter period monitored, outdoor temperatures in the area decreased below zero and the indoor average in the UKU house was 14.8 degrees in the lounge and 13.4 degrees in the bedroom which was 3.2 and 4.6 degrees below the BRANZ recommended limits respectively.

Another aim of the research was to compare the thermal performance of the UKU house to a light timber framed house. This was done to compare the measured performance of the UKU house against a code compliant house. The results show that the average indoor temperature in the UKU house was cooler in the summer and warmer in the winter than the light timber framed house.

From these observations the UKU house is shown to have a comparable performance to a code compliant timber framed house and will perform adequately during the summer, autumn seasons and by inference spring as well. The UKU research team at the University of Auckland have reason to believe that the Ahipara UKU house will be able to keep the internal temperatures within the recommended limits specified by BRANZ during winter for the following reasons.

- The earth walls of the Ahipara house are 200 mm thick whereas the earth walls of the Rotoiti house were 150 mm thick.
- Ahipara is in Climate Zone 1 whereas Rotoiti is in Climate Zone 2
  - The Northland region has a sub-tropical climate and an average winter temperature of 14 degrees. Rotorua and the surrounding districts have a temperate climate and an average winter temperature of 12 degrees.
- Although both houses were built using passive solar design principles and have high thermal mass, the house at Ahipara has no obstructions to the sun on the North side. In Rotoiti the trees around the property reduce exposure to the winter sun.
The Ahipara UKU house will be monitored for two years in a similar way the Rotoiti houses were monitored.

Does the building design meet E3 Internal Moisture requirements?

DBH E3 specifies that for single skin normal weight masonry construction without a cavity a minimum R value of 0.6 is required to minimize indoor condensation and fungal growth (mildew).

The calculated R value for the Ahipara earth wall is 0.53 m² K/W which is less than the specified minimum of 0.6 thus bringing into question whether condensation and fungal growth will be a problem in this house during the colder winter months.

The Earth Building Association of New Zealand has conducted a survey of earth buildings around the country and one of the questions they asked was whether or not there was condensation in the house. 53 survey responses were received. The survey is attached for reference. From the description of the earth walls given it is likely that many of the walls have an R-value less than 0.6. One survey response observed condensation during construction. Apart from this no condensation issues were reported.

An explanation why earth buildings are not as prone to having condensation issues as normal weight masonry is because the wall contains an active (unfired) clay component. Clay is known to have some ability to regulate internal relative humidity to between 40 – 60%. The effect of the clay on regulating the internal relative humidity and the rare occurrence of condensation in earth buildings is explained in many earth building guides including Building with Earth by (Mirkke 2006) and Earth Masonry: Design and Construction by (Morton 2005).

The Ahipara UKU house is well ventilated with a large proportion of windows and doors. The total area of the external walls in the house is 92 m². The area of openable windows is 7.4 m² (8% of the total external wall area). There are also 3 large glass doors on the North side of the house and 3 doors on the South side which can be used for ventilation as needed. The openable door area is 17.4 m² (19%). A passive ceiling vent is suggested by the research team for the bathroom area as well as a rangehood extractor fan over the stove in the kitchen area.

Roof insulation

The roof insulation for the Ahipara UKU house is the same as that used for the Rotoiti UKU house with an R-value of 2.2 and 140x45 purlins (rather than R3.2 ceiling insulation). The thermal performance of the house will be monitored and the justification given for H1 above is valid for this level of ceiling insulation.

Other comments

The approach used to address H1 does not use the existing methods available to achieve compliance. Despite this, it is the research team’s opinion that the UKU housing method and design would work in Ahipara. The use of passive solar design and thermal mass is still a new area with the potential to create good quality, energy efficient houses. Existing methods are focused predominantly on insulation but both insulation and passive solar gain can be used to keep a dwelling at a good indoor temperature in an energy efficient manner. Is it possible to be given an opportunity to prove this from a performance based assessment? The temperatures and relative humidity of the house will be monitored for two years. After this period, the performance of the house will be known well enough to make a decision.
In the case that indoor temperatures do not meet the requirements, the house can be strapped and lined on the outside of the earth walls to the level required by H1.

The research team will continue to keep in contact with the occupants during the two years of monitoring. The owner and the research team see this as a long-term project and are committed to creating a good quality dwelling and will ensure that this result is achieved.

2) The provision of a peer review by a fellow staff member of the University of Auckland is not considered independent and the PS2 provided excludes code clause B2. Thus please provide an “independent” peer review from a suitably qualified insured expert and include both code clauses B1 and B2.

An independent peer review from a suitably qualified insured expert has been provided for B1 and B2.

3) Please provide an independent E2 peer review and PS1 from an appropriately qualified and insured architect and ensure that this peer review does not provide comment in relation to the “future” verandah as this does not form part of the Consent and thus cannot be considered in this Building Consent Application.

An independent peer review and PS1 from a suitably qualified insured architect has been provided.

4) It is Council’s understanding that this building has proceeded without a building consent. Please detail how far the building has progressed and stop building until the consent has been issued. Please provide this information and a new building consent for the balance of the work and apply for COA as per the provision of actions required by the Council notice issued on the property BC-2010-1501.

Work on site has stopped in accordance with the stop work notice issued. The foundations, earth walls, concrete bond beam and roof have been built. Portions of the ceiling have been left open to allow the ceiling insulation to be checked.

References
## Appendix C.7 Cost of Building the Ahipara Dwelling

### Cost of building the Ahipara rammed earth dwelling

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost (NZ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excavation</strong></td>
<td></td>
</tr>
<tr>
<td>Machine hire - digger</td>
<td>3000</td>
</tr>
<tr>
<td>Labour - Excavation work (digger operator, setting out)</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5000</td>
</tr>
<tr>
<td><strong>Foundation</strong></td>
<td></td>
</tr>
<tr>
<td>Materials (steel, plastic, wood for formwork)</td>
<td>2000</td>
</tr>
<tr>
<td>Concrete (2 concrete truck loads - 10 m³)</td>
<td>3000</td>
</tr>
<tr>
<td>Labour - Concrete foundations</td>
<td>5000</td>
</tr>
<tr>
<td>Concrete - floor slabs</td>
<td>10000</td>
</tr>
<tr>
<td>Materials - Paint for floor slab</td>
<td>5000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>25000</td>
</tr>
<tr>
<td><strong>Wall and Bond beam construction</strong></td>
<td></td>
</tr>
<tr>
<td>Machine hire for construction</td>
<td>3000</td>
</tr>
<tr>
<td>Machine repair and maintenance</td>
<td>1000</td>
</tr>
<tr>
<td>Compressor</td>
<td>Donated</td>
</tr>
<tr>
<td>Diesel and petrol</td>
<td>3000</td>
</tr>
<tr>
<td>Food</td>
<td>3000</td>
</tr>
<tr>
<td>Earth for walls</td>
<td>No cost</td>
</tr>
<tr>
<td>Flax for walls</td>
<td>No cost</td>
</tr>
<tr>
<td>Labour - Youth from community</td>
<td>13500</td>
</tr>
<tr>
<td>Labour - Experienced tradesmen from community</td>
<td>15000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>38500</td>
</tr>
<tr>
<td><strong>Roof Construction</strong></td>
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</tr>
<tr>
<td>Timber (macarapa)</td>
<td>15000</td>
</tr>
<tr>
<td>Roof materials (insulation, coloursteel)</td>
<td>5000</td>
</tr>
<tr>
<td>Roofing labour</td>
<td>5000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>25000</td>
</tr>
<tr>
<td><strong>Window and door fittings</strong></td>
<td></td>
</tr>
<tr>
<td>Windows and doors</td>
<td>18000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>111500</td>
</tr>
</tbody>
</table>
NOTES:
1. CONTRACTOR TO CONFIRM ALL DIMENSIONS ON SITE PRIOR TO COMMENCING ANY WORKS.
2. DO NOT SCALE DRAWINGS.
3. ALL CONSTRUCTION TO BE IN ACCORDANCE WITH NZS 3604, NZBC AND APPROVED DOCUMENTS AND LOCAL AUTHORITY REQUIREMENTS.
4. ALL SAFE BUILDING PRESSURE OF 100PA.
5. DO NOT BUILD ON ANY FILL WHICH HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE 25MPa AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF AS DARRAGGANWELL TIED BRACED WALLS TO ROOF FLOOR.
8. ALL FRAMING TIMBER TO BE H1 TREATED UNLESS OTHER WISE SPECIFIED.
9. ALL EXPOSED STEEL TO BE STAINLESS STEEL UNLESS OTHER WISE SPECIFIED.
10. ALL PLUMBING AND DRAINAGE WORK TO COMPLY WITH NZSAS 3500.2.
11. ALL WINDOW JOINTER TO COMPLY WITH NZS4211.
12. WINDOW GLAZING TO COMPLY WITH NZS4223:1993.
14. GRANULAR FILM TO COMPLY WITH NZS 3604:1990 CLAUSE E5.2.
15. ROOF BRACING TO COMPLY WITH NZS 3604:1999 SECTION 10.
PLUMBING NOTES

LEGEND:
- 50mm diameter
  Grade: 1.40
- 115mm diameter service line
  Grade: 1.20
- 115mm diameter drain line
  Grade: 1.10
- 115mm diameter main drain line
  Grade: 1.10
- 50mm diameter soil line
  Grade: 1.00

ALL FIXTURE PIPES TO BE 40mm diameter
GRADE: 1.00

NOTES:
ALL PLUMBING AND DRAINAGE WORK
TO BE IN ACCORDANCE WITH AS/NZS 3500.2 1996

AS/NZS 3500.2.2
ORG & ORP
- 20mm above paved areas sloping away.
- 75mm above grass & garden areas.
- 100mm below finished floor level.

TO WATER TANKS

TO ONSITE WASTE WATER TREATMENT SYSTEM

NOTES:
1. CONTRACTOR TO CONFIRM ALL DIMENSIONS ON SITE PRIOR TO COMMENCING ANY WORKS.
2. DO NOT SCALE DRAWINGS.
3. ALL CONSTRUCTION TO BE IN ACCORDANCE WITH NZS 3604, NZBC AND APPROVED DOCUMENTS.
5. DO NOT BUILD ON ANY FILL WHICH HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE 25MPa AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF AS DAPRAGM AND TIE BRACED WALLS TO ROOF/FLOOR.
8. ALL FRAMING TIMBER TO BE H1 TREATED UNLESS OTHERWISE SPECIFIED.
9. ALL EXPOSED STEEL TO BE STAINLESS STEEL UNLESS OTHERWISE SPECIFIED.
10. ALL PLUMBING AND DRAINAGE WORK TO COMPLY WITH NZS AS/1552.2
11. ALL WINDOW JOINERY TO COMPLY WITH NZS4241.
12. WINDOW GLAZING TO COMPLY WITH NZS4223:1993.
15. ROOF BRACING TO COMPLY WITH NZS 3604:1998 SECTION 10.

Job Title: Proposed New Dwelling
For: Unaik Mare Whanau Trust.
At: Ngakaroa Road, Ahipara

N

Drawing Title: Plumbing Plan

Drawing Number: 05

Scale: 1:100

Creation Date: 18/11/08

Heremaia Hepl

28/05/2010

Chang
NOTES:
1. CONTRACTOR TO CONFIRM ALL DIMENSIONS ON SITE PRIOR TO COMMENCING ANY WORKS.
2. DO NOT SCALE OF DRAWINGS.
3. ALL CONSTRUCTION TO BE IN ACCORDANCE WITH NZS 3604 NZBC AND APPROVED DOCUMENTS AND LOCAL AUTHORITY REQUIREMENTS.
4. A SAFE BUILDING PRESSURE OF 100kPa.
5. DO NOT BUILD ON ANY FILL WHICH HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE 25MPa AT 28 DAYS MINIMUM.
7. NAIL FLOORING AND CEILINGS TO ROOF AS DIFFERENTLY TIED BRACED WALLS TO ROOF FLOOR.
8. ALL FRAMING TIMBER TO BE H1 TREATED UNLESS OTHER WISE SPECIFIED.
9. ALL EXPOSED STEEL TO BE STAINLESS STEEL UNLESS OTHER WISE SPECIFIED.
10. ALL PLUMBING AND DRAINAGE WORK TO COMPLY WITH NZSAS 3502.2
11. ALL WINDOW JOINERY TO COMPLY WITH NZS 4229:1999 SECTION 13.
12. WINDOW GLAZING TO COMPLY WITH NZS4223:1993.
14. GRANULAR FILL TO COMPLY WITH NZS 3604:1990 CLAUSE 6.2.
15. ROOF BRACING TO COMPLY WITH NZS 3604:1996 SECTION 10.
BOND BEAM LINTEL DETAIL

Birds mouth
190x45 Macrocarpa Rafters at 900mm

140x45 Top plate

200x200 BOND BEAM

Stainless Steel M12 Bolts at 600mm

200 Earthwall

4D12 horizontal reinforcing bars
R6 Stirrups at 400mm
100mm thick concrete slab, 17.5MPa with 665
reinforcing mesh laid on DPM over 25mm
sand blinding over 100mm min
COMPACTED HARD CORE FILL

D16 reinforcement, Centers
to be determined by ENGINEER

Two layers of Bitumenous

50mm high CONCRETE NIB
FINISHED GROUND LEVEL

300x450 Perimeter footing

D10 Starters at 600mm

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NZBC AND APPROVED DOCUMENTS
AND LOCAL AUTHORITY REQUIREMENTS.
5. DO NOT BUILD ON ANY FILL WHICH
HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE
25MPa. AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF
AS D ر R A G M A N E L TIED BRACED WALLS
TO ROOF FLOOR.
8. ALL FRAMING TIMBER TO BE H1
TREATED
UNLESS OTHER WISE SPECIFIED
9. ALL EXPOSED STEEL TO BE
STAINLESS STEEL
UNLESS OTHER WISE SPECIFIED
10. ALL PLUMBING AND DRAINAGE WORK
TO COMPLY WITH NZS2445:30002.2
11. ALL WINDOW JOINTS TO
COMPLY WITH NZS4241.
12. WINDOW GLAZING TO COMPLY
WITH NSZ4223:1993.
13. BRICK MOVEMENT CONTROL JOINTS
REQUIRED IN ACCORDANCE WITH
14. GRANULAR FILL TO COMPLY WITH
NZS 3604:1996 CLAUSE E5.2.
15. ROOF BRACING TO COMPLY
Ridge beam as per Engineers design
375x150

Each rafter to be housed 15mm min into beam
6x8 connection or 25x1mm strap
with 9/30x2.5mm nails into each rafter
Fix each Rafter to beam with
4/75x3.15mm skew nails

Ridge beam to extend out to soffit line
and fascia in copper box

A102 Rafter Fixing Detail 1:7

20mm macrocarpa sarking

FRANKLIN CONSULTANTS LTD
1A Harrison Ave, Belmont, Auckland
City 0623, Phone 09 445 8420
Alan Franklin BE MIPENG

PS2 check by

NOTES:
1. CONTRACTOR TO CONFIRM ALL
DIMENSIONS ON SITE PRIOR
TO COMMENCING ANY WORKS.
2. DO NOT SCALE OF DRAWINGS.
3. ALL CONSTRUCTION TO BE IN
ACCORDANCE WITH NZS 3684
NZBC AND APPROVED DOCUMENTS
AND LOCAL AUTHORITY REQUIREMENTS.
4. A SAFE BUILDING PRESSURE OF 100kpa.
5. DO NOT BUILD ON ANY FILL WHICH
HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE
25MPa AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF
AS DIAPRAGMANEL TIED BRACED WALLS
TO ROOF) FLOOR.
8. ALL FRAMING TIMBER TO BE H1
TREATED UNLESS OTHER WISE SPECIFIED
9. ALL EXPOSED STEEL TO BE
STAINLESS STEEL UNLESS OTHER WISE SPECIFIED

10. ALL PLUMBING AND DRAINAGE WORK
TO COMPLY WITH NZS2658
11. ALL WINDOWN JOINERY TO
COMPLY WITH NZS4211.
12. WINDOW GLAZING TO COMPLY
WITH NZS4223:1993.
13. BRICK MOVEMENT CONTROL JOINTS
REQUIRED IN ACCORDANCE WITH
NZS 4229: 1999 SECTION 13
14. GRANULAR FILL TO COMPLY WITH
NZS 3664: 1996 CLAUSE E3.2.
15. ROOF BRACING TO COMPLY
WITH NZS 3664: 1996 SECTION 10.

20mm thick macrocarpa
sarking or sheet lining.

25x1mm strap nailed to rafter first
then bent up each side and nailed
to purlin

4/30x2.5mm flat head
nails (2 each side)
Breather type self supporting
Building paper

4/75x3.15mm flat head nails
immediately adjacent to intended
bend in steel strap, skewed
slightly inward. (2 each side)

A101 Purlin Fixing Detail 1:5

A140x45 Purlins at 900rcrs

190x45 macrocarpa Rafters at 900rcrs

Corrugated Coloursteel longrun iron

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AND LOCAL AUTHORITY REQUIREMENTS.
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25MPa AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF
AS DIAPRAGMANEL TIED BRACED WALLS
TO ROOF) FLOOR.
8. ALL FRAMING TIMBER TO BE H1
TREATED UNLESS OTHER WISE SPECIFIED
9. ALL EXPOSED STEEL TO BE
STAINLESS STEEL UNLESS OTHER WISE SPECIFIED

10. ALL PLUMBING AND DRAINAGE WORK
TO COMPLY WITH NZS2658
11. ALL WINDOWN JOINERY TO
COMPLY WITH NZS4211.
12. WINDOW GLAZING TO COMPLY
WITH NZS4223:1993.
13. BRICK MOVEMENT CONTROL JOINTS
REQUIRED IN ACCORDANCE WITH
NZS 4229: 1999 SECTION 13
14. GRANULAR FILL TO COMPLY WITH
NZS 3664: 1996 CLAUSE E3.2.
15. ROOF BRACING TO COMPLY
WITH NZS 3664: 1996 SECTION 10.

20mm thick macrocarpa
sarking or sheet lining.

25x1mm strap nailed to rafter first
then bent up each side and nailed
to purlin

4/30x2.5mm flat head
nails (2 each side)
Breather type self supporting
Building paper

4/75x3.15mm flat head nails
immediately adjacent to intended
bend in steel strap, skewed
slightly inward. (2 each side)
Ridge beam to extend out to soffit line and lined with Hardiflex

25x1 strap with 6/30x2.5mm nails into each rafter

190x45 Macarapa Rafters at 900crs

Ridge beam size as per ENGINEER’S design 375x150

2M12 galv bolts with 50x50x3mm galv. square washers

140x45 solid built up studs for full width of ridge beam

Corrugated Coloursteel longrun iron over Breather type self supporting Building paper

140x45 Purlins at 900crs

200mm Eave flashing

250x20 Timber Fascia

4.5mm Hardiflex Soffit Lining

90x45 H1.2 Soffit sprocket

190x45 Macarapa Rafters at 900crs

200 Earthwall

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4. A SAFE BUILDING PRESSURE OF 100kPa.
5. DO NOT BUILD ON ANY FILL WHICH HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE 25Mpa. AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF AS DIARRAGEMELL TIED BRACED WALLS TO ROOF FLOOR.
8. ALL FRAMING TIMBER TO BE H1 TREATED UNLESS OTHER WISE SPECIFIED.
9. ALL EXPOSED STEEL TO BE STAINLESS STEEL UNLESS OTHER WISE SPECIFIED.
10. ALL PLUMBING AND DRAINAGE WORK TO COMPLY WITH NZSAS 3600.2.
11. ALL WINDOW JOINERY TO COMPLY WITH NZS4241.
12. WINDOW GLAZING TO COMPLY WITH NZS4223.1993.
14. GRANULAR FILL TO COMPLY WITH NZS 3604: 1990 CLAUSE E5.2.
15. ROOF BRACING TO COMPLY WITH NZS 3604: 1899 SECTION 10.

20mm macarapa sarking

R 3.2 Ceiling Pink Batt insulation

M16 Bolts at 900crs max with 50x50x3mm square washers

200x50 Permanent Formwork

BOND BEAM

Reinforced with 4D12 longitudinal with R6 ties at 400crs lapped 800mm

FIXING RIDGE BEAM TO WALL

SOFFIT DETAIL

Job Title: Proposed New Dwelling
For: Unaiki Mare Whanaupu Trust.
At: Ngakaroa Road, Ahipara

Drawing Title: Details
Details: ALL DIMENSIONS TO BE VERIFIED ON SITE

Drawn: Heremaa Hapi
Revised: 28/05/2010
Creation Date: 18/1/08

Scale: 1:40
Driving Number: 10
**WINDOW JAMB DETAIL**

- BOND BEAM
  - Reinforced with 4/12 longitudinal with R6 ties at 400crs lapped 800mm

- Water resistant AIR SEAL to perimeter of trim cavity

- Aluminium Window Flashing

- Aluminium Side flashing to extend behind window flange

- Sealant to flashing and Earth wall

- Temporary packers to support unit during installation

- Aluminium Side flashing to extend behind window flange

- Sealant to flashing and Earth wall

- Ex. 100x50 H3.2 Pine jamb fixing block in Earthwall with H.D Galv. 100x3.75mm nails into earth jamb at 450crs

- Water resistant AIR SEAL to perimeter of trim cavity

- 200 Wide Earth Wall

- Aluminium Jamb cover

- Poured Concrete Sill Sealed with 3 coats of Aquashield Clear

**WINDOW HEAD DETAIL**

- Aluminium Side flashing to extend behind window flange

- Sealant to flashing and Earth wall

- Approved DPC or similar to sill platform and extend 200mm up the jamb

- Wanz Sill pan and unit support block

- Poured Concrete Sill Sealed with 3 coats of Aquashield Clear

- Water resistant AIR SEAL to perimeter of trim cavity

- Flat packers to support unit

- SIKA Blackseal to Sill rebate

- H3.1 Treated timber reveals

- FINISHED GROUND LEVEL

- 200 Wide Earth Wall

**WINDOW SILL DETAIL**

- Door Sill Detail

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4. A SAFE BUILDING PRESSURE OF 100kPa.
5. DO NOT BUILD ON ANY FILL WHICH HAS NOT BEEN CERTIFIED.
6. CONCRETE STRENGTH TO BE 25MPa. AT 28 DAYS MINIMUM.
7. NAIL FLOORS AND CEILINGS TO ROOF AS DRAINAGE WALLS TIED BRAZED WALLS TO ROOF POINT.
8. ALL FRAMING TIMBER TO BE H1 TREATED UNLESS OTHERWISE SPECIFIED.
9. ALL EXPOSED STEEL TO BE STAINLESS STEEL UNLESS OTHERWISE SPECIFIED.
10. ALL PLUMBING AND DRAINAGE WORK TO COMPLY WITH NZS AS 3502.2
11. ALL WINDOW JOINERY TO COMPLY WITH NZS 2421.
12. WINDOW GLAZING TO COMPLY WITH NZS 2422:1993.
14. GRANULAR FILL TO COMPLY WITH NZS 3604:1990 CLAUSE 15.2.
15. ROOF BRACING TO COMPLY WITH NZS 3604:1998 SECTION 10.
Note:
- Allow to install drier type - US5020 to all corners of window opening.
- Do not use ProtecWrap #500 Primer on polyethylene. Prime with Protec Tape primer.

Internal lining

Air seal
(By other trade)

Panthers
(By other trade)

Brush or Roll ProtecWrap #500 primer along all, head and up both jamb face full height

Cut 400mm lengths of detail joint US5000 (one piece for each corner of opening). Place 150mm of expanded membrane into all and press firmly into the aliphato junction and the remaining membrane firmly into position up the joints, from the corner stretch and apply to outside face. Repeat on all four corners.

Install 1000mm Protec tape - (EF5) tape for full length of head ensure tape is flush with inside edge of window opening. Fold Protec tape - (EF5) tape) to front face of blockwork.

Install flexible assisted to window head and jambs (not all) from massed priming unit to finished plaster surface

Apply standard double reset coat of plaster as soon as possible over surface of Protec tape - (EF5) tape) after installation extend 50mm beyond extent of Protec tape - (EF5) tape)

Selected 3 coat texture coating (by other trade) provide 5mm depth to front of lintel as shown.

Note:
- ProtecWrap products are designed to be covered and are therefore not UV stable - dey in four weeks of installation.

Note:
- Do not allow flexible assisted direct contact with Protec Tape product.

Window Finishing System
Detail Tape - US5000
Protec Tape - EF5S Tape

Revision 15.0