The effect of cement Partial replacement by lime on shear strength of brick-mortar interfaces

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Abstract
Partial replacement of cement with lime can offer an economic advantage in the use of jointing mortar between bricks. This article studies the effect of the introduction of lime in the jointing mortar on the shear strength of masonry walls. The amount of lime used by a rate of 0, 25, 50, 75 and 100% of the volume of cement. Compression and flexural test were used to define the mechanical characteristics of these mortars. Then, a shear test on bricks triplet was adopted to assess the sliding at the brick-mortar interface.
The mechanical characterization of the different mortars showed a significant improvement in their ductility when the percentage of lime increases. This despite, the decrease observed on the compressive and flexural strengths. In the shear test on bricks triplet, the results showed that the incorporation of lime at the cement binder increases the capacity of sliding at the interface between the brick and the mortar. Thus, the brick-mortar interface ductility was improved by increasing the amount of lime.

Keywords: *brick, mortar, lime, masonry, brick triplets, interface, shear test, ductility.*

1. Introduction
Masonry is an ancient construction technique which represents a large part of the building stock throughout the world. Generally, these buildings are located in old urban and rural cities. Masonry is also used for façades and partition walls in reinforced concrete structures.
A lot of scientific works have focused on studying the effect of the mortar strength on the masonry behaviour. Under compressive loads, [1], [2], [3], [4],and [5], noted that the increasing of the mortar strength improves slightly the bearing capacity of masonry and makes its behaviour more brittle. In parallel, recent studies have examined the behaviour of the masonry constructions under horizontal stresses due to wind or seismic actions.

In this mind, many researchers used shear tests on triplets or couplets of bricks to study the sliding between brick and mortar, [6], [7], [8], and [9].

It is obviously that it's the arrangement between the brick and mortar that governs the shear behaviour of masonry.

In order to improve the masonry shear performance, it is appropriate to study both elastic and inelastic behaviour of the arrangement between the brick and mortar. In the elastic field, the shear at the interface brick-mortar can be estimated by the peak shear stress. ASTM [10], [11], [12], [13 [14], [15], [16], and [7], have determined this peak through the cohesion and the friction coefficient. They have also found that shear behaviour can be correlated with the Mohr-Coulomb failure criterion only for low pre-compression levels.

In the inelastic behaviour, and in order to follow the post peak response of the brick-mortar interface, [18] , [19],and [20] have added the ratio between the normal and shear displacement as a parameter to describe the masonry wall failure. They have found that the increase of this ratio leads to decreasing the shear displacement.

However, when the level of pre-compression increases largely, the crushing of brick units arises before the interface of the mortar.

Noting that, the most research has been tested on the rubble stone masonry. However, the effect of lime dosage in walls masonry with regular bricks is less explored. In this article and in order to build masonry walls with low cost, the cement was partially replaced by lime in mortar joints. Hence, this paper describes the shear behaviour of the triplets of bricks assembled by mortars with different percentages of lime. [21], [22] and [23].

2. Experimental

In this article, the main test was performed to study the behaviour of the interface of brick triplets. Each triplet (consisting of three bricks joined together by 5 mm mortar thickness) was subjected to a shear test.

2.1. Materials properties

Perforated clay bricks with dimensions of (210x105x55 mm^3) were used. The binder employed in the different mortar joints is the combination of cement and lime materials. The lime used was an aerial lime with a density of 750 kg/m^3. According to EN459-1 [24], the calcium lime is described as CL80. The cement used was a Portland cement type CEMII A-LL/42.5R with a density of 3200 kg/m^3. Table 1 shows the chemical composition of the lime and the cement. The sand used was a crushed calcareous type with 5 mm nominal maximum size.

Table 1. Chemical composition The of the aerial lime and the cement

Compositions	Lime (%)	Cement (%)
Cao	>85.37	59.7
MgO	<0.35	1.11
Fe_2O_3	<0.09	3.81
SiO_2	<0.23	18.57
Al_2O_3	<0.16	4.28
SO_3	<0.23	2.43

Na_2O	<0.063	0.22
CO_2	<5	0.9

2.2 Mortar preparation

The test program consists of five mixes with different rates of aerial lime (CL80). The lime was added as a replacement for cement accordingly in the range of 0, 25, 50, 75 and 100% by volume of cement. Table.2 gives the composition of the different mortars obtained.

To approach the conditions of manufacturing of mortar in masonry work, the different mortars were prepared manually by two successive homogenizations procedures: First, sand and aerial limes were homogenized, then the cement was added and the dry mixture was homogenized again. Secondly, water was added and the mixture was remixed to achieve a workable consistency. In order to measure the mechanical properties of these mortars, the prepared mixtures were cast into molds and then maintained in the standard curing.

Table 2. Composition of lime-cement mortars

Mortar designation	Proportions by volume Cement : Lime : Sand	Lime (%)	Cement (%)
M0	1 :0 :3	0	100
M25	*1 :3 :12*	25	75
M50	1 :1 :6	50	50
M75	3 :1 :12	75	25
M100	0 :1 :3	100	0

2.3. Mechanical properties of brick units

Perforated bricks were tested in compression and in bending. The tests were carried out with a hydraulic press according to the EN 771-1 [25]. The values of compressive, flexural strength and the elasticity modulus were presented in table 3.

Table 3 mechanical Characteristics of brick units

Characteristics	
Density	1820
Compressive strength (Mpa)	*16.8*
Flexural strength (Mpa)	4
Elasticity Modulus (Gpa)	14.2

2.4 Brick triplets preparation

Five groups of fifteen samples of brick triplets were prepared. For each group, the cement of mortar joints was replaced respectively by 0, 25, 50, 75 and 100% of lime. Thus, to evaluate the shear strength, each group was divided into 5 series, each of which was submitted to one of the following lateral pre-compression levels (0 Mpa, 0.5 Mpa, 1 Mpa, 1.5 Mpa and 2Mpa). They were stored at temperature of 25°C and the 60 RH.

2.5 Testing method of mortars

The mechanical properties of mortars were determined 3, 7, 14 and 28 days after de-molding. Flexural and compressive strength tests have been measured according to EN 1015-11 [26]. By using the universal testing machine, the flexural strength has been measured on specimens in shape of prism (40x40x160 mm^3). Afterward, the half-prisms obtained after breaking into two parts from the specimen during the flexural test were subjected to the uniaxial compressive test.

2.6 Shear test on triplets

The shear test on brick triplets has been performed according to EN 1052-3 [27]. It is employed to establish the Mohr-Coulomb law. In addition, it is used to study the Brick-Mortar interfaces behaviour under a sliding displacement. To define the cohesion and the friction angle of the interface brick-mortar, 5 different levels of lateral pre-compressions were adopted in each triplet: 0Mpa, 0.5Mpa, 1Mpa, 1.5Mpa and 2Mpa. The pre-compression was applied by using a plate-rod system composed of four steel rods and two steel plates (figure. 1(a)).

First, the two plates which surrounded both sides of the triplet were subjected to a compressive force by a hydraulic jack and when the desired pre-compression level was reached, the 4 bolts were fixed for confining the brick triplets (figure.1 (b)). Second, once the pre-compression stress level was kept constant, a vertical load was applied at the top of the middle brick to obtain shear stress at the interface brick-mortar (figure 1(c)). That loading was applied by means of a jack of a hydraulic press under controlled displacement of 1 mm/min. Hence, the shear stress of the interface Brick-Mortar was calculated by the following formula-:interface brick- mortar (figure 1(c)). That loading was applied by means of a jack of a hydraulic press under controlled displacement of 1 mm/min. Hence, the shear stress of the interface Brick-Mortar was calculated by the following formula: $\tau = \frac{V}{2\ A_j}$

Where, (V) is the shear load and (Aj) is the cross area of the interface between brick and I

(a) (b) (c)

Figure 1. Shear test setup on brick triplets, (a) steel system consisting of two plates and four rods, (b) Precompression by the fixation of four bolts, (c) Applying the shear stress at the middle brick.

3. Results and discussion

3.1. Compressive strength of mortars

Figure. 2 shows that the compressive strength of mortar decreases with the increasing percentage of lime. At the age of 28 days, the compressive strength of mortars containing 25, 50, 75 and 100% of lime was reduced by 19, 47, 74 and 87.5% respectively compared to the cement mortar with 0% lime. However, this reduction cannot affect the bearing capacity of masonry. [28] and [29], confirmed these results and have reported that the mortar compressive strength had a little influence on the compressive strength of the masonry. Moreover, [30], [31] and[3] noted that the mechanical properties of masonry are more affected by the compressive strength of bricks than those of mortar. Thus, the principal role of mortars is bonding the bricks together.

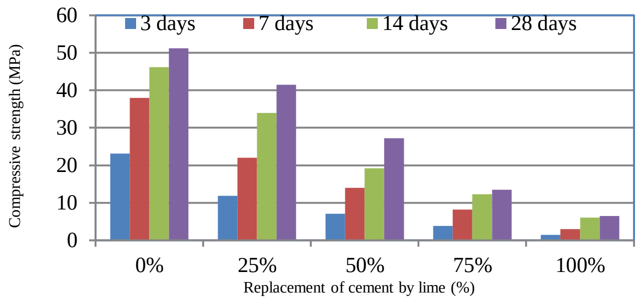


Figure 2. Peak compressive strength of mortar at 3, 7, 14 and 28 days of age and with various lime rates.

3.2 Flexural strength of mortars

Like the compressive behaviour, the flexural strength for all the cement-lime mortars was significantly less than the cement mortar as shown by the figure. 3. At the age of 28 days, the flexural strength of mortars containing 25, 50, 75 and 100% of lime was reduced by 26.3, 43.2, 53.3 and 80.3% respectively compared to cement mortar without lime.

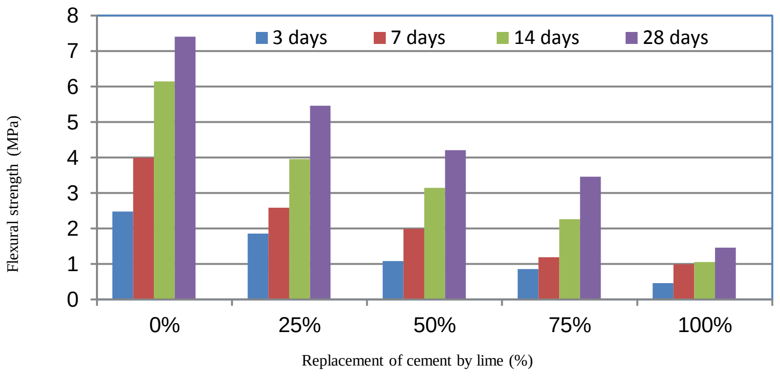
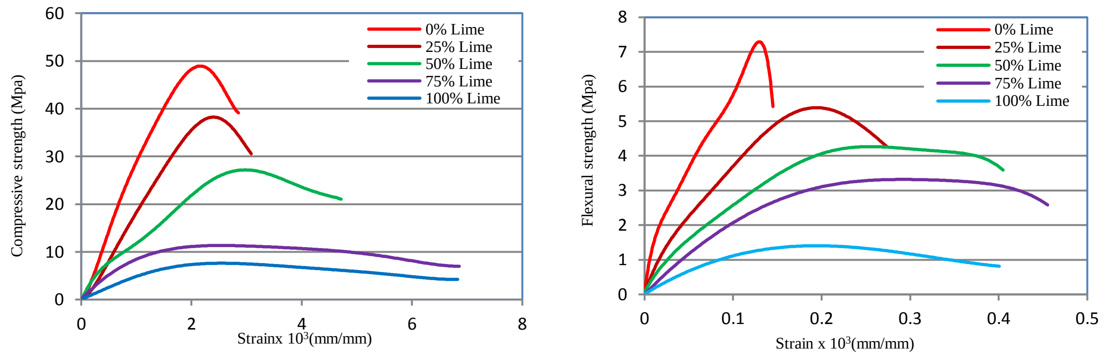


Figure 3. Peak flexural strength of mortar at 3, 7, 14 and 28 days of age and with various lime rates

Despite the decreasing of the peak values of the compressive and flexural strength observed respectively in figures. 2 and 3, Figure. 4 shows the beneficial effect of lime on the deformability of the mortars. Indeed, in terms of stiffness, the Young's modulus decreases with increasing of the lime rate. Besides, in terms of softness, the post-peak shape becomes less steep for the mortar curves containing different rates of lime in comparison with the cement mortar (0% lime) which presents a brittle behaviour with a sudden dropping.

Consequently, more ductility and deformability are obtained by adding lime to the cement-mortar figure. (4a) and figure. (4b).

Therefore, we observe from the compressive test, that the value of the ultimate strain of mortars without lime jumped from 0.2 to 0.6% for the mortar with 75% of lime. Similar behaviour has been reported by [31] , [32], [33] and all.



(a) Compressive behavior (b) Bending behavior

Figure 4. Mortars Stress-Strain curves with different ratio of lime at 28 days

3.3 Shear strength of brick triplet

As there were 5 levels of pre-compression, the curves depicting the evolution of the shear-stress in function of sliding are shown for each level (figure.5). For all the pre-compression levels, the peak shear stress decreases with the increase of lime rate in mortar joints which coincides with the results of [34], [35], [17], and [36]. Hence, when no pre-compression has been applied, figure.(5a) shows that the percentage of 25, 50, 75 and 100% of lime in mortar joints decreases the peak shear stress by 20, 45, 72 and 82% respectively.

At the value of 2 Mpa of the pre-compression level, figure.(5e) shows that the peak shear stress values of the triplets assembled by mortars containing 25, 50, 75 and 100% of lime were reduced respectively by 4.4, 3.23, 2.97, 2 and 1.4% compared to those jointed by cement mortar (0% Lime). The same trend is observed for the intermediate curves namely fige(5b,c, d).

It is worth noticing, that the increasing of lime rate delays the appearance of cracks. This is confirmed by the displacement collected at the peak stress as shown by the histogram of figure. 6. It is clearly observed that the presence of lime shifts the peak shear stress to a large movement. Unlike the case of the mortar with 0 % lime, the peak shear stress is reached for very small displacements which accelerate the failure of the triplets. For instance, in the absence of pre-compression level, the sliding at the peak stress for triplets assembled by mortars containing 25, 50, 75 and 100% of lime increases by 121, 182, 279 and 317% respectively compared to cement mortar with 0% of lime.

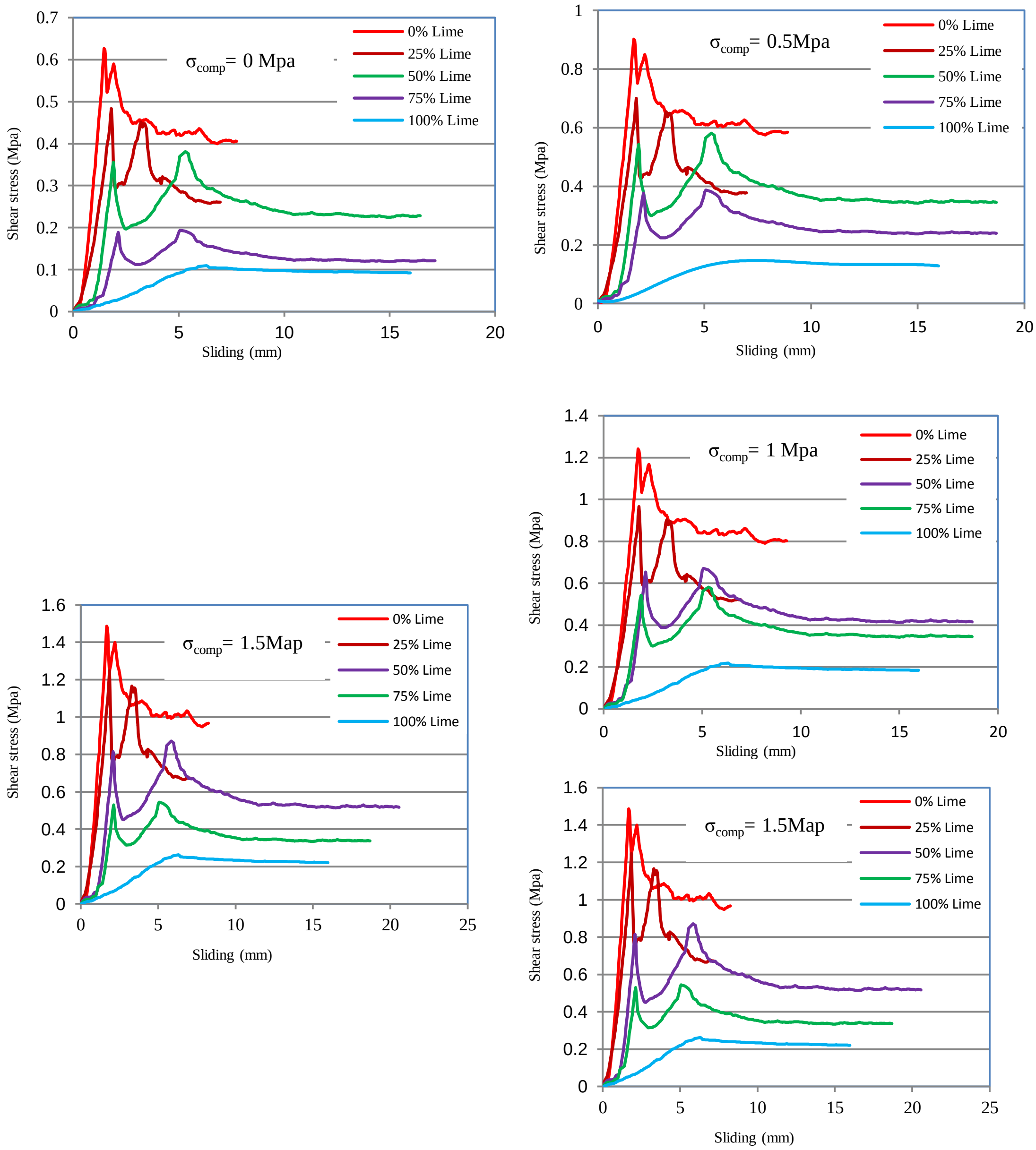


Figure 5. The shear stress-sliding curves of brick-mortar interface for brick triplets for various precompression levels,

(a) σ_{comp}= 0 Mpa, (b)σ_{comp}= 0.5Mpa, (c) σ_{comp}= 1Mpa, (d) σ_{comp}= 1.5Mpa, (e) σ_{comp}= 2Mpa

In addition to the delays of cracks, ductility of triplets gathered by the cement-lime mortars was significantly improved. Hence, figure.5 showed that the addition of lime maintains the post-peak sliding constance or decreases progressively, whereas the cement mortar without lime failed at a very low displacement. This result corroborates that of Booth by [37], who found a softening branch corresponding to plastic deformations.

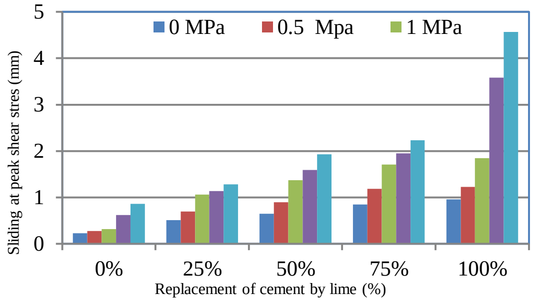


Figure 6. The sliding of brick-mortar interface collected at peak shear stress for different mortar compositions with different pre-compression level: σ_{comp} = 0, 0.5, 1, 1.5 and 2Mpa

Through the correlation between peak shear stress and pre-compression level and the corresponding failure modes presented respectively in figure.7 and 8, two different types of behaviours could be distinguished:

First, for pre-compression level from 0 to 1.5 Mpa, it can be seen that the curves of all triplets could be presented by linear interpolation (figure.7). Moreover, figure (8.a) shows that shear failure occurs at the mortar join following the sliding of the middle brick. Thus, the increasing of lime rate decreases the cohesion values. Therefore, for the pre-compression levels below 1.5 Mpa, the shear behaviour can matchs Mohr-Coulomb criterion. This relation was also established by [38], and[39].

Second, beyond the value of 2 Mpa of the pre-compression level, the peak shear stress values are clearly above the linear interpolation observed at the range of 0-1.5 Mpa. Indeed, the brick triplets failed by other manner, such as the middle bricks splits before the sliding of the mortar joint (figure.7) [40], and [41].(This indicates, that shear stress is not related to the cohesion properties). Hence, the high pre-compression level does not describe the shear strength of the joint mortar. Consequently, the Mohr-Coulomb criterion is not valid.

This means that the role of the jointing mortar is omitted by the high clamping of the triplet which quickly leads to the fragility of the bricks. (The bricks became more fragile than the jointing mortar).

This has caused a sudden increase in the shear stress of the triplets that is observed in figure 7. (Consequently the Mohr-Coulomb pattern is no more valid).

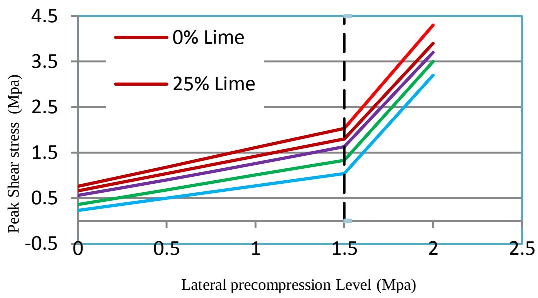


Figure 7. The relationship between peak shear stress of brick-mortar interface and lateral pre-compression level for different mortar compositions.

(a) Under 1.5Mpa

(b) Up to 2Mpa

Figure 8. The failure type of brick triplets at the compressive level: (a) Under 1.5Mpa, (b) up to 2 Mpa

5 Conclusions

Based on experimental studies, on mechanical properties of mortars containing lime as partial replacement of cement and as well as on the shear behaviour of brick triplets, the following conclusions can be drawn. Regarding the mechanical characterization of mortars, partial replacement of cement by lime confers a lower stiffness of these mortars and improved their ductility when the percentage of lime increases.

Concerning the effect of the partial replacement of lime in the mortar on the shear behaviour of brick triplets, the peaks of the curves showed that the appearance of cracks was delayed. Besides, the softening post-peak curves showed that the ductility was significantly improved by the partial replacement of the cement by lime.

Through the correlation between peak shear stress, the pre-compression level as well as the failure types of triplets, the experimental study showed linear regression only in the pre-compression level lower than 1.5Mpa. Beyond this value, the linear regression is lost also the failure mode occurs by bricks splitting instead in the mortar joints. This means that shear behaviour of bricks-mortar interfaces can match Mohr-Coulomb criterion for the pre-compression level interval lower than 1.5 Mpa.

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