MECHANICAL PERFORMANCE OF LIME-CEMENT MORTAR FOR STRAW-BALE CONSTRUCTION

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ABSTRACT

Experimental data describing the mechanical performance of Portland cement-hydrated lime mortars used for straw bale construction is presented. Straw bale construction uses stacked straw bales plastered on each side to form load-bearing elements. Mortars used have slumps of approximately 50 mm, compared to slumps up to 279 mm for conventional masonry mortars. Cylinder and cube tests of a range of typical straw bale mortar mixes were carried out. The mortars had compressive strengths ranging between 0.3 MPa and 13 MPa. Empirical equations describing the relationships between compressive strength and curing time, w/cm ratio, proportions of lime, cement and sand, and modulus of elasticity are presented. The data show that cement-lime mortars for straw bale construction will have a higher modulus of elasticity and lower failure strain than a conventional mortar of equivalent compressive strength. The Modulus of Elasticity is on average 818 times the compressive strength of a straw bale mortar, compared to 100 to 200 times as reported in the literature for conventional mortar. The average failure strain for straw bale mortar is 0.00253 compared to 0.0087 to 0.0270 reported in the literature for conventional mortar.

KEYWORDS

Straw-bale construction, mortar, cement, hydrated lime, compressive strength, constitutive model

INTRODUCTION

With the ever-increasing global desire to live in a more environmentally friendly and sustainable manner, the modern construction industry has begun to utilize alternative materials and construction methods on a more regular basis. There have been thousands of buildings worldwide constructed using straw bale construction (King, 2006). This simple but effective technique involves walls with an inner core of stacked straw bales and two outer mortar skins. The straw provides excellent low cost insulation while the mortar protects the straw from moisture and provides fire resistance. The embodied energy of a straw bale wall is about 1/6 that of a conventional wood frame wall with glass fiber insulation and brick siding (Offin 2010).

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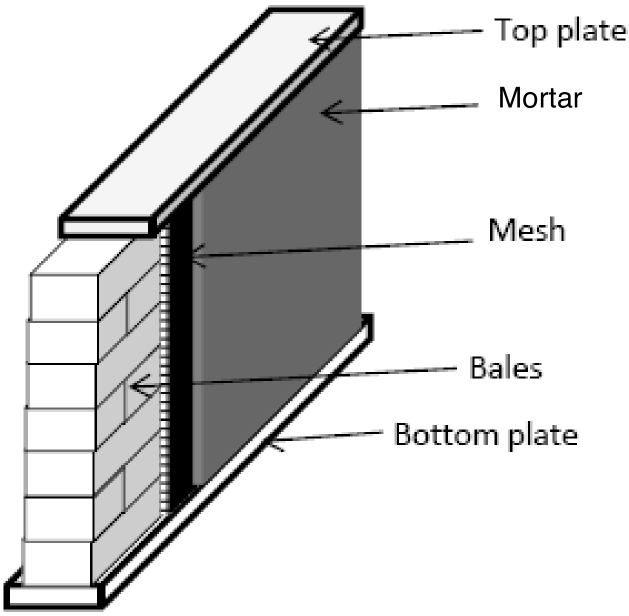

FIGURE 1. Simplified typical straw-bale wall details.

A typical load-bearing straw bale wall is shown in Figure 1. The top and bottom beams ensure that the vertical deformations in the straw and mortar are identical. However, the stiffness of the mortar exceeds that of the straw by several orders of magnitude (Vardy 2009). Thus, the mortar provides the primary structural strength and stiffness for the wall (Lawrence et al. 2009, Vardy and MacDougall 2007, Vardy 2009, Vardy and MacDougall 2012). However, the straw provides a critical structural function in that it ties the two thin mortar skins together, and provides support to prevent buckling of the mortar. In a single story straw bale wall of usual dimensions (typically 2.4 metres in height and 350 mm in width), the failure mode under vertical loads is crushing the mortar. With taller walls or other wall dimensions, global buckling of the wall is possible.

A variety of mortars are used for straw bale construction, including clay and lime plasters. In Europe, the use of lime plaster and natural hydraulic lime for straw bale construction is common. In North America, one of the most common mortars is a hydrated lime-Portland cement mortar. The mix used is based on a common mortar mix that consists of volume proportions 1:1:6 of cement, lime and sand. There are no standards specific to straw-bale construction that govern the preparation of these mortars. Mortars are prepared on-site, using drum mixers and volumetric batching. There is little quality control, and builders will adjust levels of water added to ensure the mortar adheres to the straw when applied using a hand trowel. Some of these mortars have compressive strengths as low as 1 MPa (King 2006) and yet have been successfully used to construct single storey residential buildings.

In today's world, straw bale construction is finding wider use in more mainstream construction (Gross et al. 2009; Beadle et al. 2009). Approval of an engineer is often required in order to obtain a building permit for load-bearing straw bale construction. As mentioned above, it is the mortar that governs the strength and stiffness of a straw bale wall. King (2006) suggests that the compressive strength of a single storey load-bearing straw bale wall can be determined by the product of the mortar cross-sectional area and the mortar compressive strength. For engineers to check the strength and stiffness of a straw bale wall design, they need to know the compressive strength and elastic modulus of the mortar. To assign rational

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factors of safety (or resistance factors for limit states design), the variability in these properties needs to be quantified. In addition, cement has the highest embodied energy of the materials in a straw bale mortar (Offin 2009), so to reduce environmental impact, cement content should be minimized while achieving acceptable mortar strength.

The main focus of this paper is the experimental quantification of the mechanical properties of cement-lime mortars typical of straw bale construction. Although a vast array of research has been conducted on cement-lime mortars, much of this literature is relevant to masonry mortar or grout. Although straw bale "plaster" or "mortar" is generally similar, there are some unique performance criteria for straw-bale mortar that makes a direct comparison invalid. Mortar for straw-bale construction must be flowable enough to allow it to be hand-applied using a trowel, and yet stiff enough that it does not simply flow down the vertical face of the wall due to gravity after application to the straw. For example, Sriboonlue and Wallo (1990) presented experimental data for cement-lime mortars and grouts with cement : lime : sand volumetric proportions of 2.25 to 3.0 : 1.0 : 0 to 2.5. Their mixes had slumps up to 279 mm, which is far in excess of the typical slump of 50 mm for a straw-bale mortar.

The specific objectives of this work are:

- Examine the relationship between compressive strength and modulus of elasticity for straw bale mortars to determine if there is a significant difference from the relationship reported in literature for conventional mortars;
- Determine typical failure strains for straw bale mortars and determine if there is a significant difference from the values reported for conventional mortars;
- Examine the differences in compressive strength measured using cube specimens and using cylinder specimens for straw bale mortars;
- Quantify the variability in compressive strength for mortars mixed using procedures typical of those used for straw bale construction projects.

BACKGROUND

Boynton and Gutschick (1964) summarize a number of experiments on cement : lime : sand mortars giving the proportions of dry materials and corresponding compressive strength and Kaushik et al. (2007) provide strength results for three different lime-cement mortar mixtures. In addition, the National Lime Association (NLA) (2002) has produced a fact sheet on the use of hydrated lime in mortar giving specified strengths for four different mixtures.

The relationship between Modulus of Elasticity and strength varies depending on the mix composition for concrete, mortar or other similar materials. Kaushik et al., (2007) and Sriboonlue and Wallo, (1990) observed a linear relationship between Modulus of Elasticity and strength for masonry mortar and grout. These authors found modulus of elasticity to be approximately 100 to 200 times the strength for mixes with varying quantities of lime, cement and sand, and for strengths which varied from approximately 1-2 MPa to greater than 25 MPa.

Kaushik et al. (2007) found the strain at peak stress for masonry mortar to vary from 0.0087 to 0.0270, nearly 10 times the values noted by Tasnimi (2004). Kaushik et al. (2007) did not observe the strain at peak stress to increase with increasing strength, but rather found the maximum strain to correspond to the specimens containing the greatest proportion of lime as a binder. Nichols and Raap (2001), and Boynton and Gutschick (1964) provide results for experiments on mortars tested after a variety of ages. Allen et al. (2003) explain that hydraulic lime mortar continues to gain strength even beyond 375 days.

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There have been numerous papers examining the stress-strain response of cement-lime mortars, but to a large extent the work has been applied to the prediction of the response of masonry (bricks or concrete blocks with mortar in between) (e.g. McNary and Abrams 1985, Kaushik et al. 2007). In this type of construction, the mortar is subjected to a state of triaxial compression (McNary and Abrams 1985; Kaushik et al. 2007). The mortar stress state in straw bale construction will approach uniaxial compression. There are numerous models to predict the stress-strain response of concrete, such the classic Hognestad parabola. Vecchio and Collins (1993) found that for low-strength concretes (f'_c < 20 MPa), the Hognestad parabola tends to underestimate stresses at intermediate levels. They suggest the use of the Thorenfeldt et al. (1987) model:

$$f_c = f'_c \left(\frac{n(\varepsilon/\varepsilon_o)}{n - 1 + (\varepsilon/\varepsilon_o)^{nk}} \right) \tag{1}$$

$$n = 0.8 + \frac{f'_c}{17} \tag{2}$$

$$k = 1.0 \quad 0 < \varepsilon < \varepsilon_o \tag{3a}$$

$$k = 0.67 + \frac{f'_c}{62}; \quad \varepsilon > \varepsilon_o \tag{3b}$$

where f_c is the stress in concrete at any strain ε, ε_o is the strain in concrete at ultimate stress (the peak strain), and f'_c is the specified ultimate compressive strength of the concrete.

The constants n and k in Equations 2 and 3 are specific to structural concrete. Weak mortars shown little evidence of post-peak softening (Kaushik et al. 2007), thus it can be assumed k = 1.0 for the entire stress-strain response (i.e. k does not increase for $\varepsilon > \varepsilon_o$, as suggested by Eq. 3b). The derivative of Eq. 1 (i.e. the slope) evaluated at $\varepsilon = 0$ is:

$$\left.\frac{df_c}{d\varepsilon}\right|_{\varepsilon=0} = \frac{f'_c n \left(\frac{1}{\varepsilon_o}\right)}{n - 1}$$

Setting the left-hand side of the expression equal to E_c, the Modulus of Elasticity, and rearranging to obtain an expression for n:

$$n = \frac{E_c \varepsilon_o}{E_c \varepsilon_o - f'_c} \tag{4}$$

MATERIALS

The mortar mixes were prepared using various proportions of water, sand, cement, and hydrated lime. Masonry sand as per ASTM C144 (2004a) was used. Portland cement as per ASTM C150 (2007a) was provided as either standard Type I Portland cement or as a constituent of Type N Portland Lime, which contains equal portions (by volume) of Type I Portland cement and Hydrated Lime. The lime was provided to meet ASTM C207 (2006). There were two sources of lime. The first was as a constituent of Type N Portland Lime and the second source was a Mason's Lime which consists of 100% Hydrated Lime.

The method for mixing the mortar was modified from ASTM C305, the Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency

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(ASTM, 1994). Typical straw bale construction practice often utilizes large drum mixers and thus a larger mixer than that specified in ASTM C305 (1994) was used for specimen preparation. During mixing, sand with known moisture content was added to the mixer first. The lime and cement were then added, and mixed with the sand. Finally, tap water was added and mixed with the dry materials.

Three cube samples (50 mm side length) (ASTM C109 1998) and three 100 × 200 mm cylinders (ASTM C192 2007b) were prepared for each mortar batch.

The specimens were typically kept in a moisture room for seven days before the molds were removed. The specimens were then allowed to cure in the laboratory, outside of the moisture room. In some cases the curing conditions varied from those described above as a result of the specific parameters being studied for the specimens (i.e., when studying varying aging times).

TEST DETAILS

Mortars with a range of cementitious material proportions have been prepared and tested. Recently, builders have experimented with reducing the cement and hydrated lime in their mixes to reduce the environmental impact of the mortar. The proportions selected for testing reflect the wide range of mortar mixes that straw bale builders employ. To quantify the variability, the mortars are prepared using materials and methods similar to those used by straw bale builders: volumetric proportioning and mixing using drum mixers. A range of water contents that reflects those builders may use to ensure the mortar adheres to the straw is examined. The stress-strain response of these mortars is compared to models that have been previously proposed in the literature for structural concrete.

Cube compression tests in accordance with ASTM C109 (1998) were conducted. The rate of loading was approximately 0.5 mm/min. The load was applied to the cubes until failure. The ultimate load was recorded and the compressive strength was calculated for each cube.

Cylinder compression experiments were conducted to determine compressive cylinder strength, Modulus of Elasticity, and stress-strain profile. The cylinder compression experiments generally followed the methods described in ASTM C39 (2004b) and ASTM C469 (2002). There were some deviations from these methods. The loading procedure first involved installing the deflection measuring device on the cylinder. Once this was completed, the cylinder was placed in the testing machine. The cylinder was then loaded at a rate of approximately 0.5 mm/min until ultimate failure. The ultimate load was recorded and the corresponding compressive strength was calculated. The deflection measuring device remained fixed to the cylinder for the entire duration of the experiment in order to capture the entire stress-strain curve. The weakness of the mortar ensured that there were no violent failures which may have damaged the deflection measuring devices. The stress and strain values were calculated from the load and deflection data and the Modulus of Elasticity and stress-strain curves were obtained. The modulus of Elasticity referenced herein is the secant modulus from 0% to 40% of ultimate load. Figure 2 shows the test set-up for a typical cylinder test. The set-up for cube tests was similar. A swivel head on the test machine ensured no accidental eccentricity of the loading.

Fifteen different mixes (Table 1) were prepared to examine the effect of cure time (aging), and to examine the effect of water to cementitious materials (w/cm) ratio. In calculating w/cm, the mass of both Portland cement and hydrated lime is included in the cementitious materials (cm). For each mix, a number of identical batches were prepared to quantify the

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variability in the strength of the mortar. Each batch consisted of enough mortar to make at least three 50 mm cube test samples, and in some cases three 100 mm diameter x 200 mm cylinders. The basic mix consisted of cement : lime : sand volumetric proportions of 0.25 : 1.25 : 4.5. This is a much leaner mix than the standard 1 : 1 : 6, with comparatively much lower compressive strengths. Cure times for the cube and cylinder samples ranged from 7 to 32 days. The w/cm ratio ranged from 1.08 to 1.33, resulting in slumps that ranged from approximately 50 mm to 80 mm.

The effect of variation on the mix proportioning on the strength of the mortar was investigated. Batches were prepared with nominally four different ratios (approximately 0.12, 0.20, 0.33, 1.20) of the volume of cement to the volume of lime (V_c/V_l). For each ratio, the ratio of the volume of binder to the volume of sand (V_{cm}/V_s) was varied. For each batch, three 50 mm cube samples were prepared. Table 2 summarizes the batches prepared. In addition, batches from Table 1 with a cure time of 7 days were also included in this analysis.

FIGURE 2. Set-up for compression tests.

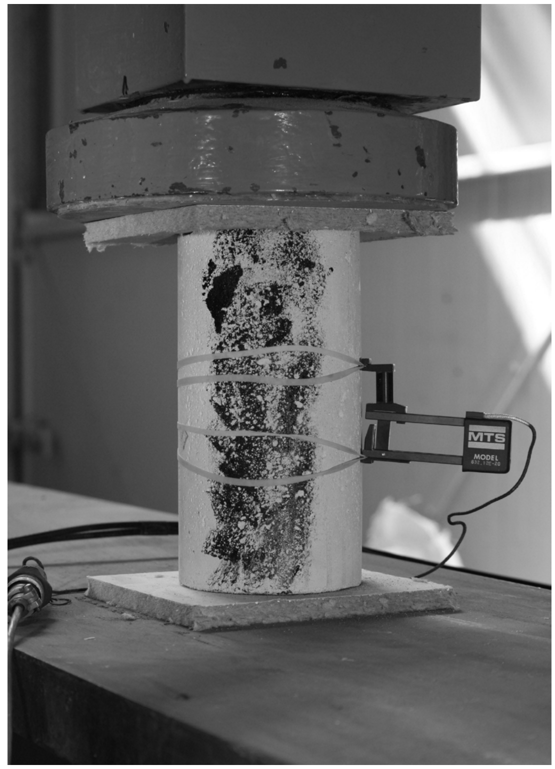

TABLE 1. Summary of mortar batches of 0.25 : 1.5 : 4.5 cement : lime : sand, by volume.

w/cm (mass)	Cure Time (days)	# Batches
1.08	7	11
1.08	8	3
1.08	11	2
1.08	13	2
1.08	14	1
1.08	28	2
1.08	32	3
1.18	7	1
1.18	14	1
1.18	28	2
1.13	28	2
1.23	28	1
1.28	28	2
1.31	28	1
1.33	28	1

RESULTS AND DISCUSSION

Variability in Strength

Obla (2010) suggests that concrete can be expected to have a coefficient of variation for strength of approximately 10 to 18% for different batches of concrete with the same mix proportions. Furthermore, Obla (2010) suggests that even with the same batch, the coefficient of variation for concrete strength can be expected to be in the range of 3 to 6%. Cosgrove and Pavia (2009) observed same-batch coefficient of variation for various hydraulic lime and Portland cement mortars to be in the range of 4.2 to 11.5%.

Figure 3 presents the results of the 11 batches of the 0.25 : 1.25 : 4.5 cement, lime, and sand mortar with *w/cm* ratio of 1.08.

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TABLE 2. Summary of mortar batches for investigating mix proportioning effect on strength.

V_c/V_l	V_{cm}/V_s	cement	lime	sand	w/cm
0.12	2.00	0.43	3.57	2.00	0.60
	0.71	0.268	2.23	3.5	0.81
	0.49	0.224	1.75	4.026	0.924
	0.31	0.15	1.27	4.58	1.35
0.20	11.0	0.92	4.58	0.50	0.59
	2.0	0.67	3.33	2.00	0.66
	0.71	0.417	2.083	3.50	0.732
	0.20	0.17	0.83	5.0	2.05
	0.09	0.08	0.42	5.5	4.75
0.33	2.0	0.99	3.01	2.00	0.48
	0.71	0.62	1.88	3.50	0.69
	0.33	0.375	1.125	4.50	1.121
1.2	0.61	1.25	1.03	3.72	0.57
	0.10	0.30	0.25	5.45	3.09

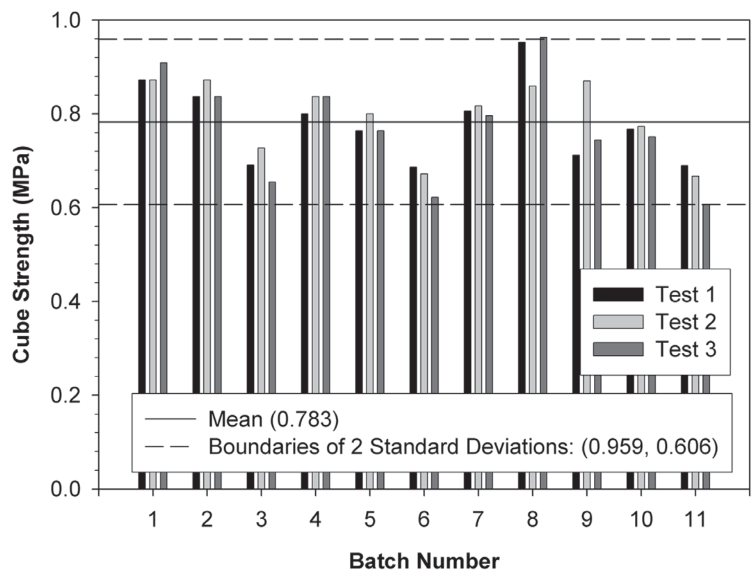

FIGURE 3. Variability of compressive strength between batches.

The results are the cube compressive strengths tested after 7 days aging. There are differences between the compressive cube strengths for each batch, despite each batch containing the same proportions of mix materials. A one-way analysis of variance was conducted at a 95% confidence level to determine the probability that the data from the eleven experiments can be considered to come from the same population. The P-value is the probability of obtaining a statistic at least as extreme as the one actually observed. The P-value from this analysis was found to be 9.59×10^{-8}. The results show that the strengths of the eleven batches are significantly different from one another, even though the proportions of materials are nominally consistent.

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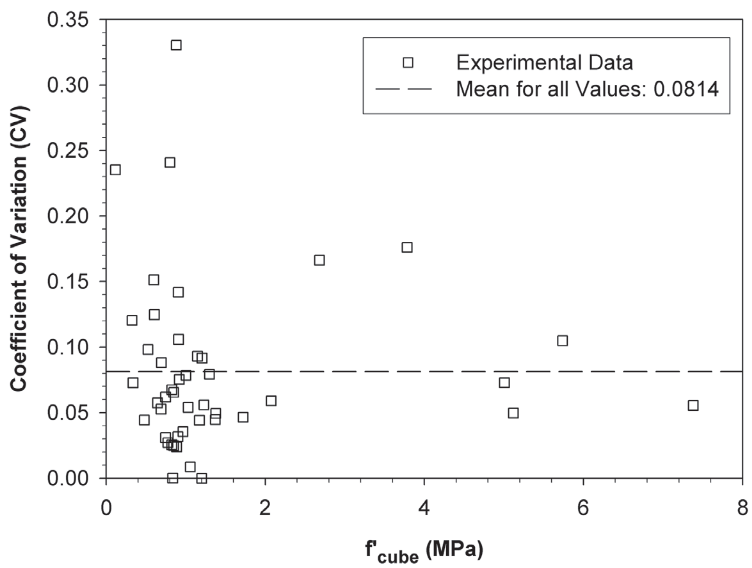

FIGURE 4. Coefficient of variation for cement-lime mortars for a range of mortar strengths.

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The average cube strengths for each of the eleven batches were calculated and considered as individual data points representing the compressive cube strength for each batch (f'_{cube}). The mean and standard deviation of these eleven values of f'_{cube} were then calculated. The mean value is plotted in Figure 3 as a solid horizontal line at 0.783 MPa. Two lines representing the mean value +/- two standard deviations are also shown in Figure 3. It can be seen that there is a range of +/- 0.176 MPa around the mean value of 0.783 MPa, or +/- 22.5%. This is higher than the between-batch variability for structural concrete as reported by Obla (2010).

In addition to variability between batches, there is also variation of strength within a specific batch of mortar. This variation was quantified for the 35 mortar batches listed in Table 1, by calculating the coefficient of variation, *CV,* (standard deviation normalized by the average strength) for each mortar batch (Figure 4). There is no significant influence of mortar strength on *CV*. The average *CV* is 0.0814 with a maximum average *CV* found to be 0.3304. This suggests that the standard deviation of three cube tests of a mortar will be approximately 8.1% of the average strength of the cubes but may be upwards of 33% of the average strength of the cubes. The average value is similar to the same-batch coefficient of variation reported by Cosgrove and Pavia (2009) for mortars.

Age and Strength

Figure 5 presents a relationship between the age and the average compressive cube strength for ages 28 days and less. The strengths of each of the cubes at each of the ages were calculated, and the values were normalized by dividing the cube strengths at the various ages by the average 28 day compressive strength (f'_{cube}/f'_{cube28}). Also included in Figure 5 are data points representing the expected relationship between 7 and 28 day concrete strengths presented in the literature (Kosmatka et al., 2002) and data for cement-lime mortars (Boynton and Gutschick 1964). A trendline, with R^2 = 0.991, was forced to fit the origin and provide a best-fit to the data from the current study and the Boynton and Gutschick (1964) study:

$$\frac{f'_{cube}}{f'_{cube28}} = 0.329\sqrt[3]{t} \qquad (5)$$

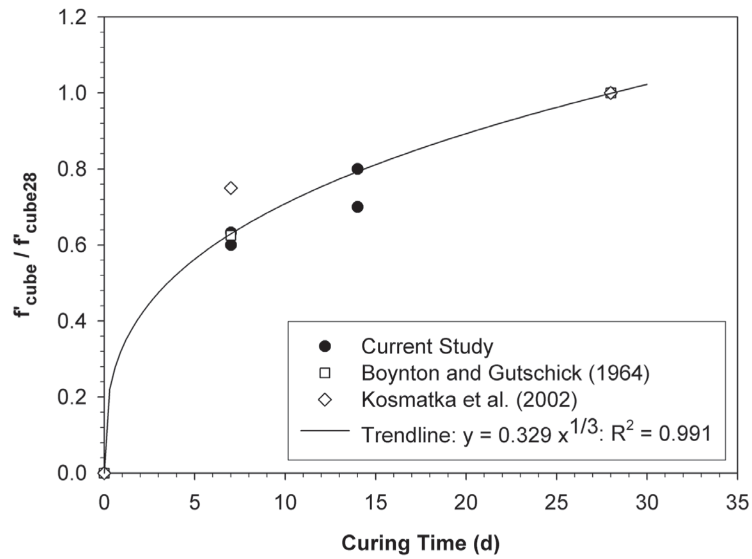

FIGURE 5. Influence of curing time on lime-cement mortar ultimate strength.

where t is the age in days. The curve has a trend similar to that of conventional concrete. However, it should be used with caution for ages less than 7 days.

Effect of w/cm ratio

Figure 6 compares the average cube strength of mortars with *w/cm* ratios of 1.08, 1.18, 1.23, and 1.28 and cured for 28 days. Also included in Figure 6 is the relationship between w/cm ratio and strength for a typical concrete mix (Kosmatka et al., 2002).

The strength of the lime-cement mortar was found to vary between 0.69 MPa and 1.72 MPa, as the water content was decreased. Typically for straw bale construction, mixes are applied to the straw wall and observed for their flow, with the water content adjusted to suit. The range in strength from 0.69 MPa to 1.72 MPa indicates that this practice leads to highly variable mortar strengths.

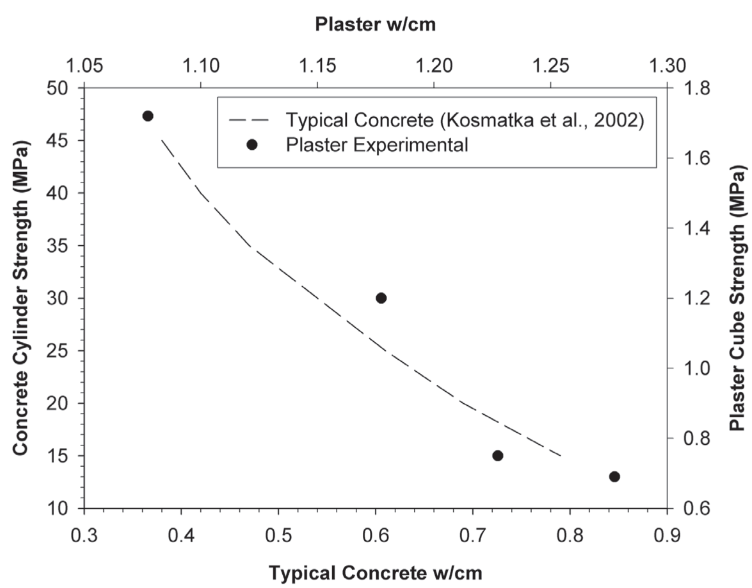

FIGURE 6. Relationship between w/cm ratio and compressive strength.

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Comparison of Cylinder and Cube Tests

The compressive strength of concrete is typically determined by cylinder test as described in ASTM C39 (2004a), while the compressive strength of cement-lime mortars is typically determined by cube experiments as described in ASTM C109 (1998). Figure 7 shows a plot of the ratio of cylinder strength to cube strength, f'_{cyl}/f'_{cube}, (as determined by the average of three specimens of each type) for a number of mortar mixes with a variety of cube compressive strengths, f'_{cube}. On average, cylinder tests of the mortars tested were (0.741)* (cube test values) of the equivalent mortar. This is lower than the case for structural concrete, for which cylinder tests are typically 0.8*(cube test values) (Hansen et al. 1962 and Lyse and Johansen 1962).

The difference between cube and cylinder strengths is in part a result of confinement of cube specimens in the testing apparatus. However, cube test results for predicting the strength of plastered straw bale assemblies has been shown to be appropriate (Vardy 2009, Vardy and MacDougall 2012).

Modulus of Elasticity

Modulus of Elasticity (E_{cyl}) values for mortars with strengths up to 25 MPa were found to range from 528 MPa to 20333 MPa (Figure 8). The values were generally found to increase with increasing cylinder compressive strength (f'_{cyl}). A linear relationship is observed between the cylinder strength and the Modulus of Elasticity:

$$E_{cyl} = 818\, f'_{cyl} \tag{6}$$

The R^2 value for this relationship was determined to be 0.914, with the linear regression line presented in Figure 8 bounded by upper and lower 95% regression interval lines, which represent the region within which there is 95% confidence that the linear trendline will fall. Differences between this relationship and the linear relationships presented by Kaushik et al. (2007) and Sriboonlue and Wallo (1990), can most likely be attributed to the greater proportion of lime in the current study.

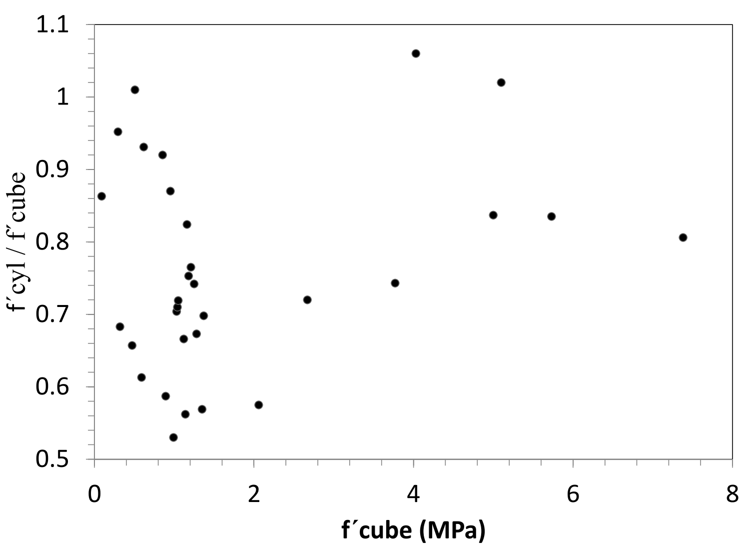

FIGURE 7. Comparison between cube and cylinder compressive strengths.

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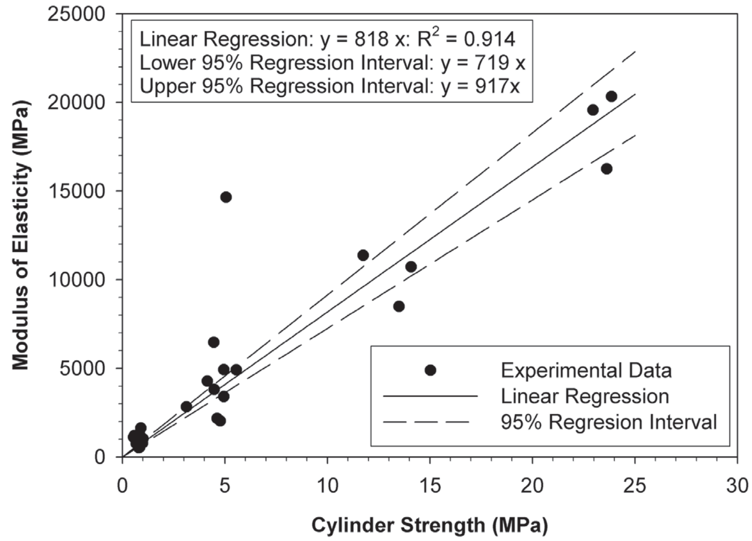
FIGURE 8. Mortar modulus of elasticity as a function of cylinder strength.



Failure Strain

A correlation was not found between the failure strain and the mortar strength, or the failure strain and the mortar Modulus of Elasticity. The anticipated strain at peak stress for low-strength lime-cement mortar is estimated as the average failure strain for all cylinder experiments conducted in this study. This value was found to be 0.00253 with standard deviation of 0.000857 indicating that 95% of all experiments will have a failure strain between 0.000816 and 0.00424. These values are similar to the values reported in the literature for typical concrete, but do not compare well with the values reported in the literature for lime-cement mortar. The differences are likely a result of the lower strengths of the lime-cement mortars presented in this paper.

Model for Stress-Strain Behaviour

Equations 1, 3, and 4 were used to model the stress (f_c) –strain (ε) behaviour of the lime-cement mortars. The values of f'_c, E_c, and ε_o were determined from the experimental data for each cylinder (where $f'_c = f'_{cyl}$, $E_c = E_{cyl}$, and $\varepsilon_o = \varepsilon_{cyl}$). For the 22 experiments to which this modified model was fit, the average R^2 value was found to be 0.965, with a maximum R^2 of 0.996 and a minimum R^2 of 0.856.

Equation 6 is the relationship between E_{cyl} and f'_{cyl}. However, a similar relationship does not exist to provide an estimate of ε_{cyl}. The average failure strain value of 0.00253 may be used for low-strength lime-cement mortar. Using Equation 6 to define E_{cyl} and setting it equal to E_c, and setting ε_o equal to 0.00253, Equation 1 simplifies to:

$$f_c = f'_{cyl}\left(\frac{764.8\varepsilon}{0.935 + (\varepsilon/0.00253)^{1.935}}\right) \qquad (7)$$

This equation is the stress-strain behaviour of lime-cement mortar based on the strength of the mortar. Figure 9 presents a comparison between normalized experimental and theoretical stress-strain curves for 9 mortar cylinders, utilizing Equation 7. The stress values were normalized by the cylinder compressive strength, f'_{cyl}. Cylinders used for the comparison were

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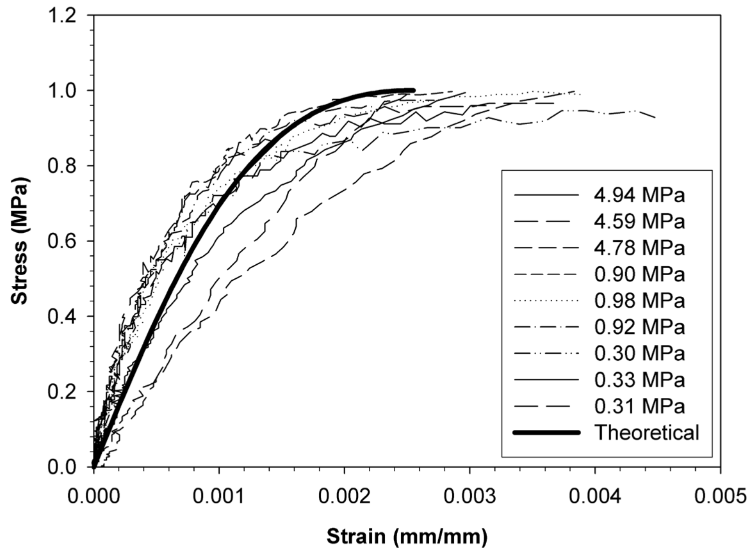

FIGURE 9. Comparison of mortar stress-strain response and theoretical model.

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obtained from three different batches with average mortar strengths ranging from approximately 0.30 MPa to 5.0 MPa. Based on Figure 9, Equation 7 predicts the ultimate strength of the mortar within 10%. There is more scatter in the results in the elastic region (typically considered to be less than 40% of ultimate stress). However, the predicted curve falls well within the scatter of the results, and so can be expected to predict on average the behaviour of the mortar in the elastic region. This is significant to understanding the ultimate capacity of plastered straw bale walls and the load-deflection behaviour under service loading.

It should be noted that data from the tests on the various mortars was used to calibrate Eq. 7, and so Figure 9 does not fully validate the model. However, Vardy and MacDougall (2007, 2012) and Vardy (2009) used the constitutive equation in Eq. 7 to develop an analytical model of plastered straw bale panels. Seven-bale high (2.4 metre high) and 3-bale high (1 metre high) walls were tested in compression until failure. The mortar constitutive model and statistical analysis of the mortar variability was used to successfully capture the structural behaviour of the straw bale panels. This model provides, for the first time, a means for predicting the structural performance (strength and stiffness) of plastered straw bale walls, and thus provides a valuable design tool for engineers who in the past have relied on full-scale testing.

Effect of Mix Proportions on Mortar Strength

A number of mixes were prepared with varying proportions of cement, lime, and sand and strengths determined from cube tests after 28 days curing. The results are presented in Figure 10. It can be seen that, as expected, increasing the volume of cementitious materials to the volume of sand (V_{cm}/V_s) will result in an increase in strength. However, beyond a V_{cm}/V_s ratio of approximately 0.80, increases in cementitious materials do not lead to significant increases in strength.

It is also evident from Figure 10 that increasing the quantity of cement relative to the quantity of lime (V_c/V_l) in the mortar will yield a stronger mortar. The mortars with V_c/V_l of 1.2 yielded significantly higher strengths than any of the other mortars. In fact, these mortars are significantly stronger than necessary for single storey straw bale construction.

FIGURE 10. Variation of mortar strength with proportions of cement, lime, and sand.

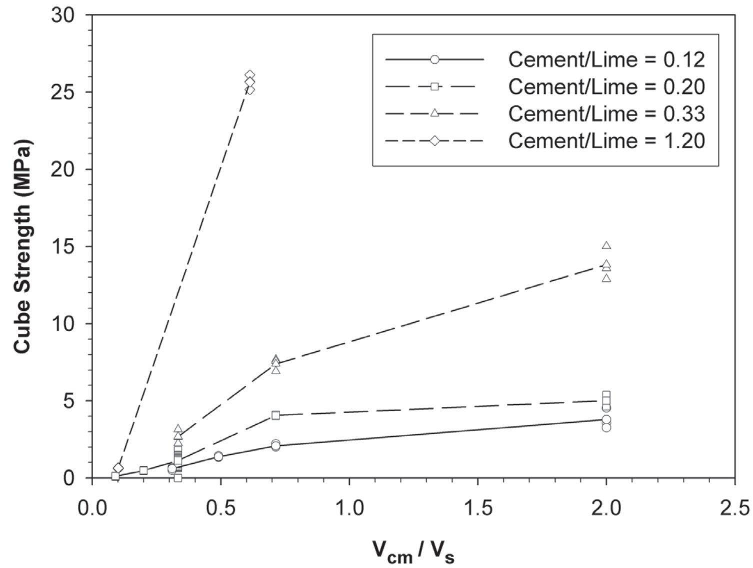
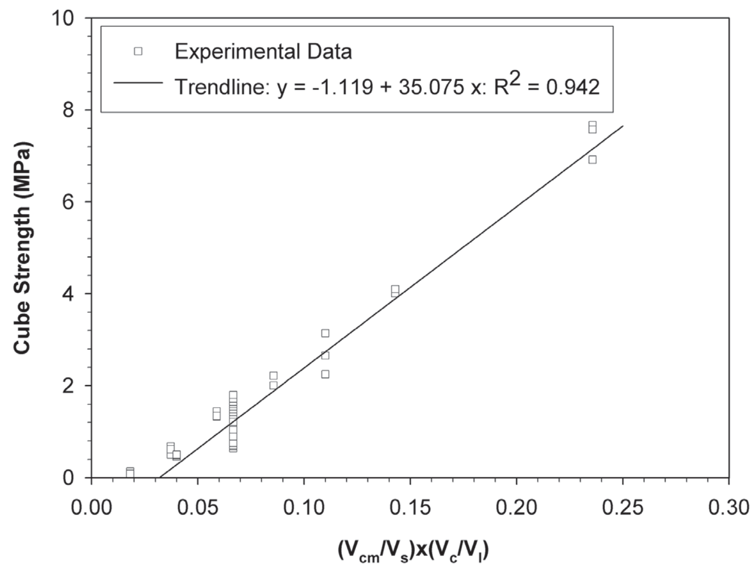


FIGURE 11. Unified curve representing the relationship between mortar strength and volumetric proportions of cement, lime, and sand.



Based on the above observations, the data from Figure 10 was re-plotted in Figure 11 with the data excluded for V_{cm}/V_s ratio of greater than 0.80 and for V_c/V_l of 1.2. Furthermore, the values plotted on the x-axis were modified to also account for the varying values of V_c/V_l (thus creating only one relationship to study in the Figure). The resulting plot in Figure 10 indicates a linear relationship:

$$f'_{cube28} = -1.119 + 35.075\left(\frac{V_{cm}}{V_s}\right)\left(\frac{V_c}{V_l}\right) \quad (8)$$

This relationship gives an estimate of the mortar strength from the proportions of dry materials for a mortar of average workability (slump = 50 mm). This equation has a R^2 value of 0.942 and is valid for V_{cm}/V_s values approximately 0.8 and below, and V_c/V_l values

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TABLE 3. Comparison of Experimental vs. Theoretical Average Cube Strengths.

Proportions (By Volume)			Compressive Strength (MPa)		
Cement	*Lime*	*Sand*	*Theoretical, Eq.8*	*Experimental*	*Exp./Theo.*
1	3	12	2.78	3.10[a]	1.12
1	2	9	4.73	5.17[b]	1.09
1	2	7.5	5.90	3.96[a]	0.67
1	2	9	4.73	5.11[a]	1.08

[a]Boynton and Gutschick, 1964
[b]NLA, 2002

approximately 0.5 and below. Note that if a mix is created with very low ratios of V_{cm}/V_s or V_c/V_l, Equation 8 will suggest the mix has negative strength. This suggests that the equation is not valid for extremely low V_c/V_l or V_{cm}/V_s values. Thus it is suggested that Equation 8 is only valid for V_c/V_l values between 0.12 and 0.5, and V_{cm}/V_s values between 0.1 and 0.71 representing the range of experimental data used to determine the equation.

Table 3 presents a comparison between experimental cube strength results available in the literature and the values obtained from Equation 8. Only the reported results with V_{cm}/V_s and V_c/V_l values within the suggested applicable range for Equation 8 are presented. As shown in Table 3, the theoretical values do not agree completely with the experimental data. One value is off by as much as 33%, which is significantly greater than the expected deviation of no more than 22.5% (the expected deviation from the mean strength for batches designed to be of the same strength). However, the average of the experimental to theoretical strength ratios is 0.99, indicating that, on average, Equation 8 is valid.

CONCLUSIONS

The following conclusions can be drawn from this research:

- Cement-lime mortars for straw bale construction have a higher modulus of elasticity and lower failure strain than a conventional cement-lime mortar of equivalent compressive strength. The Modulus of Elasticity is on average 818 times the compressive strength of the mortar, compared to 100 to 200 times as reported in the literature for conventional mortar. The average failure strain for straw-bale mortar is 0.00253 compared to 0.0087 to 0.0270 reported in the literature for conventional mortar.
- Compressive strengths for straw bale mortars obtained from cylinder tests are on average 0.741*(cube test values). As reported in the literature, cylinder tests of structural concrete are typically 0.8*(cube test values).
- The coefficient of variability of the compressive strength of straw bale mortars is on average 0.0814, but can reach as high as 0.3304 when typical materials and mixing methods are used (volumetric proportioning and using drum mixers). This is similar to the variability in strength reported for other cement-lime mortars.

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