PRELIMINARY ANALYSIS OF THE COMPRESSIVE STRENGTH OF NEW ZEALAND'S UNREINFORCED MASONRY

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ABSTRACT

New Zealand's unreinforced masonry (URM) buildings have proven to perform poorly during earthquakes. Building damage during the magnitude 7.8 1931 Hawke's Bay earthquake provided evidence of the vulnerability of this form of construction, where most URM buildings were destroyed during the event, resulted in the death of nearly 260 people. Due to this poor earthquake performance, seismic assessment and retrofit of URM buildings is necessary as these buildings not only represent a significant architectural heritage, but also occupy a significant portion of the nation's building stock. In order to achieve an accurate seismic assessment and a cost effective seismic retrofit, it is important to accurately establish the constituent material properties of these buildings.

A research programme has been initiated to investigate the material properties of New Zealand's URM buildings. This research aims to establish better URM material data for structural seismic designers in order to improve the accuracy, and therefore cost effectiveness of their seismic assessments, computer modelling and retrofit designs. The work reported here focuses on the compressive strength of brick, mortar and the brick/mortar composite. Three brick high prisms were constructed out of three brick types and four different mortar grades. The samples were tested in compression to determine brick, mortar and prism compressive strengths. Predictive equations relating brick, mortar and the brick/mortar composite properties were developed using the results obtained from the tests. These predictive equations are intended to facilitate prediction by structural seismic designers of masonry design properties based upon known brick and mortar properties.

KEYWORDS: unreinforced masonry, material properties, compressive strength, young's modulus, predictive equation.

INTRODUCTION

Unreinforced masonry (URM) buildings in New Zealand have proven to perform poorly when subjected to lateral earthquake forces. The popularity of URM construction in New Zealand began to rise during the 1870s, and reached its peak at the beginning of the 20th century [1]. The popularity of this form of construction continued to rise until 1931, when the magnitude 7.8 Hawke's Bay earthquake provided evidence of the vulnerability of this form of construction, as most URM buildings in the city of Napier were destroyed during the event, resulted in the death of 256 people. Following this earthquake, the use of unreinforced masonry rapidly declined and was eventually outlawed in 1965 [2-4]. As URM buildings occupy a significant portion of New Zealand's building stock, this type of structure is a risk to human life whilst being an architectural form that must be preserved in order to retain New Zealand's colonial heritage. This necessitates the seismic assessment and retrofit of URM buildings in New Zealand.

The New Zealand Building Act 2004 defines earthquake prone buildings and demands that all existing buildings must perform to a satisfactory level in an earthquake [5]. To comply with the act, the New Zealand Society for Earthquake Engineering (NZSEE) published a guideline detailing how to assess these buildings [6], which requires an understanding of the nature of the constituent materials. The current knowledge on New Zealand URM material properties is almost non-existent and the material property recommendations provided for seismic assessment are based on limited experimental testing.

A research programme has been initiated to investigate the material properties of New Zealand URM buildings. This research aims to establish improved URM material data for structural seismic designers in order to improve the accuracy, and therefore cost effectiveness of their seismic assessment, computer modelling and retrofit designs. This particular work focuses on the compressive strength of brick, mortar and the brick/mortar composite. Experimental programme involving different types of brick and mortar were conducted in the laboratory.

BRICK COMPRESSION TEST

The experimental programme involved compression tests of individual bricks, mortar samples and masonry prisms. The brick samples were classified into three different types following the NZSEE guideline, and were obtained from demolition sites, a reinstatement site and a residential house. The bricks were sorted according to the visual descriptions specified in the NZSEE guideline. The half brick compression test was used to obtain brick compressive strength (f'_b) and was performed on a number of bricks of each type according to ASTM C67 – 03a [7]. Table 1 shows the origin of the different brick types and the NZSEE descriptions used to classify the bricks.

Table 1: Origin of bricks and NZSEE descriptions for different brick types

Brick Type	Obtained from	Physical Description
Soft	Demolition sites	Probably under fired, bright orange
Stiff	Reinstatement site	Common brick, red
Hard	Residential house	Hard surface, well fired, dark reddish brown

The mean half brick compression test results of the different brick types are presented in Table 2, where CoV = Coefficient of Variation. The NZSEE suggested range for each brick type is also included. Table 2 shows that whilst the mean compressive strength of soft bricks closely matched the NZSEE suggested range, the values for stiff and hard bricks were far beyond the

NZSEE suggestion. The stiff and hard bricks had a similar mean compressive strength (43.4 MPa and 43.1 MPa respectively) although the physical appearance of the two types was very different. However, previous studies have proven that the compressive strength of the stiff bricks from this reinstatement site were exceptionally high compared to the stiff bricks tested previously, which were closer to the NZSEE suggestion. Further studies regarding hard bricks are required as the sample size was limited. Comparison with previous test results also could not be made as there were no hard bricks tested in the past.

Table 2: NZSEE suggested range and the actual mean strength

	Bricks used for half brick compression test				
Grade	NZSEE suggested range (MPa)	Sample size	Average dimensions (mm^3)	Actual mean (MPa)	CoV
Soft	1 – 5	54	218 x 106 x 82	5.9	0.58
Stiff	10 – 20	9	224 x 110 x 78	43.4	0.15
Hard	20 – 30	10	202 x 97 x 65	43.1	0.11

MORTAR COMPRESSION TEST

Four different mortar grades as per Table 3 were generated to simulate the NZSEE guideline. These mortar compositions were estimated by an experienced mason and are commonly used in masonry construction practice in New Zealand. The mortar samples were tested in accordance with ASTM C780 – 06a to obtain the mortar compressive strength (f'_j) [8]. The samples were 28 days old at the time of testing. There were five mortar cube samples for each mortar type. The mean compression test results of the different grade mortar cubes are presented in Table 4, which shows that the mean mortar cube compressive strengths varied as predicted, as mortar grade A and grade D had the lowest and highest compressive strengths respectively.

Table 3: Mortar compositions

<table>
<tr><td></td><td colspan="5">Proportion in Volume</td></tr>
<tr><td>Mortar</td><td colspan="2">Lime Putty</td><td>Plaster Sand</td><td>Coarser Sand</td><td>Red Bricks</td></tr>
<tr><td>A</td><td colspan="2">1</td><td>2.5</td><td></td><td></td></tr>
<tr><td>B</td><td colspan="2">1</td><td>1.5</td><td>0.5</td><td>0.5</td></tr>
<tr><td>C</td><td colspan="5">Mortar B + 10% Microsilica 600</td></tr>
<tr><td></td><td>Cement</td><td>Hydrated Lime</td><td colspan="3">Plaster Sand</td></tr>
<tr><td>D</td><td>0.5</td><td>0.5</td><td colspan="3">3</td></tr>
</table>

Table 4: Mean mortar cube compression test results

Mortar Grade	Mean Cube Strength (MPa)	CoV
A	1.62	0.35
B	1.70	0.06
C	2.43	0.16
D	10.68	0.53

PRISM COMPRESSION TEST

Three brick high masonry prisms were constructed using the three different brick types and four mortar grades. There were five prisms for each brick and mortar combination. The prism compression test was similar to the half brick compression test, except the result obtained was the compressive strength of the brick/mortar composite (f'_m) [9]. Table 5 presents the average compression test results of the different prism types including the ranges from the minimum to maximum values. The results show that prisms with mortar grade D had higher compressive strengths and wider variability in comparison to prisms with other mortar grades. Table 5 also shows that the prism compressive strength rose as the brick and mortar compressive strengths increased. The low average strength of prisms with soft bricks and mortar grade B (5.56 MPa) was due to the lowest test result (3.67 MPa). It is believed that the average compressive strength of this prism type will increase with more data points. The average dimensions of the prisms with soft, stiff and hard bricks were 218 mm x 106 mm x 270 mm, 224 mm x 110 mm x 259 mm and 202 mm x 97 mm x 221 mm respectively.

Table 5: Prism compression test results

Mortar \ Brick		Soft (MPa)	Stiff (MPa)	Hard (MPa)
Grade A	Average:	6.05	13.41	17.04
	Range:	5.76 – 6.47	11.42 – 15.12	15.00 – 18.86
Grade B	Average:	5.56	15.04	17.9
	Range:	3.67 – 6.50	10.07 – 18.24	13.66 – 23.27
Grade C	Average:	6.88	16.99	18.44
	Range:	6.14 – 7.64	14.92 – 19.46	16.66 – 23.72
Grade D	Average:	9.02	21.20	30.07
	Range:	6.31 – 11.84	10.17 – 27.12	24.74 – 33.99

To monitor the deformation during the prism compression test, displacement gauges were attached to both sides of the prism. The displacement readings were used to plot the stress against strain curve, and furthermore to obtain the prism Young’s Modulus (E). Figure 1 shows an example of stress against strain plot of a prism and the Young’s Modulus value. The Young’s Modulus values were determined following the ASTM E 111-97 procedure [10]. The stress and strain values considered in the calculation of Young’s Modulus were the values between 0.05 and 0.33 of the maximum compressive strength (see marked line in Figure 1) [9].

The Young’s Modulus values of the prisms are reported in Table 6. Prisms with mortar grade D were shown to have higher Young’s Modulus values when compared to prisms with other mortar grades. The Young’s Modulus values were inconsistent and did not necessarily follow the change of brick and mortar compressive strengths. The ranges of the results were also found to be wide, particularly for stiff D and hard D prisms. This was believed to be due to the variability of the bricks and mortar used in prism construction.

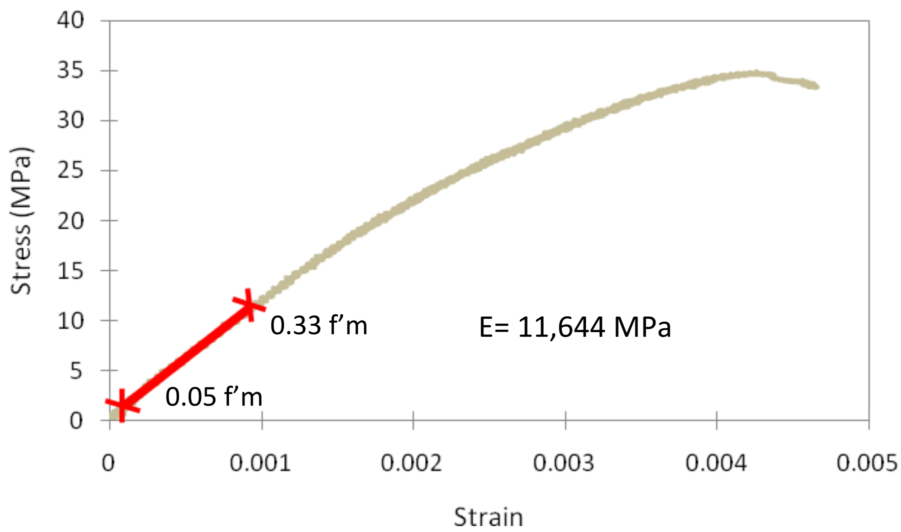

Figure 1: Example of stress vs. strain plot and the Young's Modulus

Table 6: Prism Young's Modulus values

Mortar \ Brick		Soft (MPa)	Stiff (MPa)	Hard (MPa)
Grade A	Average: Range:	556 347 – 698	686 436 – 872	820 694 – 978
Grade B	Average: Range:	484 270 – 741	711 611 – 787	724 567 – 860
Grade C	Average: Range:	839 597 – 1,286	506 412 – 653	697 570 – 769
Grade D	Average: Range:	2,044 1,496 – 4,194	8,584 4,873 – 14,677	8,913 5,231 – 11,955

Table 7 shows the average Young's Modulus (E) values of the prisms in terms of the average compressive strength (f'_m). The average E values of the prisms were significantly lower than the values suggested in internationally established documents. FEMA 306 suggests that E should be approximately equal to 550 f'_m, while the Masonry Society Joint Committee (MSJC) and Eurocode6 recommend E as 700 and 1000 times f'_m respectively [11-13]. Although the average E for prisms with mortar grade D were the highest among other prism types (see Table 7), these values are still low in comparison to the values suggested by the international documents. Further investigation on the Young's Modulus of New Zealand URM is required to determine the reason for the difference. Figures 2 to 5 show the testing process.

Table 7: Average Young's Modulus values in terms of average f'_m

Mortar \ Brick	Soft	Stiff	Hard
Grade A	88 f'_m	50 f'_m	47 f'_m
Grade B	82 f'_m	47 f'_m	40 f'_m
Grade C	120 f'_m	31 f'_m	37 f'_m
Grade D	210 f'_m	337 f'_m	355 f'_m

Figure 2: Half brick compression test

Figure 3: Mortar cube compression test

Figure 4: Prism compression test

Figure 5: Cracks developed during prism test

EXISTING PREDICTIVE EQUATIONS

Existing predictive equations were reviewed in order to understand the relationship between the brick, mortar and prism strength that were tested. Eurocode6 stipulates Equation (1), where K varies between 0.4 – 0.6 depending on brick properties and joint type. The values for α and β are 0.65 and 0.25 respectively [13].

$$f'_m = K f'^{\alpha}_b \times f'^{\beta}_j \quad (1)$$

Equation (2) is the expression used by the Masonry Society Joint Committee (MSJC) in USA. The value for A is 1.0 for inspected masonry and B varies from 0.2 to 0.25 depending on the mortar grade [11].

$$f'_m = \frac{A(400 + B \times 145 f'_b)}{145} \tag{2}$$

Equation (3) was developed in India and is in a similar form to the Eurocode6 equation apart from the different constants. The average size of the five brick high prisms used to develop this equation was 230 mm x 110 mm x 400 mm [14].

$$f'_m = 0.63 f'^{\,0.49}_b \times f'^{\,0.32}_j \tag{3}$$

These equations were used to predict the compressive strengths of the different prism combinations using the average compressive strengths of the corresponding brick types and mortar grades. The 50% to 100% error in the predictions generated by these equations suggested that the development of a unique predictive equation for New Zealand URM is necessary.

PREDICTIVE EQUATION ESTABLISHMENT

A predictive equation relating the brick, mortar and prism compressive strengths was developed based on the obtained test results. The equation developed is in the form of Equation (1) for easier comparison. The following 3-D plot relating the three different properties was produced to obtain the values of K, α and β. The shaded area represents the predicted prism compressive strengths for different brick and mortar compressive strengths.

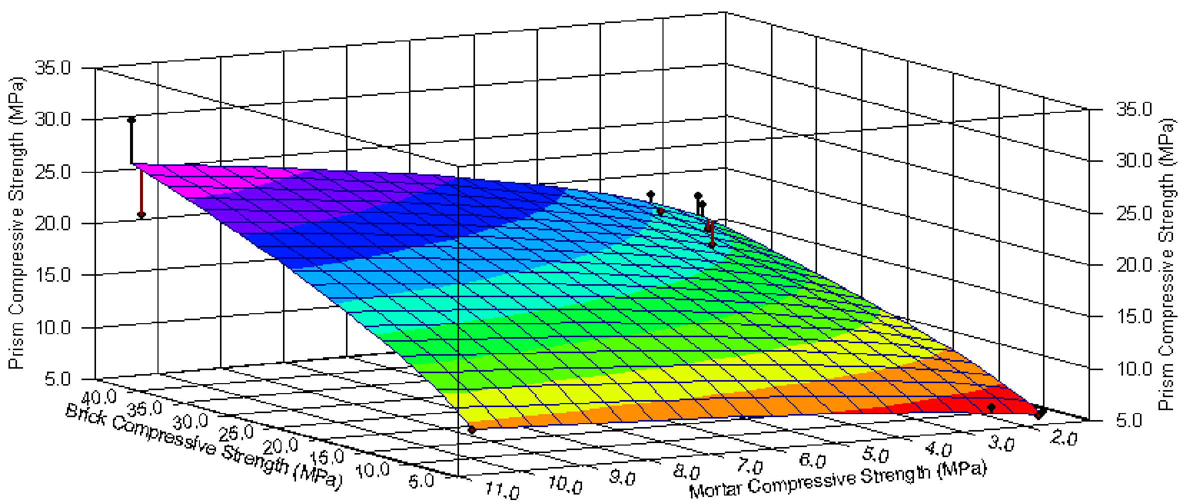

Figure 6: 3-D Plot of average brick, mortar and prism compressive strengths

A nonlinear regression analysis was performed and the values of K, α and β were found to be 2.1, 0.5 and 0.25 respectively. Equation (4) was used to calculate the predicted prism compressive strength based on the average brick and mortar compression test results. These predicted values were plotted against the actual average prism compressive strength as per Figure 7. R^2 measures how well the predicted values estimate the actual test results. The R^2 value of 0.9148 (see Figure 7) shows that the predicted results have a correlation of 91.5% with the actual data. The 91.5% correlation is deemed to be acceptable given that a number of samples possessed extremely low or high compressive strengths that are likely to be outliers.

$$f'_m = 2.1 f'^{0.5}_b \times f'^{0.25}_j \qquad (4)$$

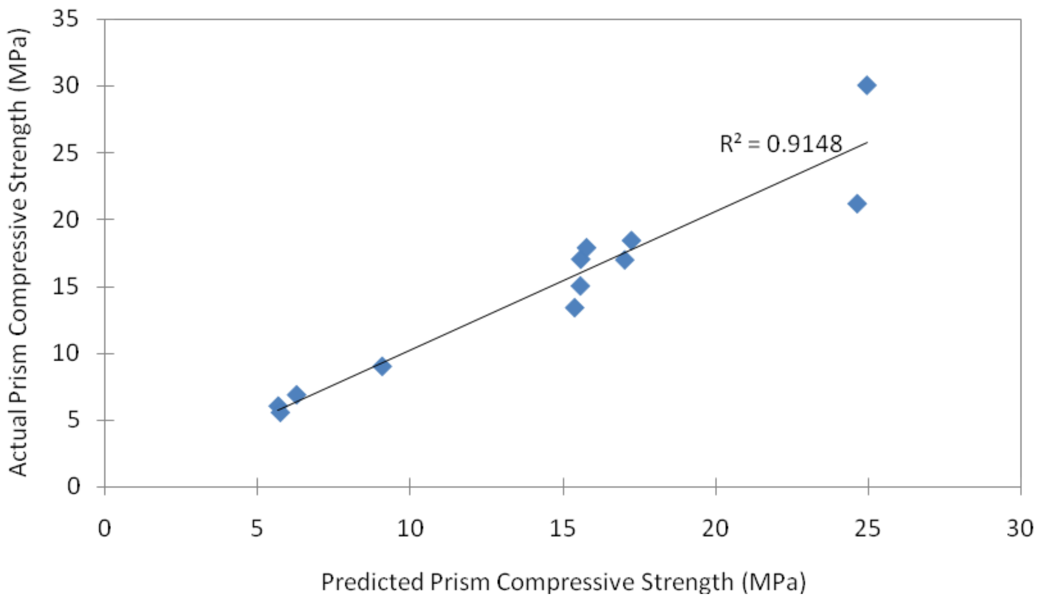

Figure 7: Predicted prism compressive strength against actual prism compressive strength

The prism compressive strengths predicted by different equations are compared in Table 8. The actual average prism compressive strengths are also included in the table. The K value of 0.6 was used for the Eurocode6 equation, while the A and B in the MSJC equation were assumed to be 1.0 and 0.25 respectively. Table 8 shows that the compressive strengths predicted by the equations from Europe and India are significantly lower than the actual average values. The predictions by the MSJC equation are closer to the actual values, particularly for prism type stiff A. The difference between the MSJC predicted values and the actual average prism compressive strengths rises as the mortar strength increases.

A predictive equation relating the prism compressive strength to the Young's Modulus could not be developed due to the scarcity and inconsistency of the data. It is believed that a more accurate predictive equation could be achieved as the number of data increases.

Table 8: Comparison between the actual values to the predictions by different equations

Mortar \ Brick		Soft (MPa)	Stiff (MPa)	Hard (MPa)
Grade A	Actual:	6.05	13.41	17.04
	Eurocode6:	2.10	7.70	7.83
	MSJC:	4.18	13.28	13.56
	India:	1.72	4.59	4.65
	Predicted:	5.66	15.37	15.57
Grade B	Actual:	5.56	15.04	17.9
	Eurocode6:	2.12	7.79	7.92
	MSJC:	4.18	13.28	13.56
	India:	1.75	4.67	4.73
	Predicted:	5.72	15.56	15.76
Grade C	Actual:	6.88	16.99	18.44
	Eurocode6:	2.32	8.52	8.66
	MSJC:	4.18	13.28	13.56
	India:	1.96	5.23	5.30
	Predicted:	6.26	17.01	17.23
Grade D	Actual:	9.02	21.20	30.07
	Eurocode6:	3.36	12.33	12.54
	MSJC:	4.18	13.28	13.56
	India:	3.15	8.40	8.51
	Predicted:	9.06	24.63	24.95

CONCLUSION

Compression tests of brick, mortar and masonry prism samples were conducted in the laboratory. It was observed that the average compressive strengths of stiff and hard bricks used in prism construction were far beyond the NZSEE suggestions for the corresponding brick types. The stiff bricks tested had a very high mean compressive strength although their physical appearance matched the NZSEE description for stiff bricks. Previous test results proved that the compressive strengths of the stiff bricks used in this experimental programme were high in comparison to the stiff bricks tested in the past. The mean compression test result for hard bricks was also higher than the suggested range, while the value for soft bricks was found to be close to the NZSEE suggestion. Four different mortar grades were generated following the common New Zealand masonry construction practice. The mean mortar compressive strengths varied as expected.

A total of 60 prisms were tested and it was found that prisms with mortar grade D had higher average compressive strengths as well as wider variability compared to prisms with other mortar types. It was observed that the average prism compressive strength rose as the average brick and mortar compressive strengths increased, except for prisms with soft bricks and mortar grade B. The stress vs. strain curves, and furthermore the Young's Modulus values of the prisms were extracted. The Young's Modulus values were found to be highly inconsistent and extremely low in comparison to the values suggested in internationally established documents. This was supposed to be due to the variability of the bricks and mortar used in prism construction.

An equation to predict the prism compressive strength based upon the brick and mortar compressive strengths was developed. The predictions by this equation showed 91.5% correlation to the actual average prism compression test results, and therefore the predictive equation was deemed to be sufficiently accurate. The development of an equation relating the prism compressive strength to the Young's Modulus will be the focus in future efforts as it is not possible at this time due to the scarcity of the data.

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