MECHANICAL CHARACTERIZATION OF LIME CEMENT MORTARS: E-MODULUS AND FRACTURE ENERGY

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Abstract

In masonry constructions, the choice of mortar composition is usually guided by requirements of the final application, which could range from new constructions to conservation projects. Often, lime and cement are combined together, to overcome their individual shortcomings and consequently serve as a suitable binder in masonry mortars. Depending on their proportion in the mixture, it may be possible to obtain a desired range of characteristics in different mechanical properties like strength and stiffness. However, existing studies exploring this subject are scarce. Therefore, this work aims at adopting a systematic approach to studying the effect of different lime-cement ratios on the mechanical properties of masonry mortars, specifically targeting a discussion on E-modulus and fracture energy. Three distinct mixes with quantities of lime varying from 25% to 67% (by volume) have been studied. The benefits and trade-offs associated with substitution of different quantities of cement with lime in mortars, have been explored with regard to resistance to crack propagation.

Keywords: Lime-cement mortars, E-modulus, Fracture energy, Shear modulus, mechanical strength

1. INTRODUCTION

To understand the mechanical behaviour of masonry as a system, it is important to be aware of the mechanical performance of its individual components namely, unit and mortar. For the latter, two of the most common binder materials involve air lime and cement which in the recent few years have been increasingly often mixed together [1]. Multiple works of research have studied different mechanical properties of lime-cement blended mortars, in an attempt to overcome the individual shortcomings of either type of binder [1-4]. It has been fairly well established that an increase in the quantity of cement in the binder leads to an increase in mechanical strength of the mortar [5-8]. Workability and permeability, on the other hand have been reported to improve with increase in quantity of lime in the mortar [8][9]. Other parameters, such as drying shrinkage, ultrasound velocity and static E-modulus, were found to have been studied but past works were focussed on discussing other issues and only coincidentally addressing different lime-cement proportions [6,10-11]. Especially with regard to static E-modulus, values were found to vary widely, ranging from 3 GPa to 24 GPa as a function of binder content and composition [12-13]. Furthermore, no work discussing the shear (or G-) modulus or fracture energy of lime-cement mortars could be found in literature. Scattered data on important mechanical properties makes it difficult to consolidate requisite information for characterization of any material. In general, it is difficult to make direct comparisons of experimental data from any two works of different sources, due to differences in more than one variable: type of air lime or cement employed, the proportions used, nature and quantity of aggregate employed, the amount of water used and the workability targeted. These observations make ample room for a systematic experimental campaign which explores the evolution of mechanical properties of mortar as a function of the proportions of different constituents in its binder.

This work aims at a discussion of important mechanical parameters such as E-modulus, G-modulus, fracture energy and mechanical strength of blended mortars, as a function of the quantity of lime or cement in the mortar. The paper studies the evolution of the above mentioned parameters at ages of 7, 28 and 90 days of curing age. The goal is to facilitate the choice of an appropriate mortar in conjunction with the chosen unit, for better performing masonry construction.

2. RESEARCH PROGRAM

2.1 Materials

Air lime, type CL-90S and cement, type CEM I – 42.5 R were used to compose the binder of all the mixes. Despite the fact that CEM II is the cement used more often in field applications, CEM I was chosen to ensure consistency and repeatability of properties in the experimental campaign, as well as to facilitate interpretation of the mechanisms at stake (since the cementitious binder chosen would result in a simpler set of reactions). The binding materials were pre-conditioned at 20°C temperature and 65% relative humidity for up to 7 days prior to casting of the mixes. In accordance with the standard BS 1200-1976, sand with customized particle size range of 0/4 mm, was employed as the aggregate [11]. Before each casting, the aggregates were oven dried at 105°C and cooled down to room temperature, for the sake of consistency in their moisture content.

2.2 Mortar composition

Three different mix compositions were selected with a binder-aggregate ratio of 1:3 by volume. The binder consisted of air lime replacing cement in different proportions by volume, namely 25%, 50% and 67%.

The notations used (Table 1), indicate the proportion of the constituents of the mix, i.e. cement, lime and sand, for instance 1C1L6S denotes a mix ratio of 1:1:6 in the sequence of cement, lime and sand. Additionally, all notations have been supplemented with quantity of lime in the binder in parenthesis, to facilitate comprehension of the reader. Apparent density was employed to convert the proportions from volume to mass. Following EN 1015-3, a flow value of 175±10 mm was targeted for all mixes, to ensure adequate workability with regard to application of mixes on field [14]. Water-binder ratios were determined accordingly (Table 1). The standard EN 1015-11 was used to decide curing conditions for the specimens:

temperature was maintained at 20°C up to the point of testing, with relative humidity maintained at 95% for the first seven days and 65% thereafter [15]. The specimens were demoulded either two or five days after casting, based on the lime content in the binder being less or greater than 50% by mass, respectively as per standard EN 1015-11.

Table 1: Mortar composition – For every 1 m^3 of mortar produced

Nomenclature of mixes		Cement: Lime: Sand (Ratio by volume)	Cement (kg)	Lime (kg)	Water (kg)	Water-Binder ratio (By weight)
Notation	Lime in binder (Volume %)					
3C1L12S	25	3:1:12	262.7	33.4	295.6	1.00
1C1L6S	50	1:1:6	175.1	66.8	303.1	1.25
1C2L9S	67	1:2:9	116.8	89.0	325.0	1.58

2.3 Specimens and experiment specifications

Tests of unconfined uniaxial compression, three point bending (flexural strength), fracture energy, unconfined cyclic compression (static E-modulus) and Poisson's ratio were performed for all three mixes at curing ages of 7, 28 and 90 days. According to standard EN 1015-11, three point bending test was performed on prismatic specimens of size 40×40×160 mm [15]. Displacement control was used at 0.006 mm/s with a preload of 150 N and values were averaged from three specimens. Subsequently, the broken halves were used to measure compressive strength, for which load was applied at the rate of 50 N/s.

In this work, fracture energy has been defined and measured according to RILEM recommendation 50 FMC [16]. It was measured using prismatic specimens of size 40×40×160 mm (Fig 1), with a trapezoid shaped precast notch; 5 mm in depth, equal length of non-parallel sides inclined at an angle of 15° and the shorter parallel side being 2.5 mm in length [16]. Displacement control was used at 0.006 mm/s with a preload of 50 N. Static E-modulus was measured using the conventional unconfined cyclic compression test (Fig 2) with procedures adapted from concrete testing practices [17]. Cylindrical specimens were used, with a height to diameter ratio of 2, and diameter of 60 mm. Load was applied in four continuous loading and unloading cycles, employing a 25 kN hydraulic actuator, and a pre-load of 50 N. To ensure constant duration of each loading cycle, pre-determined at 60 seconds, the loading rate was calculated for each case. Maximum load of each cycle was fixed at approximately one-third of the maximum compressive strength of the mortar at that age. Exactly the same cyclic loading was used to measure lateral deformation in the same cylindrical specimens, in order to calculate Poisson's ratio. A metallic ring with a hinge was fastened at the centre of the specimen with an LVDT attached in the horizontal direction (Fig 3). Results obtained for flexural strength, E-modulus, Poisson's ratio and fracture energy were all averaged from measurements of three specimens each and have been presented with error bars calculated using standard error of the mean value (Standard deviation divided by square root of the number of specimens). Compressive strength was obtained from an average of six measurements from three specimens, i.e. six halves of the three samples used for the flexure test.

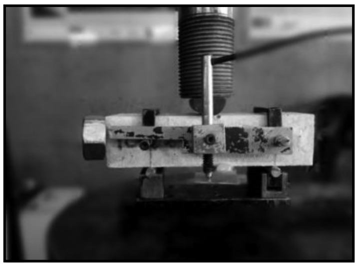

Figure 1: Set-up of fracture energy

Figure 2: Set-up of static E-modulus

Figure 3: Set-up of Poisson's ratio

3. RESULTS AND DISCUSSION

Results obtained for compressive strength (Fig 4) and flexural strength (Fig 5) exhibit expected trends, with the increase in the quantity of cement in the mix leading to higher values of mechanical strength in the mortar. In the case of compressive strength (Fig 4), the mixes with greater quantities of lime, continue to gain strength between 28 and 90 days of curing age with mix 1C2L9S (67%) exhibiting a gain in strength of 2%, and the mix 1C1L6S (50%) exhibiting a gain in strength of almost 30%. This difference in behaviour needs to be investigated further. It may be observed (Fig 4) that the mix 3C1L12S (25%), with the least amount of lime does not demonstrate any increase in strength in the period between 28 and 90 days of curing age. In the case of flexural strength (Fig 5), all mixes exhibit a continued gain in strength up to 90 days of age. One of the reasons for decreasing mechanical strength of mixes with increasing quantities of lime has been attributed to higher specific area of lime compared to cement, which leads to an increase in demand for water of the mix, for the same workability [3, 8]. Additionally, since cement hydration contributes significantly to early gain of strength in blended mixes, a reduction in the weight of cement used in the mixes will cause a drop in strength of the mixes [1]. On the other hand, the presence of lime in the mix, which endures carbonation that induces relevant hardening of this binder, leads to a continued gradual increase in values of mechanical strength which is not observed in mixes consisting of only cement, up to the age of 90 days [2]. Change in mechanical strength of blended mortars has been observed by other authors as well and appears to be adequately validated [3].

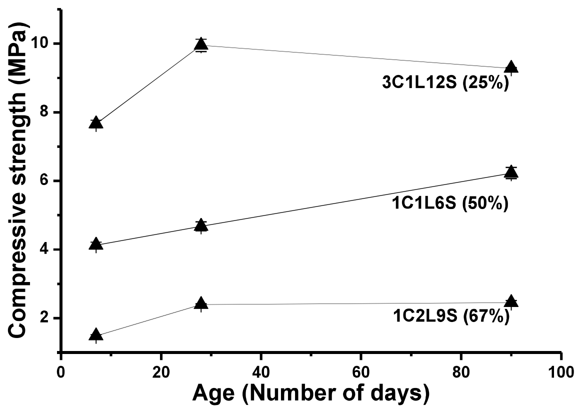

Figure 4: Evolution of compressive strength

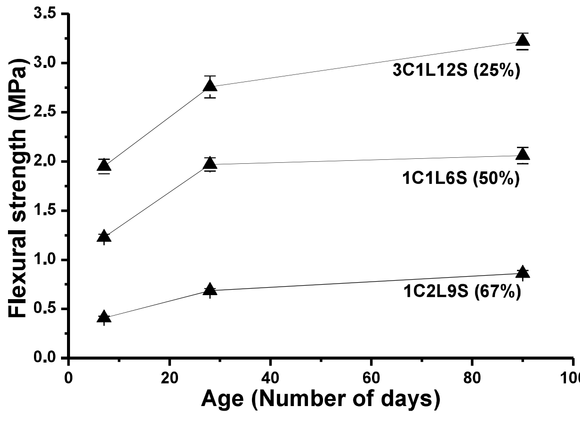

Figure 5: Evolution of flexural strength

Evolution of static E-modulus as a function of lime content in the binder of the mix has been recorded, and shown in Fig 6. It may be observed that the greater the quantity of lime in the mix, the lower is the stiffness of the mortar. While stiffness of all the mixes is observed to evolve with time, the mixes with greater quantities of cement in them seem to gain most of their stiffness in the first 7 days (Fig 6). The increase in stiffness of the mixes between day 7 and day 90 is found to be 7%, 19% and 27% for the mixes 3C1L12S (25%), 1C1L6S (50%) and 1C2L9S (67%) respectively. One may therefore conclude that greater the amount of lime in the binder of the mix more is the continued increase in stiffness, up to the age of 90 days. The most plausible explanation for this increase in stiffness over time may be attributed to stiffening induced by carbonation of the lime, since hydration processes are expected to have been almost completed by 28 days of curing age [3].

Fracture energy exhibits an interesting trend (Fig 7). The mix with the maximum amount of lime, 1C2L9S (67%) shows a continued increase in fracture energy while, the other two mixes, show an increase up to 28 days of age, followed by a drastic decrease in value at 90 days of curing age. This pattern deserves further investigation, especially due to differences in trends observed on comparison with flexural strength (Fig 5) which was measured using the same method of three-point bending. Regardless, it is possible to conclude that greater the quantity of lime in the mix, lower is the energy required for crack propagation through the mortar.

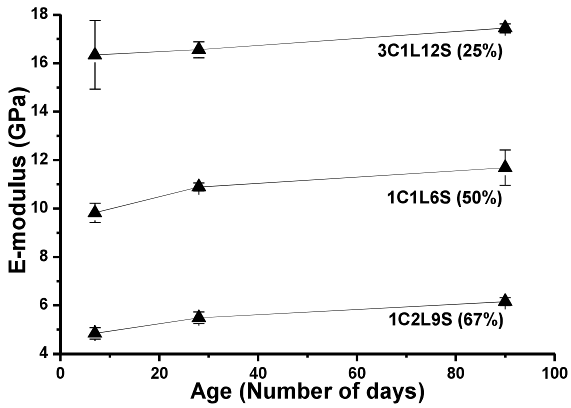

Figure 6: Evolution of E-modulus

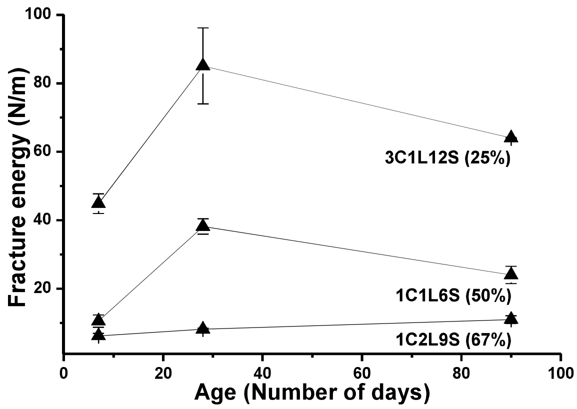

Figure 7: Evolution of fracture energy

Table 2: Evolution of poisson's ratio and shear modulus

Property	Poisson's ratio (COV %)			Shear modulus (GPa)		
Mix/Age (Days)	1C2L9S (67%)	1C1L6S (50%)	3C1L12S (25%)	1C2L9S (67%)	1C1L6S (50%)	3C1L12S (25%)
7	0.12 (17.3)	0.13 (21.4)	0.11 (13.5)	2.16	4.36	7.36
28	0.11 (5.9)	0.09 (8.2)	0.12 (9.7)	2.47	5.00	7.36
90	0.11 (16.7)	0.08 (0.2)	0.13 (14.2)	2.77	5.39	7.70

Poisson's ratio was recorded for the different mixes and has been displayed along with the percentage of variation of each measurement, adjacent to it (Table 2). No specific pattern could be discerned, and almost all values were observed to be in the same range (0.08-0.13). For this reason, shear modulus (G) for each of the mixes was calculated using the average value of E-modulus (E) and Poisson's ratio (υ) measured (Equation 1).

$$G = \frac{E}{2(1+\upsilon)} \quad (1)$$

It was possible to observe that the greater the quantity of lime in the mix, the lower was the value of shear modulus obtained (Table 2). It may also be noted that the value of shear modulus increased with time for all mixes, regardless of binder content. However, the quantity of lime in the binder of the mix was found to influence the extent of increase in values of shear modulus recorded. For instance, between day 7 and day 90 of curing age, shear modulus was found to increase by 28%, 24% and 5% in the mixes 1C2L9S (67%), 1C1L6S (50%) and 3C1L12S (25%) respectively. However, it is worth noting that Poisson's ratio is a parameter that is difficult to measure very accurately and tends to have high values of dispersion, due to the precision and sensitivity of the set up and instrumentation involved. Hence, values of Poisson's ratio were averaged for different mixes regardless of the age at which they were measured (i.e. 7, 28 and 90 days) and it was found that the values were very close; 0.12, 0.10 and 0.12 for the mixes 1C2L9S (67%), 1C1L6S (50%) and 3C1L12S (25%) respectively. Therefore, G-modulus was once again calculated (using Equation 1) for all mixes using one common Poisson's ratio value, 0.11 which resulted from an average of all values (Table 3). It was found that the values of G-modulus did not change much. Rather, the trend of G-modulus increasing with time only became more evident for all lime-cement mixes, at all ages. It may thus be concluded that the greater the quantity of lime in the binder of the mix, the lower is the rigidity or stiffness of the mortar with regard to shear strains.

Table 3: Shear modulus values for lime-cement mixes with averaged value of poisson's ratio

Property	Shear modulus (GPa) with poisson's ratio equal to 0.11 for all mixes		
Mix/Age (Days)	1C2L9S (67%)	1C1L6S (50%)	3C1L12S (25%)
7	2.18	4.42	7.36
28	2.47	4.90	7.46
90	2.77	5.27	7.86

4. CONCLUSIONS

The aim of this paper has been to facilitate the choice of mortar for construction or repair of masonry, such that its behaviour together with the corresponding unit is appropriate for the masonry system. To do so, it is not only important to know the absolute values of different mechanical properties that may be obtained from different combinations of lime and cement in a mortar, but also to be aware of the trends that may be obtained from changing the proportions of constitutes of the binder of the mortar. Values of E-modulus, fracture energy and shear modulus have been discussed as a function of lime content in the binder resulting in the following conclusions:

– Compressive strength and flexural strength of the mortar decrease with increasing quantities of lime in the binder of the mix. However, the presence of lime was found to lead to a more gradual increase in strength especially between 7 and 90 days of age.

- Static E-modulus was found to decrease with increase in quantity of lime in the binder of the mix. Increased quantities of lime in the mixes, led to a continued gain in stiffness of the mortars up to 90 days of curing age.
- Fracture energy was found to be a function of lime content in the binder of the mix with an inversely proportional relationship. Only the mix with maximum amount of lime in the binder 1C2L9S (67%) displayed a continued increase in fracture energy, with time. The other two mixes initially exhibited increase in values of fracture energy up to 28 days of age, followed by a sharp decrease at the age of 90 days. This phenomenon requires further investigation.
- Evolution of Poisson's ratio with time was found to result in values ranging from 0.08 to 0.13 for different lime-cement mixes. Values of shear modulus, on the contrary showed a consistent increase up to the curing age of 90 days for all the mixes. Mixes with greater amount of lime in the binder, displayed lower values of shear modulus.

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