MECHANICAL PROPERTIES OF CLAY BRICK MASONRY BOUND WITH HYDRAULIC LIMES AND HYDRATED CALCIUM LIME.

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ABSTRACT:

Due to their physical and chemical properties, mortars made with lime are considered to be more compatible with historic fabrics than those made with artificial cements. This paper explores the mechanical properties of clay brick masonry bound with hydraulic limes of different strengths, and hydrated calcium lime (CL90-s) with no hydraulic properties. Masonry wallettes built with a CL90-s mortar and two natural limes of hydraulic strengths 3.5 and 5 MPa (NHL 3.5 and NHL 5) respectively were tested for compressive and flexural strength. The strength of the bond between the mortar and the brick was also measured. The paper concludes that CL mortar masonry displays a plastic behaviour in compression while the mechanical behaviour of the HL mortar masonry is of a brittle nature, with wallettes splitting along the centre, cracks above and below the vertical joints and spalling of brick and mortar.

It also concludes that neither the rate of late strength gain of masonry, nor its ultimate compressive strength or its bond strength are determined by the mortar nature, thus a mortar of low hydraulic strength can provide stronger masonry than an emminetly hydraulic mortar. The paper agrees with previous authors on that the masonry's compressive strength is more sensitive to the brick-mortar bond strength than to the compressive strength of the mortar. Finally, the paper demonstrates that the NHL-mortar compressive strength increases at a higher rate, and reaches higher final values than that of the NHLmasonry whereas, in contrast, the CL90-s mortar is weaker in compression than the CL90-s mortar masonry.

Keywords: *CL mortar, hydrated lime, NHL mortar, hydraulic lime, brick masonry, compressive strength, bond strength, flexural strength*

1 INTRODUCTION

Masonry is a layered composite consisting of mortar and masonry units. A good bond between the units and the binding material is essential and determines how the masonry transfers and resists stresses due to various applied loads [1]. Masonry failure is generally accompanied by bond failure in situations where very low brick-mortar bond strengths are noted. Results presented by Sarangapani et al. [2] clearly show a relationship between the compressive strength of the masonry and the strength of the bond. They indicate that an increase in bond strength, while keeping the mortar strength constant, results in an increase in the compressive strength of the masonry.

During the compression of masonry prisms constructed with bricks that are stiffer than the mortar, the mortar in the bed joint has a tendency to expand laterally more than the bricks due to its lesser

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stiffness. However, in a composite material such as masonry the mortar is confined laterally at the brick-mortar interface by the bond between them, hence shear stresses at the brick-mortar interface result in an internal state of stress which initiates vertical splitting cracks in bricks that lead to failure of the prisms [3][4]. It is hence interesting to explore the increase in compressive, flexural and bond strengths of masonry over time and compare this to the strength gains of the mortar (both in flexion and compression) over the same time frame.

There are a large number of studies on the strength of masonry. Gumeste et al. [5] conclude that the crushing of weakest brick in a wallet specimen often determines the masonry strength rather than the interaction between brick and mortar and may mask the influence of the mortar strength on the masonry strength. Gumeste et al. also conclude that the failure of masonry specimens using weak mortar is primarily due to loss of bond between mortar and brick units and in the case of stronger mortars failure is due to splitting of bricks. Venkatarama and Uday Vyas [1] results show that masonry compressive strength is not sensitive to bond strength variations when the masonry unit is stiffer than the mortar. Francis et al. [6] discuss the nature of stresses developed in the masonry unit and the mortar. The development of the brick-mortar bond is generally attributed to the mechanical inter-locking of cement hydration products into the surface pores of the bricks.

Rao et al. [7] state that the flexural bond strength and the masonry's compressive strength are not significantly impacted by the strength of the mortar. The authors demonstrated that mortars with distinctly different compressive strengths but similar bond strength resulted in similar masonry compressive strengths.

Several factors affecting brick-mortar bond were studied by Groot [8]. This study highlights the importance of moisture transport between mortar and brick as this influences hydration of cements. Groot suggests that moisture transport is determined by the rate of absorption of the brick and the mortar's moisture retention therefore these play an important role in bond strength development.

Pavía et al. [9] agreed with the above, demonstrating through testing that the parameter that greatest influences the bond strength of NHL-mortar masonry is water retention, followed by water content and, finally, hydraulic strength. The authors conclude that the strength of the bond is not determined by the hydraulic strength of the binder, as it is generally believed in many sectors of construction, but rather, the strength of the bond is determined by the mortar's water retention: the higher the water retention the strongest the bond. The authors [9] also established a relationship between the masonry's bond strength and the mortar's workability, concluding that the water content that provides the mortar with an optimum workability not always provides the best bond. The authors state that, for the lower hydraulic strengths, the higher the initial flow the stronger the bond whereas for NHL5, a medium flow value (185 mm) resulted in the strongest bond simultaneously providing the highest water retention and best workability.

The objective of this research is to investigate, the bond strength as well as the flexural and compressive strengths of lime mortar masonry after one, two and six months; and relate the types of failure and strength of the masonry to the physical properties of the mortar.

2 MATERIALS AND METHODS

2.1. Materials

Masonry wallettes were built using calcium lime mortar (CL90-s) and two natural-hydraulic-lime mortars of hydraulic strength 3.5 (NHL 3.5) and 5 MPa. (NHL 5) respectively. A well graded aggregate of siliceous composition, was used for all mortar mixes. The aggregate was passed through a sieve analysis in accordance with the requirements of EN 196-1:2005 [10]. The particle

size distribution ranges within the limits specified by the standards. Winchester multi-stock bricks were used for all masonry wallets constructed. The properties of the bricks are set out in table 1.

Table 1. Brick characteristics

Property *(Tested according to EN 771-1 :2003)* [11]	
Compressive strength (N/mm^2)	≥ 12
Water absorption (%)	Max 15
Unit size (mm)	215 x 102.5 x 65
Size tolerance	T2 - R1
Gross density (kg/m^3)	1630
net density (kg/m^3)	1920
Initial rate of absorption (IRA) (kg/m^2/minute)	1.0

2.2. Initial flow and workability

Water content is the main contributor to a mortar's workability and determines its initial flow; the initial flow measurement takes into account various variables affecting workability, such as porosity, size and shape of aggregate, type of binder and relative proportions aggregate/binder [12]. It is not possible to obtain the same workability by mixing CL90-s, NHL 3.5 and NHL5 lime with the same amount of water because of the differing water demands of each of these binders. Hence, in order to ensure consistency, a specific initial flow of 165±3mm, rather than a water content, was specified for all mortars. Initial flow tests were carried out in accordance with EN 459-2:2001[13].

2.3. Mortar mixing and wallette construction

The mortars were mixed in accordance with EN 459-2, which also refers to procedures set out in EN 196-1. The binder to aggregate ratio of 1:3 was kept constant for all mixes. Twelve prisms of each mortar were made in accordance with EN 196-1 for testing compressive and flexural strength. Masonry wallettes and prisms were constructed in accordance with EN 1052-1:1999 [14] for compressive strength, EN 1052-2:1999 [15] for flexural strength and EN 1052-5:2005 [16] for bond strength. Each brick was brushed free from dust and immersed in water for 3 minutes prior to laying. Mortar joints were kept constant at 12mm. Further details of these tests are discussed below.

2.4. Curing

The curing and storage of the wallettes was carried out according to EN 459-2. All wallets were covered with wet hessian and polythene and left for 24hrs to gain an initial set before being moved to storage. Wallettes made from NHL 5 mortar were placed in a curing chamber with a relative humidity of 95±5% and 20±2℃ temperature for 27 days, after which time they were either tested or placed into storage at 60±5% r.h. and 20±2℃ temperature for a further 28 days. The NHL 3.5 mortar masonry was cured in the same manner. The CL90-s mortar masonry was placed into a curing chamber at 60±5% r.h. and temperature of 20±2℃ until tested. The mortar specimens were cured as per the masonry wallettes.

2.5. Mortar testing

The mortar compressive strength tests were conducted according to EN 196-1 with modifications from EN 459-2. Equation 1 below was used to determine compressive strength:

$$R_c = \frac{F_c}{6400} \tag{1}$$

where R_c is the compressive strength, in N/mm^2; F_c is the maximum load at fracture in Newtons; 6400 is the area of the prism face in millimetres (160x40).

The flexural strength of the mortar was determined using the three point flexural test in accordance with EN 196-1 using equation 2 below:

$$R_f = \frac{1.5 \times F_f \times l}{b^3} \tag{2}$$

where R_f is the flexural strength (N/mm^2); F_f is the load applied to the middle of the prism at fracture, in Newtons; b is the side of the square section of the prism, in millimetres; I is the distance between the supports, in millimetres.
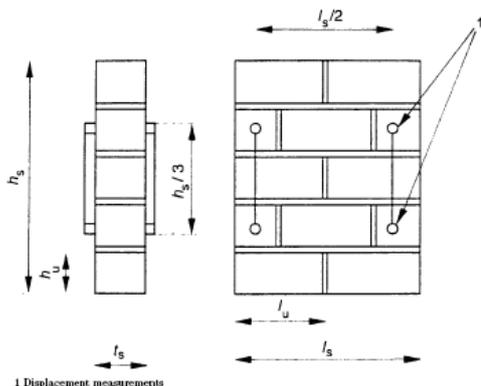
Figure 1. Masonry compression setup [14]

2.6. Compressive strength of masonry

As aforementioned, the compressive strength was tested in accordance with EN 1052-1. Lateral variable displacement transducers (L.V.D.Ts) were set-up on each wallette as shown in figures 1 and 3 to record the strain values during compression.

Equation 3 was used to determine the compressive strength of each wallette:

$$f_i = \frac{F_{i,max}}{A_i} \text{ N/mm}^2 \tag{3}$$

where f_i is the compressive strength of an individual masonry specimen, (N/mm^2); $F_{i,max}$ is the maximum load reached on an individual masonry specimen, (N); A_i is the loaded cross-section of and individual specimen, (N/mm^2). The characteristic compressive strength was determined using the following equation 4:

$$f_k = \frac{f}{1.2} \text{ or } f_k = f_{i,min} \text{ N/mm}^2 \tag{4}$$

(whichever is smaller)

2.7. Flexural strength of masonry

The flexural strength was calculated for both a plane of failure parallel to the bed joints and one perpendicular to the bed joints [15]. Thus two different size wallets and two different testing rig setups are required (figure 2). Equation 5 was used to calculate the flexural strength:

$$f_{xi} = \frac{3F_{i,max}(l_1 - l_2)}{2bt_u^2} \text{ N/mm}^2 \tag{5}$$

where f_{ix} is the flexural strength of an individual masonry specimen, (N/mm^2); $F_{i,max}$ is the maximum load reached on an individual masonry specimen, (N); b is the height or width of a masonry specimen perpendicular to the direction of span, (mm); t_u is the width of a masonry unit, (mm).

The characteristic flexural strength was calculated from equation 6:

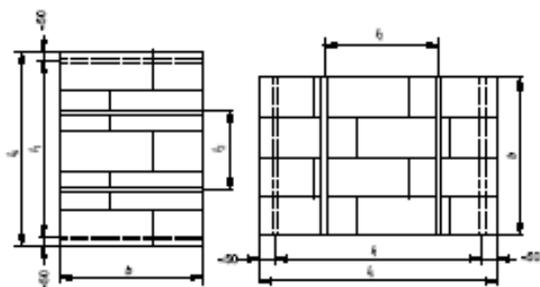$$f_{xk} = \frac{f_{mean}}{1.5} \text{ N/mm}^2 \quad \text{(for five specimens)} \tag{6}$$

Figure 2. Masonry flexural test setup [15]

2.8. Bond strength of masonry.

The bond strength of the brick masonry was determined by testing five-brick-high bonded prism stacks [16]. After curing, the clamping vice and bracket were tightened to the second and top brick respectively. The load was then applied incrementally by adding weights to the extension arm. Following failure, the brackets were removed and the prism risen in order to test the next joint. The flexural bond strength was calculated using equation 6 below:

$$F_n = \frac{(PL + P_1L_1)}{S} - \frac{(P + P_1)}{A} \tag{7}$$

Where:

F_n = net area flexural tensile strength (MPa),
P = maximum machine applied load (N),
P1 = weight of loading arm and brick unit (N)
L = distance from center of prism to loading point (mm),
L1 = distance from center of prism to centroid of loading arm (mm)
S = section modulus of actual net bedded area (mm^3),
A = net bedded area (mm^2).

3 RESULTS AND DISCUSSION

3.1. Mortar properties

As aforementioned, water content is the main contributor to mortar workability and determines initial flow. In table 2, the water content is reported as the ratio of water to total mortar by mass [13]. Results evidenced that a water content of 17.2%, 19.4% and 27.1% was required by the NHL 5, NHL 3.5 and CL90-s limes respectively to give an initial flow of 165 mm.

The mortars were tested for compressive and flexural strength at 28 days and 56 days and 6 months. The results are included in table 2 and figures 3 & 4. According to these, at 56 days, the compressive strength of the CL90-s mortar is 0.89 N/mm^2, corresponding to a M1 [14] and M2 [17] mortar strength class. A 28 day (mean) compressive strength value of 4.39 N/mm^2 and 4.23 N/mm^2 for the NHL 5 and the NHL 3.5 mortars respectively, are equivalent to a M4 strength class [17].

According to the results obtained, the compressive strength of the NHL 5 mortar increases by 60% (to 7.02 N/mm^2) between 28 and 56 days and a further 74% between 56 and 6 months. Both the NHL 3.5 and the NHL 5 mortars gain initial strength at approximately the same rate up to 28 days after which the NHL5 mortar increases strength at a higher rate- figure 3.

The flexural strength of NHL 5 and NHL 3.5 mortars increases by approximately 20% between 28 days and 56 days and by a large margin of 90% and 230% between 56 days and 6 months. The CL90-s mortar gains the vast majority of its strength between 56 days and 6 months.

Table 2. Characteristics of mortars

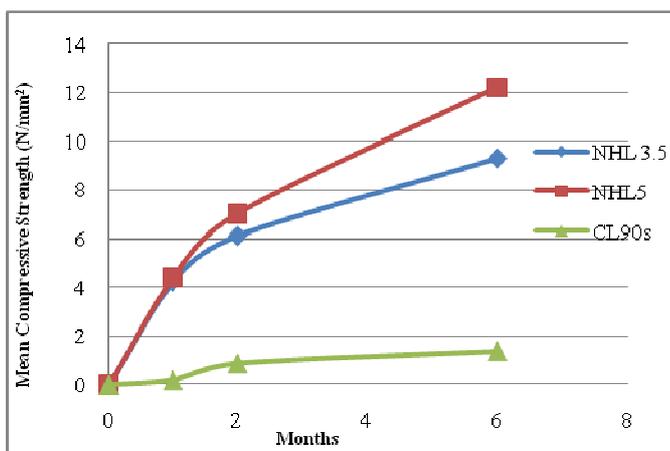| Property	Type of mortar		
	NHL5	NHL 3.5	CL90-s
Proportion (Lime: sand) by weight	1:3	1:3	1:3
Initial Flow (mm)	165	165	165
Water content % (by weight, required to give an initial flow of 165mm)	17.2	19.4	27.1
Compressive strength (N/mm^2)			
28 days	4.39	4.23	-
56 days	7.02	6.11	0.89
6 mts.	12.21	9.86	1.39
Flexural strength (Nmm^2)			
28 days	1.92	0.97	-
56 days	2.33	1.14	0.55
6 mts.	4.47	3.74	2.2

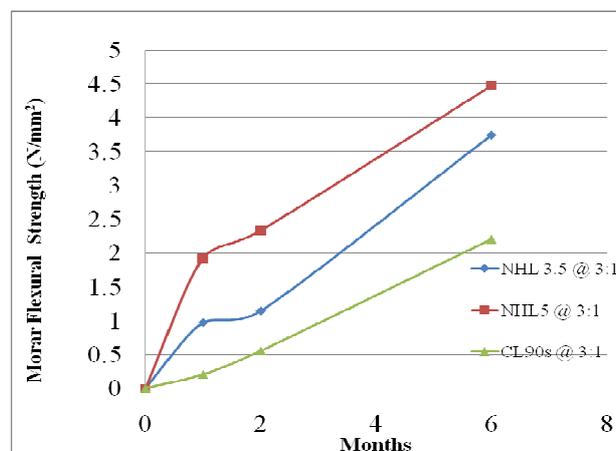**Figure 3.** Compressive strength of mortars

Figure 4. Flexural strength of mortars

3.2. Compressive strength of masonry

Quality and consistency of workmanship has an enormous effect on the strength of masonry [18]. To ensure consistency all wallettes and mortar batches were made by the same mason and the specimen size was kept constant by undertaking rigorous dimensional checks during manufacture. The results of the compressive strength testing of masonry are presented in figure 5. Data are missing for CL90-s masonry 28 days due to the masonry not gaining sufficient strength in order to be tested.

The compressive strength results for NHL 5 and NHL 3.5 (bound) masonry are very similar. They both gain initial strength up to 28 days at approximately the same rate, however, after 28 days, the NHL 3.5 masonry gains strength at a slightly faster rate and, at 6 months, the NHL 3.5 masonry is 6 % stronger in compression than the NHL5 masonry. The compressive strength of the CL90-s

masonry at 6 months is high (3.94 N/mm^2) whereas the compressive strength of the CL90-s mortar at 6 months was only 1.93 N/mm^2.
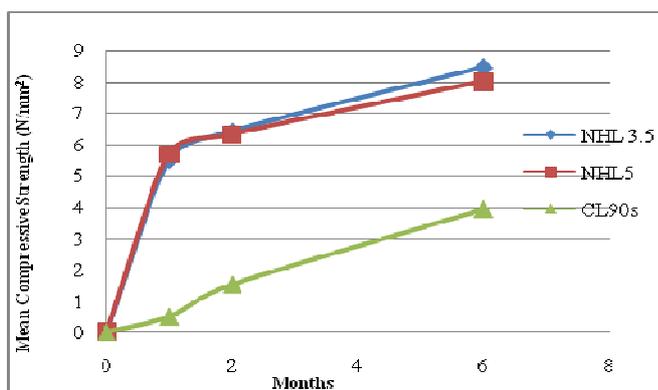

**Figure 5.** Comparison of masonry compressive strengths

Failure of CL90-s masonry in compression was generally due to failure of the mortar: the mortar spread out of the joints as the load increased, indicating both collapse of the bond and mortar downfall. Cracking occasionally occurred in the bricks above and below the vertical joints. These support conclusions by Sarangapani et al [2] suggesting that masonry failure is generally accompanied by bond failure in situations where very low brick-mortar bond strengths are noted.

The mode of failure of the NHL 5 and NHL 3.5 brick masonry is quite different to that of the CL90-s masonry. Generally, the hydraulic lime mortar wallettes split down the centre and develop cracks above and below the vertical joints- figures 6 and 7. Spalling of brick and mortar from the face of the specimen was also common. Sarangapani et al. [2] states that, in this mode of failure, the brick will be in tri-axial compression while the mortar will be in bi-axial tension and compression. The horizontal compression in the brick is the result of the stiff mortar pulling it inwards for strain compatibility. The shear stress of the brick-mortar interface also leads to horizontal compression in the brick. When bond failure finally occurs, the horizontal compression induced will disappear and the brick fails by the lateral tension. The increased stresses caused by the confinement of the mortar in the brick's frog may also influence this mode of failure.

The failure modes discussed above agree with the conclusions of Gumeste et al [5] where the failure of masonry specimens using weak mortar is primarily due to loss of bond between mortar and brick units and in the case of stronger mortars failure due to splitting of bricks.

3.3. Masonry compressive strength as a function of mortar compressive strength

Figure 8 shows the relationship between the compressive strength of the mortar and that of the masonry. As aforementioned, the compressive strength of the NHL5 masonry increases by 11% between 28 days and 56 days however, the corresponding mortar strength increases by 60%. From this, it can clearly be seen that significant increases in mortar compressive strength do not lead to significant increases in masonry compressive strength. The results show that after 56 days and 6 months, the NHL5 mortar is stronger in compression (7.0 & 12.21 N/mm^2) than the NHL5 masonry (6.32 & 8.01 N/mm^2). The NHL3.5 mortar and masonry results show a similar trend, whereas the compressive strength of the CL90-s masonry shows the opposite trend: the mortar being weaker in compression than the masonry. These results support Rao et al [7] and Reddy's [1] conclusions that masonry compressive strengths are not significantly impacted by the mortar strength.
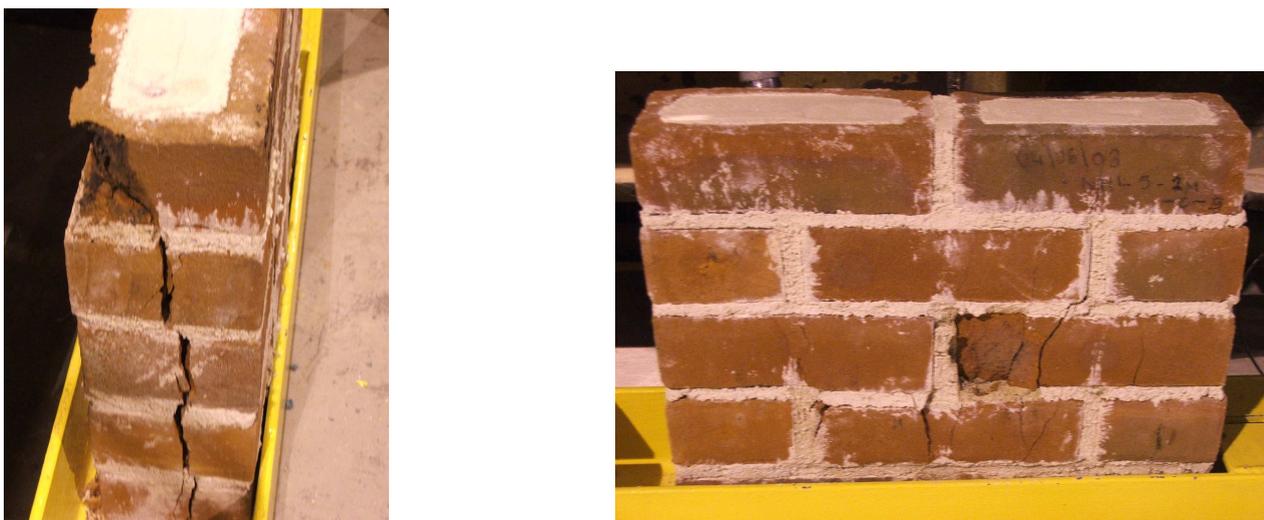
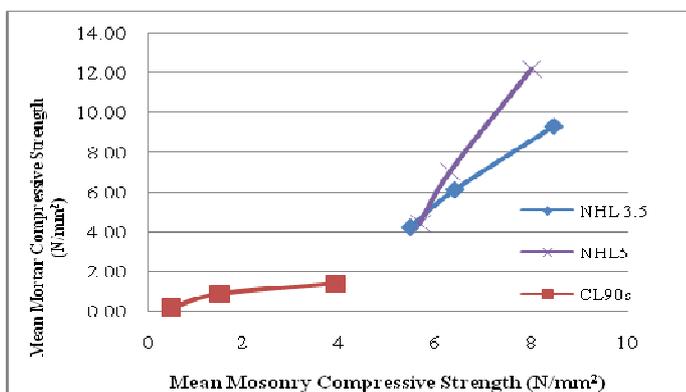**Figures 6 and 7.**   56-day compression test failure of NHL5 masonry

Figure 8. Relationship between the compressive strength of mortar and that of masonry at 28, 56 & 180 days.

3.4. Flexural and bond strength of masonry

Results from both the flexural and bond strength tests are presented in table 3. The results from the bond wrench test [16] compare well with those obtained from the flexural strength parallel to the bedding planes [15]. Both tests show a large increase in the strength of the bond (70% and 90% for the bond wrench and the flexural strength test respectively) for both the NHL5 and the NHL3.5 mortar masonry, between 28th and the 56th day. It is interesting to note that the bond strengths recorded for the NHL 3.5 masonry are greater than those of the NHL 5 masonry (figure 9): at six months, the bond strength of the NHL3.5 masonry is 8 % greater than that of the NHL5 masonry.

The results for the flexural strength perpendicular to the bedding planes cannot be compared with those from the the bond wrench and flexural strength parallel to the bedding, due to the additional force required to overcome the friction within contra-rotation portions of masonry (in a scissor like motion) [19]. In this test, the load increases and approaches a plateau where the wallette has clearly failed. As the loading continues, the wall hinges generally about two points.

Table 3. Flexural and bond strength of masonry

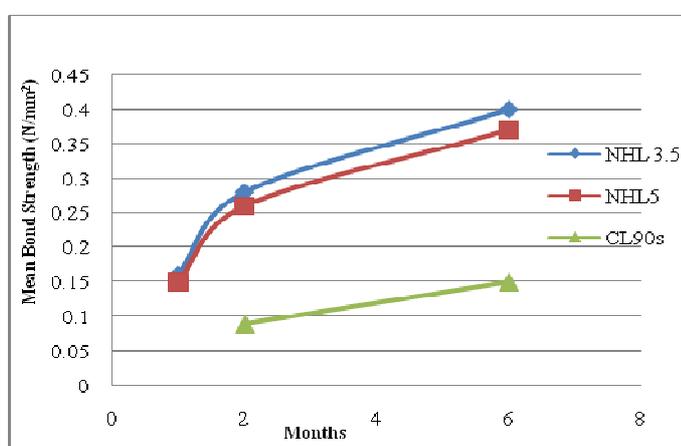| Mortar Type	Specimen Age	Mean flexural strength parallel to horizontal bed joints (N/mm^2) (test 1)	Mean flexural strength perpendicular to bed joints (N/mm^2) (test 2)	Mean bond strength (Bond wrench test) (N/mm^2) (test 3)
NHL5	28 days	0.22	1.08	0.15
NHL5	56 days	0.42	1.23	0.26
NHL 5	6 mts.	0.44	1.54	0.37
NHL 3.5	28 days	0.19	0.72	0.16
NHL 3.5	56 days	0.21	0.88	0.28
NHL 3.5	6 mts.	-	-	0.4
Cl90-s	28 days	-	-	-
Cl90-s	56 days	0.12	0.18	0.09
Cl90-s	6 mts.	0.19	0.25	0.15

Figure 9. Comparison of masonry bond strengths

3.5. Influence of bond strength on masonry's compressive strength.

The bond between brick and mortar is critical for the composite behaviour. The development of lateral tension and compression in the brick and mortar, or vice versa, is based on the assumption that there is no bond failure at the interface. It is hence useful to understand the correlation between bond and compressive strength.

As demonstrated, large increases in mortar strength do not lead to substantial increases in masonry compressive strength (see lack of correlation-figure 8). In contrast, the bond strength has a stronger correlation with the compressive strength of masonry (figure 10) than the mortar strength.

The results also evidenced that a weaker mortar (NHL3.5) with a good bond can often perform better than a stronger mortar (NHL5) with a poorer bond strength.

These agree with previous authors [2] which conclude that the masonry's compressive strength (tested as prisms) is more sensitive to the brick-mortar bond strength than to the compressive strength of the mortar.
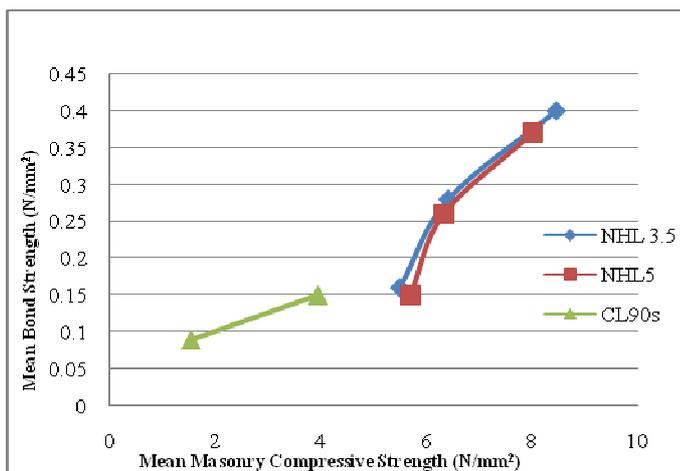
Figure 10. relationship between the bond strength and compressive strength of masonry at 28, 56 & 180 days.

3   CONCLUSION

This paper concludes that calcium lime mortar masonry displays a plastic behaviour in compression (with failure involving mortar spreading out of the joints and rare fractures) whereas, in contrast, the behaviour of the hydraulic-lime brick masonry is of a brittle nature, with wallettes splitting down the centre, cracks above and below the vertical joints and spalling of brick and mortar.

This paper also concludes that neither the rate of late strength gain of masonry, nor its ultimate compressive strength or its bond strength are determined by the mortar nature: a mortar of low hydraulic strength can provide stronger masonry than an eminently hydraulic mortar.
This is based on the following evidence:
- The initial compressive strength gain of NHL 5 and NHL 3.5 masonry is approximately the same, however, after 28 days, the NHL 3.5 masonry gains strength at a slightly faster rate and, at 6 months, the NHL 3.5 masonry is 6 % stronger in compression than the NHL5 masonry.
- The final bond strength (at six months) of the NHL 3.5 masonry is 8 % greater than that of the NHL 5 masonry.
- At 6 months, the compressive strength of the CL90-s masonry is high (3.94 N/mm^2) whereas the compressive strength of the CL90-s mortar is only 1.93 N/mm^2.

The paper demonstrates that the compressive strength of the NHL mortars increases at a significantly higher rate and reaches higher final values than that of the NHL masonry whereas, in contrast, the CL90-s mortars and masonry show the opposite trend. This is based on the following results:
- the NHLmortars are stronger in compression than the NHL mortar masonry (values reached 7.0 and 12.21 N/mm^2 for the NHL5 mortar, and 6.32 and 8.01 N/mm^2 for the NHL5 masonry at 56 days and 6 months respectively).
- the compressive strength of the NHL5 mortar increases by 60% between 28 days and 56 days, however, the corresponding masonry strength only increases by 11%.
- the CL90-s mortar is weaker in compression than the CL90-s mortar masonry.

This paper agrees with previous authors on that the masonry's compressive strength is more sensitive to the brick-mortar bond strength than to the compressive strength of the mortar: the results also evidenced that a weaker mortar (NHL3.5) with a good bond, can often perform better than a stronger mortar (NHL5) with a lower bond strength.

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AKNOWLEDGEMENTS