INFLUENCE OF MORTAR WATER CONTENT ON THE STRENGTH OF LIME MORTAR MASONRY

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Abstract
Water content affects mortar properties and the quality of the resultant masonry, however, it is often subjectively determined by the mason by assessing workability. This lack of explicit methodology and data, can lead to lack of mortar consistency and field performance, adversely affecting full uptake of lime mortars into mainstream technology. The aim of this research is to assist develop consistent lime mortars of high quality, that would improve the strength and durability of masonry. To this aim, the paper investigates the compressive, flexural and bond strength of clay brick masonry bound with natural hydraulic lime mortar (NHL2), at variable water contents delivering different workabilities. The results evidenced that increasing the water content by 1% yields a 5mm increase in initial flow (from 165 to 170mm). It was found that this water increment significantly increases the mortar's compressive strength simultaneously reducing its flexural strength, but it does not increase stiffness under compression. It was also evidenced that the 1% water increment significantly enhances the masonry's compressive, bond and flexural strengths. From these, it was concluded that mixing NHL2 mortars to produce a 170mm initial flow will result in a consistently adequate strength and mechanical behaviour for mortar and masonry.

Keywords: compressive and flexural strength, flexural bond strength, initial flow, lime mortar masonry, water content, workability.

1. Introduction

Despite their successful role in construction over many centuries, the use of hydraulic limes declined with the introduction of Portland cement in the early part of the twentieth century along with the knowledge of how to use them. The use of lime mortars has revived in the past two decades with the understanding that they are more compatible with historic fabrics than any other mortars.

Water content is one of the main factors that affect mortar properties and, therefore, the quality of the resultant masonry. It can have a stronger influence on the properties of mortar and masonry, than the binder type or the nature of the aggregate. For example, it has been proven that mortar porosity, density and water absorption are more significantly affected by water content than by the aggregate quality (Pavía & Toomey 2008). In addition, excessive water adversely affects mortar properties lowering mechanical strength and increasing the risk of failure due to shrinkage. Water excess can also render a mortar too fluid to be workable and weaken adhesion at the mortar-masonry interface thus lowering bond strength. Chemical processes such as lime leaching can also be related to a water excess.

However, despite the great importance of water content, in practice, it is often subjectively determined by the mason by assessing the mortar's workability. This lack of explicit methodology and data, can lead to a lack of consistency of mortar properties and field performance, and these adversely affect the large scale uptake of lime mortars into new building and mainstream technology.

Water contents cannot be universally specified for site works due to differences in the composition and nature of aggregates, binders and additions as well as differences in the material moisture content that depend on the environment and storage. As a result, adding the same amount of water to a 3:1 calcium lime mortar in two different building sites can produce mortars with different properties, workability and performance. However, water content can be determined by making a mortar flow to a specific diameter in a flow table, this can ensure consistency in the amount of water added and the mortar's workability, avoiding the variation in mortar properties trigered by differences in water content and providing mortars with consistent properties and field performance.

Water content determines mortar workability. Mortars should contain the maximum amount of water consistent with optimum workability (Davison 1974). The influence of workability (measured as initial flow) on the flexural and compressive strength of NHL mortars was studied by Hanley & Pavía (2008). The authors concluded that one universal flow value is inadequate and that, in order to optimize mortar strength, NHL3.5 and 5 mortars should be mixed to attain a high (185 mm) flow whereas NHL2 mixes require a significantly lower value (165 mm).

The influence of mortar water content on the bond strength of masonry was studied by Pavía & Hanley (2009). They established relationships between masonry bond strength and mortar properties, concluding that, for NHL5 mortars, a high (185 mm) flow results in the strongest bond, simultaneously providing the best workability and highest water retention while, in contrast, for lower hydraulic strengths (NHL2/3.5 mortars), the flow that optimises workability (165 and 165–185 mm respectively) does not lead to the strongest bond, but it is the highest workable flow that results in the strongest bond and, mostly, highest water retention.

This paper investigates the influence of water content and hence workability, on the compressive and flexural strength of NHL2 mortar and the compressive, flexural and bond strength of NHL2-mortar masonry. It also studies the mechanical behaviour of mortar and masonry by assessing their elastic modulus and their strength development over time at 28 and 56 days.

2. Materials and Methods

2.1 Materials

Mortars were made with a feebly hydraulic lime (NHL2) complying with EN 459-2: 2001 and a siliceous aggregate (particle size distribution ranging within the standard limits - EN196–1: 2005). They were mixed with water to attain two initial flows (165 and 170mm). Moulded, frogged, fired-clay bricks (Table 1) were used to build the masonry.

2.2 Mixing and curing; initial flow and workability

Water content is the main contributor to mortar workability and determines initial flow, a measurement that takes into account variables affecting workability, such as porosity, size/shape of aggregate, binder type and aggregate/binder. (Hanley & Pavía 2008). Mortars were mixed to two distinct flows, 165$\pm$3mm and 170$\pm$3mm, measured in accordance with EN459-2, and the water content reported as the ratio of water to total mortar by mass. Mixing, curing and storage was also in accordance with EN 459-2. A binder: aggregate ratio of 1:3 by weight was kept constant. Masonry wallettes and prisms were constructed in accordance with the relevant parts of EN1052 (1999, 2005) for compressive, flexural and bond strength respectively.

Table 1 Brick Characteristics

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

2.3 Mechanical properties of mortar

Compressive (R_c,) and flexural (R_f,) strength were determined using Equations 1 and 2 (EN196-1:2005, EN459-2:2001). Where: F_c is the max load at fracture (N); 6400-area of the face (mm); F_f -load at fracture (N); b-prism section (mm); l -distance between supports (mm). The mortar's elastic modulus in both compression and flexion were determined from stress vs strain curves. The modulus of elasticity in compression was found using Equation 3. Where: ϵ_c is the strain; σ_c - stress; d_0 - original depth of the prism (mm) and d_i-d_0 - change in prism depth. Equation 3 was also used to determine the modulus of elasticity of masonry. The modulus of elasticity in flexure was found using Equation 4 (EN1052–5:2005). Where: σ_f is the flexural stress (N/mm^2); ε_f is the strain; m the slope of the linear stress-strain plot and D the deflection in mm.

$$R_c = \frac{F_c}{6400} \quad (\text{N/mm}^2) \tag{1}$$

$$R_f = \frac{1.5 \times F_f \times l}{b^3} \quad (\text{N/mm}^2) \tag{2}$$

$$E_c = \frac{\sigma_c}{\varepsilon_c} = \frac{\sigma_c}{\frac{d_i - d_0}{d_0}} \quad (\text{N/mm}^2) \tag{3}$$

$$E_f = \frac{\sigma_f}{\varepsilon_f} = \frac{\sigma_f}{6Dd/l^2} \frac{l^3 m}{4bd_0{}^3} \quad (\text{N/mm}^2) \tag{4}$$

2.4 Properties of masonry

Lateral variable displacement transducers recorded strain during compression (EN1052–1:1999). Equation 5 and 6 were used to determine the compressive (f_i) and characteristic compressive strength. Where: $F_{i,max}$-max load (N); A-loaded cross-section (mm^2). Bond strength was determined with five-brick-high bonded prism stacks (EN1052–5:2005).

$$f_i = \frac{F_{i,\max}}{A_i} \quad (N/mm^2) \qquad (5)$$

$$f_k = \frac{f}{1.2} \text{ or } f_k = f_{i,\min} \quad (N/mm^2) \text{ whichever is smaller} \qquad (6)$$

The flexural strength was calculated for both a plane of failure parallel to the bed joints and one perpendicular to the bed joints according to the methodology and equations in EN 1052–2:1999.

3 Results and Discussion

3.1 Influence of water content on mortar properties

As aforementioned, water content is a main factor affecting workability. Water content is reported in Table 2 as the ratio of water to total mortar mass (EN 459-2). The results (Table 2) evidenced that increasing the water content of the NHL2 mortar by 1% yields a 5mm increase in initial flow and a significant increase in compressive strength (a 24% increase at 28 days and a 37% increase at 56 days- Figure1). This agrees with previous authors (Hanley & Pavía 2008) who tested three different flows (165, 185 and 195 mm) concluding that, for a NHL2 mortar, a flow value closer to 165mm produces the greater compressive strength and an optimum workability.

Table 2 Characteristics of mortars

Property	Type of mortar – NHL 2	
Proportion (lime:sand) by weight	1:3	1:3
Initial Flow (mm)	165	170
Water content (% of total mass)	16.9	17.8
Compressive strength R_c (N/mm^2)		
28 days	1.87	2.32
56 days	2.29	3.14
Elastic Modulus E_c (N/mm^2) under compression		
28 days	26	25
56 days	39	32
Flexural strength R_f (N/mm^2)		
28 days	0.51	0.49
56 days	0.73	0.57
Elastic Modulus E_f (N/mm^2) in flexion		
28 days	100	128
56 days	246	153

Surprisingly, the results also suggest that an increase in compressive strength does not lead to an increased stiffness under compression (Figure 2): the mortar's elastic modulus in compression remains nearly constant at 28 days but reduces by 18% at 56 days. This indicates that over time, under compression, the mortar increases strength simultaneously becoming more plastic.

At 28 days, the flexural strength of NHL 2 mortar does not appear to be greatly affected by the water content increase (it reduces by 0.02 N/mm^2). However, at 56 days the flexural strength reduces by 22% (Figure 3). The elastic modulus in flexion does not show a consistent trend (Figure 4).

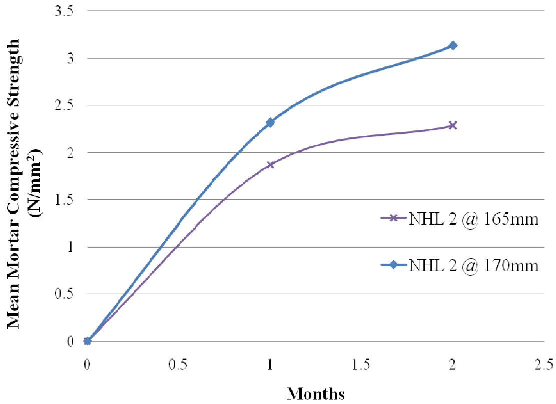

Figure 1 - Compressive strength of mortars

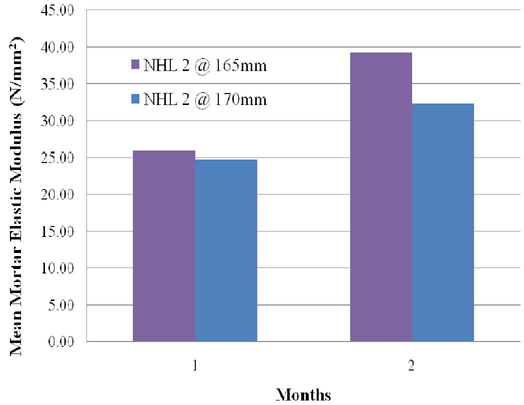

Figure 2 - Elastic modulus of mortars under compression

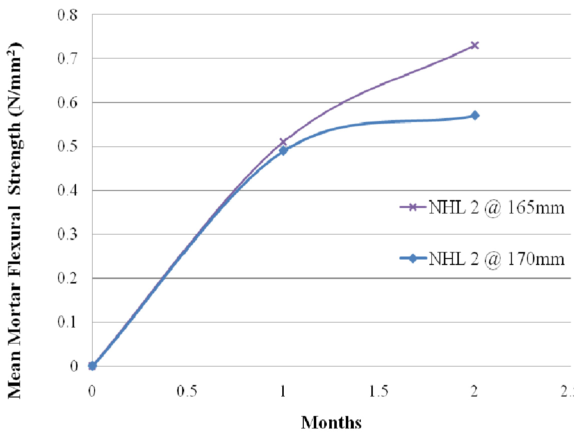

Figure 3 - Flexural strength of mortars

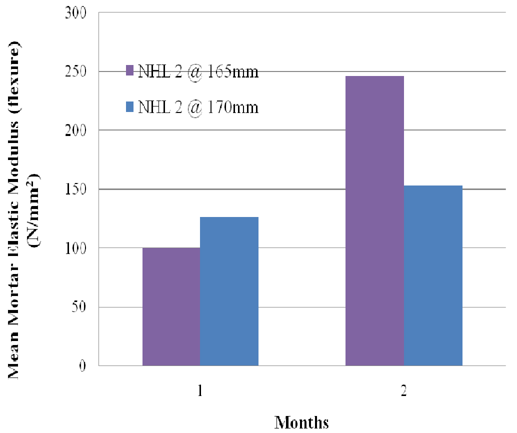

Figure 4-Elastic modulus of mortars in flexion

3.2 Influence of mortar water content on masonry properties

As it can be seen from the results in Table 3 and Figures 5 and 6, increasing the initial flow from 165 to 170mm leads to significant increases in both the bond strength and the compressive strength of the masonry: at 56 days, the compressive strength of the masonry increases by 24% (from 4.59 to 6.53) while the masonry bond strength increases by 29%.

The results also show that, while the mortar's elastic modulus in compression reduces due to the increase in water content (Figure 2), in contrast, the elastic modulus of the masonry increases both at 28 and 56 days, showing an increase of approximately 20% at 56 days (Figure 7). These indicate that, as the water content increases by 1% (from 165 to 170 mm flow), the mortar becomes less stiff while the masonry becomes stiffer. Finally, the masonry's flexural strength both parallel and perpendicular to the joints (Figure 8) increases with the water increment (11% and 22% for the flexural strength parallel to the joints and 2 and 4% for that perpendicular to the joints at 28 and 56 days respectively) in contrast, as aforementioned, the flexural strength of the mortar drops with increasing flow.

This lack of correlation between the strength and mechanical behaviour of the mortar and those of the masonry has been evidenced before (Costigan & Pavía 2009 and 2010). These agree with previous authors concluding that the masonry's compressive strength is more sensitive to the brick-mortar bond strength than to the compressive strength of the mortar (Sarangapani et al. 2005), and that the masonry's bond and compressive strengths are not significantly impacted by the strength of the mortar (Venumadhava Rao et al. 1997).

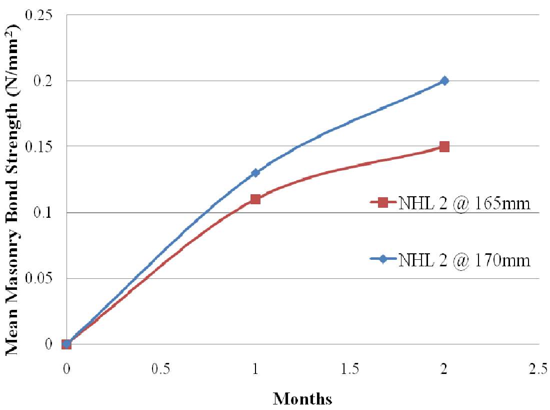

Figure 5 - Influence of mortar's water content on the compressive strength of masonry

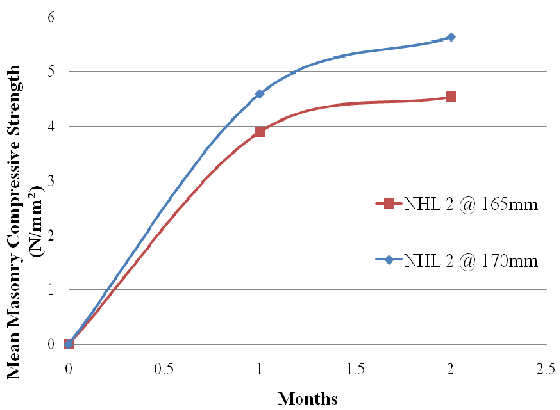

Figure 6 - Influence of mortar's water content on masonry's bond strength

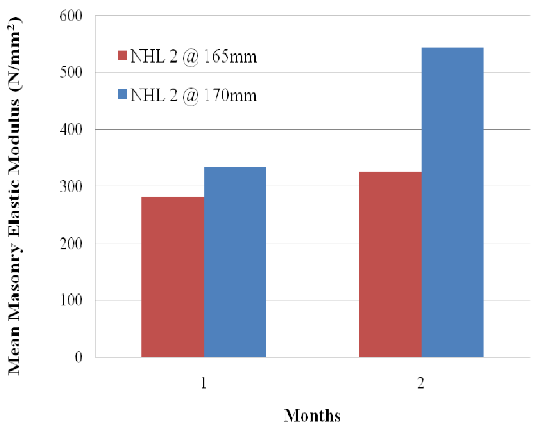

Figure 7 - Influence of mortar's water content on the elastic modulus of masonry

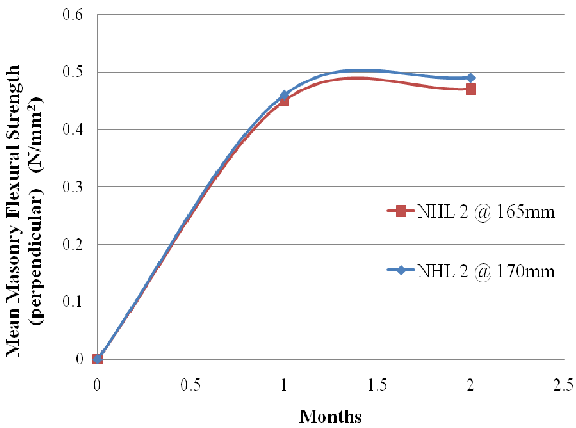

Figure 8 - Influence of mortar's water content on the flexural strength of masonry

Table 3 - Properties of masonry built with NHL 2 mortar with different water contents.

Mortar Initial Flow (mm)	Age (days)	Compressive Strength (N/mm^2)	Elastic Modulus (N/mm^2)	Mean flexural strength parallel to bed joints (N/mm^2)	Mean flexural s. perpendicular to bed joints (N/mm^2)	Mean bond strength (Bond wrench test) (N/mm^2)
165 mm	28	3.90	281	0.08	0.45	0.11
170 mm		4.59	334	0.09	0.46	0.13
165 mm	56	4.54	325	0.14	0.47	0.15
170 mm		5.63	544	0.18	0.49	0.20

(Mean of 3 specimens for compressive/bond strength/elastic modulus; 5 for flexural strength)

4 Conclusions

Increasing the water content of NHL2 mortar by 1% yields a 5mm increase in the initial flow value (from 165 to 170 mm). It was found that, while this increase in water content leads to a significant increase in mortar compressive strength (24% increase at 28 days and 37% at 56 days), it does not lead to an increased stiffness in compression.

Increasing the water content by 1% reduces the flexural strength of the mortar simultaneously raising the masonry's flexural strength both parallel and perpendicular to the joints (by 11% and 22% for the flexural strength parallel to the joints at 28 and 56 days respectively and 2 and 4% for that perpendicular to the joints).The masonry's flexural strength parallel to the bedding joints experiences a greater increase than that perpendicular to the joints.

A 1% increase in mortar water content leads to significant increases in both the bond strength (29% increase at 56 days) and the compressive strength of the masonry: 24% increase at 56 days. Therefore a 170mm flow value enhances NHL 2 mortar masonry strength.

Under compression, as the water content increases by 1%, the mortar becomes more plastic while the masonry becomes stiffer.

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