Assessment of Mortar Properties in Vintage Clay Brick Unreinforced Masonry Buildings

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ABSTRACT

Mortar is a principal structural component of unreinforced masonry (URM) buildings, with mortar mechanical properties having an important influence on the behaviour of URM buildings when subjected to earthquake induced shaking. However, the mechanical properties of in-situ mortar have long been known to be difficult to obtain. Recommendations on mortar properties for preliminary assessment of URM buildings, as well as details of field assessment procedures for in-situ mortar characterisation have been previously suggested in national standards and guidelines in the USA, New Zealand and seismically active countries in Europe. An experimental study was implemented in order to investigate an improved characterisation procedure for vintage mortars, to be used by structural engineering practitioners with the aim to improve the accuracy of building seismic assessments, computer modelling and subsequent seismic retrofit designs. The tested mortar samples were extracted from 60 different vintage URM buildings throughout New Zealand. A non-standard mortar compression test procedure was developed, and an alternative in-situ assessment technique to estimate mortar compressive strength was investigated. Supplementary tests to estimate the mortar aggregate/binder ratio and to predict the presence of cement in the mortar are also discussed.

1 INTRODUCTION

Mortar is a principal structural component of unreinforced masonry (URM) buildings, and therefore the mechanical properties of mortar need to be understood in order to study the structural behaviour of this building type. Vintage URM buildings, such as typically

encountered in New World countries of North America and European colonies in the Southern Hemisphere, are particularly vulnerable to severe damage and potential collapse during earthquake induced shaking (Dizhur et al. 2010; Dizhur et al. 2011; Moon et al. 2014). The mechanical properties of mortar have particular importance when assessing the likely behaviour of URM buildings in earthquakes. Similar to that of clay bricks, the mortar compressive strength is used in the prediction of masonry compressive strength, which furthermore is the basis for estimating masonry Modulus of Elasticity and stress-strain behaviour (Kaushik et al. 2007a; Kaushik et al. 2007b; Lumantarna et al. 2014)). However, determining the compressive strength of in-situ mortar has long been known to be difficult. Previous researchers (Moropoulou et al. 2000; Moropoulou et al. 2005; Papayianni 2006; Cizer et al. 2008) have focused primarily on the chemical and microstructural analyses of mortar, which enabled in-depth characterisation of the mineralogical and chemical constituents of the mortar mix. This primary focus on the chemical and microstructural analyses was due to the difficulty in extracting mortar samples of a representative quantity and size from existing buildings which typically have high heritage value associated with them. Given that the mortar samples that are extracted from existing buildings are almost always of an irregular geometry and due to the lack of knowledge in performing compression tests on mortar samples having non-standard dimensions (Drdácký et al. 2008; Magalhães and Veiga 2009) physical testing of extracted mortar samples was typically not undertaken.

A number of authors (Valek and Veiga 2005; Drdácký et al. 2008; Magalhães and Veiga 2009) have previously investigated different methods for the compression testing of non-standard mortar samples and have attempted to interpret the compression test results. Also, methods to predict mortar compressive strength in-situ were proposed by previous researchers (RILEM 1997b, a; Rocky Mountain Masonry Institute et al. 1999) for potential application in situations when mortar sample extraction is not possible. Recommended mortar properties for preliminary assessment of URM buildings are provided by NZSEE (2006).

A study was undertaken to seek an improved characterisation procedure for New Zealand mortars found in vintage URM buildings to be used by industry practitioners in order to improve the accuracy of building seismic assessments, computer modelling and subsequent seismic retrofit designs. A compression test procedure was developed for non-standardised mortar sample sizes, and an alternative in-situ assessment technique to estimate mortar compressive strength was investigated. Supplementary tests that were conducted in order to estimate the mortar aggregate/binder ratio and to predict the presence of cement in the mortar as suggested by (Moropoulou et al. 1995; Biggs and Forsberg 2001; Sabbioni et al. 2001; Middendorf et al. 2005) are also presented and discussed in the subsequent sections.

2 TYPES OF MORTAR

An ordinary lime based mortar is made from a mixture of sand, water and quicklime, either in the form of hydraulic lime or non-hydraulic lime. Lime and sand are firstly mixed thoroughly on a platform or in a container in order to avoid contact with potential impurities. When lime putty is used, the lime putty is sieved prior to mixing with sand (Mulligan 1942; McKay 1947; Mortar Industry Association 2004).

Cement based mortar was introduced following the invention of Portland cement in the 19th century. Cement mortar has a faster setting time and is known to have a high mechanical strength and low level of porosity in comparison to lime mortars (Mulligan 1942; McKay 1947; Palomo et al. 2004).

Cement-lime mortar is made from a proportioned mixture of lime, Portland cement, sand and water. Due to the faster setting time of Portland cement, lime and sand are first mixed, and the cement is added to the mix shortly before the mortar is used. Cement-lime mortar has the merits of both pure cement mortars and pure lime mortars, where it has the workability, deformation capacity and autogenous healing ability of a lime mortar whilst also having the bond quality and compressive strength of a cement mortar. These properties can be varied by altering the cement : lime proportion (McKay 1947; Tate 2005). ASTM C 270 - 08a (2008b) presented the categorisation of cement-lime mortars into five different groups according to their mix proportions by volume.

Lime-pozzolan mortar is a lime mortar that also contains pozzolanic materials. The reaction between pozzolanic materials and lime enhances the mechanical strength of the mortar, and therefore lime-pozzolan mortar generally has a higher mechanical strength than an ordinary lime mortar. However, lime-pozzolan mortar has a higher level of porosity, and consequently a lower compressive strength than does cement based mortars. Lime-pozzolan mortar also has similar deformation characteristics to lime mortar, and therefore lime-pozzolan mortar can accommodate minor movements within the building structure (Martinez-Ramirez and Thompson 1999; Palomo et al. 2004; Papayianni and Stefanidou 2006).

3 TESTING PROGRAMME

An experimental programme was undertaken to determine the compressive strength of mortar samples extracted from existing New Zealand URM buildings and to identify an adequate non-destructive assessment technique to predict the mortar compressive strength in-situ. The experimental programme was divided into two stages.

3.1 Stage 1 of testing programme

The Mohs hardness test and the irregular mortar compression test were performed on 365 irregular mortar samples that were extracted from 60 existing New Zealand URM buildings. Similar to that performed by Válek and Veiga (2005), the irregular mortar samples were cut using a diamond tipped circular saw to form parallel top and bottom loading surfaces. These samples were furthermore trimmed to form approximately rectangular test pieces as shown in **Figure 1a**. The cutting process was controlled to minimise disturbance to the mortar samples, which were then capped using gypsum plaster to ensure a flat loading surface.

Prior to compression testing, the rectangular test pieces were subjected to the Mohs scratch test, which was modified to be suitable for use on vintage mortars (referred to here as the "modified Mohs scratch test"). Because the Mohs minerals are not commonly available, and with the aim to simplify the scratch test for possible future use by industry practitioners, materials which are known to have similar hardness values to the Mohs minerals (denoted as "equivalent materials") were sourced (Nicholson and Shaw 2000; MineralTown 2010). The validity of adopting these equivalent materials was confirmed by testing 365 mortar specimens that were extracted from 60 different building sites. The mortar surface was cleaned and levelled using a 400 grit sandpaper prior to performing the modified Mohs scratch test (see **Figure 1b**).

Table 1 shows the number of mortar samples that were scratched using both the actual Mohs minerals and the equivalent materials. Most field extracted mortar samples were found to have hardness values corresponding to being scratched by gypsum, which was equivalent to being scratched by a fingernail. However, extremely weak mortars could be easily scratched using a fingernail, where the mortar was scraped (heavily raked) and the particles became loose as the fingernail was drawn along the sample. When this scraping of mortar occurred, a Mohs number of 1.5 was assigned. A Mohs number of 2 was assigned when a fingernail left an indented scratch mark in the mortar while the mortar was not heavily raked. It was found that the strongest mortars incorporated in the experimental programme were scratched using calcite or an aluminium pick.

Following the scratch tests, the mortar samples were tested in compression using a 100 kN Instron machine. It is noted that these mortar samples were in irregular shapes, having various height to thickness (h/t) ratio and thickness to length (t/l) ratio. Drdácký et al. (2008) described that the influence of sample dimensions on the mortar compressive strength was apparent, and therefore the compression test results required normalisation with respect to a sample having an h/t ratio and a t/l ratio of 1.0. Lumantarna (2012) describes the development of compressive strength correction factors to normalise mortar samples having

a height to thickness (*h/t*) ratio and a thickness to length (*t/l*) ratio other than 1.0. Thus, all mortar samples included in the experimental programme were normalised using the mortar compressive strength normalisation technique described by Lumantarna (2012). **Figure 2** shows the compression testing of irregular mortar samples.

3.2 Stage 2 of testing programme

Mortar samples from each group were disaggregated using a hammer, and then crushed into a fine powder using a grinding mill, as shown in **Figure 3**. The powder samples were used for 2 different tests: the acid digestion test and the powder X-ray diffraction analysis.

3.2.1 Acid digestion test

18 field extracted and 11 laboratory constructed mortar sample groups were subjected to the acid digestion test. The acid digestion test was performed following the procedure prescribed in Rilem TC 167-COM (Middendorf et al. 2005), and 10 grams of powder from each sample group was used for the acid digestion test. It is noted that the acid digestion test shall not be performed when the mortar aggregate consists of calcareous sand. The sand used for the mixing of heritage mortars was likely to have originated from quarries, river beds or beaches near the construction area. Knowing that the presence of limestone is one indicator of the presence of calcareous sand, a geological map of New Zealand was used to study the locations of limestone in New Zealand, and therefore the presence of calcareous sand in the mortar could be predicted (White 2003; GNS Science 2011b, a). The cities where the extraction of mortar samples was performed are summarised in **Table 2**, showing the types of rocks present in those regions. Based on the geological map of New Zealand (White 2003; GNS Science 2011b, a) and **Table 2** it was shown that limestone is not present in the cities where the extraction of mortar samples was performed. This finding suggests that the aggregates used for the mixing of field extracted mortar samples included in this experimental programme were likely to be non-calcareous. It was then assumed that performing the acid digestion test on these field extracted mortar samples was appropriate.

Table 3 shows the 11 different mortar grades constructed in the laboratory using ordinary Portland cement, hydrated lime and river sand. Most of these mortar mixes were selected following the recommendations provided in NZSEE (2006) and ASTM C 270 - 08a (2008b), except for mortar grades d, f, h and k, which were chosen in order to vary the mortar binder:aggregate ratio. These mortar samples were left to cure for at least 28 days at room temperature (20 ± 5º C) before being ground into powder and subjected to the acid digestion test. The incorporation of these laboratory constructed samples was intended for calibrating the accuracy of the acid digestion test, and to observe whether the acid digestion test would

enable variations in the mortar binder:aggregate ratio to be identified. **Figure 4** shows the acid digestion test procedure. It is noted that after the acid digestion test, separation between the liquid and the aggregate was achieved using a centrifuge which rotated at 4000 rounds per minute (see **Figure 4** (b) and (c)).

3.2.2 Powder X-ray diffraction analysis

22 field extracted mortar sample groups were subjected to the powder X-ray diffraction analysis technique. It is noted that for the research reported herein, the focus was to use the powder XRD analysis to aid the identification of the binder constituents, such as to identify the presence of cement in the mortar extracted from existing URM buildings. Therefore, knowledge of the constituents present within cement was considered to be important.

The powder X-ray diffraction analysis was performed to predict the presence of cement in the mortar mix, by considering the presence of mineral phases as well as the average mortar compressive strength. The fine powder from mortar samples was placed on a disc and fed into the XRD machine (Rigaku D/max-2500) with Cu Kα radiation at a scanning speed of 2° 2θ increment per minute. It is also noted that the powder X-ray diffraction analysis was used only as an indicative measure due to its semi-quantitative nature.

4 DESCRIPTION OF FIELD SITES

Mortar samples were extracted from 60 different field sites throughout New Zealand as described below.

- Avon House in Wellington (site AH) is a heritage residential house which was scheduled for reinstatement, and the opportunity for field testing was provided by the consulting engineer to determine the building's material properties, facilitating improved accuracy of the retrofit design;
- Site BC was the heritage Rob Roy Hotel, a three storey heritage URM building;
- Site HC was the Old High Court building in Wellington. The building was scheduled for restoration in 2008, and therefore provided an opportunity to obtain samples for laboratory testing;
- Site RB was a two storey Irish Pub in Central Auckland which was demolished in March 2009;
- Site TA was a single storey horse stable at Te Awamutu, Waikato. The building was scheduled for demolition due to subdivision purposes;

- Site CFK was the 1910 Campbell Free Kindergarten, intersection between Victoria Street West and Franklin Road. This building was scheduled for seismic strengthening;
- Site D was a single storey warehouse at Dominion Road, Auckland that was demolished in early 2010;
- Site AL is a two storey, stand-alone commercial building that was damaged during the 20 December 2007 Magnitude 6.8 Gisborne earthquake, and therefore this building was scheduled for reinstatement;
- Site AU was the Aurora Tavern built in 1886, which is located in Auckland's Central Business District. The building was demolished in 2011. Samples AUST and AUW both originated from this building, but were in noticeably different condition;
- Site MR was the two storey Manuka Restaurant in Devonport, Auckland.;
- Sites C1 to C51 were unreinforced masonry buildings in the Canterbury area that were damaged during the 2010-2011 Canterbury Earthquakes. Two different types of mortar samples were collected from site C11: ordinary mortar samples (C11 samples) and yellow coloured mortar samples (C11y samples).

5 TEST RESULTS AND DISCUSSION

5.1 Stage 1 test results

The irregular mortar compressive strengths (f'_{ji}) and modified Mohs scratch test results (MH) are presented in **Table 4**. The measured irregular mortar compressive strengths were adjusted following Lumantarna (2012) to normalise the compressive strengths of mortar samples having irregular dimensions to the compressive strength of a mortar sample having an *h/t* ratio and a *t/l* ratio of 1.0. These adjusted compressive strengths are referred to as the normalised mortar compressive strengths (f'_j).The average measured irregular mortar compressive strengths and the average normalised mortar compressive strengths varied from 0.75 MPa to 38.58 MPa and from 0.53 MPa to 25.88 MPa respectively. **Table 4** also illustrates that the coefficients of variation (CoV) of the normalised mortar compressive strengths were mostly lower than those of the measured irregular mortar compressive strengths, showing that the variation in the irregular mortar compression test results was reduced as the individual test results were normalised. This decrease in variability shows that the normalisation technique prescribed in (Lumantarna 2012) was adequate for normalising the compressive strength of irregular mortar samples.

The average Mohs hardness number (MH) of each field extracted mortar group is also shown in **Table 4**. It was found that the normalised mortar compressive strength generally

increased with an increase in the Mohs scratch number. The Mohs scratch numbers were generally consistent within each mortar group, except for some mortar groups where slight variability in the scratch numbers was observed. **Figure 5** illustrates the relationship between the normalised mortar compressive strength and the Mohs scratch number. The majority of the samples (315 samples out of 365 samples) were scratched using a fingernail, where 223 samples out of 315 samples could be scratched easily using a fingernail. There were 42 and 8 mortar samples that were scratched using an aluminium pick and a copper coin respectively.

The normalised mortar compressive strength-Mohs scratch number relationship was expressed using the box and whisker plot shown in **Figure 5**, with data calculated according to Peck et al. (2009). The group median was used to express each mortar category (each box and whisker plot) as median is less influenced by data extremes than is the mean, and therefore was considered to be suitable when dealing with a large data population. **Figure 5** shows that the median normalised compressive strengths of mortar samples having scratch numbers of 1.5, 2.0, 2.5 and 3.0 were 1.1 MPa, 3.3 MPa, 7.0 MPa and 22.7 MPa respectively. It is noted that mortar groups C15 and C39 were modern repointing mortars that were likely to be cement based, and therefore these mortar groups had high compressive strengths and scratch numbers of 3.0.

The test data was further analysed to determine the presence of statistical differences between the four mortar categories. The Kruskal-Wallis test revealed that each mortar category originated from samples which had a distinct median, suggesting that the modified Mohs scratch test is an adequate technique to categorise mortar samples according to their compressive strengths. However, each Mohs scratch number represents a wide mortar compressive strength range, and thus this testing technique should be reserved for cases where there is no budget available for destructive testing and should only be used when extraction of samples from heritage URM buildings is not permitted.

5.2 Stage 2 test results

5.2.1 Acid digestion test results

The main aim of the acid digestion test for the laboratory constructed mortar samples was to compare the actual mortar aggregate to binder (A/B) ratio with the mortar aggregate to binder ratio estimated using the acid digestion test. It is noted that whilst the mortar C:L:S ratio and the commonly known aggregate:binder ratio of 3:1 were prescribed as volumetric proportions, the acid digestion test measured the mass proportions of the binder and the aggregate. Therefore, the apparent, non-compacted densities of the cement (ρ_c), hydrated

lime (ρ_l) and river sand (ρ_s) used for mixing these mortar samples were determined by filling containers of a known volume and weighing them. The non-compacted density was measured because masons 100 years ago used proportions of non-compacted cement, lime and sand when constructing vintage URM buildings. The non-compacted densities of the cement (ρ_c), hydrated lime (ρ_l) and river sand (ρ_s) used were found to be 1,065 kg/m^3, 408 kg/m^3 and 1,004 kg/m^3 respectively. Using the relationship prescribed in Equation (1) and Equation (2), the actual mass C:L:S proportion ($Act\ m_{c,l,s}$) for each mortar mix was determined.

For the acid digestion test results, the estimated mass of the sand, $Est\ m_s$, was equated to the mass of the remainder of the acid digestion test, m_a (see Equation (3)). The mass of the digested proportion (mass of binder, m_b) was separated into the estimated masses of cement and lime ($Est\ m_c$ and $Est\ m_l$) as per Equation (4) and Equation (5). The estimated volumetric proportions of cement, lime and sand from the acid digestion test results were calculated using Equation (6), Equation (7) and Equation (8). Lastly, the actual and the estimated volumetric aggregate to binder (A/B) ratios were calculated as per Equation (9). These calculated results are shown in **Table 5** and **Figure 6**. It is noted that the calculated results are presented as a ratio with respect to the material which had the lowest mass or volumetric proportion.

$$\rho = \frac{m}{V} \tag{1}$$

$$Act\ m_{c,l,s} = Act\ V_{c,l,s} \times \rho_{c,l,s} \tag{2}$$

$$Est\ m_s = m_a \tag{3}$$

$$Est\ m_c = m_b \times \frac{Act\ m_c}{Act\ m_c + Act\ m_l} \tag{4}$$

$$Est\ m_l = m_b \times \frac{Act\ m_l}{Act\ m_l + Act\ m_c} \tag{5}$$

$$Est\ V_c = \frac{Est\ m_c}{\rho_c} \tag{6}$$

$$Est\ V_l = \frac{Est\ m_l}{\rho_l} \tag{7}$$

$$Est\ V_s = \frac{Est\ m_s}{\rho_s} \tag{8}$$

$$Vol.\ A/B = \frac{V_s}{(V_c + V_l)} \tag{9}$$

where:

$Act\ m_{c,l,s}$ = Actual mass of cement, lime or sand

$Act\ V_{c,l,s}$ = Actual volume of cement, lime or sand

$Est\ m_{c,l,s}$ = Mass of cement, lime or sand estimated using acid digestion

$Est\ V_{c,l,s}$ = Volume of cement, lime or sand estimated using acid digestion

m_a = Mass of aggregate = the remainder from acid digestion

m_b = Mass of binder = material digested by acid

m = Mass, kg

ρ = Density, kg/m^3

$\rho_{c,l,s}$ = Density of cement, lime or sand

V = Volume, m^3

$Vol.A/B$ = Volumetric aggregate to binder ratio

Table 6 and **Figure 6** show that the estimated aggregate/binder volumetric ratios were mostly close to the actual aggregate/binder volumetric ratios, although there were differences between the estimated and the actual ratios for some mortar mixes. **Figure 6** also shows that in general, the actual aggregate/binder volumetric ratios were approximately 24% greater than the estimated aggregate/binder volumetric ratios (with an R^2 value of 82%). This difference was possibly present due to inconsistency in the mortar mix and the loss of material during the testing process. However, the 24% difference was considered to be reasonable and adequate in order to obtain an indicative measure of the mortar aggregate/binder ratio, and therefore the acid digestion test was performed on field extracted mortar samples that originated from 18 different New Zealand URM buildings.

It was theorised that the lime used for the construction of vintage New Zealand heritage mortars was traditional lime putty instead of pre-bagged hydrated lime. Previous authors (Margalha et al. 1985; ASTM 2008a) have recommended lime putty densities varying from 800 kg/m^3 to 1,400 kg/m^3, which were close to the density of the cement used to construct the laboratory constructed mortars included in this experimental programme (1,065 kg/m^3). Therefore, the densities of cement and lime putty for the field extracted mortars were both assumed to be equal to 1,000 kg/m^3 for ease of estimating the aggregate/binder volumetric proportion. The density of the aggregate (sand) in heritage mortars was assumed to be similar to the density of the sand used to construct the laboratory constructed mortars included in this experimental programme (1,004 kg/m^3).

The acid digestion test results of the field extracted mortars are shown in **Table 6** and **Figure 7**. It is noted that the calculated results are presented as a ratio with respect to the material which had the lowest mass or volumetric proportion. The mass of aggregate (m_a) was equated to the remainder of the acid digestion test, whilst the mass of binder (m_b) was equated to the digested proportion. The mass proportions of the binder and the aggregate were then converted to volumetric proportions as per Equation (10):

$$Est\ V_{a,b} = \frac{m_{a,b}}{Asu\ \rho_{a,b}} \tag{10}$$

where:

$Est\ V_{a,b}$ = Estimated volume of aggregate or binder

$Asu\ \rho_{a,b}$ = Assumed aggregate (1,004 kg/m^3) or binder (1,000 kg/m^3) density

Whilst being consistent with the above mentioned assumptions associated with the aggregate and binder densities, **Table 6** and **Figure 7** show that in general, the tested heritage mortar samples were likely to be constructed following the widely known 3:1 aggregate to binder ratio. Where present, variation in the estimated aggregate/binder volumetric ratio was attributed to the difference between the assumed binder density and the actual binder density, and to inconsistencies in the construction process. Some mortar groups, in particular groups CFK and C6, had high estimated aggregate/binder volumetric ratios (6.1 and 4.7 respectively). These high estimated aggregate/binder volumetric ratios were either due to inaccuracy of the estimated aggregate and binder densities, inconsistencies in the construction process, or because these mortars were not mixed following the widely known 3:1 aggregate to binder ratio. Also, **Table 6** shows that the masses of the aggregate (remainder from the acid digestion test) were significantly higher than the masses of the digested binder, which implied that the aggregates were not digested by the HCL solution. This non-digestive nature suggested that these aggregates were non-calcareous, in agreement with the study of the geological map of New Zealand (see section 3.2.1), where it was theorised that calcareous sand was unlikely to be present in the cities where sample extractions were performed. In alignment with the findings of Biggs and Forsberg (2001), the above observations show that although the acid digestion test is associated with a degree of uncertainty and inaccuracy, this testing technique is an adequate tool to obtain an indicative measure of the aggregate/binder ratio of heritage mortars, given that the aggregate used was non-calcareous and that reasonable assumptions on the material densities were adopted.

5.2.2 Powder X-ray diffraction analysis results

The results of the powder X-ray diffraction analysis are detailed in **Table 7**. As noted previously, the powder X-ray diffraction analysis was performed to obtain an indicative measure of the presence of cement in heritage mortars whilst also considering the average compressive strength of the corresponding mortar group. The presence of each mineral phase was determined using DIFFRAC.EVA XRD software (Bruker AXS 2011), and additional information on the Powder Diffraction File (PDF) numbers of C_3A, C_2S, C_3S and C_4AF was obtained from the work presented by Idris et al. (2007) to assist in the mineral phase determination process. The presence of these minerals was then categorised following Rilem TC 167-COM (Middendorf et al. 2005) into dominantly present, present,

362 traces, possibly present and not detected (see bottom of **Table 7**) according to the relative
363 proportion of the phase peaks.

364 **Table 7** shows that the observed mineralogical compositions of the field extracted mortars
365 were generally in alignment with the findings of Sabbioni et al. (2001), where quartz and
366 calcite were dominantly present or present in most mortar groups analysed. Albite, andesite,
367 anorthite and labradorite, which are included in the plaglioclase feldspar series (Society for
368 Mining Metallurgy and Exploration 2006), were also commonly present. Diopside was
369 dominantly present in sample groups BC, RB and CFK, whilst augite was dominantly present
370 and present as traces in sample groups CFK and BC respectively. As reported by Sabbioni
371 (2001), the presence of diopside and augite suggested that mortar groups BC, RB and CFK
372 were made using pozzolanic aggregates.

373 The absence of C_3A, C_2S, C_3S and C_4AF in most of the field extracted samples indicated
374 that these mortars were likely to have been made without cement. Instead, in alignment with
375 the findings of Moropolou et al. (1995), most of these field extracted samples were likely to
376 be lime mortars as they were mainly composed of quartz and calcite. Traces of C_3A were
377 present in mortar groups BC and C6, while more abundant proportions of C_3A were present
378 in mortar groups RB and CFK. Also, traces of C_4AF were present in sample groups RB and
379 CFK. Considering the literature studies (Moriconi et al. 1994; Sabbioni et al. 2001; Marques
380 et al. 2006; Puertas et al. 2006), it was theorised that different proportions of cement were
381 present in mortar groups BC, C6, RB and CFK. This supposition is in alignment with the
382 average normalised compressive strength of these four mortar groups (f_j' ranged between
383 1.56 MPa to 6.65 MPa), which were within the upper bound of the average normalised
384 compressive strengths of all mortar groups considered (refer to **Table 7**).

385 The above observations suggested that the powder X-ray diffraction analysis is an
386 appropriate tool to obtain an indicative measure of the mineralogical composition of heritage
387 mortars. However, powder X-ray diffraction analysis is a semi-quantitative technique that is
388 associated with a degree of uncertainty and inaccuracy, and therefore it is recommended
389 that this technique be used whilst also considering the mortar compression test results. For
390 example, both the XRD analysis and compression test results shall be considered when
391 predicting the presence of cement in mortar.

392 ## 6 SUMMARY AND CONCLUSIONS

393 An experimental programme was undertaken to determine the compressive strength of
394 mortar samples extracted from existing New Zealand URM buildings and to identify a

suitable non-destructive assessment technique to predict the mortar compressive strength in-situ. The following conclusions were drawn based on the experimental results:

The Mohs hardness test and the irregular mortar compression test were performed on 365 irregular mortar samples that originated from 60 existing New Zealand URM buildings. It was found that an increase in the normalised mortar compressive strength generally led to an increase in the Mohs scratch number. The Kruskal-Wallis test revealed that each mortar category originated from samples which had a distinct median, suggesting that the modified Mohs scratch test is an adequate technique to categorise mortar samples according to their compressive strengths, although each Mohs scratch number represents a wide compressive strength range. It was also suggested that this testing technique be reserved for cases where sample extraction is not permitted.

The acid digestion test was performed to estimate the sample aggregate/binder ratio. A pilot study on 11 laboratory constructed mortar samples showed that the actual aggregate/binder volumetric ratios were approximately 24% greater than the estimated aggregate/binder volumetric ratios due to inconsistency in the mortar mix and the loss of material during the testing process. However, the 24% difference was considered to be reasonable and adequate to obtain an indicative measure of the mortar aggregate/binder ratio, and therefore the acid digestion test was performed on field extracted mortar samples that originated from 18 different New Zealand URM buildings.

The acid digestion test outcome for the field extracted mortar samples showed that, although the acid digestion test is associated with a degree of uncertainty and inaccuracy, this testing technique is an adequate tool to obtain an indicative measure of the aggregate/binder ratio of heritage mortars, given that the aggregate used was non-calcareous and that reasonable assumptions on the material densities were adopted.

22 field extracted mortar samples were subjected to the powder X-ray diffraction technique in an attempt to predict the presence of cement in the mortar mix. The experimental outcome showed that the presence of cement in the mortar mix could be predicted if both the presence of C_3A, C_2S, C_3S and C_4AF in the mortar and the average normalised mortar compressive strength were considered. The powder X-ray diffraction analysis technique is generally an appropriate tool to obtain an indicative measure of the mineralogical composition of heritage mortars.

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(a) Preparation of irregular mortar samples

(b) Modified Mohs scratch test procedure

Figure 1: Preparation of mortar samples

(a) Preparation of extracted mortar samples

(b) Field extracted mortar compression test

Figure 2: Irregular mortar samples prepared for compression testing

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562 **Figure 3:** Preparation of fine mortar powder using a grinding mill
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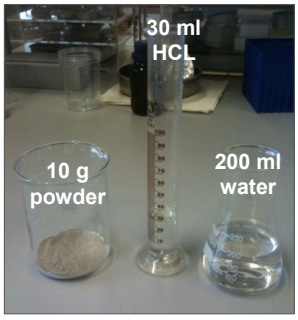

(a) Mortar powder, HCL and water

(b) Placement of liquid + aggregate in centrifuge tubes

(c) Placement of centrifuge tubes in the centrifuge machine

(d) Separated aggregate after drying

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565 **Figure 4:** Acid digestion test procedure
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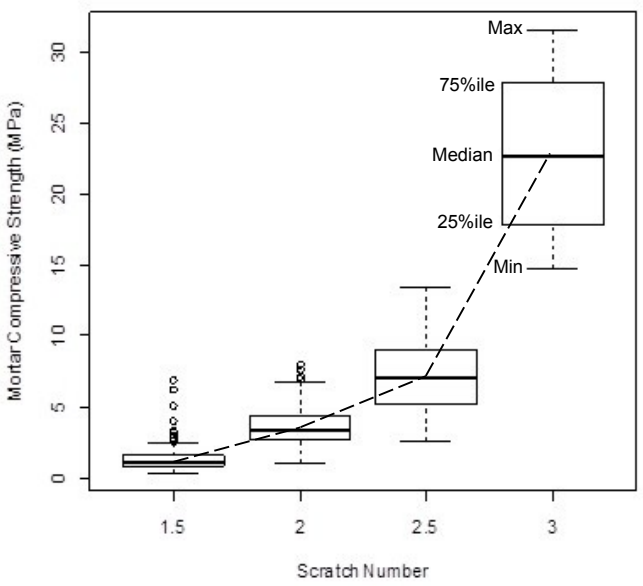


Scratch Number 1.5 (223)
Minimum = 0.4 MPa
Median = 1.1 MPa
Maximum = 6.9 MPa

Scratch Number 2.0 (92)
Minimum = 1.0 MPa
Median = 3.3 MPa
Maximum = 8.0 MPa

Scratch Number 2.5 (42)
Minimum = 2.6 MPa
Median = 7.0 MPa
Maximum = 13.4 MPa

Scratch Number 3.0 (8)
Minimum = 14.8 MPa
Median = 22.7 MPa
Maximum = 31.6 MPa

Figure 5: Relationship between normalised compressive strength and Mohs scratch number

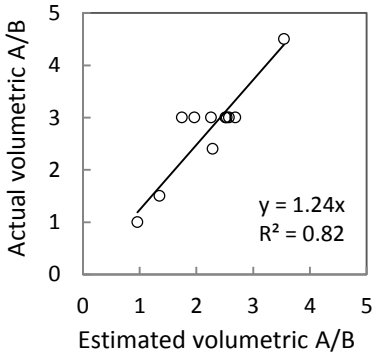


Figure 6: Comparison between actual volumetric A/B ratio and estimated volumetric A/B ratio

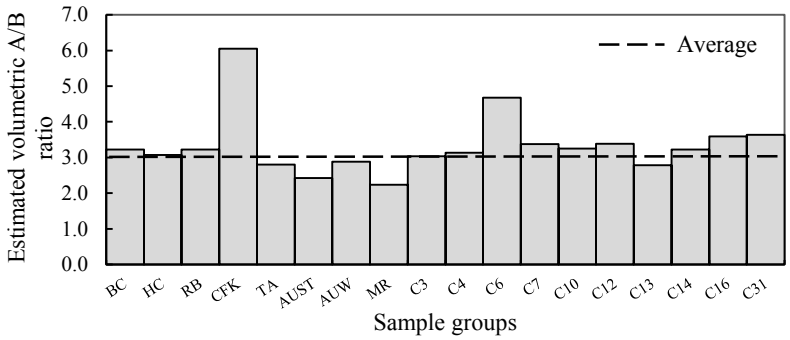
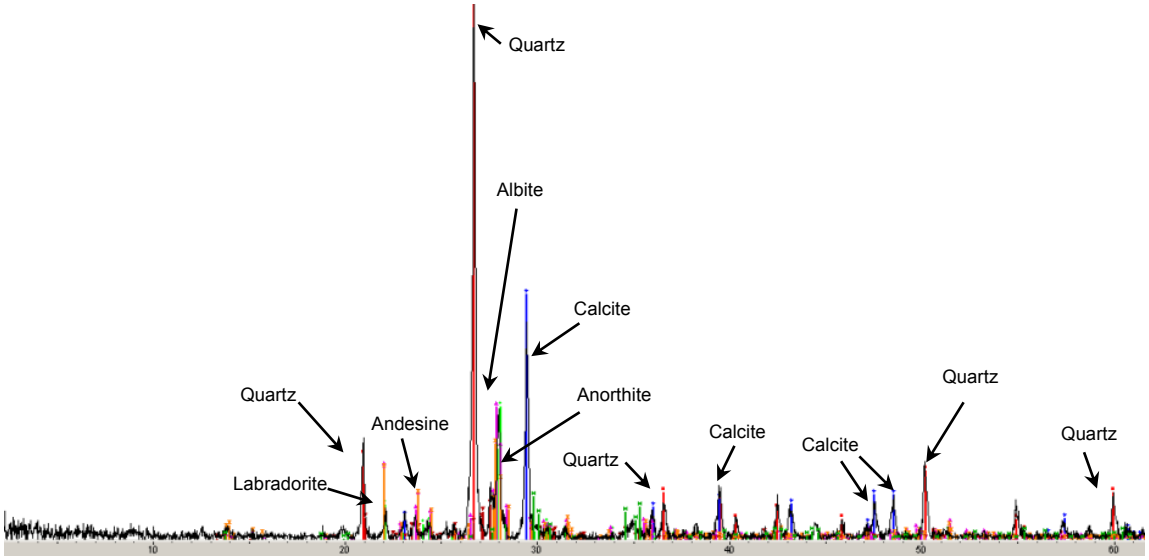
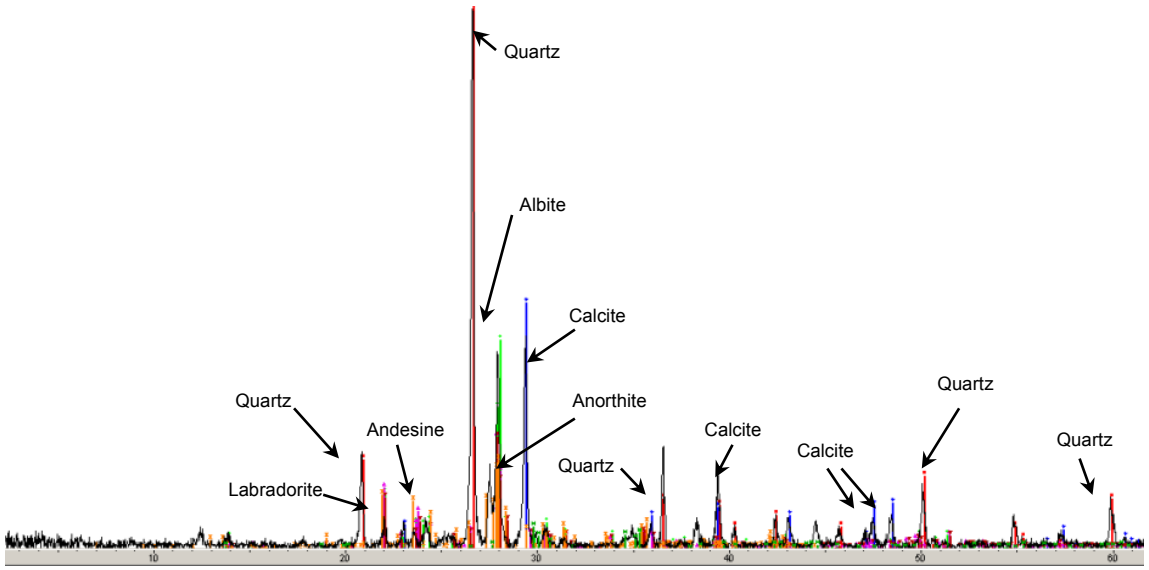


Figure 7: Estimated volumetric A/B ratio of field extracted samples



(a) XRD pattern of mortar group C1



(b) XRD pattern of mortar group C13

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Figure 8: Examples of XRD patterns for mortar samples

578 **Table 1:** Comparison between the numbers of mortar samples scratched using the Mohs minerals
579 and the equivalent materials
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Mohs Number	Mineral	No. of mortar samples scratched	Equivalent Materials	No. of mortar samples scratched
1	Talc	-	Baby powder	-
1.5	Gypsum	315	Fingernail (easy)	223
2			Fingernail	92
2.5	Calcite	50	Aluminium Pick	42
3			Copper coin	8

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584 **Table 2:** Locations of sample extraction, showing the type of rocks present
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City	Region	Type of rock
Auckland	Auckland	sedimentary and volcanic
Te Awamutu	Waikato	sedimentary, volcanic and volcaniclastic
Gisborne	Hawke's Bay	sedimentary
Wellington	Wellington	greywacke
Christchurch	Canterbury	sedimentary and volcanic

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588 **Table 3:** Laboratory constructed mortar mixes used for the acid digestion test
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Grade	Cement:Lime:Sand volumetric proportion	Aggregate:Binder ratio	Equivalent qualification
a	0:1:3	3:1	NZSEE 'firm'
b	1:3:12	3:1	ASTM 'K'
c	1:2:9	3:1	ASTM 'O'
d	1:1:9	9:2	-
e	1:1:6	3:1	ASTM 'N'
f	1:1:3	3:2	-
g	2:1:9	3:1	ASTM 'S'
h	4:1:12	12:5	NZSEE 'stiff'
i	4:1:15	3:1	ASTM 'M'
j	1:0:3	3:1	-
k	1:0:1	1:1	-

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Table 4: Irregular and normalised mortar compressive strengths

Mortar Group	No. of samples	Avg f'_{ji} (MPa)	*CoV* f'_{ji}	Avg f'_j (MPa)	*CoV* f'_j	MH	*CoV* MH
AH	7	1.47	0.17	1.23	0.17	1.5	-
BC	6	6.84	0.12	4.54	0.13	2.17	0.12
HC	16	9.32	0.15	8.58	0.14	2.47	0.05
RB	11	8.32	0.24	6.65	0.19	2.41	0.08
TA	8	8.28	0.19	5.92	0.17	2.13	0.11
CFK	14	6.65	0.24	4.14	0.19	2.07	0.09
D	16	3.04	0.20	2.62	0.19	2.0	-
AL	8	6.56	0.19	5.53	0.18	1.94	0.22
AUST	16	1.66	0.26	1.21	0.22	1.5	-
AUW	8	1.08	0.24	0.74	0.19	1.5	-
MR	6	1.82	0.17	1.62	0.12	1.5	-
C1	3	3.26	0.15	2.62	0.17	1.63	0.15
C2	4	1.50	0.31	1.01	0.15	1.5	-
C3	6	0.90	0.24	0.66	0.23	1.5	-
C4	5	2.07	0.27	1.08	0.22	1.5	-
C5	4	0.75	0.36	0.53	0.26	1.5	-
C6	6	2.21	0.32	1.56	0.29	1.5	-
C7	5	1.98	0.23	1.07	0.18	1.5	-
C8	5	2.77	0.50	1.45	0.30	1.5	-
C9	5	1.59	0.27	1.18	0.16	1.7	0.16
C10	6	1.56	0.34	1.02	0.24	1.5	-
C11	3	1.45	0.13	1.01	0.19	1.5	-
C11y	4	3.75	0.30	2.80	0.11	2.0	-
C12	4	0.99	0.57	0.76	0.25	1.63	0.15
C13	4	1.52	0.25	1.21	0.10	1.5	-
C14	4	5.22	0.26	3.39	0.15	2.0	-
C15	5	38.58	0.23	25.28	0.22	3.0	-
C16	3	2.40	0.30	1.39	0.31	1.5	-
C17	4	3.93	0.31	2.45	0.18	2.0	-
C18	4	3.78	0.15	2.30	0.11	1.63	0.15
C19	3	9.94	0.11	6.12	0.32	2.0	-
C20	4	3.25	0.13	2.64	0.09	1.5	-
C21	3	1.49	0.16	1.05	0.12	1.5	-
C22	4	1.84	0.18	1.21	0.18	1.5	-
C23	4	5.54	0.32	3.82	0.09	1.88	0.13
C24	5	1.90	0.21	1.11	0.19	1.5	-
C25	4	9.03	0.27	7.01	0.23	2.13	0.12
C26	5	1.18	0.22	0.90	0.18	1.5	-
C27	5	3.97	0.25	2.59	0.20	1.5	-
C28	4	1.06	0.18	0.86	0.12	1.5	-
C29	5	1.17	0.31	0.80	0.18	1.5	-
C30	6	4.19	0.10	3.65	0.12	2.0	-
C31	6	0.99	0.28	0.94	0.19	1.5	-
C32	6	3.90	0.29	2.38	0.11	1.5	-
C33	7	1.36	0.25	0.94	0.19	1.5	-
C34	4	4.03	0.13	2.92	0.14	1.5	-
C35	6	2.74	0.19	1.55	0.14	1.5	-
C36	4	7.17	0.30	3.57	0.17	2.0	-
C37	4	3.64	0.24	2.52	0.06	2.0	-
C38	4	1.38	0.43	0.96	0.27	1.5	-
C39	3	27.85	0.18	18.88	0.29	3.0	-
C40	6	2.98	0.24	2.47	0.11	2.08	0.10
C41	8	2.38	0.24	1.69	0.14	1.5	-
C42	6	1.34	0.21	0.94	0.08	1.5	-
C43	7	1.83	0.34	1.50	0.30	1.5	-
C44	5	0.95	0.40	0.55	0.21	1.5	-

C45	6	1.64	0.14	1.19	0.05	1.5	-
C46	4	1.17	0.33	0.74	0.16	1.5	-
C47	3	1.57	0.21	0.84	0.04	1.5	-
C48	4	15.76	0.25	11.00	0.20	2.5	-
C49	7	6.34	0.23	3.99	0.21	2.29	0.12
C50	6	1.30	0.30	1.12	0.25	1.5	-
C51	7	1.45	0.34	1.06	0.22	1.5	-

Table 5: Acid digestion test results for laboratory constructed samples

Grade	Actual proportions						Estimated proportions from acid digestion						Act *Vol. A/B*	Est *Vol. A/B*
	$Act\ V_{c,l,s}$			$Act\ m_{c,l,s}$			$Est\ m_{c,l,s}$			$Est\ V_{c,l,s}$				
	C	L	S	C	L	S	C	L	S	C	L	S		
a	0	1	3	0	1.0	7.4	0.0	1.0	4.8	0	1	2.0	3.0	2.0
b	1	3	12	1.0	1.1	11.3	1.0	1.2	8.5	1	3	9.0	3.0	2.3
c	1	2	9	1.3	1.0	11.1	1.3	1.0	6.4	1	2	5.2	3.0	1.7
d	1	1	9	2.6	1.0	22.2	2.6	1.0	17.5	1	1	7.1	4.5	3.6
e	1	1	6	2.6	1.0	14.8	2.6	1.0	12.5	1	1	5.1	3.0	2.6
f	1	1	3	2.6	1.0	7.4	2.6	1.0	6.6	1	1	2.7	1.5	1.4
g	2	1	9	5.2	1.0	22.2	5.2	1.0	18.5	2	1	7.5	3.0	2.5
h	4	1	15	10.4	1.0	36.9	10.4	1.0	31.7	4	1	12.9	3.0	2.6
i	4	1	12	10.4	1.0	29.5	10.4	1.0	28.1	4	1	11.4	2.4	2.3
j	1	0	3	1.0	0	2.8	1.0	0	2.5	1	0	2.7	3.0	2.7
k	1	0	1	1.0	0	0.9	1.0	0	0.9	1	0	1.0	1.0	1.0

Table 6: Acid digestion test results for field extracted samples

Mortar Group	Mass		Proportion
	Aggregate, g	Binder, g	m_a/m_b and $Est\ V_a\ /Est\ V_b$
BC	7.74	2.39	3.2
HC	7.54	2.44	3.1
RB	8.69	2.69	3.2
CFK	8.04	1.32	6.1
TA	7.74	2.73	2.8
AUST	7.26	2.98	2.4
AUW	7.89	2.73	2.9
MR	7.60	3.38	2.2
C3	8.15	2.68	3.0
C4	8.37	2.66	3.1
C6	8.99	1.91	4.7
C7	7.76	2.29	3.4
C10	8.14	2.49	3.3
C12	7.81	2.30	3.4
C13	7.72	2.76	2.8
C14	7.97	2.46	3.2
C16	8.36	2.32	3.6
C31	8.77	2.40	3.7

610 **Table 7:** Key constituents determined from XRD analysis
611

Group	f'_j	Q	Ca	Al	Ad	An	La	C1	C2	C3	C4	Di	Au
AH	1.23	+++	+++	+	+	+	+	-	-	-	-	-	-
BC	4.54	+++	-	+	+	+	+	+	?	-	-	+++	+
RB	6.65	-	-	+	-	+	-	++	?	?	+	+++	-
TA	5.92	+++	+	-	-	+	+	-	?	-	-	-	-
CFK	4.14	+++	+++	++	-	++	-	++	-	+	+	+++	+++
AL	5.53	+++	+++	++	?	?	+	?	-	-	-	-	-
AUST	1.21	+++	++	+	+	+	+	-	-	-	?	-	-
MR	1.62	+++	++	+	?	+	-	-	-	-	-	-	-
C1	2.62	+++	++	++	+	+	+	-	-	-	-	-	-
C2	1.01	+++	+++	+	+	-	+	-	-	-	-	-	-
C3	0.66	+++	++	+++	+	+	+	-	-	-	-	-	-
C4	1.08	+++	+	+	-	?	-	-	-	-	-	-	-
C5	0.53	+++	+	+	+	?	+	-	-	-	-	-	-
C6	1.56	+++	++	+++	-	+++	-	+	?	-	-	-	-
C7	1.07	+++	++	++	++	+	+	-	-	-	-	-	-
C8	1.45	+++	+	+	+	-	+	-	-	-	-	-	-
C9	1.18	+++	+	?	-	-	-	-	-	-	-	-	-
C10	1.02	+++	++	+	+	+	-	-	-	-	-	-	-
C11	1.01	+++	+++	+	+	+	+	-	-	-	-	-	-
C13	1.21	+++	++	+	+	-	-	-	-	-	?	-	-
C14	3.39	+++	+++	+++	-	-	-	-	-	-	-	-	-
C30	3.65	+++	++	++	+	+	-	-	-	-	-	-	-

612 [a] Q = quartz; Ca = calcite; Al = albite; Ad = andesite; An = anorthite; La = labradorite;
613 C1 = C_3A; C2 = C_2S; C3 = C_3S; C4 = C_4AF; Di = diopside; Au = augite.
614 [b] +++ = dominantly present; ++ = present; + = traces; ? = possibly present; - = not detected.