Title: Compressive, flexural bond and shear bond strengths of in-situ New Zealand unreinforced clay brick masonry constructed using lime mortar between the 1880s and 1940s

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ABSTRACT

The importance of sufficient masonry mortar joint bond strength when a structure is subjected to in-plane and out-of-plane loads has been emphasised by several authors. However, masonry unit/mortar bond strength is difficult to predict and performing mechanical tests on existing masonry buildings to determine masonry flexural bond and shear bond strengths is generally not practical, such that predictive expressions relating the masonry flexural bond and shear bond strengths to other masonry properties are desirable. Although relationships between brick/mortar bond and compressive strength have been investigated previously by researchers located in many different parts of the world, most of these studies were laboratory based and did not include the testing of existing masonry buildings within their scope. The present study aimed to characterise the material properties of New Zealand unreinforced clay brick masonry (URM) buildings that were generally built between 1880 and 1930, with in-situ testing and sample extraction performed on 6 heritage buildings. Masonry compression, bond wrench and shear bond tests were undertaken. The experimental results indicate that the masonry flexural bond strength and the bed joint cohesion can be satisfactorily related to the mortar compressive strength.

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INTRODUCTION

The importance of sufficient masonry mortar joint bond strength when an unreinforced masonry bearing wall building is subjected to in-plane and out-of-plane loads has been emphasised by several authors (Russell 2010; Venkatarama Reddy and Gupta 2006), and therefore methods for characterising masonry flexural bond and shear bond strengths are desirable. As described by Hilsdorf (1969), McNary and Abrams (1985) and Khoo and Hendry (1975), the failure of masonry in compression is governed by deformation of the brick units and mortar when subjected to a multi-axial stress state, whilst assuming that the brick/mortar bond remains intact until the ultimate compression load is reached (Venkatarama Reddy and Uday Vyas 2008). However, it was revealed that bed joint bond failure occurred during compression testing when the brick/mortar bond was poor (Sarangapani et al. 2005). Sarangapani et al. (2005) also found that the brick/mortar bond characteristics are not directly related to the deformation characteristics of the brick unit and mortar, but instead are influenced by factors such as the roughness of the brick surface and the mortar water retentivity. Roughness is an indication of the open pore structure of the brick surface.

Predictive expressions relating the masonry flexural bond and shear bond strengths to other masonry properties were desired as performing tests on existing masonry buildings to determine these properties is generally not practical. The mortar and masonry compressive strengths were the first candidates to be related to the masonry flexural bond and shear bond strengths as they can be easily obtained through mechanical testing of extracted samples. The relationships between brick/mortar bond and compressive strengths have often been investigated (Sarangapani et al. 2005; Venkatarama Reddy and Gupta 2006; Venkatarama Reddy et al. 2007; Venkatarama Reddy and Uday Vyas 2008; Venu Madhava Rao et al. 1996). However, most of these studies were laboratory based and did not include the testing of existing masonry buildings within their scope. The present study aimed to characterise the material properties of New Zealand URM buildings that were generally built between 1880 and 1930 (Russell and Ingham 2010), and therefore the relationships between flexural bond strength, shear bond strength, masonry compressive strength and mortar compressive strength for masonry samples extracted from actual URM buildings were explored. These relationships were intended to enable structural engineers to undertake effective detailed seismic assessment of regular URM buildings without requiring comprehensive and time consuming material testing.

PAST STUDIES ON THE MASONRY BOND STRENGTH

Factors affecting the development of brick/mortar bond

Several studies have been previously conducted to investigate masonry bond properties. The brick/mortar bond development is effectively a mechanical process that is influenced by binder hydration occurring at the brick surface and in the brick unit pores (Groot 1993; Lawrence and Cao 1987; Sugo et al. 2001). The brick unit initial rate of absorption (IRA), surface roughness and mortar water retentivity are the governing factors for this hydration (Pavia and Hanley 2010; The brick Industry Association 2003).

Scrivener et al. (1992) performed bond wrench tests at construction sites in Australia and found wide variation in masonry flexural bond strengths, especially when wall construction was performed subject to uncontrolled environmental conditions. Grenley (1969) investigated various brick/mortar combinations and found that the masonry flexural bond, tensile bond and compressive strengths generally increased with increasing brick unit and mortar compressive strengths. The masonry bond-compressive strength relationships that were obtained for the various combinations showed strong correlations, although the influence that mortar compressive strength had on the masonry bond strength could not be neglected.

Samarasinghe and Lawrence (1992) performed shear tests on masonry triplets replicating new masonry construction and observed that masonry prisms that were constructed using pre-wetted brick units had higher bed joint shear strengths than those constructed using dry or completely saturated brick units. These researchers also observed that the bed joint shear strength increased with increasing mortar compressive strength.

Sarangapani et al. (2005) performed bond wrench tests and shear bond tests on prisms that were constructed using three different brick types and four different mortar grades. Four different bond enhancing techniques were also implemented, thus resulting in an increase in the masonry bond and compressive strengths without altering the mortar composition. It was found that the prism compressive strength was generally more sensitive to variations in the brick/mortar bond strength than to variations in the mortar compressive strength.

Venu Madhava Rao et al. (1996) investigated masonry bond-compressive strength relationships using clay bricks, stabilised mud blocks and stabilised soil-sand blocks, whilst the mortars used were a variety of cement:sand, cement:soil:sand and cement:lime:sand mortars. Their main observations were:

- For all types of masonry units, the masonry flexural bond strength increased with increasing mortar compressive strength when cement mortar was used.

- The addition of soil or lime into the mortar mix improved the masonry flexural bond strength.
- The masonry flexural bond strength was high when masonry units with deep and wide frogs were used in comparison to units without frogs.

Venkatarama Reddy and Gupta (2006) investigated cement-soil block/cement:soil:sand mortar masonry and found that the masonry tensile bond strength increased with increasing block unit compressive strength. Similarly, Venkatarama Reddy and Uday Vyas (2008) investigated three cement-soil block/mortar combinations incorporating five different bond enhancing techniques. They found that when soft block-stiff mortar combinations were used, the masonry flexural bond strength increased with increasing masonry compressive strength.

Masonry bond failure types

The brick/mortar bond failure of masonry prisms when subjected to bond wrench and shear bond tests can be classified as follows (Pavia and Hanley 2010; Sarangapani et al. 2005; Venkatarama Reddy and Gupta 2006):

- Type A: Failure at one brick/mortar interface;
- Type B: Failure at both brick/mortar interfaces;
- Type C: Failure within the mortar joint;
- Type D: Failure within the brick unit;
- Type E: Combination of failure within the brick unit and mortar joint.

Pavia and Hanley (2010) tested masonry prisms that were constructed using natural hydraulic lime mortars. They subsequently found that 65% of the samples experienced failure type A, whilst the remaining prisms exhibited failure type B. The average mortar compressive strengths were not reported, and therefore it was not possible to assess if the brick/mortar bond failure modes observed were governed by the strength of the mortar or by other factors.

Venkatarama Reddy and Gupta (2006) observed four different types of failure (types A, C, D and E) for their experiments. Failure type E was the most common type observed, whilst failure types C and D generally occurred when weak mortar and weak block units respectively were used. Failure type A was exhibited by prisms that were constructed using moderately strong cement-soil blocks.

Sarangapani et al. (2005) did not observe failure type C when testing masonry prisms, whereas failure type D and a combination of failure types A and D were frequently observed for prisms constructed using weak brick units and strong mortar. These researchers also reported that failure type A mostly occurred when the brick/mortar interface bond strength was lower than the mortar joint flexural strength, and therefore this failure type was exhibited by almost all prisms that were constructed without bond enhancement.

The findings from the studies reported above indicate that (1) the masonry flexural bond and shear bond strengths are possibly related to the masonry or mortar compressive strength; and (2) the brick/mortar bond failure type depends on the brick/mortar interface bond strength as well as on the relative comparison between the brick and mortar compressive strengths. However, previous authors have not attempted to link the brick/mortar bond failure type to the bond-compressive strength relationship. It was also established that past investigations mainly focused on newly constructed samples and that the properties of assemblages extracted from existing heritage URM buildings have not been thoroughly studied.

In the present study, an attempt was made to investigate the material properties of existing URM buildings located in New Zealand. The aim was to determine the relationships between flexural bond strength, shear bond strength and masonry compressive strength, as well as the magnitude of mortar compressive strengths of masonry samples extracted from existing buildings. The brick/mortar bond failure types were also considered in the investigation.

The past studies reported above were mainly based on newly made laboratory samples and revealed that bond failure in masonry commonly occurs at the brick/mortar interface.

However, previous authors (Sarangapani et al. 2005; Venkatarama Reddy and Gupta 2006) have not investigated prisms that were constructed using lime-rich mortar. Also, although Pavia and Hanley (2010) studied prisms that were constructed using natural hydraulic lime mortars, the brick units used in the experimental programme were perforated, hollow-cored brick units, which are different to heritage New Zealand solid clay bricks. These differences between the past and present studies have to be noted when making comparisons, especially considering that the current experimental programme mainly focused on samples obtained from New Zealand heritage URM buildings constructed during the 1880s to 1940s using lime-rich mortars.

EXPERIMENTAL PROGRAMME

In-situ material testing and sample extraction were performed for 6 New Zealand clay brick URM buildings. When the project permitted, bond wrench tests and in-situ shear tests were performed on-site to determine the masonry flexural bond and shear bond strengths. Also, extracted masonry assemblages were cut in-situ using a masonry chainsaw or retrieved as irregular masonry segments. These extracted samples were further trimmed in the laboratory to form single leaf two and three brick high prisms to be used in laboratory compression, bond wrench and triplet shear tests.

Prism compression test

Single leaf three brick high extracted prisms were capped using gypsum plaster to ensure a uniform stress distribution, and were tested in compression using a 2000 kN instron machine following the prism compression test protocol of ASTM C 1314 - 03b (2003a) (see Figure 1).

Bond wrench test

The bond wrench test AS 3700-2001 (Standards Australia 2001) was adopted for both in-situ and laboratory applications due to its greater portability in comparison to the ASTM C 1072 - 00a (2000) test setup, and therefore the bond wrench test was more suitable for in-situ testing. The bond wrench arm (see Figure 2) was constructed as stipulated in AS 3700-2001 (Standards Australia 2001), with a hook connector installed at the end of the bond wrench arm. An empty container was attached to the hook and then gradually filled using sand to apply bending stresses to the mortar joint until flexural bond failure occurred. The weight of the bucket and sand was measured to the nearest 0.01 gram and used to calculate the flexural bond failure stress.

Shear bond tests

The in-situ shear test ASTM C 1531 - 03 (2003b) and the triplet shear test Rilem TC 127-MS.B.4 (1996) were adopted for on-site and laboratory shear bond testing respectively. The in-situ shear tests were performed without flat jacks, and the triplet shear tests were performed whilst subjected to different levels of axial pre-compression load.

Figure 3 illustrates the in-situ shear test setup. The hydraulic jack was loaded using a pressure controlled hydraulic pump and a displacement gauge was attached on the wall face adjacent to the vertical cut joint, to identify when bed-joint sliding failure occurred. It was also noted that the contribution of collar joints was not considered in the bed joint shear strength calculation as the collar joints were mostly poorly laid, and therefore their contribution to the bed joint shear strength was minimal.

The triplet shear test setup is shown in Figure 4. Prisms were placed between two steel plates that were interconnected using four steel rods. The axial pre-compression load was applied by tightening the nuts at the ends of the steel rods and was recorded using a load cell. The sample was prepared such that the middle course of the prisms consisted of a full brick unit.

The triplet shear tests were performed whilst being subjected to axial pre-compression stresses of 0.2 MPa, 0.4 MPa and 0.6 MPa. The shear strength of the mortar joints can be represented by the Mohr-Coulomb friction law as per Equation (1) (ASTM 2003b; Lourenço et al. 2004; Rilem 1996)

$$\tau = c + \mu N \quad (1)$$

where τ = shear stress at a given axial compression; c = shear stress at zero axial compression (cohesion); μ = coefficient of friction; and N = axial compression stress. Therefore, the mortar bed joint cohesion could be derived because the triplet shear tests were performed under different levels of axial pre-compression loads.

SOURCE AND PROPERTIES OF EXTRACTED SAMPLES

The source of the field extracted samples is described in

Table 1. These buildings (referred to as field sites) were constructed between 1881 and the 1940s, which coincides with the time period during which URM construction was popular in New Zealand. Although variability in the constituent material properties amongst URM

buildings is expected, these field sites are deemed to be representative of the majority of New Zealand URM buildings. Two of the field sites are shown in Figure 5.

Individual brick units and irregular mortar samples were sourced from each field site. The brick unit compressive strength was determined using the half brick compression test ASTM C 67 - 03a (2003c), whilst the irregular field extracted mortar samples were carefully cut to form rectangular test pieces, capped using gypsum plaster and tested in compression as prescribed in Lumantarna (2012). A normalisation technique that accounts for the mortar sample footprint dimensions and height to thickness ratio was implemented, as these factors clearly influence the measured mortar compressive strength (Lumantarna 2012). Therefore, the compressive strength of the irregular mortar samples could be accurately interpreted. X-ray diffraction analysis and acid digestion test results reported in Lumantarna (2012) suggest that most New Zealand vintage mortars were likely to be lime based.

The average brick unit (f'_b) and mortar (f'_j) compressive strengths of the different field sites are shown in

Table 2, where n_b and n_j show the number of brick units and mortar samples tested respectively. The tests performed for each field sample group were also included, and it is noted that group D prisms were not subjected to triplet shear tests due to their limited availability. The average compressive strength of the brick units was found to vary between 8.5 MPa and 27.3 MPa, whilst the average mortar compressive strength ranged from 1.23 MPa to 8.58 MPa. The CoV values of the brick unit and mortar compressive strengths were similar.

MASONRY ASSEMBLAGE TEST RESULTS AND DISCUSSION

Prism compression test results

The average compressive strength of the masonry prisms (f'_m) extracted from each field site is shown in

Table 3, where n shows the number of prisms tested in compression. A minimum of four prisms were tested in compression for each brick/mortar combination. The average masonry compressive strengths were found to vary between 3.3 MPa and 14.7 MPa, and their CoV values were similar to those of the brick unit and mortar compressive strengths. As the field extracted samples were comprised of brick units that were stronger than the mortar, the prism compression failures were mostly initiated by splitting failure of the brick units, followed by crushing of the mortar joints as the loading continued.

Bond wrench test results

The average flexural bond strengths (f'_{fb}) and bond failure types of the field samples are shown in

Table 3. A minimum of three samples were tested for each brick/mortar combination, with most prisms exhibiting a flexural bond failure within the mortar joint (failure type C). It was thought that these bond failures within the mortar joints occurred because the heritage buildings investigated in this experimental programme were constructed using lime-rich mortars, and therefore the mortar did not have sufficient strength to resist the applied tensile force. Also, it is noted that the buildings included in the experimental programme were New Zealand URM buildings which were built during a specific time period (1880s-1940s), and hence the observations from this study may not be applicable for newer URM construction, where cement-based mortars had been used. Furthermore, it was found that samples which exhibited brick/mortar interface bond failure (failure type A) had lower flexural bond strengths than those which exhibited failure type C. It was thought that the samples that exhibited brick/mortar interface bond failure were disturbed during their preparation, resulting in low flexural bond strengths being recorded and therefore those results were disregarded from the analysis. Figure 6 and Figure 7 illustrate the observed bond failure types. The average mortar compressive strength (f'_j) for each field site is also included in

Table 3 to enable the relationship between f'_{fb} and f'_j to be investigated.

The average flexural bond strengths of the field samples ranged from 0.031 MPa to 0.345 MPa. The variability in the bond wrench test results (CoV between 0.11 and 0.33) was thought to be reasonable considering the irregular nature of URM construction.

Table 3 shows that the average masonry flexural bond strength increased with increasing average mortar compressive strength. Also, it is noted that most of the field samples exhibited bond failures within the mortar joints, which is a failure mode that previously has rarely been reported. Cizer et al. (2008) and Moropoulou et al. (2005) reported that both the compressive and flexural strengths of mortar increased over time, which suggests that there is a time-dependent relationship between these properties. Therefore, the masonry flexural bond strength was related to the mortar compressive strength for those results where flexural bond failure occured within the mortar. Figure 8 illustrates the average flexural bond strength-average mortar compressive strength relationship and the average flexural bond strength-average masonry compressive strength relationship, revealing that masonry flexural bond strength is better characterised using the mortar compressive strength than using the masonry compressive strength. Figure 8 also shows that the masonry flexural bond strength, f'_{fb}, can be satisfactorily equated to 0.031 f'_j (coefficient of determination, R^2 = 82%). The negative R^2 value of -0.079 shows that the relationship between flexural bond strength and masonry compressive strength is poor. It is noted that although there is an apparent outlier in Figure 8 (see circled data point), this data point originated from a legitimate dataset, where the test results were reasonably consistent for all samples used to calculate this data point (refer to

Table 3). Therefore, it was decided that this circled data point should not be ignored. Also, all samples considered in Figure 8 experienced flexural bond failures within their mortar joints, and therefore relating the flexural bond strength to the mortar compressive strength was considered to be more suitable than relating the flexural bond strength to the masonry compressive strength.

Shear bond test results

Bed joint shear strength

The mortar bed joint shear strength (τ) of the different prism groups at each level of axial pre-compression stress (N) is shown in

Table 4, with a minimum of two samples tested at each level of axial pre-compression stress. Sample groups HC and RB were tested at axial pre-compression stress levels of approximately 0.2 MPa, 0.4 MPa and 0.6 MPa. In-situ shear tests were performed for the other field sample groups (sample groups AH, CFK and TA), with the in-situ axial pre-compression loads estimated based upon the amount of overburden located above the test locations. These estimated overburden loads were considered as the first axial pre-compression stress level, which for sample groups AH, CFK and TA were determined to correspond to 0.02 MPa, 0.04 MPa and 0.04 MPa respectively. Three brick high prisms were also extracted for laboratory triplet shear tests, and therefore the bed joint shear strength at two additional levels of axial pre-compression stress was obtained. It was decided that for sample groups AH, CFK and TA, the triplet shear tests be performed at axial pre-compression stresses of 0.2 MPa and 0.4 MPa. A large number of TA prisms were available, and therefore these prisms were also tested at a 0.6 MPa axial pre-compression stress.

The observed bed joint failure types were consistent with those observed during the bond wrench tests, where almost all of the field samples experienced shear bond failures within the mortar joints (failure type C) as the buildings investigated in this experimental programme were constructed using lime-rich mortars. The samples that experienced failure type A (interface bond failure) had lower bed joint shear strengths than those that experienced failure type C as they were likely to be disturbed during the sample preparation process, and hence these samples were disregarded from the analysis.

Table 4 shows that the bed-joint shear strength (τ) increased with increasing axial pre-compression stress (N), and it was noted that there was wide variation in the bed joint shear strength of prism groups HC and RB when N = 0.6 MPa. In addition, the bed joint shear strength at each level of axial pre-compression stress generally increased with increasing average mortar compressive strength (f'_j), which was expected as most field samples experienced shear failures within the mortar joints, and therefore their bed joint shear strengths were influenced by the mortar properties instead of by the brick/mortar interface bond characteristics.

Bed joint cohesion

Figure 9 illustrates the bed joint shear strength (τ)-axial compression stress (N) relationships. The best fit equations were used to derive the coefficient of friction (μ) and bed-joint cohesion (c) of each group based on the Mohr-Coulomb friction law, as reported in

Table 5. Figure 9 shows that the sample groups had comparable Mohr-Coulomb friction slopes (coefficient of friction, μ), whilst

Table 5 indicates that their y-intercepts (cohesion, c) increased with increasing average mortar compressive strength. Figure 10 illustrates the relationships between mortar bed joint cohesion and average mortar compressive strength, and between mortar bed joint cohesion and average masonry compressive strength. The mortar bed joint cohesion is better characterised using the mortar compressive strength than using the masonry compressive strength, where c can be satisfactorily equated to 0.055 f'_j (R^2 = 82%). The negative R^2 value of -0.146 shows that the relationship between mortar bed joint cohesion and masonry compressive strength is poor. Similar to that shown in Figure 8, there is an apparent outlier in Figure 10 (see circled data point). However, this data point originated from a legitimate dataset, where the cohesion value was calculated based on a reasonably consistent dataset as shown in Figure 9, whilst the average masonry compressive strength was obtained from consistent compression test results (refer to

Table 3). It is noted that the outlier in Figure 10 originated from the same site as did the outlier shown in Figure 8. Also, all samples considered for derivation of the relationship between cohesion and masonry/mortar compressive strength experienced shear bond failures within their mortar joints, and therefore relating the bed joint cohesion to the mortar compressive strength was considered to be more suitable than relating the bed joint cohesion to the masonry compressive strength.

SUMMARY AND CONCLUSIONS

In-situ material testing and sample extraction were performed on 6 New Zealand URM buildings to investigate the relationships between flexural bond strength, shear bond strength and compressive strength of existing URM bearing wall buildings. The following conclusions were drawn based on the experimental results:

When subjected to bond wrench and shear bond tests, almost all of the field samples exhibited bond failures within the mortar joints (failure type C). The samples that exhibited failure type A (interface bond failure) were judged to be disturbed during the sample cutting process, resulting in lower flexural bond strengths than those that exhibited failure type C, and were consequently disregarded from the analysis. It was theorised that the heritage buildings investigated in this experimental programme were constructed using lime-rich mortars, and therefore the mortar did not have sufficient strength to resist the applied tensile force, leading to failure type C. Also, it is noted that the buildings included in the experimental programme were New Zealand URM buildings which were built during a specific time period, and hence the observations from this study may not be applicable for newer URM construction.

A review of past investigations suggests that there is a relationship between mortar compressive strength and mortar flexural strength. Therefore, the masonry flexural bond strength was related to the mortar compressive strength as most field samples exhibited bond failures within the mortar joints. The masonry flexural bond strength is better characterised using the mortar compressive strength than using the masonry compressive strength.

The mortar bed joint shear strength increased with increasing axial pre-compression stress, and the bed joint shear strength at each level of axial pre-compression stress generally increased with increasing average mortar compressive strength. These observations were expected as most field samples exhibited shear failure within the mortar joints, and therefore their bed joint shear strengths were influenced by the mortar properties instead of the brick/mortar bond characteristics.

Comparable coefficients of friction were derived for all field sites, whilst the measured cohesion increased with increasing average mortar compressive strength. It was shown that the mortar bed joint cohesion is better characterised using the mortar compressive strength than using the masonry compressive strength.

It is suggested that future studies attempt to further investigate the material properties of existing heritage masonry buildings. The brick/mortar bond failure type shall also be considered when determining the factors that can be related to the masonry flexural and shear bond strengths.

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TABLES

Table 1: Details of field sites

Material Code	Year Built	City	Building Details	Sample(s) extracted	In-situ test(s) performed
AH	1884	Wellington	Single storey residential house	Brick units, mortar, prisms	Bond wrench, in-situ shear
D	1940s	Auckland	Single storey warehouse	Brick units, mortar, prisms	None
CFK	1910	Auckland	Two storey kindergarten	Brick units, mortar, prisms	In-situ shear
TA	1946	Te Awamutu	Single storey horse stable	Brick units, mortar, prisms	In-situ shear
RB	1930s	Auckland	Two storey Irish Pub	Brick units, mortar, prisms	None
HC	1881	Wellington	Two storey government building	Brick units, mortar, prisms	None

Table 2: Brick unit and mortar compressive strengths

Field	Average f'_b	n_b	Average f'_j	n_j	Compression	Bond wrench		Shear bond	
Site	MPa *(CoV)*		MPa *(CoV)*		Lab	In-situ	Lab	In-situ	Lab
AH	8.5 *(0.18)*	17	1.23 *(0.17)*	7	Yes	Yes	Yes	Yes	Yes
D	17.1 *(0.15)*	7	2.62 *(0.19)*	16	Yes	No	Yes	No	No
CFK	16.0 *(0.11)*	10	4.14 *(0.19)*	14	Yes	No	Yes	Yes	Yes
TA	21.1 *(0.23)*	9	5.92 *(0.17)*	8	Yes	No	Yes	Yes	Yes
RB	27.3 *(0.21)*	32	6.65 *(0.19)*	11	Yes	No	Yes	No	Yes
HC	16.3 *(0.20)*	8	8.58 *(0.14)*	16	Yes	No	Yes	No	Yes

Table 3: Prism compression strength and flexural bond strength

Prism group	Average f'_m MPa *(CoV)*	n	Average f'_j MPa *(CoV)*	Average f'_{fb} MPa *(CoV)*	No of samples and bond failure type(s)
AH	3.3 *(0.19)*	5	1.23 *(0.17)*	0.031 *(0.25)*	7 type C
D	6.1 *(0.15)*	4	2.62 *(0.19)*	0.057 *(0.11)*	3 type C
CFK	7.4 *(0.12)*	6	4.14 *(0.19)*	0.116 *(0.20)*	4 type C, 1 type A*
TA	12.1 *(0.12)*	6	5.92 *(0.17)*	0.127 *(0.28)*	5 type C
RB	14.7 *(0.21)*	6	6.65 *(0.19)*	0.172 *(0.24)*	6 type C, 2 type A*
HC	6.6 *(0.23)*	6	8.58 *(0.14)*	0.345 *(0.21)*	5 type C, 2 type A*

* Samples experiencing failure type A were disregarded from the calculations

Table 4: Mortar bed joint shear strengths at different levels of axial compression

Prism Group	Average f'_m (MPa)	Average f'_j (MPa)	Sample No.	τ (MPa)					No of samples and failure type(s)
				$N =$ 0.02 MPa	$N =$ 0.04 MPa	$N =$ 0.2 MPa	$N =$ 0.4 MPa	$N =$ 0.6 MPa	
AH	3.3	1.23	1	0.146	-	0.404	0.480	-	All type C
			2	0.157	-	0.330	0.510	-	
			3	0.170	-	-	-	-	
			4	0.159	-	-	-	-	
CFK	7.4	4.14	1	-	0.295	0.409	0.576	-	6 type C,
			2	-	0.289	0.348	0.558	-	1 type A
HC	6.6	8.58	1	-	-	0.584	0.720	1.152	11 type C,
			2	-	-	0.608	0.880	0.775	2 type A
			3	-	-	0.659	0.754	1.122	
			4	-	-	0.622	-	0.882	
TA	12.1	5.92	1	-	0.367	0.483	0.651	0.763	11 type A,
			2	-	0.280	0.505	0.683	0.874	1 type A
			3	-	0.373	-	0.693	-	
			4	-	0.437	-	-	-	
RB	14.7	6.65	1	-	-	0.690	0.737	0.955	12 type C,
			2	-	-	0.455	0.660	1.089	2 type A
			3	-	-	0.666	0.699	0.731	
			4	-	-	-	0.711	0.918	
			5	-	-	-	-	1.104	

Table 5: c and μ of the field samples

Prism Group	f'_m (MPa)	f'_j (MPa)	c (MPa)	μ
AH	3.3	1.23	0.149	0.829
CFK	7.4	4.14	0.243	0.829
HC	6.6	8.58	0.430	0.917
TA	12.1	5.92	0.328	0.842
RB	14.7	6.65	0.391	0.907

Figure
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FIGURES

Figure 1: Prism compression test

Figure 2: Bond wrench test

Figure
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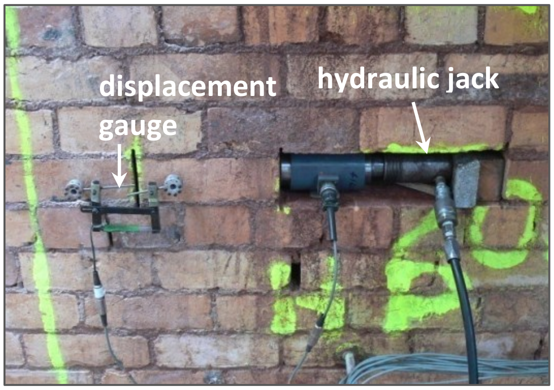


Figure 3: In-situ shear test

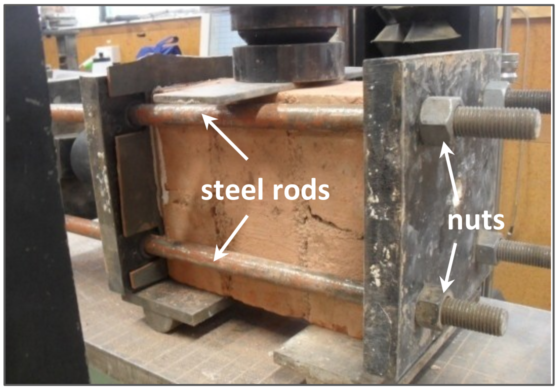
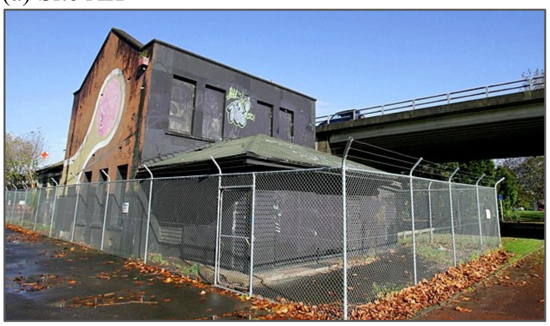


Figure 4: Triplet shear test

(a) Site AH



(b) Site CFK

Figure 5: Representative field sites

Figure 6: Bond failure type A, failure at brick/mortar interface

Figure 7: Bond failure type C, failure within mortar joint

Figure
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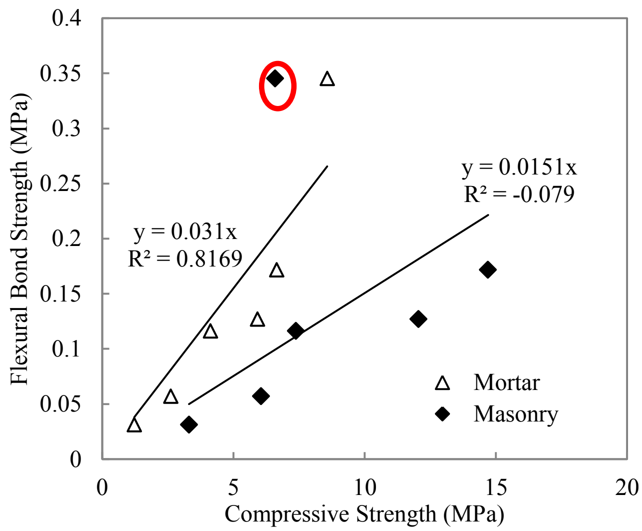

Figure 8: Flexural bond strength-compressive strength relationships of the field samples

Figure
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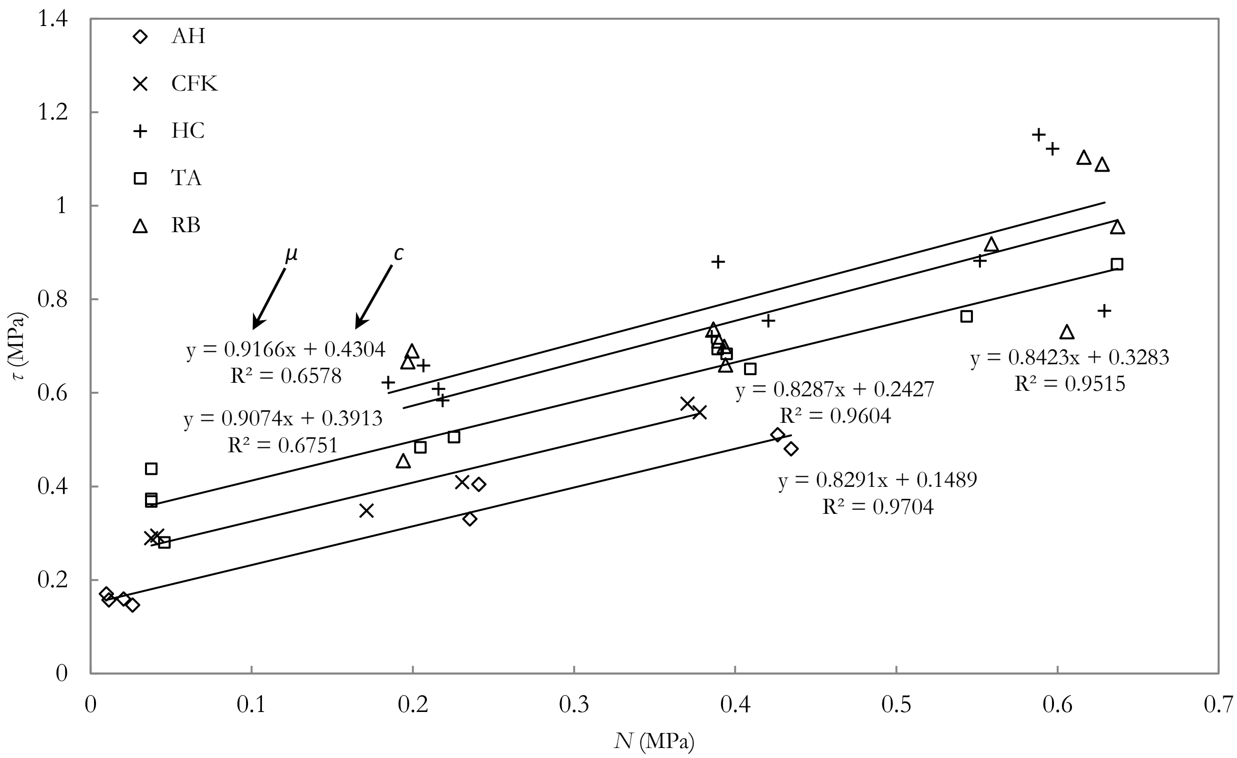

Figure 9: τ - N relationships of the field samples

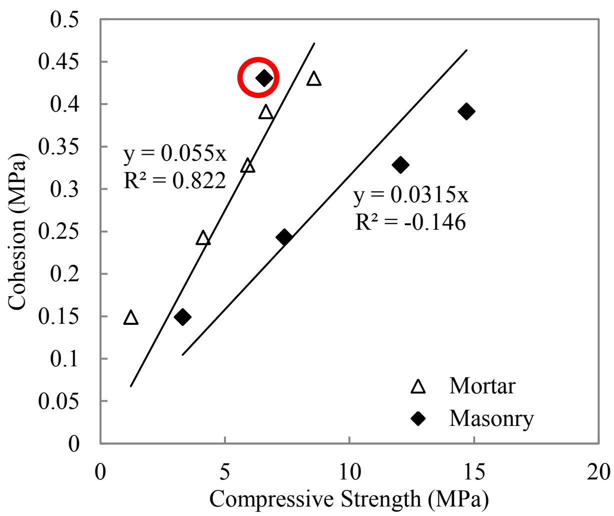

Figure 10: Cohesion-compressive strength relationships of the field samples

LIST OF FIGURES