INFLUENCE OF MORTAR MIX PROPORTIONS ON THE BEHAVIOR OF MASONRY EXPOSED TO HARSH ENVIRONMENTAL CONDITIONS

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Abstract

In masonry construction, effective bond between mortar and unit is required in order to provide structural integrity and durability to the masonry assemblage. Bond is dependent on material properties, workmanship, curing environment and age. The present research work aims at improvement of the long-term performance of masonry load-bearing structural elements exposed to harsh environmental conditions through use of different mortar constituents. An experimental program was conducted in order to investigate the effect of varying the mix constituents and proportions on the bond strength between mortar and clay bricks subjected to different exposure conditions. Local clay masonry units were used and ten different mortar mixes were investigated. The studied additives are lime, silica fume (SF) and polypropylene fibers (PPF) with different ratios. The specimens were exposed to harsh environmental conditions of wetting-drying cycles of water and sulphate salts solution, and the long term performance is compared to control specimens left in air. Tests were made to determine the mortar and prism compressive strength of mortar and the bond strength. The experimental results indicate that adding SF or PPF with a percentage of 2% to 5% of cement weight significantly improves the bond strength and deterioration resistance.

Keywords: masonry; mortar; bond strength, harsh environment; mix proportions; additives.

1. Introduction

Masonry construction is globally recognized to constitute the majority of the existing building stock and a significant percentage of the newly constructed buildings worldwide. The structural performance of masonry construction depends mainly on the properties of the constituent materials in addition to workmanship and construction quality control. The primary function of hardened mortar in masonry is to provide a durable and weather-tight joint with adequate bond strength. Bond strength is necessary for effective performance of masonry under the imposed loads, particularly shear and out-of-plane loads.

Because many factors contribute to bond strength, several published studies addressed the relationship of bond strength and brick and mortar properties, mortar curing conditions, effects of mortar aging and mortar mixture compositions. The initiation of the bond development phase takes place with the assembly of fresh mortar and masonry units. The subsequent setting of the cement compounds is preceded by the absorption of mortar water into the masonry unit and the resultant transport of mortar fines in the joint to the mortar–brick interface [1]. Since development of flexural strength in mortar is due to the hydration of Portland cement, it could be expected that continued hydration over longer periods of time would further increase the bond strength. However, previous research reported that a continuous increase in strength is not always observed, with both strength losses and gains occurring over time. The cause for strength gain and strength loss behavior at the latter ages was explained that the observed bond strength is the result of a combination of several mechanisms; hydration of CSH and carbonation of $Ca(OH)_2$ contributing to strength gains, with (drying) shrinkage and carbonation of CSH phases resulting in volume changes and micro-cracking being responsible for reductions in strength [2]. Strength reductions were observed at 14 or 28 d and 180 d with long-term strengths greater than at 7 days [3]. Bond strength decrease was also observed at 90 days and 365 days for unexplained reasons [4. This strength reduction was attributed to shrinkage drying and/or carbonation shrinkage and changes in the fracture toughness of the cementitious paste, associated with loss of moisture from the mortar [4].

The absorption of the brick used also greatly influenced the bond strength. As brick water absorption increased the bond strength reduced. This is a well-known effect caused by the dewatering effects of the bricks [5]. While the total amount of water absorbed is not a great factor, the rate at which the water is absorbed is important [6]. The initial rate of absorption (IRA) exerted by a brick initiates early bond development. Experimental results indicated that flexural bond is reduced at high and low brick IRA, and that optimum IRA range is between 5 and 10 g/min/30 in^2 for type N mortar and between 5 and 15 g/min/30in^2 for type S mortar [7].

Previous authors have investigated admixtures for mortar strength improvement. Walker et al [5] studied the effect of addition of hydrated lime versus air entraining admixture. Lime as an admixture raises water retention. It was reported that cement lime mortars provide less compressive strength though significantly greater flexural bond strengths [5]. Another study showed that mortars of low lime content (about 1/4 the cement) have superior flexural and compressive strengths than their plasticized equivalents at both early and mature age [8].

New materials have been recently used in the mortar mix such as fly ash and blast furnace slag in order to improve the mortar properties in terms of strength and resistance to environmental factors with time. Reda and Shrive [9] tested masonry prisms with fly ash for partial replacement of cement in cement-lime mortar and masonry cement mortar, and observed improvement in bond strength both mortar types with the addition of fly ash and significant increase in the 28 d flexural strength. Further increases in strength were also observed at 90 and 180 d [9]. Replacement of cement by ground granulated blast furnace slag (GGBS) or fly ash (FA) materials was shown to cause reduced bond strengths for varying proportions of GGBS and FA replacement [10]. The results showed that following an initial increase in masonry bond strength, a general reduction in bond strength occurred when high levels of cement replacement materials were used in the mortar [10]. An experimental study by Ambi and Habeeb [11] showed that silica fume mortar improved the compressive strength, flexural strength and permeability, and the optimum percentage of cement replacement with silica fume was found 10%. The increase in strength is mainly due to the aggregate-paste bond improvement and enhanced microstructure [11]. Use of silica fume 5% by weight of the cement resulted in significant deterioration of early strength [12, 13].

The present research work aims at improvement of the long-term performance and resistance of masonry load-bearing structural elements exposed to harsh environmental conditions through use of different constituents in the masonry mortar. The paper presents an experimental program conducted in order to investigate the effect of varying the mix constituents and proportions on the bond strength between mortar and clay bricks subjected to different exposure conditions. The influence of using additives of industrial by-products such as fly ash, silica fume, lime powder and polypropylene fibers on the mortar properties is studied.

2. Experimental Program

In the experimental program, ten mortar types were studied using different additives which are lime, silica fume (SF) and polypropylene fibers (PPF) with ratios of 2, 5 and 10% of cement weight. Brick specimens were constructed using local clay bricks and bonded using the studied mortar types. The specimens were exposed to harsh environmental conditions of wetting-drying cycles of water and sulphate salts solution and the long term performance is compared to control specimens exposed to air. Laboratory tests were carried out to determine the compressive strength of mortar and the bond strength between mortar and clay bricks. All experimental work including specimens' preparation, exposure and testing were carried out in the Materials and Quality Control Laboratory of the Faculty of Engineering at Shoubra, Benha University.

2.1 Materials

Masonry units: The bricks used in the research are local vertically perforated fired clay bricks of uniform shape and size. The dimensions of the bricks measured using measuring scale had average dimensions of 250 x120 x 65 mm. The experimentally determined properties are given in Table 1.

Cement: The cement used is Ordinary Portland Cement (OPC) CEM I 32.50 N produced by 'Amereya Factory', complying with ASTM C91/C91M (2012). The physical properties are given in Table 2.

Fine aggregate: A well graded siliceous aggregate was obtained from a sand quarry in 10th of Ramadan City, sand bulk density is 1650 kg / m^3.

Water: Clean potable water free from impurities was used for mixing, curing and exposure tests by wetting and drying process.

Hydraulic lime: Hydrated lime complying with ESS 584 (1979) is used, with bulk density 500 kg/m^3. Lime retained at sieve No 37 and 42 is 4% and 6% by weight, respectively.

Silica fume: The used CSF is produced locally from the Ferro-silicon alloy industry in Aswan. The bulk density of is 290 kg/m^3, specific gravity is 2.3, particle size is from 0.15 mm to 0.6 mm and surface area is 25 m/kg.

Polypropylene fibers: The PPF used is imported but available locally. The average length of the used PPF is 15 mm. The specific gravity is 0.9, tensile strength and ultimate elongation are reported to be 630 N/mm^2 and 25% (according to manufacturer data sheet).

Table 1 Physical and mechanical properties of the used bricks

Property	**Value**
Dimensions (mm)	250 x 120 x 65
Unit weight (kg / m^3)	1750
Initial rate of absorption, (IRA) (gm/cm^2/min)	0.2
Absorption after 24 hour, (% of dry weight)$^+$	10
Absorption after 5 h boiling, (% of dry weight)	14
Perforation (% of total volume)	30
Compressive strength (N/mm^2)	8 (5.2)*

* value in brackets is coefficient of variation

Table 2 Properties of cement used

Property		**Value**
Setting time (min)	Initial	75
	Final	100
Expansion (mm)		1.2
Specific gravity		3.15
Bulk density (kg/m^3)		1450
Compressive strength, BS 4550 (N/mm^2)	28 days	32.5

Table 3 Mix proportions for one cubic meter of mortar for all mortar types

Cement	Sand	Water	Additive
208 kg	1660 kg	143.45 lt	0-10% weight of cement

2.2 Mix Proportions

In the present experimental program, three types of additives in different percentages were used to produce ten mortar mixes, the mix proportions are given in Table 3. The mortar types are OPC-sand mortar used as control mix, and nine mortars types where lime, condensed silica fume and PPF are added with different percentages of 2%, 5% or 10% of the weight of cement, as illustrated in Figure 1. The dry components of each mortar type were manually mixed before adding the amount of water required for the flow gradually until it became homogenous.

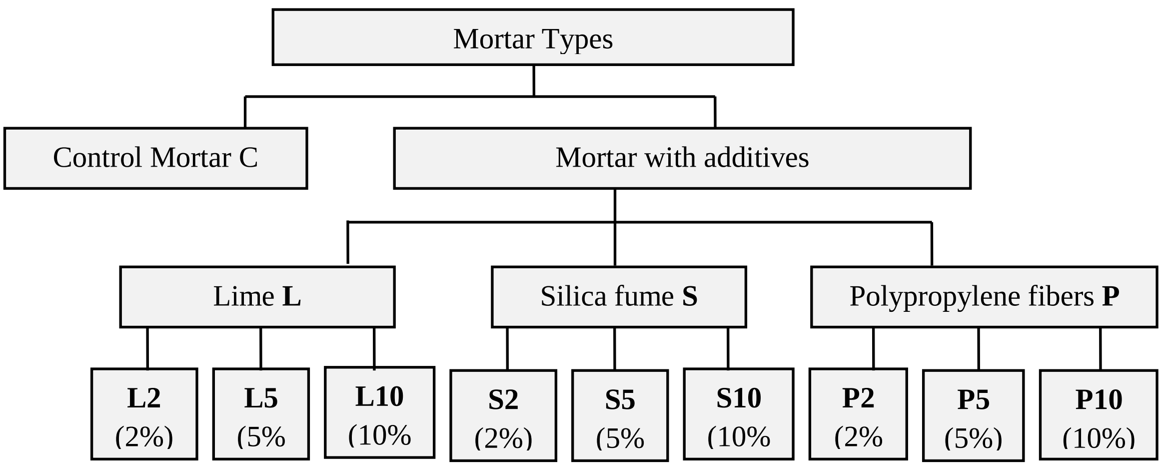

Figure 1 Tested mortar types and designation

3 Samples preparation and testing procedures

3.1 Water absorption test

Initial rate of absorption tests were conducted. Dry bricks were placed inside plastic containers with 3 mm of water above the top of the supports. After one minute, the brick was lifted from contact with the water, the surface was wiped with a damp cloth and the brick weighed. The results are reported in grams of water gained per 30 sq. in. Also, absorption tests were conducted; full bricks were completely submerged in distilled water in plastic containers. Measurements were recorded after one minute, five minutes, ten minutes, one hour, five hours and twenty-four hours.

3.2 Mortar retentivity test

Retentivity tests were conducted according to ASTM C1506 (2009) [15]. In this test, mortar is trimmed inside a brass ring of 100-mm internal diameter and 25 mm internal depth. Mortar retention capacity is then measured against the suction forces of 8 filter papers, which are placed under a constant weight of 2 kg during a period of 2 minutes. The mass of water retained in the mortar after suction is measured and expressed as a percentage of the original water content, termed water retentivity.

3.3 Curing and exposure conditions for test specimens

The test specimens were placed in the laboratory and either left in normal room conditions or were exposed to wetting / drying cycles by water or salt solution. The salt solution was prepared by dissolving 150g of the magnesium sulphate salt in 1 lt of clean water. Wetting was made by spraying the samples two times each day. The exposure conditions were applied to six identical specimens of each of the ten mortar types. Three specimens were tested after 28 days while the other three were exposed to the same condition and tested after six months.

3.4 Compressive strength of mortar cubes

Each of the ten mortar types was cast in 50x50x50 mm cube molds and demoded after 24 hours. The cube samples were subjected to the different curing conditions in the laboratory until the age of 28 days. Compressive strength tests were performed in accordance with BS EN 1015-11(1999) [16], as shown in Figure 2, with the load gradually increased until failure. The cube strength was reported as the average of three cubes.

3.5 Compressive strength of brick prisms

Compressive test prisms were prepared using three stacked bricks accepted by some international specifications such as ASTM E447 (1984), so as to fit in the available test machine. The prisms constructed manually had mortar bed thickness of 12 mm. They were covered by polyethylene plastic sheets for 7 days, and then stored till the time of test after 28 days. The prism specimen was tested in compression testing machine of 1000kN capacity, as shown in Figure 2. Vertical load was applied gradually and the ultimate load was recorded.

3.6 Test of brick-mortar bond strength

For experimental determination of the brick-mortar bond strength, crossed brick couplet were constructed from each of the mortar types used in this research program, as shown in Figure 3. Six cross brick specimens were constructed from each type of mortar. After construction, the brick samples were covered by plastic sheets for 7 days then cured under laboratory conditions in air or water or salt solution as described in the previous section testing. Three samples tested after 28 days and the other three after 6 months. The samples were tested per ASTM C952 (2012) [17] having the setup illustrated in Figure 4, which evaluates the tensile strength of mortar using a crossed brick couplet test. The apparatus uses a lever to create a moment in the mortar joint and failure occurs at the location of maximum tensile stress. The breaking load is recorded and stress of the mortar joint is calculated.

Figure 2 Compressive strength test for mortar cube and for brick prism

Figure 3 Cross brick specimen for bond strength test and some of the specimens subjected to wetting and drying by water or salt solution

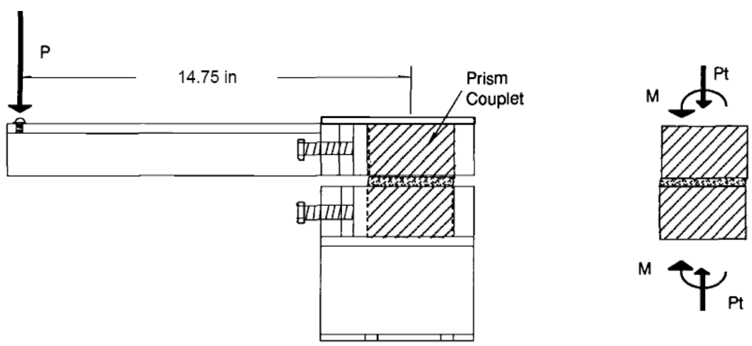

Figure 4 Diagram of the mortar-unit bond strength test (McGinley, 1996)[7]

4 Experimental Results and Discussion

4.1 Initial rate of absorption

The experimental results for the absorbed water after several time intervals are given in Table 4, as average of three values, expressed as a percent of the brick dry weight. The results are also plotted in Figure 5. The obtained experimental results show the high ability of clay brick to absorb water from the mortar. This is due to the fact that the suction force of the brick noodles has to overcome the two forces; the poetic traction force in the pores of the mortar and gravity of the water stand alone. The absorption rate is doubled in the first 5 minutes and then gradually decreases until it stops after two days. Results showed that addition of lime to the mortar gives greater absorption values followed by addition of PPF followed by CSF. In term of mixing ratios, it was found for the three additives that the ratio giving largest absorption is 2%.

Table 4 Experimental results of water absorption

Time	1m	5 m	30m	1h	2h	5h	15 h	1d	2d	3d	4d	5d	6d
Absorbed water (% brick dry weight)	2.45	8.5	8.83	8.88	8.93	9.2	9.27	9.99	10.1	10.5	10.5	10.5	10.5

m = minute h = hour d = day

Table 5 Initial rate of absorption (IRA) of bricks from mortar

Mortar type	**C**	**S2**	**S5**	**S10**	**P2**	**P5**	**P10**	**L2**	**L5**	**L10**
IRA (gm/cm /minute * 10")	3	2.85	2.2	1.5	2.5	2	1.85	2.75	2.65	2.4

Table 6 Percentage of absorbed water by filters to the total amount of water inside for the different mortars

Mortar mix	**Time (min.)**							
	2	**5**	**10**	**15**	**20**	**25**	**40**	**55**
C	24.25	36.99	44.25	44.41	45.45	45.45	45.45	45.45
S 2	22.56	29.2	36.44	37.2	39.2	39.2	39.2	39.2
S5	18.65	24.8	27.9	31.2	31.2	31.2	34	34
S 10	18.5	21.76	27.48	30.9	31.02	31.02	32.01	32.01
P 2	20.01	28.65	34.38	37.25	37.25	37.25	40.11	40.11
P 5	17.54	24.85	26.32	29.24	32.16	32.16	32.16	32.16
P 10	16.98	23.15	26.23	29.32	29.32	29.32	32.41	32.41
L 2	19.35	28.27	32.84	34.23	34.23	34.23	34.23	34.23
L 5	17.39	23.19	24.64	26.09	27.54	27.54	27.54	27.54
L 10	17.6	22	26.5	26.45	27.86	27.86	30.8	30.8

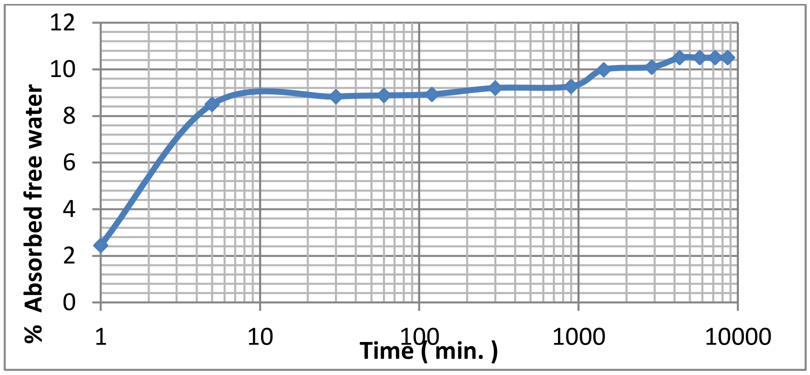

Figure 5 Variation of absorbed free water by brick with time

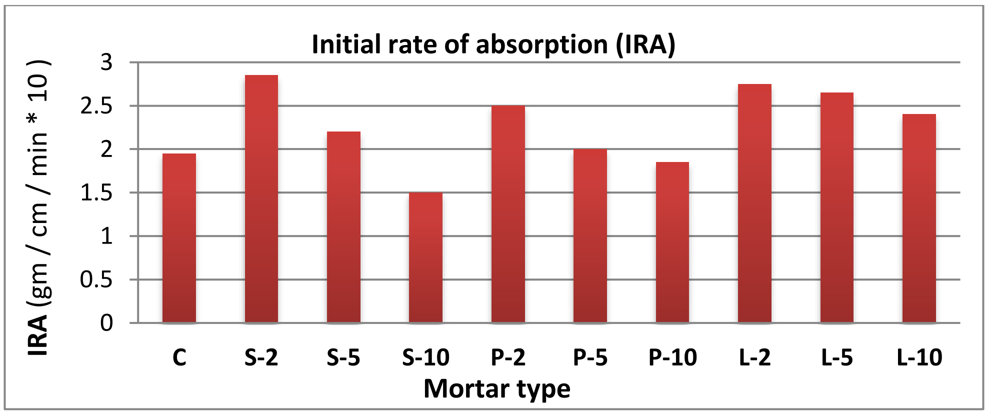

Figure 6 Initial rate of absorption of bricks from mortars of all types

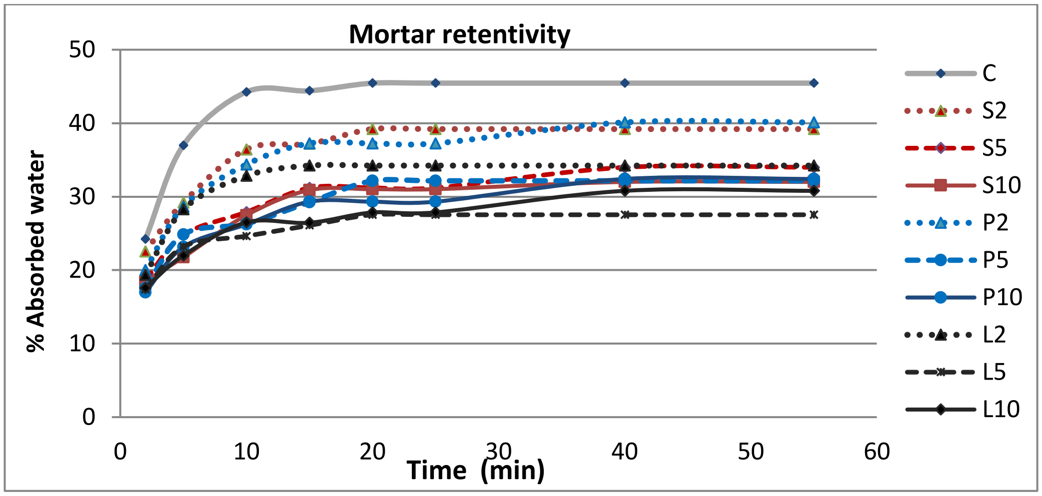

Figure 7 Absorbed water-time relationship for all mortar mixes

4.2 Mortar retentivity test

The results of the retentivity test for all mortar types are given in Table 6.The results are plotted in Figure 9 to show the relation of mortar retentivity with time for the different types of mortar. The results show that for all mortar types, retentivity increases with time and the rate is slower with time. Compared to the control mortar C with no additives, all the studied additives tend to decrease the retentivity. Increasing the percent of additives caused decrease of retentivity for mortar types L, S and P.

4.3 Compressive strength of mortar

The results of the compressive strength tests made on mortar cubes after 28 days of exposure to air or wetting drying cycles of water or salt solution are given in Table 7. The values represent the average of three cubes from each mortar type. The results are plotted in Figure 8 to show the effect of different curing methods on the different mixtures of mortar.

The highest compressive strength attained was 161.53 MPa for the mix with lime addition of 5% of cement weight subjected to wetting /drying cycles by water. The results in Table 7 indicate that that for all mortar types, water exposure gives the highest cube compressive strength followed by salt solution exposure followed by air exposure. The experimental results show that mortar strength increased by 20%, 30.8% and 35.4% due to addition of CSF by 2%, 5% and 10% of cement weight, respectively, and increased by 20%, 46.2% and 36.9% due to addition of PPF by 2%, 5% and 10%, respectively, compared to the compressive strength of control mortar C. The increase in mortar strength of PPF mortars may be attributed to the weak nature of the mortar mix used or due to experimental variations. The compressive strength decreased by 8.5% and 3.1% for 2% and 10% addition of lime, respectively, and increased by 61.5 for 5% lime addition.

Table 7 Compressive strength of cubes of different mortars

	Mortar cube compressive strength (N/mm^2)		
	Air exposure	**Water exposure**	**Salt sol. exposure**

Mortar type	N/mm^2	% of reference mortar C	N/mm^2	% of reference mortar C	N/mm^2	% of reference mortar C
C	5.8	100	6.5	100	6.1	100
L2	5.65	97.4	5.95	91.54	5.8	95.08
L5	8.3	143.1	10.5	161.53	9.6	157.37
L10	5.5	94.8	6.3	96.9	5.9	96.7
S2	6.7	115.5	7.8	120	7	114.75
S5	7.2	124.13	8.5	130.77	7.9	129.5
S10	7.6	131.03	8.8	135.38	8.2	134.42
P2	6.8	117.24	7.8	120	7.3	119.67
P5	8.4	144.8	9.5	146.15	8.9	145.9
P10	7.5	129.31	8.9	136.92	8.1	132.78

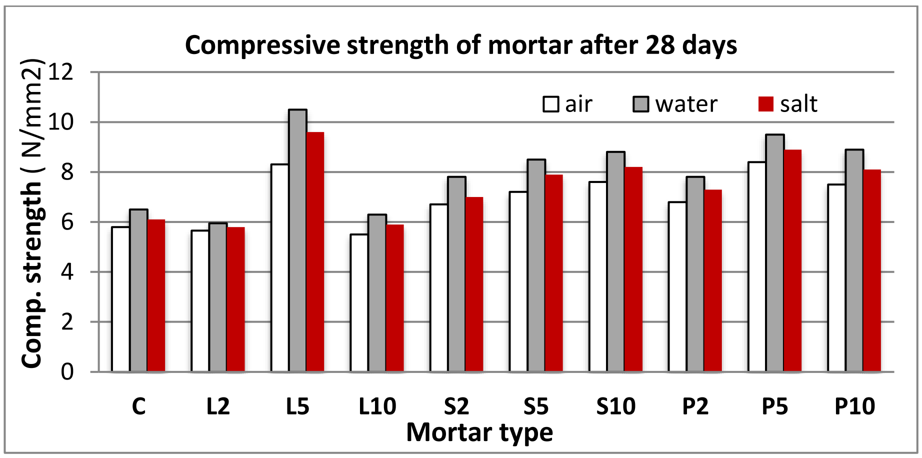

Figure 8 Compressive strength of cubes of all mortar types

4.4 Compressive strength test of brick prisms

Experimental results of compression test on masonry prisms made with perforated clay bricks and the different used mortars are given in Table 8, as average value of three tested prisms. The results are plotted in Figure 9. The low prism strength may be attributed to the low strength of the used clay brick. It is important to point out the need for improving the quality of clay brick in order to be qualified for use in unreinforced masonry.

The experimental results show that for all mortar types water exposure gives higher values for compressive strength of brick prisms followed by salt solution exposure followed by air exposure. Adding lime to the mortar 2% and 10% of cement weight caused decrease of the prism strength by about 29% and 18%, respectively, while adding 5% lime caused slight increase of 2.2% of prism strength compared to control OPC mortar. Adding PPF to mortar by 5% and 10% of cement weight increased the prism strength by 4.4 % and 2.2%, respectively. Addition of CSF by 2% of cement weight caused increase of prism strength by 6%, while addition of CSF by 5% caused decrease 6.7% in prism strength. When 10% CSF content was used, it was found that no bond between mortar and brick was developed and therefore the prism strength was considered equal to zero. PPF introduction in mortars decreased mortar strength for 2% addition but slightly increased mortar strength for 5% and 10% addition. The increase in prism strength for 5% and 10% PPF mortars may be attributed to the weak nature of the mortar mix used and improved ability of PPF mortars to resist cracking, or due to experimental variations. However, this part of the research may need further testing to verify the attained results.

Table 8 Compressive strength of brick prisms

Mortar type	Compressive strength of brick prisms (N/mm²)					
	Air exposure		Water exposure		Salt solution exposure	
	N/mm²	% of reference mortar C	N/mm²	% of reference mortar C	N/mm²	% of reference mortar C
C	3.8	100	4.5	100	4.1	100
L2	2.55	67.1	3.2	71.11	2.9	70.73
L5	2.8	73.68	4.6	102.22	4.2	102.43
L10	3	78.94	3.7	82.22	3.3	80.48
S2	3.9	102.63	4.8	106.67	4.3	104.87
S5	3.5	92.1	4.2	93.33	3.9	95.12
S10	-	-	-	-	-	-
P2	2.9	76.31	3.8	84.44	3.4	82.92
P5	3.8	100	4.7	104.44	4.4	107.31
P10	4	105.26	4.6	102.22	4.2	102.43

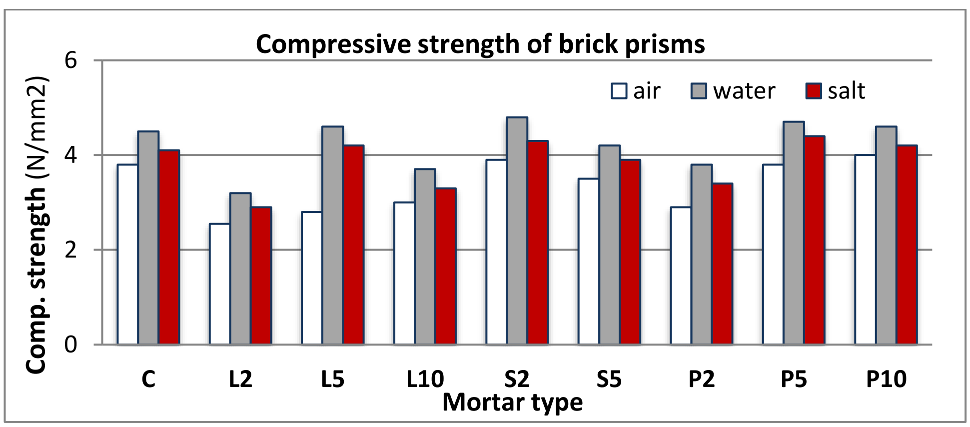

Figure 9 Compressive strength of brick prisms

4.5 Brick-mortar bond strength

The results of the testing of brick-mortar bond are given in Table 9 as the average value of three tested samples. The results are plotted in Figures 12 and 13 for bond strength test after 28 days and after 6 months, respectively.

The experimental results demonstrate overall gain in strength with age for all mortar types. These findings are also consistent with those reported previously by De Vitis et al. (1998) [3] and Reda and Shrive (2000) [9]. It is observed that addition of lime by 2% of cement weight increased the bond strength by 7%, 13.8% and 11% after 28 days of air, water and salt solution curing, respectively, and by 4%, 12.5% and 9.8% after 6 months of air, water and salt solution curing, respectively, over the bond strength of OPC. This could be due to the creation of more continuous cementitious network due to lime presence. However, increasing lime addition to 5% caused decrease of bond strength by 16.4.7%, 10.8% and 16% after 28 days of air, water and salt solution curing, respectively, and by 20%, 5.2% and 13.4% after 6 months of air, water and salt solution curing, respectively. Increasing of lime to

10% caused decrease of bond strength by 9.7%, 7.6% and 7.9% after 28 days of air, water and salt solution curing, respectively, and by 40%, 15.5% and 29.5% after 6 months of air, water and salt solution curing, respectively. Bond strength decreases by addition of 5% or more lime, in spite of the observation that mortars containing 5% lime had cube compressive strength 43%, 61% and 57% higher than OPC mortar for 28 days of air, water and salt exposure, respectively.

Table 9 Results of tensile bond strength of clay brick with different mortars

Mortar type	Additive	Brick-mortar bond strength (x10^{-2} N/mm^2)					
		After 28 days			After 6 months		
		air	water	salt	air	water	salt
C	none	2.99	3.25	3.15	9.8	13.5	11.2
L2	lime 2%	3.2	3.7	3.5	10.2	15.2	12.3
L5	lime 5%	2.5	2.9	2.65	7.8	12.8	9.7
L10	lime 10%	2.7	3	2.9	5.8	11.4	7.9
S2	SF 2%	7.3	8.2	7.8	14.5	20.3	16.7
S5	SF 5%	8.2	9.4	8.8	8.3	12	9.6
S10	SF 10%	-	-	-	-	-	-
P2	PP 2%	4.8	5.6	5.1	11.3	23.2	18.5
P5	PP 5%	4.6	5.8	5	10.3	19.3	14.7
P10	PP 10%	5.7	6.5	6.1	10.1	17.4	14.2

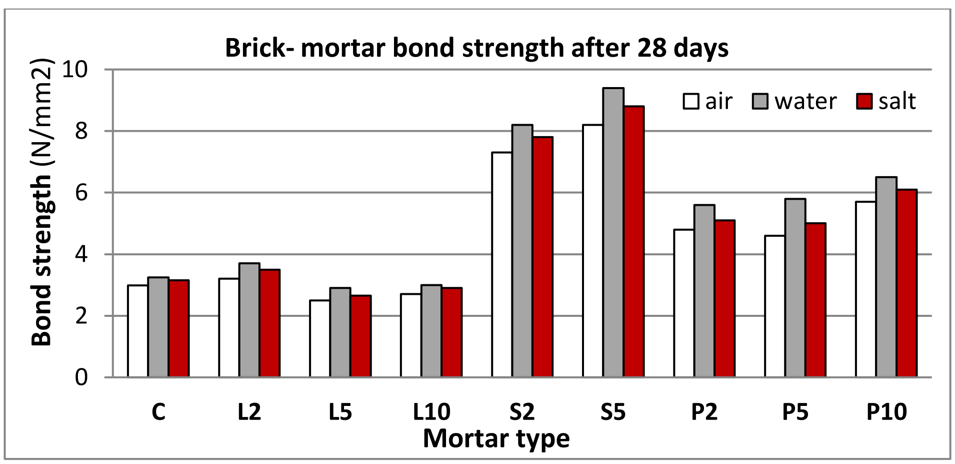

Figure 10 Bond strength after 28 days

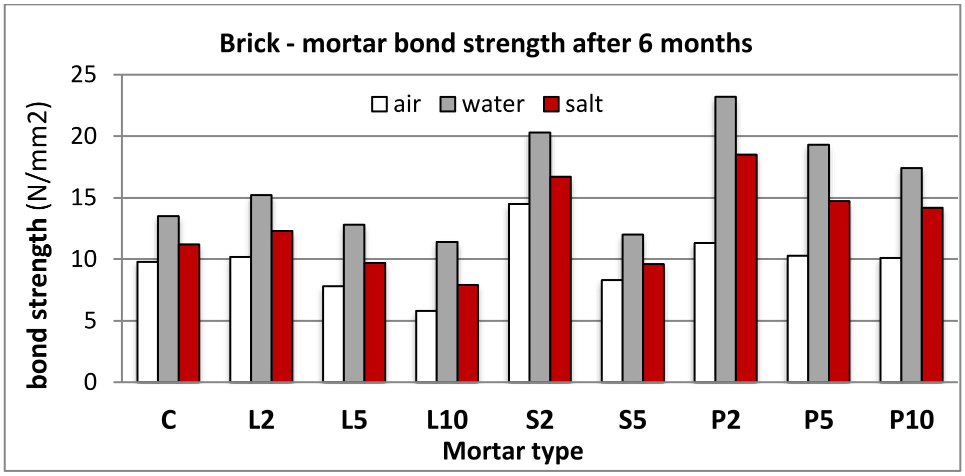

Figure 11 Brick-mortar bond strength after 6 months of exposure

It is observed that adding CSF by 2% increases bond strength by more than 200% compared to control OPC mortar. Increasing CSF ratio more than 5% has no significant positive effect on bond strength. Increasing CSF up to 10% of cement weight leads to complete destruction to bond, where separation happens at the contact surface of mortar and clay brick under zero loading. This could be interpreted as CSF presence with a little amount, such as 2%, could adjust mortar retentivity, water carrying capacity and consistency, which is noticed during flow test, to match with the clay brick absorption without reducing mortar flow which assures good bond.

Result show that addition of PPF by 2% , 5% and 10% increases 28 days bond strength for water exposure by 72%, 78% and 100%, respectively, over reference OPC mortar, and after 6 months of water exposure the bond strength increases by 72%, 43% and 29%, respectively, than reference mortar. This could result from the marked improvement in mortar water carrying capacity and the prevention of the phenomenon of water bleeding or separation from mortar on standing. This preserved water inside mortar, till the time of its absorption into brick with the necessary amount of hydrated cement grains, is essential for obtaining good bond.

5 Conclusions

This paper presented an experimental program where ten mortar mixes with hydraulic lime, condensed silica fume (CSF) and polypropylene fibers (PPF) were added at different ratios of 2%, 5% and 10% of cement weight. The mortar compressive strength and clay brick-mortar bond were evaluated after exposure to harsh environmental conditions of wetting/drying cycles of water and sulphate salts solution. The influence of the different additives as well as the long term performance is compared to control specimens exposed to air.

Following the experimental work outlined above the following conclusions have been made:

- IRA test and mortar-brick absorption standard tests did not give similar results because of the great dissimilarity of pore size distribution and suction ability of filter papers compared to bricks.
- Bond strength increases by decreasing the ratio of the absorbed water by upper to the lower brick for clay brick.
- CSF addition to mortar improves its bond strength with clay brick up to 289.2% at the age of one month and 150.4% for 6 months.
- The most suitable percentage recommended by this research for CSF addition to mortar is between 2% to 5% of cement weight.

- It is not recommended to increase CSF in OPC: sand mortar up to 10%, as this will cause mortar-brick separation.
- PPF improves OPC: sand mortar bond strength by about 190.6% for air cured couplets and by more than 200% for sulphate solution sprinkled couplets.
- Mortar with lime addition 2% of cement weight improve bond strength by 104% for air cured, 115% for water cured and 110% for sulphate solution (10% concentration).
- It is recommended to use lime in mortar with a reasonable amount as this increases mortar bond with clay brick.
- The most suitable percentage recommended by this research for lime addition to mortar is about 2% of cement weight.

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