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Mechanical and fluid transfer properties of some lime and Portland cement mortars.

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ABSTRACT: The type of binder determines mortar properties, and these impact the durability of masonry. This paper intends to assist on the choice of mortar for a particular fabric, by investigating the properties of mortars made with calcium lime (CL90), Portland cement (PC) and natural hydraulic limes of three hydraulic strengths (NHL2, NHL 3.5, NHL5), and the influence of water content on mortar properties. The results evidenced an inverse relationship between the binder's hydraulicity and the mortar's shrinkage, porosity, capillary suction and water absorption; and a direct relationship between the binder's hydraulicity and the mortar's density and mechanical strength. The paper concludes that even though the volume of voids accessible to water in lime and cement mortars is comparable, the pore system of lime mortars is much more efficient transporting moisture by capillarity. It was noted that an increase in the mortar's water content lowers bulk density, but does not significantly affect neither shrinkage nor the amount of voids accessible to water. It was also noted that, for the more hydraulic limes, mechanical strength tends to increase when mortars are mixed to higher flows, whereas feebly hydraulic mortars mixed to lower flow possess a superior mechanical resistance.

1 INTRODUCTION

The nature of the binder greatly impacts the physical properties of a mortar because it determines a mortar's cohesiveness and its intrinsic bond (Pavía 2008). Limes and Portland cement are common binders for masonry mortars.

Mortars containing hydrated material within their binder are hydraulic, and this hydrated material is the main responsible for strength. When water is added to a hydraulic binder such as hydraulic lime or Portland cement, the C_3S (alite) and C_2S (belite) react with water and hydrated calcium silicate (C-S-H) and other hydrates are formed as the mortar hardens, reactions known as hydraulic set. The C-S-H is the main responsible for the mortar binding properties, faster hardening (early strength development) and higher ultimate strength.

Hydraulic and non-hydraulic limes differ in their properties, composition and the manner by which they harden. Hydraulic limes harden to a greater or lesser extent due to hydraulic set (depending on their hydraulic strength- EN 459-1 (2005)), whereas non-hydraulic limes such as calcium lime (CL), harden by carbonation: a slow reaction between their CaO and atmospheric CO_2.

CLs typically show higher permeability; flexibility; plasticity; shrinkage in early hardening stages; solubility in carbonic water and lower mechanical strength (Vicat 1837, Ashurst & Ashurst 1988). They are generally advised for use with porous and weathered masonry units of lower strength (Gibbons 1995, Pavía & Bolton 1997, Holmes & Wingate 1997, St Astier/CESA 2005, Traditional Lime Co. 2000). Hydraulic limes display an early strength and a higher ultimate strength due to their hydraulic set. When compared to CLs, they are assumed to posses a lower permeability and deformability, and a better resistance to moisture, frost and salt attack, being used with strong, impermeable masonry units in exposed, damp environments.

Mortars influence the durability of masonry. It is generally accepted that a mortar must not be stronger than necessary (EN 5628-1, 2005), as excessively strong mortars can concentrate stresses in fewer and wider joints transferring stresses to masonry units causing fracturing. Under stress, an ideal mortar needs to initially behave as an elastic material absorbing stress to recover part of its strain when unloaded, simultaneously suffering a certain degree of plastic deformation due to re-arrangement of mineral components, a strain not completely recoverable (Pavía 2006). However, eminently hydraulic binders such as PC tend not to absorb movement, thus transferring stresses into the adjacent masonry, and this may lead to failure. The mortar quality also determines moisture movement within the masonry, an important factor in the onset of weathering processes. For example, impermeable mortars increase moisture transport through masonry units, enhancing pollutant deposition, mineral alteration, biological colonization, salt crystallization and frost damage.

It is generally accepted that lime mortars possess lower strength, a greater capacity of deformation and higher fluid transfer ability than PC mortars and, as a result, they are more compatible with certain masonry materials than PC mortars. However, normally, this is not quantified and no physical property values are presented in order to support such compatibility statements. This paper provides specific property values that can assist on making an informed choice on the appropriate use of a specific mortar with a particular type of masonry unit.

2 MATERIALS AND METHODS

2.1 *Mixing and curing*

This was carried out according to EN 459-2 (2005). All mortars are 1:3 mixes (binder: sand by weight). Initially, five mortars were mixed to 175 mm flow, each using a different binder: CL90, NHL2, NHL3.5, NHL5 and PC. In addition, three mixes were made using NHL2, NHL3.5 and NHL5, each mix including the amount of water required in order to attain the specific flows of 165, 185 and 185 mm respectively. The water content, expressed as a percentage of the mortar's mass, is included in table 1. The CL90 and NHL2 mortars were demoulded after 3-4 days, and placed in a curing chamber, for 56 days, at 20°C temperature and 60% humidity; while the NHL3.5, NHL5 and PC mortars were demoulded after 1-2 days, and placed in a curing chamber, for 56 days, at 20°C temperature and 90% humidity.

Table 1. Water content of 1:3 mortars mixed to specific flows.

Mortar type	water content %
CL90- 175mm	8.84+X*
NHL2- 165mm	17.76
NHL2- 175mm	19.09
NHL3.5- 175mm	15.96
NHL3.5- 185mm	16.55
NHL5- 175mm	14.77
NHL5- 185mm	15.25
OPC- 175mm	14.52

* *% water in the hydrated lime (slaked with a water excess).*

2.2 *Water content and initial flow*

A mortar's water content determines its initial flow, and workability. As aforementioned, five mortars were mixed to 175 mm flow (EN459-2 2005), each using a different binder: CL90, NHL2, NHL3.5, NHL5 and PC. In addition, three mixes were made using NHL2, NHL3.5 and NHL5, each mix including the amount of water required in order to attain the specific flows of 165, 185 and 185 mm respectively.

2.3 *Shrinkage*

The decrease in length of the specimens was measured, along the longitudinal axis, according to American cement standards (ASTM 1996). Shrinkage was measured with gauges accurate to 0.002 mm, on a daily basis, for the first 28 days of curing.

2.4 *Capillarity*

The water absorption coefficient by capillary rise C (kg.m^{-2}.s$^{-0.5}$) was measured according to EN 1925 (1999). The dry mass (m_{d}) and the area (A) of the specimen's base were noted. The samples were immersed in water to a depth of 3±1mm, at time intervals their masses (m_{i}) were measured, and C expressed according to equation 1 below:

$$C = \frac{mi - md}{A\sqrt{t_i}}$$

(1)

2.5 *Water absorption*

In order to quantify the volume of voids accessible to fluids, the mortars were submerged in water until a constant weight was achieved (m_a), and absorption expressed as the percentage of water absorbed in relation to the dry mass (m_{ad}) (UNE 1984)- equation 2.

$$WA\ (\%) = (m_a - m_d\ / m_d) \times 100 \qquad (2)$$

2.6 *Density and porosity*

These were tested according to RILEM (1980). The samples were dried to a constant mass m_d; the hydrostatic weight m_h and the weight at atmospheric pressure m_s noted and the bulk density (δ) determined with equation 3 below:

$$\delta = \frac{m_d}{m_s - m_h} \qquad (\text{g/cm}^3)$$

(3)

The open porosity (ratio of the volume of voids accessible to water to the bulk volume of the sample) was calculated according to the following equation (4).

$$P\ (\%) = \frac{m_s - m_d}{m_s - m_h} \times 100 \qquad (4)$$

2.7 *Flexural strength*

The flexural strength (R_f) was determined with the three point flexural test (EN196-1 2005), and calculated using equation 5. Where: F_f is the peak load (N); b the side of the square section of the prism (mm) and l the distance between supports (mm).

$$R_f = \frac{1.5 \times F_f \times l}{b^3} \text{ (MPa)} \quad (5)$$

2.8 *Compressive strength*

The compressive strength (R_c) was calculated with equation 6 below (EN459-2); where A (mm²) is the sectional area of the sample and F the load at which failure occurred.

$$Rc = \frac{F}{A} \text{ (MPa)} \quad (6)$$

3 RESULTS

3.1 *Shrinkage*

The results evidenced that shrinkage was more significant in the mortars of lower or no hydraulicity (Fig. 1): as hydraulicity increases less shrinkage occurs, with the NHL5 and PC mortars showing the lowest values. The NHL2 mortars shrunk the furthest, however, shrinkage was uniform and no significant cracks appeared.

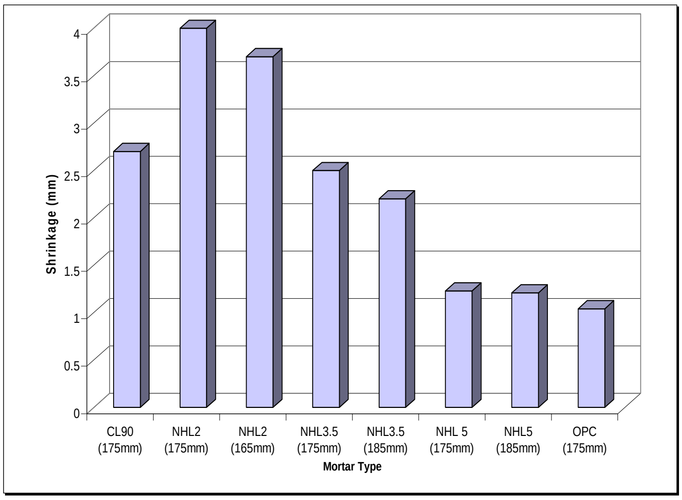

Figure 1. Mortars' decrease in length over 28 days.

According to the results, shrinkage seems to be more determined by the nature of the binder than by the amount of water in the mix (the NHL3.5 and NHL 5 mortars mixed to lower flows shrunk further than those mixed to higher flows). The results also evidenced that the shrinkage of the NHL 5 mortar is of similar magnitude to that of the PC mortar.

3.2 *Porosity*

Porosity tends to decrease as the binder's hydraulicity rises (Fig. 2): the CL90, NHL 2 and NHL 3.5 mortars show the greatest porosity whereas the eminently hydraulic mortars (NHL5 and PC) show the lowest values. However, the porosity of the NHL5 and PC mortars is similar, and only approximately 10% lower than that of the non-hydraulic (CL) and feebly hydraulic lime mortars (NHL2). The results also suggest that an increase in the amount of mixing water does not significantly raise the number of voids accessible to water in the hardened mortar (there is no significant increase in porosity for the higher initial flow values).

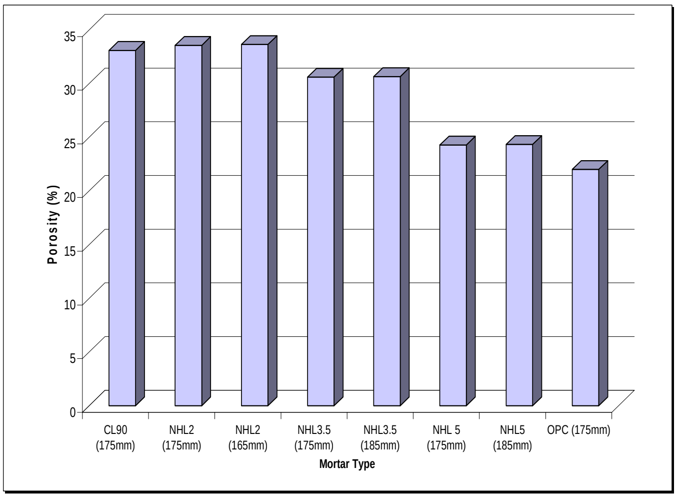

Figure 2. Porosity of PC and lime mortars.

3.3 *Water absorption*

As expected, water absorption and porosity show a similar trend (Fig. 3): the greatest water absorption occurs in the CL90, NHL2 and NHL 3.5 mortars; and the absorption of the NHL5 and PC mortars is similar, and only 6-10% lower than that of the non-hydraulic and feebly hydraulic lime mortars. In addition, there is no significant increase in absorption for the higher initial flows; therefore, an increase in the amount of mixing water does not significantly raise the mortar's water absorption.

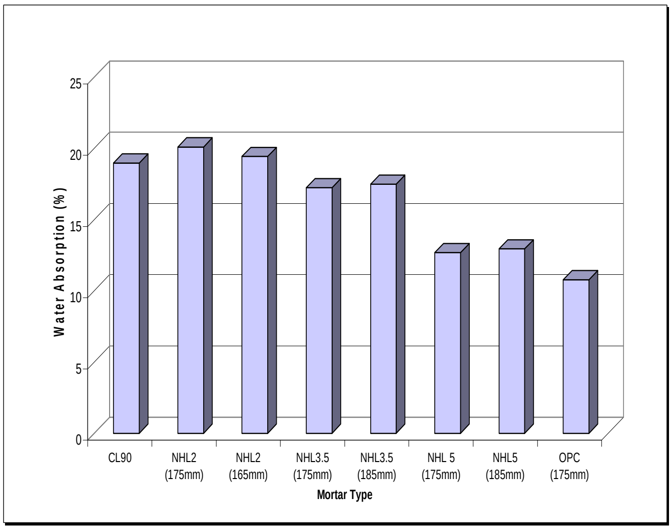

Figure 3. Water absorption of PC and lime mortars.

3.4 *Capillary suction*

According to the results (Fig. 4) all lime mortars possess a high capillary suction, significantly higher than that of the PC mortars. The CL90 and NHL 2 mortars show the highest suction: the suction of the NHL 2 is nearly 5 times greater than that of the PC mortar. This suggests that the type of binder strongly influences the mortar's capillary suction (all mortars were made with identical aggregate and aggregate to binder ratios). The water content of the mix does not seem to impact the suction of the hardened mortar: the suction of the mortars mixed to different flows is nearly identical.

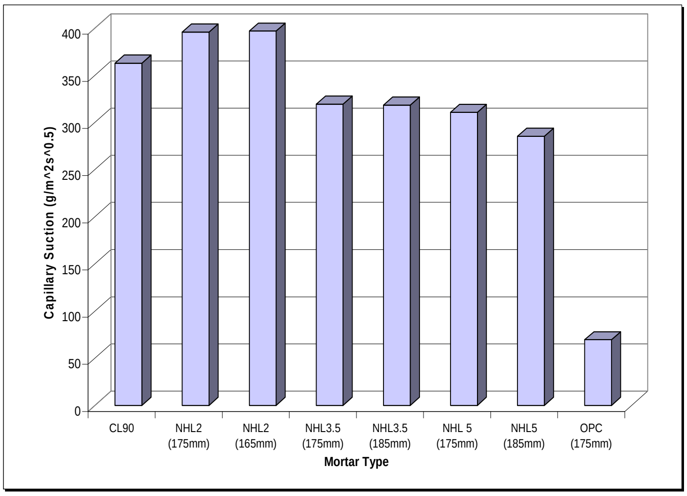

Figure 4. Capillary suction of PC and lime mortars.

3.5 *Bulk density*

As expected, the PC and NHL 5 mortars show the highest density (Fig. 5) thus they possess compact, tightly packed microstructures: the bulk density of the PC mortar is approximately 20% higher than that of the NHL2 mortar. The results also evidenced that an increase in the amount of mixing water lowers the mortar's bulk density (the mortars mixed to lower flows consistently show the greatest density), however, this tendency becomes less pronounced in the mortars of higher hydraulic strengths: the average density of the 165mm NHL2 mortar is approx. 4.9% greater than that of the 175mm NHL2 sample; while the average density of the 175mm-NHL3.5 mortar is 2.5% greater than that of the 185mm flow sample; and the density of the 175mm-NHL5 mortar is 1.9% higher than that of the 185mm flow sample.

3.6 *Flexural strength*

As expected, there are significant differences in flexural strength (Fig. 6): the strength of the PC mortar is approximately 7 times greater than that of the CL mortar and 9 times greater than that of the NHL2 mortar. The difference in flexural strength between the lower and higher hydraulic strengths is also significant: the flexural strength of NHL 5 mortar is at least 6 times greater than that of the NHL2 mortar. With respect to the amount of water in the mix, the results suggest that, for the higher hydraulic strengths, the higher the flow the greatest the flexural strength: there is an over 20% strength increase from the 175 to the 185 flow for the NHL5 mortar and a 10% strength increase from the 175 to the 185 flow for the NHL3.5.

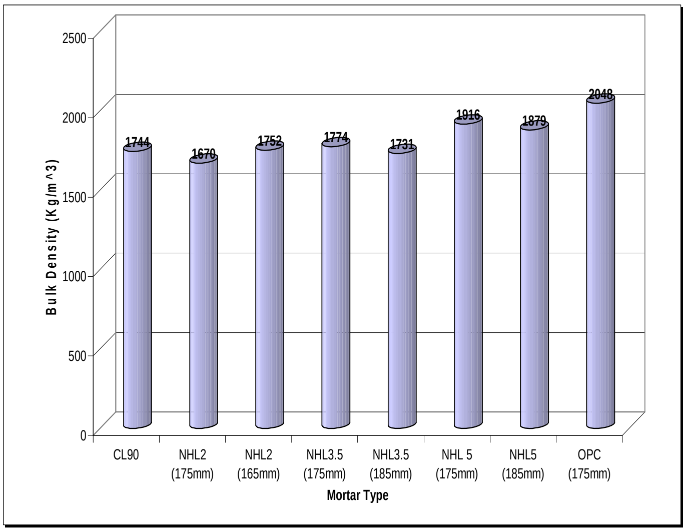

Figure 5. Bulk densities of lime and PC mortars.

On the contrary, for the NHL2 mortars the strength of the lower and higher flows sample are too close to establish a trend. The coefficient of variation suggests that the lime mortars results are less consistent than those of the PC mortar.

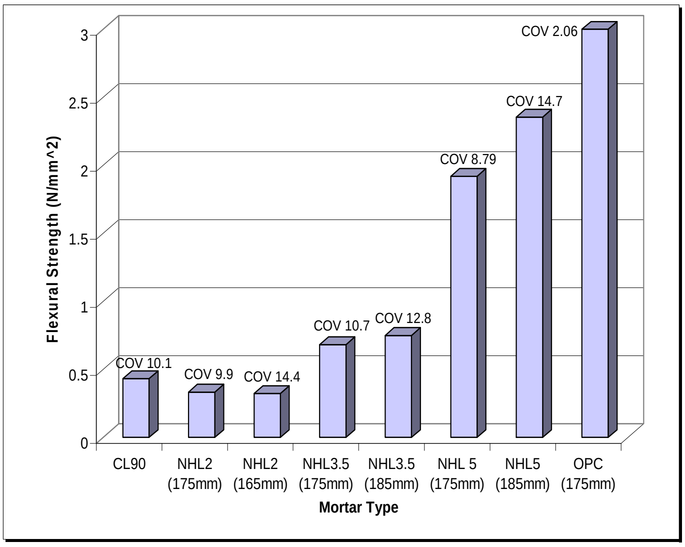

Figure 6. Flexural strength of lime and PC mortars.

3.7 *Compressive strength*

Also as expected from their hydraulic set, the eminently hydraulic binders reached the greatest compressive strengths (Fig. 7). The strength of the PC mortar is nearly 3 times that of the NHL 5 mortars and 13 times that of the NHL2 (165mm) mortar. With respect to the water content, for the NHL 2 and NHL 3.5 mortars, the lower flows reached the highest compressive strength, whereas the NHL 5 mortars of higher flow seem to reach higher strength. This agrees with previous authors (Hanley and Pavía, 2008), however, the results are too close to conclude on a definite trend. The COV is relatively low showing good consistency; with the exception of the CL90 results (COV=11%), however, some variability is to be expected in a natural material such as CL90.

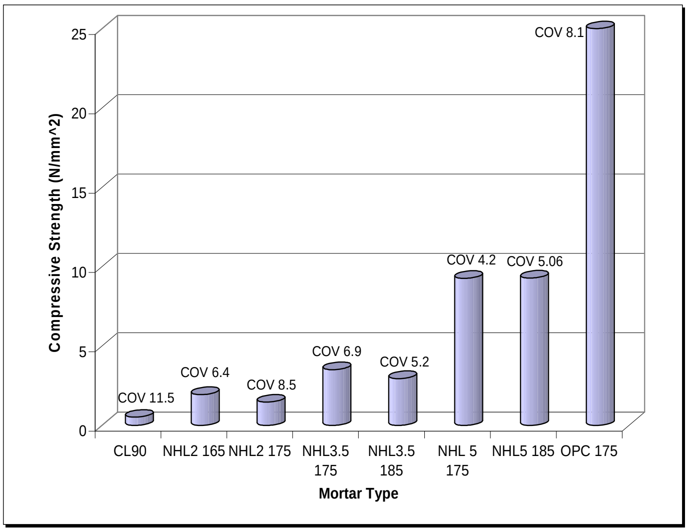

Figure 7. Compressive strength of lime and PC mortars.

4 CONCLUSION

There is an inverse relationship between the binder's hydraulicity and the shrinkage, porosity, capillary suction and water absorption of the mortar.

As the binder's hydraulicity increases, less shrinkage occurs. This is probably due to the lower water demand of the higher hydraulic strengths (less water means less evaporation shrinkage as the mortar hardens) and to their hydraulic set (in hydraulic binders, rather than evaporating, water forms mineral hydrates, and this involves expansion). This paper concludes that shrinkage is more determined by the nature of the binder than by the amount of mixing water (some mortars mixed to lower flows shrunk further than those mixed to higher flows).

Porosity, water absorption and capillary suction decrease as the binder's hydraulicity rises. However both porosity and absorption of non-hydraulic lime mortars show comparable values to those of PC mortars, only differing by approximately 10%, however, the capillary suction of the PC mortars is much lower than that of the lime mortars. This suggests that even though the overall volume of voids accessible to water in lime and cement mortars is comparable, the pore system of lime mortars is more efficient in transporting moisture by capillarity.

While an increase in water content lowers bulk density, it does not seem to affect the amount of voids accessible to water (there are no significant differences in the suction, porosity or water absorption of identical mortars mixed to different flows).

As expected, there is a direct relationship between the binder's hydraulicity and the mortar's density and mechanical strength: the more hydraulic mortars possess the densest microstructures and show the greatest compressive and flexural strengths. With regard to the water content, this paper concludes that, mortars of higher hydraulicity tend to be strnger when mixed to higher flows whereas feebly hydraulic mortars mixed to low flow possess a superior mechanical resistance.

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