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COMPOSITION STUDY OF A MORTAR APPROPRIATE FOR MASONRY CAVITIES AND JOINTS

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Abstract

It is well known that unreinforced masonry behaves as a quasi-brittle material when subjected to seismic loading. The construction in unreinforced masonry is usually not allowed in regions with moderate to high seismic hazard. The alternative to unreinforced masonry and even to reinforced concrete and steel construction is reinforced masonry, which appears to perform adequately under seismic loading. This work deals with the challenging issue of contributing to the definition of a fast and simples construction system using reinforced masonry, by replacing the grout by a general purpose bed mortar, capable of being used also to fill vertical cells with vertical reinforcement. The major difficulty is to find a mortar that is also suitable to fill vertical hollow cells of concrete units.

This work presents preliminary results from the study of different mortars, corresponding to different compositions, in order to find appropriate workability and sufficient fluidity. The analysis is based on a comparative study including the characterization of the fresh mortar properties, such as workability, and the hardened properties, such as modulus of elasticity, flexural strength and compressive strength. The assessment of the mortar adequacy to fill the hollow cells is also analyzed by the execution of masonry prisms, followed by a qualitative analysis of the fill.

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Introduction

Mortar is one of the constituents of the anisotropic masonry material. It is responsible for creating a more uniform stress distribution, for corrections of irregularities of blocks and accommodation of deformations associated to thermal expansions and shrinkage. In spite of this, mortar has been often neglected in terms of structural analysis of masonry structures, it is well known that it influences the final behavior of masonry such as compressive and bond strengths, and deformability (Edgell and Haseltine, 2005). Besides, workability of mortars plays an important role on the construction process of masonry structures. According to Sabbatini (1984), the workability may be considered one of the most important properties because it influences directly the bricklayer's work. It is important to mention that the quality of the workmanship can influence considerably the mechanical properties of masonry. The definition of workability is somewhat subjective as it depends on the person who evaluates the mortar. Panarese (1991) considers the workability as an assembly of several properties such as, consistency, plasticity and cohesion. Given the fact that plasticity and cohesion are difficult to measure in situ, consistency is frequently used as the measure of the workability.

Hollow concrete reinforced masonry is an assembly of blocks and mortar being grout usually used to fill the cores where reinforcement is allocated. In spite of mortar and grout being composed of similar raw materials, the relative proportion is quite different. Mortar, composed of a mix of cement, lime and sand, is required to have enough workability to be spread on the webs and shells of masonry units, providing at same time sufficient bond. On the other hand, grout is characterized by enough flowability which allows proper filling of the hollow cells. In terms of building technology, the substitution of grout by general purpose mortar used for the bed joints can bring economical advantages, as it can simplify the workmanship and save time of construction. According to Biggs (2005), in some regions of the United States contractors commonly substitute grout by mortar in reinforced masonry construction. The use of mortar instead of grout leads to the reduction of the installation costs with low-lift applications when the masonry is to be partially grouted and reduce the number of materials. On the other hand, this means that the mortar has to present a consistency that enables the laying of the concrete units and fills appropriately the reinforced hollow cells. It is stressed that the performance of reinforced masonry depends on both the grout/mortar-unit and grout/mortar-reinforcement bond strength. The contribution of vertical reinforcement depends on the bond between infill material and reinforcement.

This work has been developed in the scope of the research European Project *DISWall-Developing innovative systems for reinforced masonry walls*. The objective is to study the performance of a general purpose mortar to be used for filling vertical cells of concrete masonry units in substitution of grout. For this purpose, the performance of different mortars is assessed, using distinct levels of consistency, in terms of workability and mechanical properties. The mortars results from the mix of sand aggregate, Portland cement and lime. The distinct levels of consistency are achieved by considering different water/cement ratios. The idea is to evaluate the performance of mortars that combine the best workability and flowability with reasonable mechanical properties. A comparison is also made between pre-mixed and laboratory made mortars.

Experimental Program

The experimental program was divided in three stages: (a) definition of the properties of raw materials and the mortar mixes, (b) evaluation of the fresh properties (consistency and density) and (c) evaluation of hardened properties of the mortars (compressive and flexural strength, elasticity modulus and Poisson's ratio).

Three mixes of mortar were prepared keeping the same binder/aggregate ratio: 1:3 (Portland cement:sand), 1:0.5:4.5 (Portland cement:lime:sand) and 1:1:6. A pre-mixed mortar type M10 (10 MPa of compressive strength), was also used to compare the results. The pre-mixed mortar is composed of Portland cement, lime, lime aggregates and chemical additives. According to the information given by the producer, the mortar follows the requirements of European standard EN 998-2 (2003). For each mix, three different water/cement ratios (*w/c*) were considered. Given that it is not possible to define the *w/c* ratio for the dry pre-mixed mortar, the water/dry material was also considered for all types of mortar. Table 1 indicates the mixes considered in this study.

Table 1. Mixes and corresponding water/cement ratios

Mix	***Water/cement ratio (w/c)***	***Water/dry material ratio (w/dm)***
1:3 (no lime)	0.8, 0.9 and 1.0	0.159, 0.179 and 0.199
1:0.5:4.5	1.3, 1.4 and 1.5	0.176, 0.189 and 0.203
1:1:6	1.7, 1.9 and 2.1	0.174, 0.195 and 0.215
Pre-Mixed*	-	0.139, 0,144 and 0.150

* In the pre-mixed mortar the water/dry material was varied since the composition of the mortar was unknown.

Materials

Portland cement, lime and sand aggregate were the materials used to prepare all mixes of mortars, see Table 2. The cement used was CEM II/B-L 32,5N, according to European norm EN 197-1 (2000). The natural hydraulic lime used is a commercial lime of class HL5, according to European norm EN 459-1(2001). The sand has a fineness modulus of 1.8 and a maximum diameter of 2.35mm. Some physical properties of materials are indicated in Table 2.

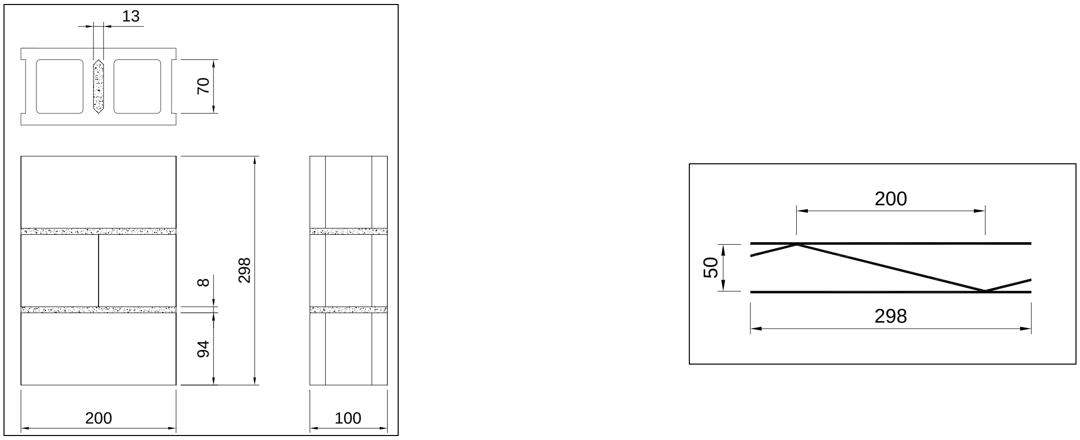
Table 2. Properties of materials

Property	***Cement***	***Lime***	***Sand***
Density (kg/m^3)	3210	2720	2640
Unit mass (kg/m^3)	1080	760	1450

Test procedures

The mix of the mortars was performed according to NBR 9287 (1986). The binder and water were mixed over a period of 30 seconds followed by the addition of the sand in a period of 30 seconds with the mixer running in a low speed. The speed of mixer was then increased and kept constant during 30 seconds. The mixer was stopped for a period of 90 seconds and restarted with high velocity for more 60 seconds.

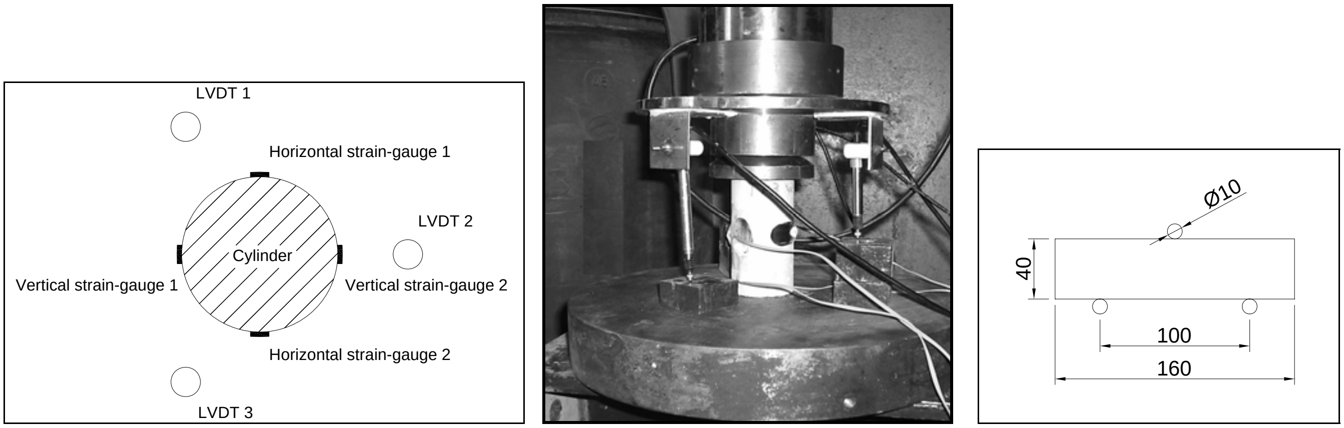
The evaluation of the fresh behaviour of mortar was carried out by means of the fresh density and the value of consistency obtained by means of the flow table test according to EN 1015-3 (1999). This standard presents some differences from ASTM C109 (1981), which is often used by other researchers. The mortar should be introduced in the mould in two layers. Each layer is compacted with, at least, 10 short strokes to ensure uniform filling of the mould. After skimming off the excess of mortar and cleaning the free area of the test disc, the mould is raised vertically, being the mortar spread out on the disc by jolting the flow table 15 times at a constant frequency (approximately one per second). The flow value is the average of diameters of the spread mortar in the disc measured in two perpendicular directions. As aforementioned, the workability is the conjunction of properties like consistency and plasticity. However, in quantitative terms only the consistency is measured. In order to gather a better insight into the workability of the different mixes and into their ability to fill the central vertical hollow cell of the concrete units, it was decided to built prisms with and without vertical truss type reinforcements (type RND/Z supplied by Bekaert), see Figure 1a. The reinforcements are to be placed in the central cells of the concrete masonry units, see Figure 1b. The influence of the diameter of the truss reinforcements on the filling by general purpose mortar is evaluated by considering distinct sizes: 4mm and 5mm diameter for longitudinal and diagonal wires.



(a) (b)

Figure 1. Masonry prisms; (a) geometry of block and prisms; (b) truss reinforcement (dimensions in mm)

The hardened properties defining the mechanical behaviour of the different types of mortar include the compressive and flexural strength and the elastic properties (elastic modulus and Poisson’s ratio). The elastic properties were obtained from compressive tests carried out on cylinders with 50mm diameter and 100mm height (height to diameter ratio of 2), NBR 13279 (1995). The elastic modulus and Poisson’s ratio were calculated by averaging the measurements of strain-gauges attached to the specimen placed in the vertical and horizontal directions, see Figure 2a. Three LVDTs were also used in the tests of the cylinders to evaluate the complete stress-strain diagrams, see Figure 2a. Compressive and flexural tests were carried out on prismatic specimens 40mmx40mmx160mm according to EN 1015-11(1999), , see Figure 2b.



(a) (b)

Figure 2. Details of the experimental tests: (a) compressive test in cylinder specimens and (b) flexural tests in prismatic specimens

Results and Discussion

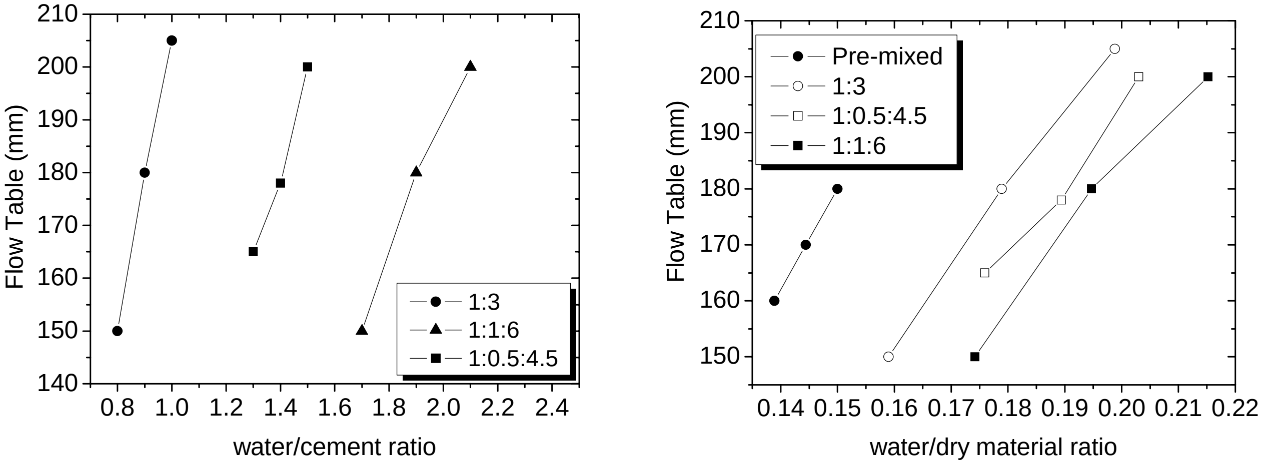
Fresh properties

Concerning fresh mortar two properties were analyzed: workability and density. The values of fresh properties of mortars under study are shown in Table 3. Density was obtained by weighting the mortar in a recipient with a known volume, following EN 1015-6 (1998).

Table 3. Values of the fresh properties

Mix	*w/c*	*w/dm*	*Density (kg/m^3)*	*Flow Table (mm)*
1:3 (no lime)	0.8	0.159	1967	150
	0.9	0.179	1974	180
	1.0	0.199	1967	205
1:0.5:4.5	1.3	0.176	1969	165
	1.4	0.189	1972	178
	1.5	0.203	1973	200
1:1:6	1.7	0.174	1913	150
	1.9	0.195	1962	180
	2.1	0.205	1978	200
Pre-Mixed	-	0.139	1978	160
	-	0.144	1990	170
	-	0.150	2003	180

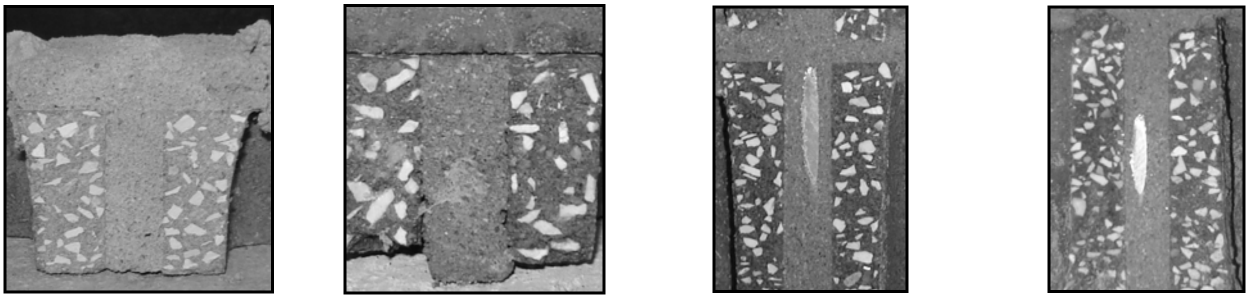
A small variation of 1% was observed in results of density. Apart from mix 1:1:6 with a *w/c* ratio of 1.7, all other admixtures exhibited values of density ranging from 1962kg/m^3 to 2003kg/m^3. The workability was evaluated quantitatively by the consistency measured through the flow table test. The qualitative analysis of the performance of the mortar to fill the central hollow cell of the concrete masonry units is undertaken by visual inspection of the cut surface of the small masonry prisms. Figure 3 points out the results of flow table tests. As expected, it is observed that the consistency increases with the addition of water, even if its variation differs for each mix. In case of the mix with low amount of cement (1:1:6), the consistency growth in relation to *w/c* or *w/dm* ratios is slower than the others mixes (1:3 and 1:0.5:4.5).



(a) (b)

Figure 3. Results of flow table tests; (a) flow table *vs. w/c* ratio and (b) flow table *vs. w/dm* ratio

Figure 4 shows the good quality of the infill in prisms with and without truss reinforcement. No voids in the infill were observed. Nevertheless, the filling of vertical cores with mortars presenting flow values lower than 150mm was difficult to carry out. On the other hand, mortars with flow values higher than 200mm were excellent for the filling but inappropriate to the laying of the concrete units. It is important to stress that the adopted values of *w/c* ratios indicated in Table 3 were the result of preliminary analysis involving other *w/c* ratios.



(a) (b) (c) (d)

Figure 4. Infill of the masonry prisms; (a) mix 1:1:6 *w/c* = 1.9, without reinforcement; (b) mix 1:3 *w/c* = 0.9, without reinforcement; (c) mix 1:1:6 *w/c* = 2.1, reinforcement with longitudinal wires of 4mm; (d) mix 1:1:6 and *w/c* = 2.1, reinforcement with longitudinal wires of 5mm

The visual aspect, workability of the mortar and the easiness of workmanship were the main parameters leading to the definition of the appropriate mortar that simultaneously fulfill the requirements of filling and embedding. As concerns the goal of this study, a qualitative scale of consistency is proposed to evaluate the workability of the mortar, see Figure 5. As it can be observed, a mortar with a consistency of about 175mm is able to be used in the bed joints and in the filling of the vertical joints of the concrete masonry units.

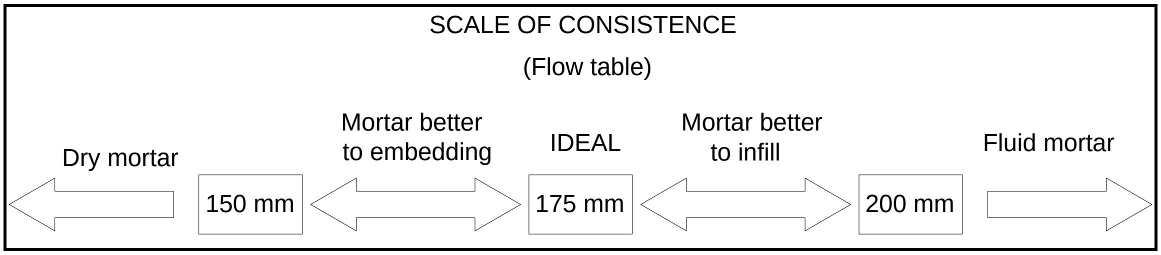


Figure 5. Scale of consistency for defining workability of mortars

The use of lime seems to improve the water retention of the mortar. For the mix 1:3, a tendency for the water to drain out of the mortar in the filled vertical cell during the construction of the masonry prisms was observed. This behavior was not seen in masonry prisms built with lime mortar 1:1:6 and 1:0.5:4.5, see Figure 6. This result appears to be in agreement with the results found by Cincotto (1995). In addition, it should be noticed that dry pre-mixed mortar exhibits higher homogeneity and plasticity than the mortars made of cement lime and sand, as can be seen from Figure 7. Probably, it is due to the fact that the pre-mixed mortar has some additives to incorporate air.

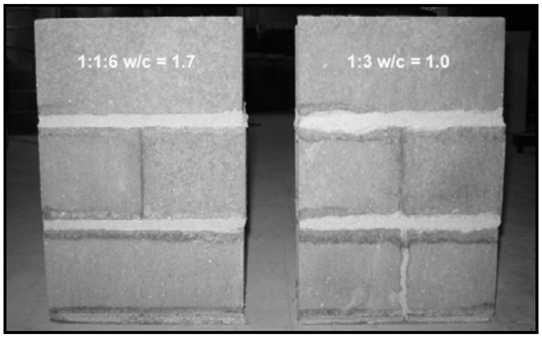
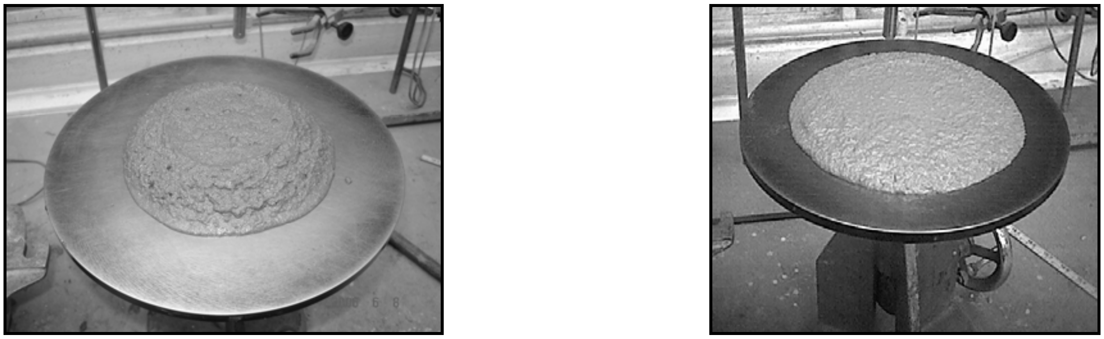


Figure 6. Drain of water in mix 1:3 indicating possible low water retention



(a) (b)

Figure 7. Comparison between pre-mixed and site mixed mortars; (a) Mix 1:3 $w/dm = 0.1590$; (b) pre-mixed $w/dm = 0.1444$

Hardened properties

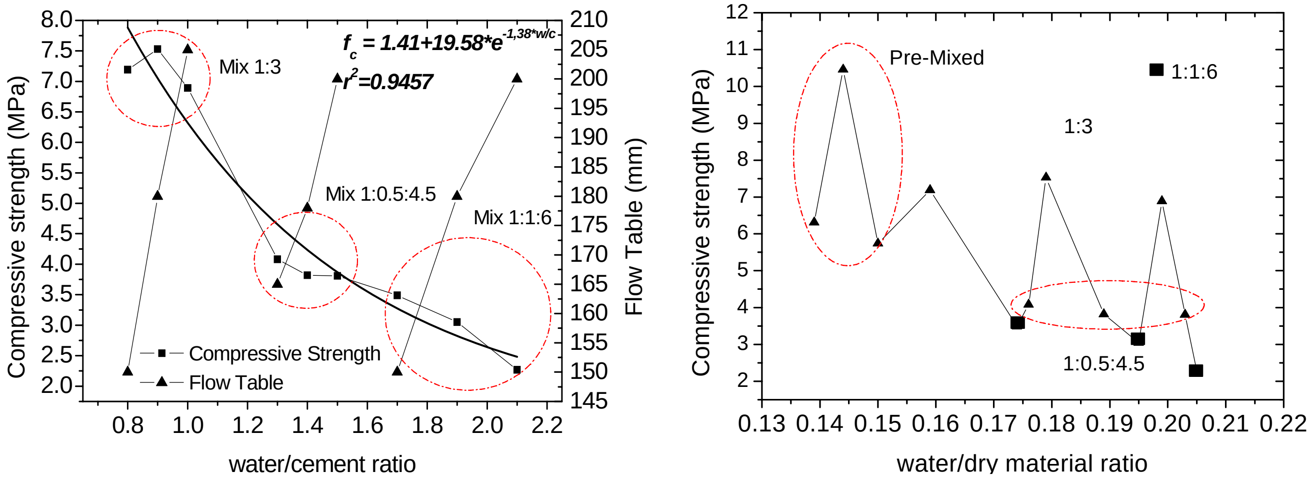
The mechanical behavior of the hardened mortars is characterized by means of the compressive, f_c, and flexural strength, f_f, elasticity modulus, E, and Poisson's ratio, ν. Table 4 shows the average results of the hardened properties evaluated in the experimental program.

It can be seen that low to moderate values of scattering were found in the compressive and flexural properties. Higher values of scattering were found in the elastic properties and particularly to the Poisson's ratio.

Table 4. Mechanical properties of hardened mortars. Coefficient of variation is inside brackets

Mix	***w/c***	***w/dm***	***Compressive strength (MPa)***	***Flexural Strength (MPa)***	***Elasticity Modulus (MPa)***	***Poisson's ratio***
1:3 (no lime)	0.8	0.159	7.19 (8%)	2.57 (4%)	10919 (33%)	0.21 (10%)
	0.9	0.179	7.53 (1%)	2.91 (13%)	9016 (14%)	0.18 (17%)
	1.0	0.199	6.89 (5%)	2.53 (15%)	10782 (8%)	0.26 (4%)
1:0.5:4.5	1.3	0.176	4.08 (10%)	2.01 (12%)	6956 (7%)	0.24 (15%)
	1.4	0.189	3.82 (16%)	2.02 (11%)	8398 (14%)	0.31 (20%)
	1.5	0.203	3.81 (2%)	1.89 (13%)	5935 (19%)	0.29 (24%)
1:1:6	1.7	0.174	3.49 (4%)	1.57 (1%)	8691 (16%)	0.50 (1%)
	1.9	0.195	3.05 (15%)	1.52 (3%)	6792 (5%)	0.39 (46%)
	2.1	0.205	2.27 (13%)	1.12 (13%)	3615 (20%)	0.23 (5%)
Pre-Mixed	-	0.139	6.31 (6%)	2.20 (5%)	7968 (4%)	0.20 (8%)
	-	0.144	10.46 (3%)	3.02 (14%)	11828 (10%)	0.31 (12%)
	-	0.150	5.74 (5%)	2.57 (3%)	9141 (17%)	0.25 (22%)

Figure 8 shows the results of the compressive strength obtained by averaging the results obtained in three prismatic specimens.



(a) (b)

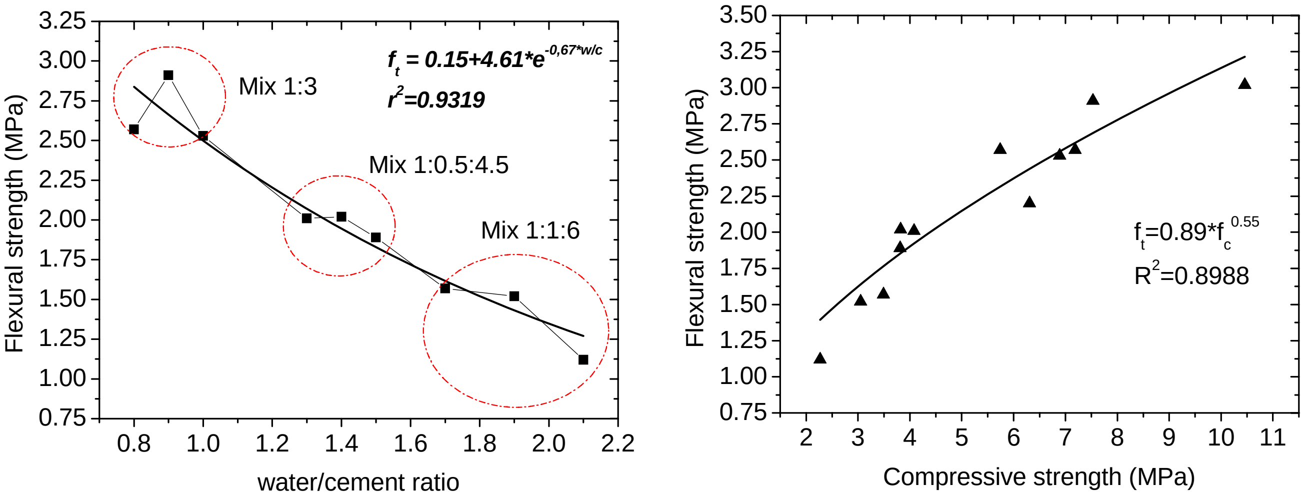
Figure 8. Experimental results; (a) compressive strength and flow table *vs. w/c* ratio; (b) compressive strength and flow table *vs.* w/*dm*

As expected, the compressive strength decreases as the *w/c* ratio increases. As shown in Figure 8a, an exponential relation was found between the compressive strength and the *w/c* ratio. The coefficient of determination characterizing the relation between both variables is r^2=0.95. With respect to water/dry material ratio, it was possible to notice an increase of the strength with the reduction of w/dm but there was no a clear tendency. From Figure 8a it can also be observed that for each mix, the consistency is much more sensitive to the *w/c* variation than the compressive strength. This behavior is even more evident in mixes with more cement. It should be referred that the level of the compressive strength is lower than the values suggested by ASTM C270 (1997) and BS 5628 (1978), see Table 5. This difference may possibly be caused by the low fineness modulus of the sand since the *w/c* ratio does not influence the compressive strength in the expected range.

Table 5. Comparison between results of compressive strength obtained in tests and suggestions by ASTM C270 and BSI 5628

Mix	***This work (MPa)***	***BS5628 (MPa)***	***ASTM C-270 (MPa)***
1:3 (no lime)	7,5	16,0	17,2
1:0.5:4.5	3,9	6,5	12,4
1:1:6	2,9	3,6	5,2

The mortars have similar flexural and compressive behavior. As shown in Figure 9a, an exponential relation between flexural strength and the *w/c* ratio was achieved. Figure 9b shows that the flexural strength and compressive strength are correlated by means of a power function with a very expressive coefficient of determination (r^2=0.90).



(a) (b)

Figure 9. Results of the flexural strength; (a) flexural strength *vs.* w/c ratio; (b) flexural strength *vs.* compressive strength

In spite of having used LVDTs and strain-gauges to measure vertical deformations for the calculation of the elastic modulus, only the results given by the strain gauges were considered. As the LVDTs were placed between steel plates, the measurements included the accommodation of the interfaces between the specimen and the steel plates, leading to considerable higher deformations, see Figure 10. Differences ranging from 12 to 30% were also pointed out by Vasconcelos (2005). An alternative scheme to measure the vertical displacements consists of the positioning of the LVDTs in the specimen by using special steel rings. The coefficient of variation obtained for the elastic modulus was in average of 14%.

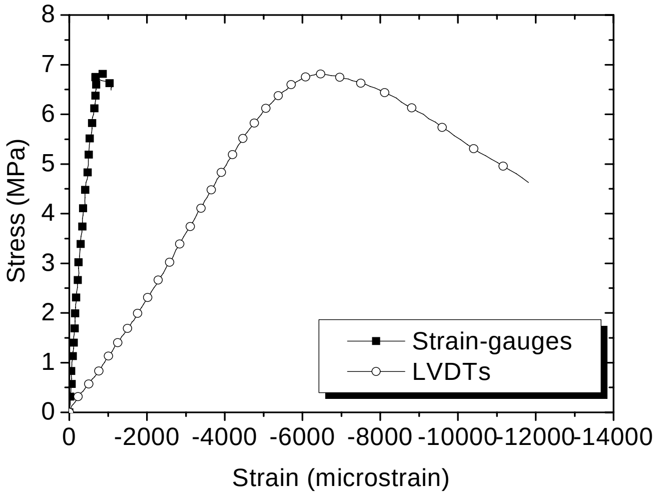
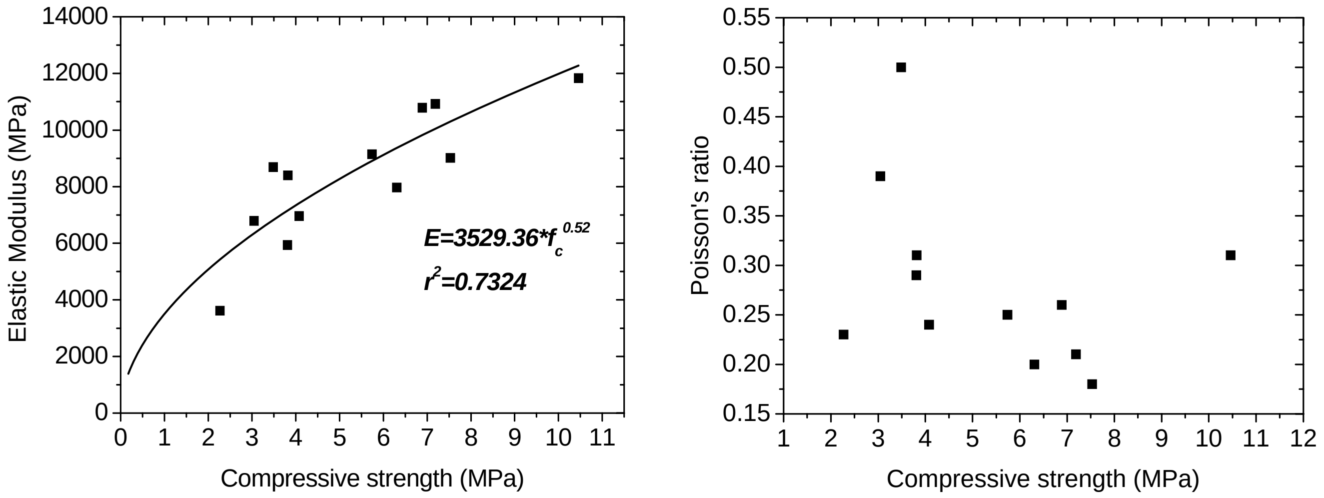


Figure 10. Comparison between the elasticity modulus measured by LVDTs and strain-gauges

Figure 11a shows the variation of the elasticity modulus with the variation of the compressive strength, being increasing as the compressive strength increases. In spite of the scatter, a power function describes reasonably well the relationship between both properties. The Poisson's ratio was also evaluated by means of strain-gauges but a large scatter was found. The Poisson's ratio did not show any tendency with compressive strength, as shown in Figure 11b.



(a) (b)

Figure 11. Elastic properties; (a) elastic modulus vs. compressive strength; (b) Poisson´s ratio vs. compressive strength

Conclusions

In order to study the possibility of designing a mortar that is suitable to be used in reinforced masonry that simultaneously fills the central cores of concrete masonry units and is used in the bed joins, an experimental study for the obtainment of fresh and hardened properties of different types of mortar was planed. Different *w/c* ratios were used for achieving different levels of workability. From the experimental results, the following conclusions can be drawn:

a) Mortars with flow values ranging from 150mm to 200mm exhibit sufficient workability to be used as infill and embedding, being recommended 175mm for the best consistency.

b) The consistency was more sensitive to the variation of the *w/c* ratio than compressive and flexural strength when each mix is analyzed separately. This was clearer for the mix with a higher percentage of cement. The increase on the consistency by increasing the w/c ratio does not seem to lower considerably the compressive and flexural strength.

c) The pre-mixed mortar presented a more homogeneous aspect and higher plasticity than mortars constituted by cement, lime and sand.

d) An exponential function was found for the correlation between compressive and flexural strengths with the *w/c* ratio. A power function was found for the correlation between the elastic modulus and flexural strength with the compressive strength.

Finally, it is important to stress that this paper only evaluates the mortar properties. Studies about the influence on the use of more fluid mortars (instead of grout) in properties of concrete masonry are needed. The role of mortar on the compressive strength of the masonry, mortar/vertical reinforcement bond strength and on the concrete unit-mortar bond strength is a key issue that demands further research.

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