Effect of outdoor curing on the strength and stiffness of lime mortar and masonry

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Abstract
Understanding how curing conditions affect mortar properties is important for the correct specification of mortars. This paper investigates the strength and stiffness of mortars and masonry externally and laboratory cured. Outdoor temperatures ranged from -7 to 19°, and numerous rain showers plus several freeze-thaw events were recorded during curing. Outdoor curing improved the compressive, flexural strength and stiffness of all mortars up to 28 days. However, later (at 2 and 6 months), the outdoor mortars became weaker and less stiff than their indoor equivalents due to freezing. Freezing was not detrimental in the long term: following freezing, strength and stiffness recovered and, at 6 months, even the weakest mortar with no hydraulic properties (CL90s) had increased compressive and flexural strength and stiffness by 33, 48 and 25-41% respectively.

In contrast, in spite of freezing, all masonries continued to gain strength and stiffness, yet remaining weaker than their indoor equivalents. This was most remarkable for the weakest masonry (CL90s) since it is the most susceptible to poor weather and yet, between 56 days and 6 months, its compressive strength, elastic modulus and bond strength increased by 14, 25 and 50% respectively. The lower vulnerability of masonry on exposure (when compared to mortar) is due to the fact that part of the masonry strength/stiffness measured belongs to the masonry unit (which is hardly affected by exposure). In addition, the masonry units probably protect mortar from harm on exposure. In general, outdoor curing within the conditions of this study only leads to a slight loss of mortar and masonry strength and stiffness at 6 months.

Introduction

A good understanding of mortar behaviour and strength under different curing conditions is important for the correct specification of mortars. However, limited research has been carried out on the influence of curing conditions on lime mortar masonry strength. The retention of mortar moisture during curing is one of the most important factors that affect mortar and masonry strength and durability, as it enables proper carbonation and hydration as well as bonding with masonry units. It is well known that ambient temperature, humidity and air movement determine the amount of water retained in the mortar subsequently impacting carbonation, hydration and hardening. High temperature and low humidity (due to high winds or heavy insolation) can cause sudden evaporation of moisture from the mortar undermining curing and hardening thus adversely affecting mortar and masonry. Conversely, expansion due to freezing temperature can also cause significant deterioration.

Previous authors agree on that increasing relative humidity on initial curing improves strength. Lanas et al. (2006) found that external exposure (5-15 ºC and RH 70-90 %) increases the compressive and flexural strength of CL90s and HL 5 mortars due to a higher degree of relative humidity. When cured indoor (20±5 ºC and RH 60±10 %), they found that lime mortars required longer curing times to improve strength. Maurenbrecher et al. (2005) state that longer initial damp curing can improve performance of hydraulic lime mortars in terms of freeze-thaw resistance and tensile bond strength. Goodwin and Saunders (1988) concluded that when curing calcium silicate brick masonry, covering for 28 rather than 3 days resulted in significant increases in flexural bond strength. Studies by Baker (1979) on Portland cement mortars agree, stating that water-cured, cement-brick-masonry reaches superior bond strength than masonry cured in laboratory conditions. According to Isbener (1969) (in Groot 1993) during curing, mortar humidity varies at different depths, resulting in differential hydration that can lead to a strength differential across the joint which may result in shrinkage and loss of bond.

This paper investigates the influence of outdoor curing on mortar and masonry strength and stiffness. It compares the compressive and flexural strength and elastic modulus of mortars and masonry sections externally cured with those of laboratory-cured specimens, at 28 and 56 days and 6 months. Outdoor temperatures ranged from-7 and 19 °, and several freeze-thaw events were recorded during curing, the first of which occurred after 6 weeks of exposure. Numerous rain showers also took place and the relative humidity varied between 60 and >95%.

The properties investigated are important in relation to building and repair. Compressive strength informs on mechanical resistance and relates to durability (stronger materials usually have longer lives). It is often used as a principle criterion for material specification and quality control: e.g. the classification and designation of limes, cements and mortars are based on compressive strength. Flexural (tensile) strength is a function of the compressive strength and determines the mortar's resistance to tensile stresses resulting from loading, differential movement, frost action and/or expansion caused by salt or swelling clays. Flexural and compressive strength increase proportionally to the binder's hydraulic content due to greater hydrate amount with increasing hydraulic strength. Elastic modulus relates to stiffness and the ability to deform on stress application. This is often more important than the ultimate strength (at peak load) as it is desirable for mortars and masonry to be able to deform under stress without cracking. Historic masonry often experiences deflection over time therefore, a low elastic modulus is of interest to those specifying mortars for repairs. Bond strength between the mortar and the masonry unit is important because it ensures the structural integrity of masonry (adequate resistance to compressive and tensile loading) and seals against weathering agents.

Materials and methods

Natural hydraulic lime (NHL) of strength 5 and hydrated lime (CL90s) complying with EN459-2 were investigated. A cement- lime mortar (CEMII+CL90s), designated as M6 in the standards, was also studied as a reference sample (Table 1). A siliceous aggregate (commercially known as sable-001) with particle size distribution ranging within the standard limits (EN196-1 2005) (Figure 1) and machine-pressed, frogged, fired-clay bricks produced by Kingcourt Brick, Co. Cavan (table 2) were used. In all compression and flexural tests, the values reported are the arithmetic mean of 3-6 specimens; and mean of 5 for flexural bond strength tests.

Table 1- Mortar composition

Mortar notation	Binder type	Mix ratio cement:lime:sand
M6	PC+CL90s	1:1/2:4 by volume
NHL5	100% NHL5	0:1:3 by weight
CL90s	100% CL90s	0:1:3 by weight

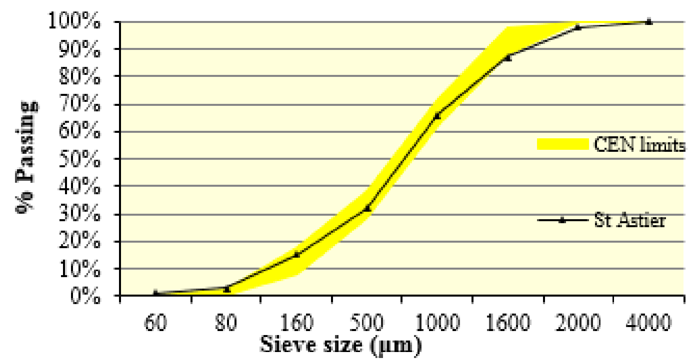

Figure 1. Aggregate particle size distribution.

Table 2- Brick characteristics

Property	(Testing standard: EN 771-1 :2003)
Compressive Strength (N/mm2)	≥ 12
Water absorption (%)	Max 15
Unit size (mm) / Size tolerance	215 x 102.5 x 65 /T2 - R1
Gross / net density (kg/m3)	1630/ 1920
Initial rate of absorption (kg/m2/minute)	1.0

Mixing, moulding, curing and compaction

The mortars and masonry were produced in accordance with EN459-2 and EN1052 respectively, and cured and stored in the same conditions. Based on previous research (Hanley and Pavia 2008), the mortars were mixed to two specific initial flow values

(165 ±3 and 170 ± 3 mm) and placed in prismatic (40x40x160mm) moulds in accordance with EN196-1. Increasing the mortar water content between 0.6 and 1.3% yielded the 5 mm increase in initial flow (from 165 to 170 mm) (Costigan and Pavia 2010). The indoor-cured mortars and masonry were covered with damp hessian and polythene to restrict moisture loss for 24 hours; then, the NHL5 and M6 mortar and masonry were placed in a humidity chamber at 95±5% relative humidity and 20±2°C temperature for 28 days (EN459-2). The CL90-s mortars and masonry were stored at 60±5% RH and 20±2°C temperature. Outdoor cured mortar and masonry sustained -7 to 19 °C temperature, 60-99% RH and sporadic freeze-thaw episodes.

Mechanical properties of mortar

During the compression and flexural mortar tests, the force-strain curves were recorded in order to calculate the elastic modulus and study the mechanical behaviour under load application. Compressive (Rc,) and flexural (Rf,) strength were determined using equ.1 and 2.

Where:

Fc is the max load at fracture (N);
6400-area of the face (mm2);
Ff-load at fracture (N);
b-prism section (mm2);
l -distance between supports (mm).

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

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

Mechanical properties of masonry

The compressive and bond strength were tested according to EN 1052-1/5 (Figures 2-3). During the compression tests, force-strain curves were recorded with the strain values provided by lateral variable displacement transducers continuously monitoring the change in length on load application. Eq. 3 and 4 were used to determine the compressive (fi) and characteristic compressive strength.

Where:

Fi,max-max load (N);
A-loaded cross-section (mm2).

The flexural bond strength was determined with the bond wrench test on five-brick prism stacks (Figure 3).

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

$$f_k = \frac{f}{1.2} \text{ or } f_k = f_{i,\min} \qquad (\text{N/mm2}) \text{ whichever is smaller} \qquad (4)$$

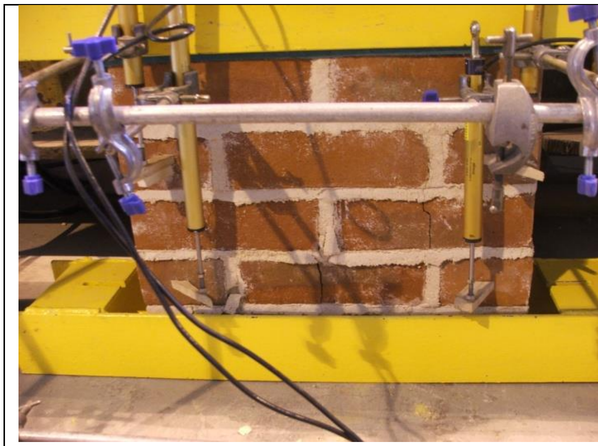

Fig.2 Compressive strength masonry test set up.

Fig.3 Bond strength test set up.

Results and discussion

Properties of mortar cured outdoor

As expected, regardless of the curing environment, the mortar strength is proportional to the hydraulic strength of its binder: the compressive/flexural strength and stiffness of the cement-lime mortar (M6) are approximately twice those of the eminently hydraulic (NHL5) mortar, irrespective of water content or curing duration. Predictably, the hydrated lime (CL90-s) mortar with no hydraulic properties is the weakest, however reaching a compressive strength between 1.30 and 1.51 N/mm^2 and an elastic modulus of 108-144 N/mm^2.

The results evidence compressive strength loss in the lime mortars between 1 and 2 months: the NHL5 mortar experiences a 25% fall in compressive strength at 165mm flow while the strength of CL90s mortar reduces by 40% - Figure 4. In contrast, the M6 (cement-lime) mortar continues to gain strength between 1 and 2 months however at a much slower rate. In spite of the strength loss, the lime mortars did not fail and continued to develop strength and stiffness up to 6 months (in particular, the CL90s mortar increased compressive and flexural strength by 33-48% and stiffness by 25-41 %). The stiffness of the M6 and NHL5 mortars consistently increases over time however, the stiffness of the CL90s mortar lessens between 1 and 2 months (figure 6). As aforementioned, several freezing episodes took place after 6 weeks of exposure. These are responsible for the fall in strength and stiffness the mortars experience between 1 and 2 months. The flexural strength loss that NHL5 mortars suffer between 1 and 2 months is lower than the compressive strength loss (figure 8). In addition, neither the M6 nor the CL90s mortars cured outdoor seem to experience any flexural strength loss over time despite freezing.

Properties of masonry cured outdoor

As expected, the cement-lime masonry (M6) displays the greatest strength and stiffness, followed by NHL5 and CL90s masonry (Figs. 5 and 7). The CL90s mortar masonry is the weakest however, it developed a significant compressive strength of 2.99 N/mm^2 and an elastic modulus ranging between 200 and 300 N/mm^2 despite the weather. Although the M6 masonry out-performs the NHL5 masonry during early curing, over time, their compressive strength becomes comparable while the stiffness of the M6 masonry remains significantly greater: at 6 months, M6 masonry (with a compressive strength of 8.9 N/mm^2) is only 11% stronger than the NHL 5 masonry, yet the NHL 5 masonry is over 30% more deformable. This means that NHL 5 mortar can produce masonry that is almost as strong as M6 masonry in compression (Fig.5), whilst simultaneously remaining considerably more elastic and deformable (Fig 7). It should be noted that the bond strength of NHL 5 masonry is significantly lower (approx.60%) than that of the cement-lime masonry (Fig. 9). This was also evidenced in laboratory cured masonry below.

In spite of the freezing episodes experienced after approximately 6 weeks, all of the masonries continued to gain significant strength and stiffness over time. This can be attributed to the fact that part of the masonry strength and stiffness measured correspond to the masonry units (which is hardly affected by exposure) however, it can also suggest that the masonry units have protected the mortar from damage by exposure. This is especially remarkable for the weakest mortars (CL90s), since they are the most susceptible to poor weather conditions and yet the properties of their masonry continue rising despite freezing: between 56 days and 6 months, the compressive strength of CL90s masonry increases by 14%, the elastic modulus by 25% and the bond strength by approximately 50% (Figs. 5, 7 and 9 respectively).

Figures 4 and 5. Compressive strength development of mortar and masonry cured outdoor

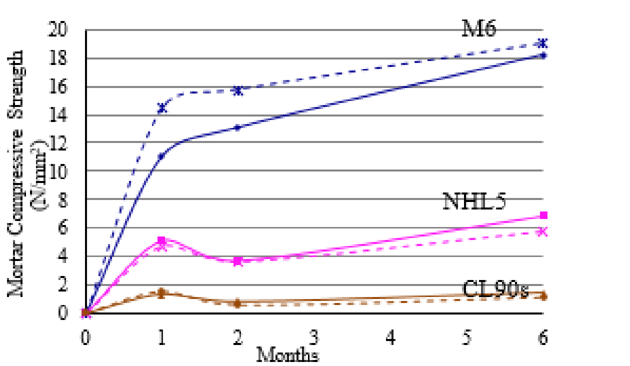

Figure 4 MORTAR

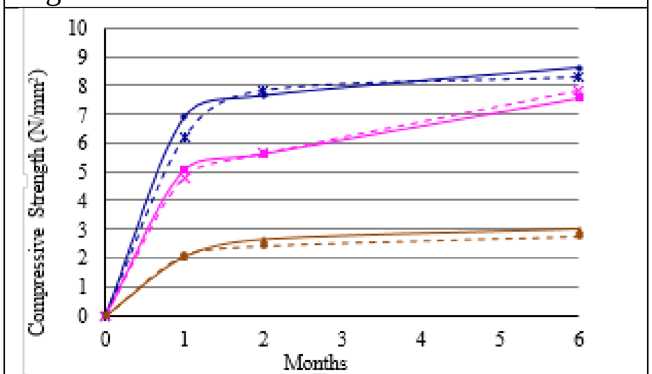

Figure 5. MASONRY

Figures 6 and 7. Elastic modulus of mortar and masonry cured outdoor over time

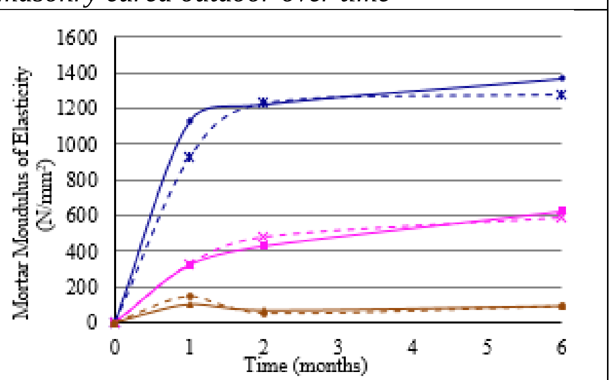

Figure. 6 Mortar

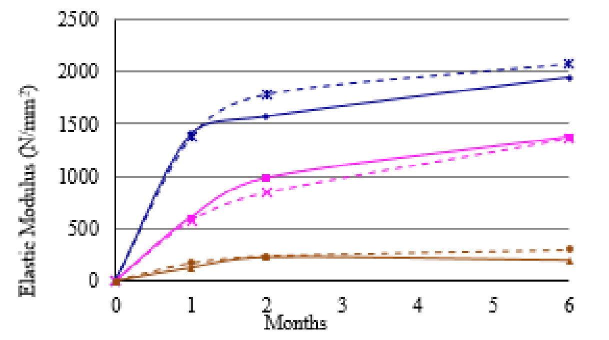

Figure. 7 Masonry

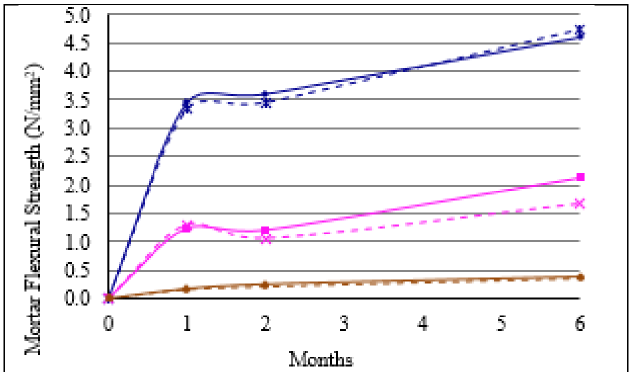

Figure 8 Flexural strength of mortar cured outdoor over time

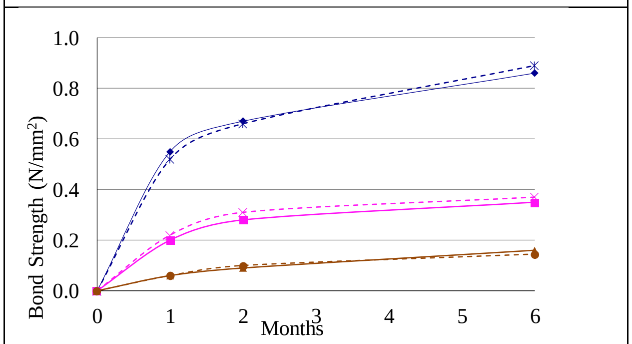

Figure 9 Bond strength of masonry cured outdoor over time

Comparison of externally cured and laboratory cured mortars

According to the results in Figures 10-12 and tables 3-5, outdoor curing improved the compressive and flexural strength and stiffness of all mortars up to 28 days.

However, at later ages (2 and 6 months), the outdoor cured mortars become weaker and less stiff than their indoor equivalents due to the freezing episodes that took place between 28 and 56 days. As it can be seen from the results, following freezing, the outdoor mortars recovered some strength and stiffness but nevertheless, their 6-month strength and elastic modulus remain lower than those of indoor cured mortars, irrespective of mortar type or flow. For example, the indoor M6 mortars are 18-27% stronger in compression than their outdoor equivalents at 2 months (11-18% stronger at 6 months); while the indoor NHL5 mortars are 42-48% stronger than their outdoor equivalents at 2 months (43-53% at 6 months) (Fig.10 and table 3). The CL90s mortar results appear inconsistent: at 6 months the outdoor cured mortars are stronger than their indoor equivalents.

The flexural strength results follow a similar trend (Fig.11 and table 4): laboratory cured M6 mortars are 10-20% stronger in flexion that their outdoor equivalents at 2 months (4-16% stronger at 6 months) while indoor NHL5 mortars are 34-51% stronger in flexion than their outdoor equivalents at 2 months (16-42% at 6 months); and CL90s indoor mortars are 25-51% stronger in flexion than their outdoor equivalents at 2 months and 11-32% at 6 months. The elastic modulus results follow the same trend however, the divergences in stiffness between the outdoor and indoor mortars are significantly less prominent (Fig.12 and table 5).

The results also suggest that lime mortars with higher flows and thus greater water content are slightly more susceptible to frost damage. For instance, the compressive strength reduction of the NHL 5 mortar due to freezing is 43 % with a 165 mm flow and 53 % when the flow is 170 mm; however the evolution of the compressive strength of CL90s mortar is inconsistent. The elastic modulus and flexural strength of both NHL 5 and CL90s mortars show a similar trend, with higher flow mortars losing more strength and stiffness as a result of freezing.

Comparison of laboratory cured and outdoor cured masonry

In contrast with the mortars which increased strength/stiffness during the first 28 days as a result of outdoor curing, the outdoor cement-lime (M6) and NHL5 masonries reached lower strength and stiffness than their indoor equivalents (Figs.13and15). In contrast, the outdoor CL90s masonry shows significantly higher compressive strength (28 and 56days) than the indoor equivalent (large coefficients of variation suggest that this is inconsistent and can relate to erratic wallete building), the trend reverses at 6 months, when the indoor CL90s masonry is stronger.

The drop in masonry strength and stiffness resulting from outdoor curing is small at all ages and, similarly to mortar, outdoor curing generally leads to a slight loss of compressive strength and elastic modulus at 6 months (Figs.13/15-tables 6/8). The masonry is less affected by the curing environment than the mortar: the mortar compressive strength dropped by 11-53% whereas the masonry only reduced by 5-24% and the mortar elastic modulus dropped by 5-44% while the masonry only reduced by 1-15% due to outdoor curing. The lower vulnerability recorded for the masonry is probably due to the fact that part of the masonry strength and stiffness measured corresponds to the masonry unit (which hardy drops strength and stiffness on outdoor exposure).

In contrast with the mortar results, increasing mortar flow does not make the masonry more vulnerable to outdoor curing, this is probably due to the strength and stiffness of the masonry units prevailing over those of the mortar. Bond strength seems to be less susceptible to outdoor curing than strength and stiffness (Figure 14 and table 7). This makes sense because the bond mainly develops initially, when the mortar is put in contact with the masonry unit therefore, it should be less affected by temperature and relative humidity variations over time.

Conclusion

The results agree with previous authors on that increasing moisture during curing improves mortar strength however, masonry behaves differently. Mortars are more susceptible to outdoor exposure than masonry: the mortars initially increase strength/stiffness due to higher outdoor humidity but then become weaker than their indoor equivalents due to freezing; whereas the masonries keep gaining strength/stiffness despite the weather, yet remaining weaker than their indoor equivalents. The lower vulnerability of masonry to exposure is due to the fact that part of the strength/stiffness measured belongs to the masonry unit (which is hardly upset by exposure). However, in addition, the masonry units probably protect mortar from outdoor damage.

Outdoor curing improved the compressive, flexural strength and stiffness of all **mortars** up to 28 days. However, later (at 2 and 6 months), the indoor cured mortars become stronger and stiffer than their outdoor equivalents due to strength reduction resulting from freezing temperatures. Despite initially lowering lime mortar strength and stiffness, freezing is not detrimental in the long term as, following freezing, strength and stiffness recover: at 6 months, even the weakest CL90s mortar with no hydraulic properties had increased compressive and flexural strength and stiffness by 33, 48 and 25-41% respectively.

In spite of freezing, all **masonries** continued to gain significant strength and stiffness over time. This is especially remarkable for the weakest masonry (CL90s) since it is the most susceptible to poor weather and yet, between 56 days and 6 months, its compressive strength, elastic modulus and bond strength increased by approximately14%, 25% and 50% respectively. Despite the weather, the CL90s masonry developed a significant compressive strength of 3 N/mm^2 and an elastic modulus between 200 and 300 N/mm^2. It can be concluded that, in general, outdoor curing within the conditions of this study only leads to a slight loss of mortar and masonry strength and stiffness at 6 months. Other remarks are as follows:

- Despite freezing and outdoor exposure, the M6 (cement-lime) mortar continues to gain strength however at a much slower rate.
- Mortar flexural strength and stiffness seem less susceptible to freezing and outdoor curing than compressive strength.
- A rise of 0.6-1.3% in water content makes lime mortars slightly more susceptible to loosing strength on freezing. This trend does not apply to the higher-flow masonry.
- NHL5 mortar can produce outdoor masonry nearly as strong as M6 masonry in compression, whilst simultaneously remaining considerably more elastic and deformable however with lower bond strength.
- Bond strength is less susceptible to freezing and outdoor curing than masonry strength and stiffness. This can be attributed to the fact that a significant part of the overall bond strength develops early, when the mortar is put in contact with the masonry unit therefore, it is less affected by variations in temperature and relative humidity over time.

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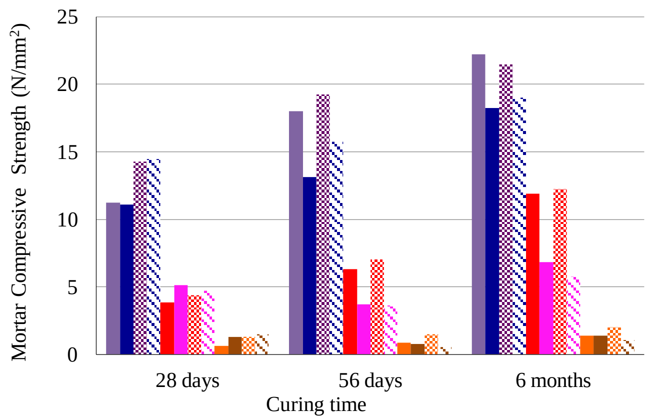
M6@165-I | M6@165-E | M6@170-I | M6@170-E
NHL5@165-I | NHL5@165-E | NHL5@170-I | NHL5@170-E
CL90-s@165-I | CL90-s@165-E | CL90-s@170-I | CL90-s@170-E

Mortar properties - Effect of outdoor curing (I- indoor; E-outdoor)

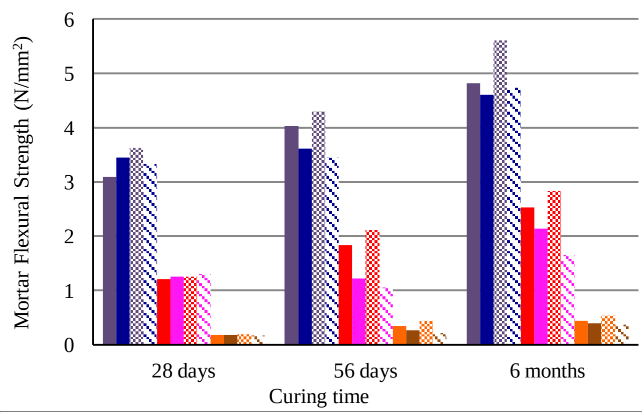
Figure 10. Compressive strength



Initial flow	Mortar type	Mix ratio	Curing Period		
			28 days	56 days	6 mts.
165	M6	1:½:4	-1 %	-27 %	-18 %
	NHL 5	0:1:3	32 %	-42 %	-43 %
	CL90-s	0:1:3	110 %	-10 %	2 %
170	M6	1:½:4	1 %	-18 %	-11 %
	NHL 5	0:1:3	8 %	-48 %	-53 %
	CL90-s	0:1:3	17 %	-63 %	-46 %

Table 3. Percentage change in compressive strength of mortar due to outdoor curing

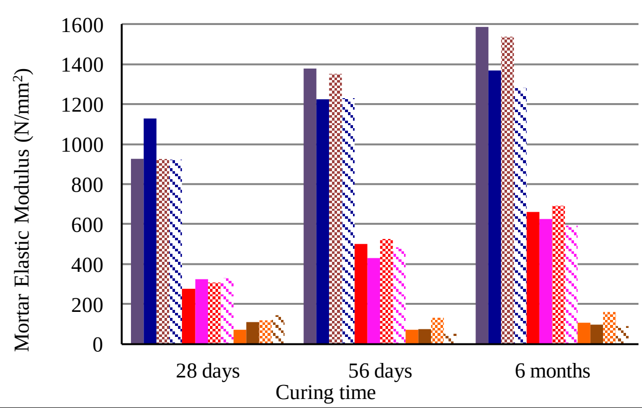
Figure 11. Flexural strength



Initial flow	Mortar type	Mix ratio	Curing Period		
			28 days	56 days	6 mts.
165	M6	1:½:4	12 %	-10 %	-4 %
	NHL 5	0:1:3	4 %	-34 %	-16 %
	CL90-s	0:1:3	-3 %	-25 %	-11 %
170	M6	1:½:4	4 %	-20 %	-16 %
	NHL 5	0:1:3	3 %	-51 %	-42 %
	CL90-s	0:1:3	-14 %	-51 %	-32 %

Table 4. Percentage change in flexural strength of mortar due to outdoor curing

Figure 12. Elastic modulus



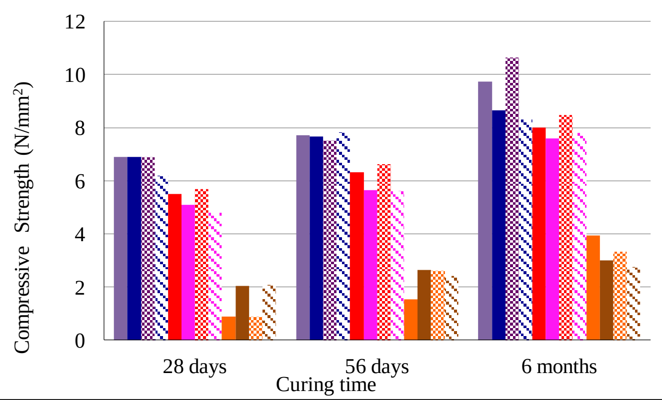
Initial flow	Mortar type	Mix ratio	Curing Period		
			28 days	56 days	6 mts.
165	M6	1:½:4	22 %	-11 %	-14 %
	NHL 5	0:1:3	17 %	-14 %	-5 %
	CL90-s	0:1:3	55 %	2 %	-9 %
170	M6	1:½:4	0 %	-9 %	-17 %
	NHL 5	0:1:3	8 %	-8 %	-14 %
	CL90-s	0:1:3	21 %	-60 %	-44 %

Table 5. Percentage change in elastic modulus of mortar due to outdoor curing

Masonry properties - Effect of outdoor curing

I – Indoor E – Outdoor Curing

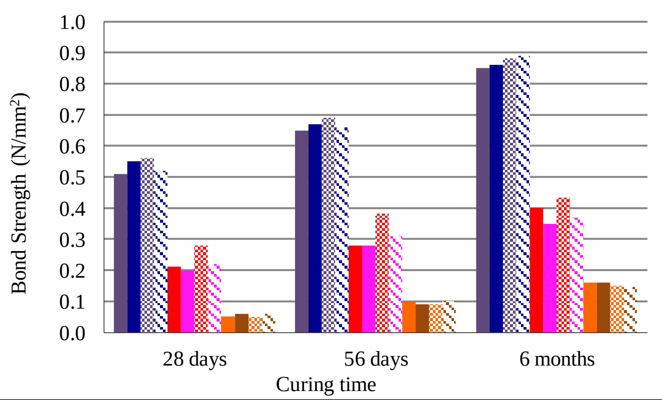
Figure 13. Masonry compressive strength



Initial flow	Mortar type	Mix ratio	Curing Period		
			28 days	56 days	6 mts.
165	M6	1:½:4	0 %	-1 %	-11 %
	NHL 5	0:1:3	-11 %	-11 %	-5 %
	CL90-s	0:1:3	128 %	72 %	-24 %
170	M6	1:½:4	-10 %	4 %	-22 %
	NHL 5	0:1:3	-13 %	-15 %	-8 %
	CL90-s	0:1:3	138 %	-8 %	-17 %

Table 6. Percentage change in compressive strength of brick masonry due to outdoor curing

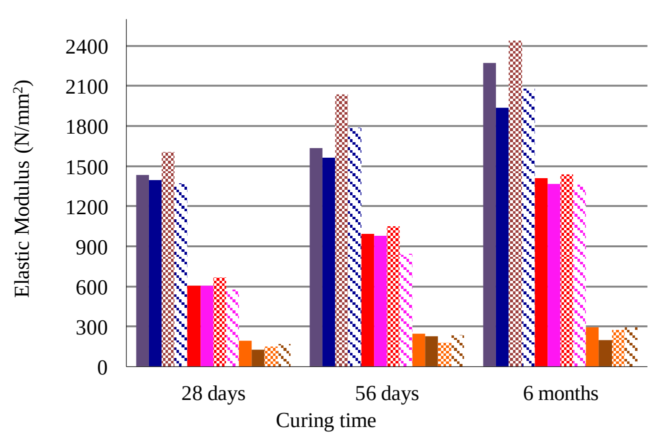
Figure 14. Masonry bond strength



Initial flow	Mortar type	Mix ratio	Curing Period		
			28 day	56 days	6 mts.
165	M6	1:½:4	8 %	3 %	1 %
	NHL 5	0:1:3	-5 %	1 %	-12 %
	CL90-s	0:1:3	18 %	-10 %	0 %
170	M6	1:½:4	-7 %	-4 %	1 %
	NHL 5	0:1:3	-21 %	-19 %	-15 %
	CL90-s	0:1:3	22 %	6 %	-3 %

Table 7. Percentage change in flexural bond strength of brick masonry due to outdoor curing

Figure 15. Masonry elastic modulus



Initial flow	Mortar type	Mix ratio	Curing Period		
			28 day	56 days	6 mts.
165	M6	1:½:4	-3 %	-4 %	-15 %
	NHL 5	0:1:3	-10 %	-1 %	-3 %
	CL90-s	0:1:3	-36 %	-6 %	-33 %
170	M6	1:½:4	-14 %	-12 %	-15 %
	NHL 5	0:1:3	-5 %	-20 %	-5 %
	CL90-s	0:1:3	10 %	30 %	7 %

Table 8. Percentage change in elastic modulus of brick masonry due to outdoor curing

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