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Improvement of clay brick masonry bonding using polyurethane foam mortars with blended cement

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ABSTRACT

Masonry is a composite material generally used in construction. It displays numerous advantages, involving significant compressive strength, thermal inertia, and aesthetic beauty. Poor bond and low bond strength are major problems of brick masonry and this aspect is fundamental in seismic regions. In this study, the improvement of brick masonry bond and shear strength using polyurethane foam mortars with blended cement has been investigated. Toward this objective, fly ash class F and nano silica were utilized in mortars by 30% and 2%, as partial cement replacement respectively. The properties of components were performed, followed by compressive strength tests on polyurethane foam mortars. Moreover, a comparison of the behaviour of the polyurethane foam mortar prisms, triplets and couplets under compressive, shear and bond tests with respect to the reference cement mortar masonry was carried out. A significant increase in shear and bond strength was achieved by using polyurethane mortar reaching up to 79% and 160% respectively at 28-day for mortar made with polyurethane foam and 30% fly ash and 2% nano silica. Results provide indications on which polyurethane foam mortars have to be used for masonry buildings in regions that are subjected to seismic hazards.

Keywords: polyurethane mortar; bond strength; shear strength; triplets; couplets

Introduction

Masonry buildings are largely composites comprised of masonry units and mortar. In developing countries, the use of masonry buildings is still moderately high due to the low cost and availability of materials. High bond strength between masonry units and mortar is essential to withstand lateral and cyclic loadings [1-5].

Poor bond strength between units and mortar is the most failures in masonry buildings as indicated by Francis et al. [1]. Many features that are related to the properties of mortar and masonry units affect the bond and bond strength. These features are the texture of surface, porosity, pores size and pore distribution in mortar and masonry units. These factors play a significant role in the improvement of masonry bond strength. Furthermore, the compressive load on the masonry has a considerable influence on the bond strength of masonry [2, 6-9].

Numerous studies have contributed to bond development by using (supplementary cementitious materials, fibers

and adhesive materials) and their governing factors [1, 10-12]. It is widely known that masonry bond is affected by different factors related to both masonry units and mortar. The effect of pozzolanic materials on hardened mortars is ascribed to its pozzolanic reaction, by which the supplementary cementitious materials chemically consume the weak portlandite crystals and convert them to strong calcium silicate hydrates fibrous gel.

Taha and Shrive [1] studied the use of pozzolans to enhance bond and bond strength. They used different partial replacement of cement with fly ash and slag. The results indicated that a significant increase in bond strength was observed with 20% substitution of fly ash at 28, 90 and 180 days and no increase was noticed with slag.

Resketi and Toufigh [11] studied the improvement of brick masonry shear bond strength by utilizing green mortars. ‘‘Taftan” as a natural pozzolan and two classes of rice husk ash were utilized in mortars. The results indicated that by using these materials, mortar ductility improved and failure strain increased.

Hamdy et al. [12] investigated the influence of different additives on the bond strength of clay bricks masonry exposed to adverse environmental conditions. These additives were silica fume and polypropylene fibers with percentages of 5 & 10% of cement weight. The masonry was subjected to wetting/drying cycles of water and sulphate salts solution for different ages. Adding 2-5% silica fume or polypropylene fibers improves the bond strength by 70-170% for the different conditions.

Dhananjay et al. [13] studied bond strength improvement of masonry by using 0.45% from recron polyester fibers. The studies on brick masonry prism suggest that the use of recron polyester fiber in mortar can increase the bond strength to enhance the performance of the masonry structure. They investigated the effect of thickness of mortar joint on the bond strength, therefore they used 8 mm and 12 mm mortar thickness. The results confirmed that the 12 mm thick mortar bed with addition of 0.45% fiber, give optimum bond strength.

Several studies examined the use of polyurethane foam alone as adhesive material for masonry to increase the bond between mortar and bricks [14-16]. But the effect of environmental conditions and durability issues make crucial problems for polyurethane alone due to its polymer properties. Moreover, the cost of polyurethane foam was higher than cement mortar. All these disadvantages of polyurethane foam can be avoided by utilizing polyurethane foam in blended cement mortar. Therefore in this study, polyurethane foam was utilized in blended cement mortar to investigate its effect on the bond between bricks and mortar.

Scope and objective

The principal objective of this study was to examine the effect of polyurethane mortar with blended cement on shear and bond strength improvement. A minor objective of this study included the use of supplementary cementitious material to increase bonding between mortars and bricks and reduce the environmental influence of cement. For this purpose, fly ash and nano silica were used in designing five classes of mortars. Figure 1 shows a summary flowchart of experimental tests.

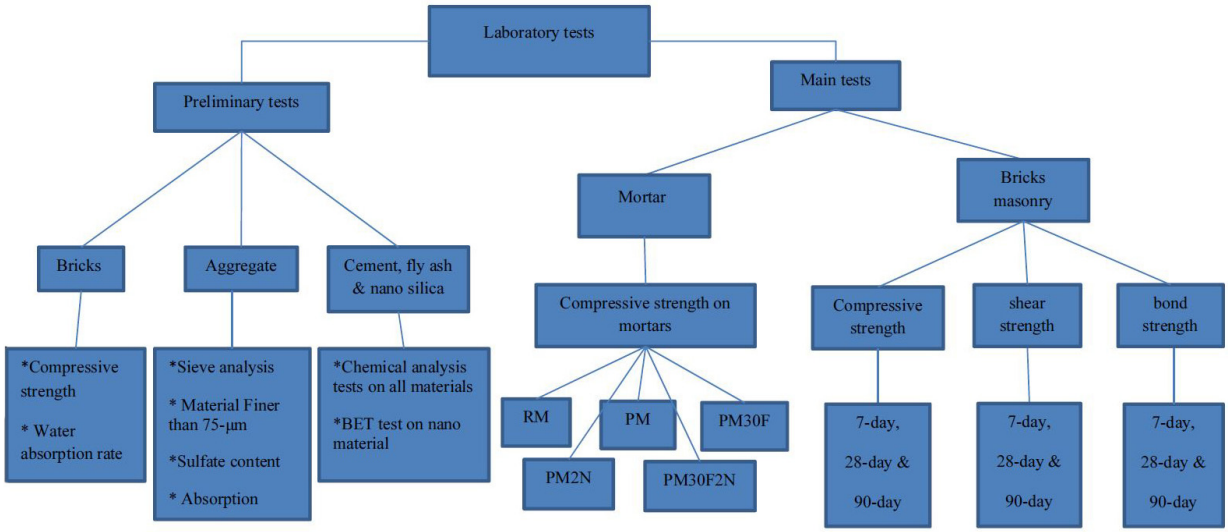

Figure 1. Overview flowchart of laboratory tests.

Experimental work

Materials

Solid fired-clay bricks having a size 24×12×8 cm were used. Test results confirm that this brick follows class B brick according to Iraqi specification IQS No. 25/1988 [17]. Portland cement was used and the test results confirm that this cement follows cement class (32.5R) according to Iraqi specification IQS No.5-2019 [18] specifications. Natural sand with grading limits in zone 2 is used as a fine aggregate. Results indicate that the fine aggregate grading and the sulfate content are within the requirements of the Iraqi specification No.45/1984 [19]. Class F fly ash that are conforming with ASTM C618 class F fly ash [20]. Powdered SiO_2 nanoparticles with a high specific surface area measured by the BET method (Brunauer-Emmet-Teller) have been used throughout this study. Potable water according to IQS 1703/2018 [21] was used in the mixing and curing process of mortars. Figure 2 refers to the binding materials (cement, fly ash and nano-silica).

Figure 2. Cement and supplementary cementitious materials.

Tables 1-5 chemical and physical analysis of all used materials and mix proportion of mortars.

Table 1. Some mechanical properties of clay bricks

IQS NO. 25/1988 [17]	Brick	Properties
(20, 24, 26)% for (A, B, C) Class	20.5	Water absorption rate (%)
(18, 13, 9) MPa for (A, B, C) Class	13.2	Compressive strength (MPa)

Table 2(a). Chemical analysis and physical properties of cement

Composition of oxide	Cement	IQS NO.5-2019 [18]
CaO	62.92	-
SiO_2	21.21	-
Al_2O_3	4.84	-
Fe_2O_3	3.33	-
MgO	1.66	≤ 5%
SO_3	2.14	≤ 2.8%
Loss on Ignition L.O.I	2.06	≤ 4%
Insoluble residue I.R.	0.70	≤ 1.5%
Specific gravity	3.15	-
Specific Surface area m^2/kg	290	≥ 250

Table 2(b). Chemical analysis and physical properties of fly ash

Composition of oxide	Fly ash	ASTM C618 class F fly ash [20]
CaO	9.15	10 (max)
SiO_2	40.19	
Al_2O_3	28.77	$SiO_2 + Al_2O_3 + Fe_2O_3$ = (70 min)
Fe_2O_3	15.75	
MgO	1.89	5 (max)
SO_3	1.91	-
Specific gravity	2.1	-
Specific Surface area m^2/kg	350	-
Strength activity index at 28 days	86.5%	75% (min)

Table 2(C). Chemical analysis and physical properties of nano silica

Composition of oxide	Nano silica
SiO_2	99.8
Specific gravity	2.2
Specific Surface area m^2/kg	200000
Strength activity index at 7 days	142%

Table 3. Physical properties of fine aggregates

Physical properties	Test results	IQS No. 45 /1984 [19]
Specific gravity	2.6	-
Material Finer than 75- μm	3.5	≤ 5%
Sulfate content %	0.34	≤ 0.5%
Absorption %	1.5	-

Table 4. Grading of fine aggregate

Sieve size (mm)	Cumulative passing %	IQS No.45/ 1984 Zone 2 [19]
9.5	100	100
4.75	100	90 -100
2.36	83.5	75 -100
1.18	75.5	55 - 90
0.6	52.2	35 -59
0.3	20.8	8 -30
0.15	4.8	0 -10
Fineness modulus	2.63	

Table 5. Mix proportion of mortars in (kg per m^3)

Mortar designation	Mix ID	Cement	Fly ash	Nano silica	Water	water-binder ratio	Sand	Polyurethane foam
Reference mortar	RM	560	0	0	280	0.5	1400	0
Mortar with polyurethane foam	PM	560	0	0	280	0.5	1000	60
Mortar with polyurethane foam and 30% fly ash	PM30F	392	168	0	280	0.5	1000	60
Mortar with polyurethane foam and 2% nano silica	PM2N	548.8	0	11.2	280	0.5	1000	60
Mortar with polyurethane foam and 30% fly ash and 2% nano silica	PM30F2N	380.8	168	11.2	280	0.5	1000	60

Specimen preparation

Five classes of mortars were used as binding mortar. All mortars were mixed in a mixer with a 1:2.5 binder: sand ratio, conferring to BS EN 1996 [22]. This weight ratio reveals the proportions presently used for binding mortars in construction buildings.

A pre-foaming method was used to produce polyurethane foamed mortars. After the mixing of mortar for 3-minutes, the ready-made foam was added to the mortar and mixed for 1-minute.

Specimens dimensions used for each test are presented in Figure 3(a)-3(c). For the tests, brick units 24×12×8 mm in dimension were used. For each test, a constant mortar thickness of 10 mm was used as a binding mortar. Mortars were cured by “curing compound” and left in the laboratory up to a period of testing.

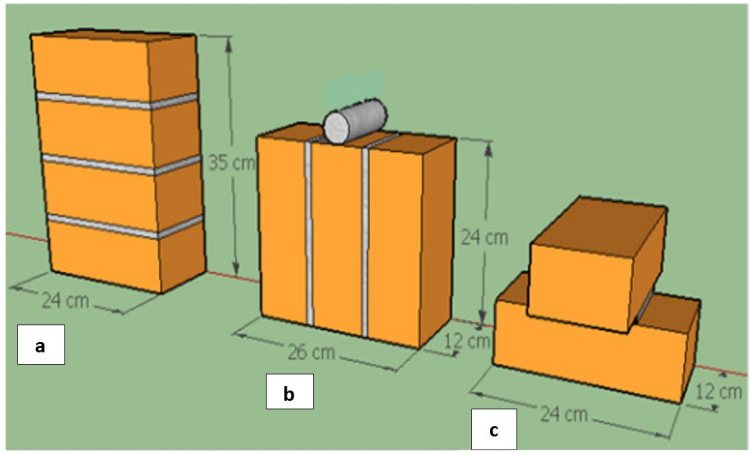

Figure 3. Arrangement of bricks used for (a) compressive, (b) direct shear, & (c) tensile bond.

Testing

The compressive strength of 50×50×50 mm of mortar cubes cured by curing compound was determined. The compressive strength of the cement mortar cube was evaluated according to European standards EN 1015-11 [23].

The axial compression tests on masonry prism were performed conferring to EN 1052-1 [24]. The masonry prisms are made from 4-bricks and 3-joints of mortar as presented in Figure 4(a).

The triplet test was used conferring to EN 1052-3 [25] to investigate the direct shear. The triplet is made from 3-bricks and 2-joints of mortar as presented in Figure 4(b). The shear strength of bricks masonry was measured using Eq. (1):

$$\text{Shear strength} = (P + W)/2A \tag{1}$$

Where:
P: the failure load,
W: the weight of the masonry unit, and
A: the area of the failure surface.

Brick couplets have been used conferring to ASTM C 952-76 [26] to measure the tensile bond strength. Cross couplets were prepared with varying mortar classes. Figure 4(c) shows the tensile bond test setup of prepared brick couplet specimens. The sketch of the concrete cap was presented in Figure 4(d). The bond strength was measured using Eq. (2):

$$\text{Tensile bond strength} = (P + W + W_c)/A \tag{2}$$

Where:
P: the ultimate load,
W: the weight of the single brick,
W_c: the weight of the concrete cap, and
A: the masonry unit-mortar contact area.

The thickness of binding mortar was maintained 10 mm for all tests.

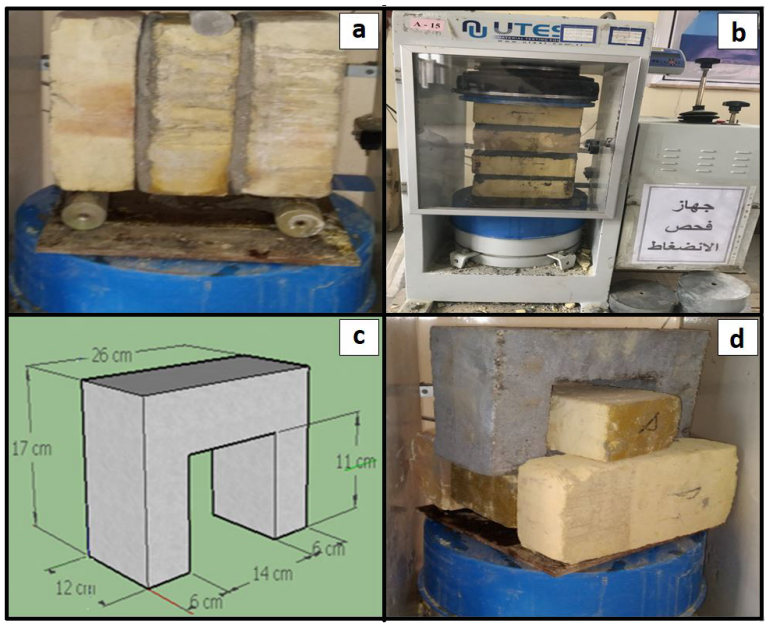

Figure 4. (a) Compressive test set up, (b) Direct shear test set up, (c) Tensile bond test set up & (d) Sketch of concrete cap.

Results and discussion

Behavior of mortars

The compressive strength of mortar specimens was measured at 7, 28 and 90 days as shown in Figure 5. The experimental results of compressive strengths at 7, 28 and 90 days varied from 14.4 to 30.1 MPa, 20.5 to 33.6 MPa and 25.4 to 39.4 MPa, respectively.

A moderate reduction in compressive strength for mixes by the inclusion of polyurethane was observed for the mix PM with respect to RM. For instance, the compressive strength of RM (23.2, 27,2 and 30.3) MPa whereas (19.1, 23.4 and 25.4) MPa for PM, at 7, 28 and 90 days, respectively. However, this reduction was diminished by inclusion of supplementary cementitious materials (i.e. fly ash and nano silica).

In general, Figure 5 point out that mortar specimens modified with nano silica have higher compressive strength results than their counter's non-modified specimens. This behaviour remained consistent for all ages of tests 7, 28 and 90 days. For instance, adding 2% nano silica to PM and PM30F to produce mortars PM2N and PM30F2N resulted in increasing the 7 , 28 and 90-day compressive strength by (58, 44 and 39)% and (62, 49 and 35)% respectively. The inclusion of nano silica results in improve the stability of the bubbles of foam and can preclude the merging of large pores. Furthermore, nano silica densifies the matrix and improves its strength, due to the pozzolanic reaction and its high surface area [27].

These results are consistent also with those observed in a preceding investigation by Abd Elrahman et al. [28]. It investigated the feasibility of the inclusion of nano silica in ultra-lightweight foamed concrete. The results confirmed that the use of nano silica is an efficient way to enhance the stability of foam bubbles in the fresh

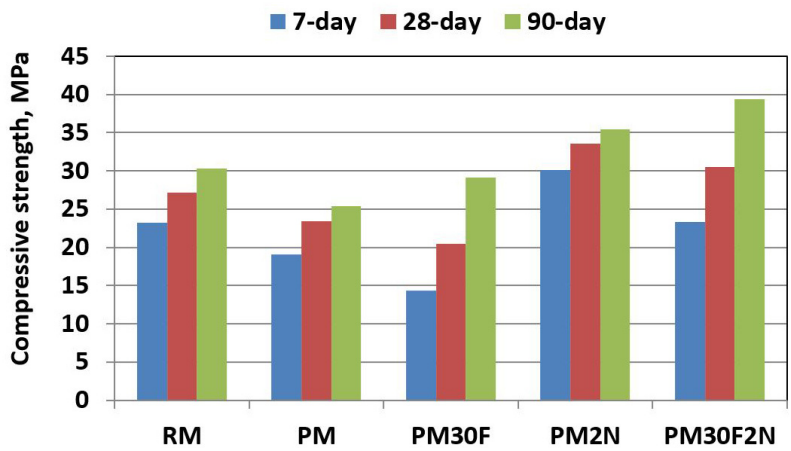

Figure 5. Compressive strength of different mortars.

concrete state. It was concluded that utilizing 5% wt nano silica increased the compressive strength of foamed concrete by 20%. The authors attributed that to its physical role in densification the matrix and decreasing the interaction between foam bubbles.

A quick observation to Figure 5, gives good evidence about the strength development of fly ash mortars (PM30F and PM30F2N) with time. This behavior is ascribed to the slow pozzolanic reaction of fly ash class F resulting in a significant improvement in strength [29-31]. The percentage of increase in the compressive strength due to the time development from 7 to 28 days and from 28 to 90 days for (PM30F and PM30F2N) mortars is (42 and 31)% and (42 and 29)%, respectively. However, fly ash has a negative effect on the compressive strength of mixtures at early ages. For example, the inclusion of 30% fly ash in the mortar PM and PM2N to produce mortars of PM30F and PM30F2N decreased the 7 and 28-day compressive strengths by (25 & 12)% and (23 & 9)%, respectively whereas the 90-day compressive strength increased by 15% and 11%, respectively as shown in Figure 5.

In summary, among the various variables considered in this investigation, the incorporation of 30% and 2% fly ash and nano silica, respectively seems to have great effects in improving the later age compressive strength values of foamed mortar.

Compressive behavior of masonry prisms

The compressive strength of masonry prisms depends on the strength of the construction unit and the binding mortar strength. Generally, the compressive strength of masonry prisms is between the compressive strength of the construction unit and the binding mortar when the strength of the construction unit was higher than binding mortar strength [32, 33]. Whereas, in this study, prisms compressive strength was detected is lower than the compressive strength of the weakest component used.

In this study, the mortar was stronger than the masonry unit, compressive failures were initiated in the brick and followed by propagating through binding mortar. The brick masonry prism was failed by vertical tensile splitting cracks along the direction of loading.

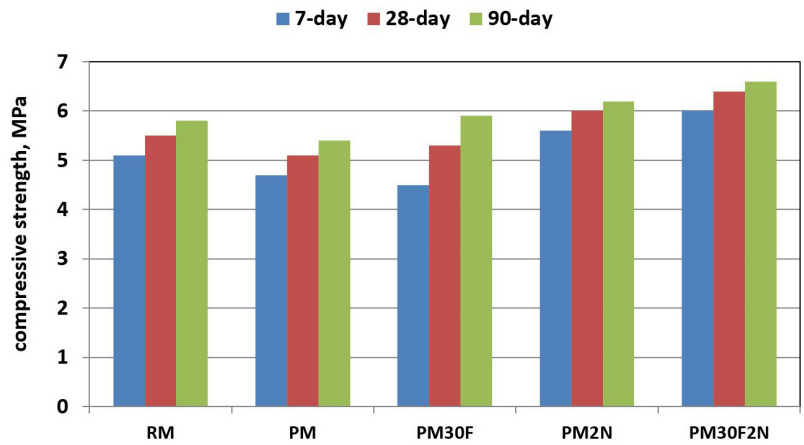

Figure 6. Compressive strength of masonry prisms.

Figure 6 illustrates the masonry prism compressive strength for the five classes of mortars. Interesting results were observed that there is a strong relation between compressive strength of mortar and compressive strength of bricks masonry prism. It can be seen from Figure 6 that, there is an increase in the compressive strength of bricks masonry prism as the mortar strength increase. The masonry prism made with PM mortar appears to have marginally lesser strength than the masonry prism made with RM. This is due to low polyurethane foam addition percent which means low bubbles content in the mortar matrix.

The masonry prisms made with polyurethane mortar contained nano silica (PM2N & PM30F2N) have higher strength than the reference polyurethane mortar prisms (PM). For example, the compressive strength of masonry prisms made with PM2N mortar increased by (19, 18 and 15)% for (7, 28 and 90) days ages, respectively with respect to PM masonry prism. As well as the compressive strength of masonry prisms made with PM30F2N mortar increased by (28, 25 and 22)% for (7, 28 and 90) days ages, respectively with respect to PM masonry prism.

For masonry prism made with polyurethane mortar contained fly ash (PM30F), the development of compressive strength with time is more obvious than other prisms. For instance, the 7-day compressive strength increased by 18% after 28-day age and 31% after 90-day. Whereas the other prisms, the development of compressive strength with time was marginally.

Shear behavior of triplets masonry

The potential failure patterns in the triplets masonry under direct shear can be classified into four classes as indicated in EN 1052-3 [25].

- Class A: Shear failure in the binding mortar only.
- Class B: Shear failure in the bond area between brick and mortar.
- Class C: Shear failure in the brick.
- Class D: Crushing and or splitting failure into the brick.

Figure 7 shows the failure pattern detected during the tests. Class A pattern was not detected due to the strong mortar used in the masonry triplets.

Class A pattern of failure appeared when the flexural strength of joint mortar was less than the unit/ mortar interface bond strength [34, 35].

Table 6 illustrated the pattern of failure noticed during this study for varying masonry triplets. For RM mortar; the shear failure of masonry triplets occurred in interface between brick and binding mortar (Class B) at different ages of test. This type of failure occurs when the bond strength between brick and mortar is much less than brick or binding mortar strength.

Interesting results were achieved for masonry triplets made with polyurethane foam mortar. A strong bond between brick and polyurethane mortar interface has been shown and caused in pattern class C and a few of them follow type D failure pattern. Shear strength of brick and mortar interface is generally influenced by the strength of mortar. In this study, the same brick class was adopted, and shear strength develops significantly by using adhesive polyurethane foam mortar and improves also with high-strength mortar.

Figure 8 illustrates the direct shear strength of brick masonry triplets at the different ages of test. It can be seen from Figure 8 that, the shear strength of all polyurethane masonry triplets increased significantly with respect to reference mortar RM. To have a good comparison between polyurethane masonry triplets shear strength and masonry triplets made with reference mortar RM, Figure 9 shows the increased percentage in shear strength of polyurethane masonry triplets with respect to masonry triplets made with reference mortar RM. According to the results, the polyurethane masonry triplets contained cementitious materials have the highest shear strength.

Polyurethane masonry triplets made with PM30F2N and PM2N mortars seem to have a higher strength than the other ones. The failure pattern class C of the bricks masonry triplets with these mortar were noticed in this study except for two of them. The shear strength increase for bricks masonry triplets made with mortar PM30F2N and PM2N was found to be (70, 79 and 86)% and (52, 61 and 63)% at (7, 28 and 90) days respectively with respect to reference mortar RM. These results demonstrate that the inclusion of nano silica in mortar affects the masonry shear strength to a great extent. Pozzolanic reaction and densification effect could be one of the reasons for this strength increase. As well as the inclusion of fly ash and nano silica together in PM30F2N has a great positive synergistic effect on shear strength.

Portlandite $Ca(OH)_2$ is present in masonry mortar as a by-product of cement hydration, particularly at the mortar-brick interface where it produces a weak layer. Henceforward, by using (fly ash type F and nano silica) which can react with the Portlandite to develop strong calcium silicate hydrates C-S-H. Therefore, the bond strength of the masonry was improved by altering the microstructure of the mortar-brick interface.

As expected, it is that the shear strength of masonry triplets made with mortar RM and PM increased slightly with time, whereas the shear strength of fly ash mortar masonry increased obviously. For instance, the increase percent in shear strength for masonry triplets made with mortars of (RM, PM, PM30F, PM2N and PM30F2N) was (4, 3, 13,

10 and 9) % when the age of the test increased from 7 days to 28 days. As well as, only (3, 5, 9, 4 and 7)% percent of the increase in shear strength when age increase from 28 days to 90 days.

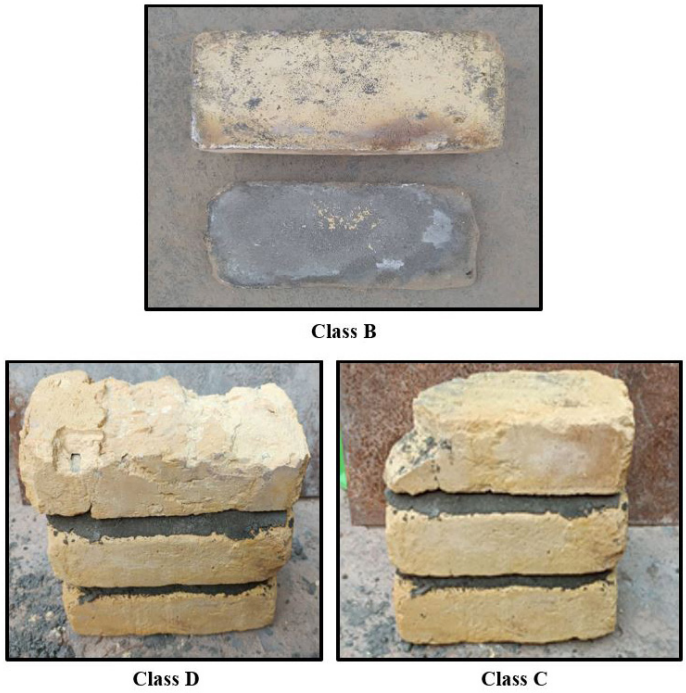

Figure 7. Classes of failures pattern noticed in direct shear test.

Table 6. Number of triplets that detected for each failure pattern in direct shear test

Mortar ID	Age of mortar	Number of triplets noticed in failure pattern		
		Class B	Class C	Class D
RM	7-day	3	-	-
	28-day	3	-	-
	90-day	3	-	-
PM	7-day	-	2	1
	28-day	-	3	-
	90-day	-	3	-
PM30F	7-day	-	2	1
	28-day	-	2	1
	90-day	-	3	-
PM2N	7-day	-	3	-
	28-day	-	2	1
	90-day	-	3	-
PM30F2N	7-day	-	3	-
	28-day	-	2	1
	90-day	-	3	-

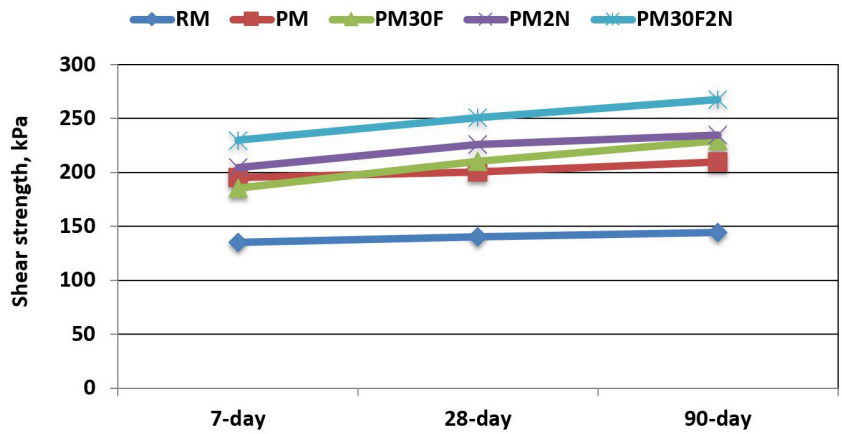

Figure 8. Shear strength of masonry triplets at the three ages of test.

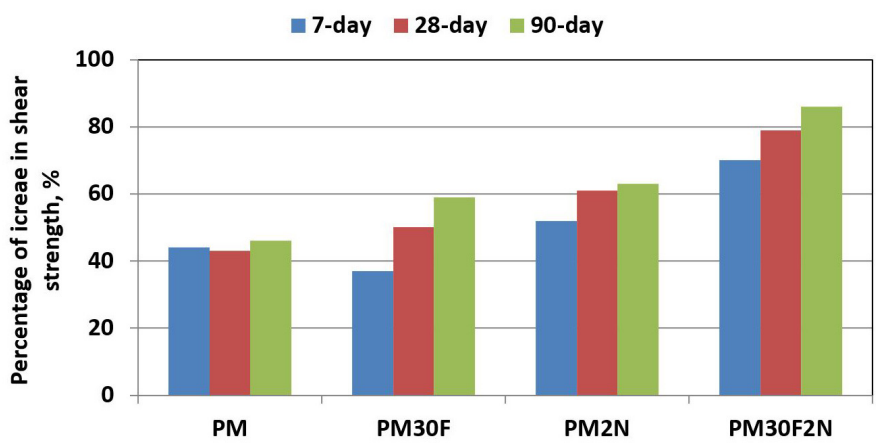

Figure 9. Efficiency of polyurethane mortars used in increasing the shear strength of masonry triplets with respect to masonry triplets made with reference mortar.

Tensile bond behaviour of couplets masonry

As in shear failure pattern, tensile bond failure pattern of couplets masonry under tensile test can be classified into:

- Class A: Tensile failure in the binding mortar only.
- Class B: Bond failure in the construction unit/binding mortar interface.
- Class C: Direct tensile or splitting tensile failure in the construction unit.
- Class D: Partially bond failure in the construction unit / binding mortar interface and tensile failure in the construction unit.

Table 7 illustrated the failure pattern type noticed during this study for masonry couplets made with different mortar types at three ages of test. In this study, because of strong mortar being used, tensile failure in the mortar

only (Class A) was not noticed. For RM mortar; the bond failure of masonry couplets occurred in the interface between brick and binding mortar (Class B) at different ages of the test (see Figure 10). This type of failure occurs when the bond strength between brick and mortar is much less than brick or binding mortar strength.

The test results in Table 7 show that the bond strength of masonry couplets follows a unique pattern except for two specimens. The main reason is efficiency of adhesive polyurethane mortar resulted in a strong bond between brick and mortar.

Similar to shear strength, interesting results were achieved for masonry couplets made with polyurethane mortar. A strong bond between unit and polyurethane mortar interface has been shown and caused failure in the masonry unit only for most of the couplets. Class C failure was achieved for most of the polyurethane masonry couplets, whereas, two specimens only from these masonry couplets was follow Class D pattern in failure (see Figure 10). Class C failure refers to strong bonding between brick and mortar, whereas Class D refer to relatively strong bonding between them. Because the failure Class D occur partially in the bond in the brick unit /mortar interface and tensile failure in brick whereas the failure Class C occur only in the brick. Therefore, it can be said that high strong bond strength can be achieved by using polyurethane mortar.

Figure 11 presented the bond strength of masonry with the five classes of mortars. For all masonry couplets made with different mortar classes, there is a little increase in the bond strength as the masonry couplets age progress.

For more comparison of the improvement of bond strength by using polyurethane mortars, Figure 12 presents the percent increase in bond strength relative to masonry couplets made with RM mortar. A significant increase in bond strength was achieved by using polyurethane mortar reaching up to 181% at 7-day, 160% at 28-day and 151% at 90-day for masonry made with PM30F2N mortar.

Table 7. Number of couplets that detected for each failure pattern in tensile bond test

Mortar ID	Age of mortar	Number of couplets noticed in failure pattern		
		Class B	Class C	Class D
RM	7-day	3	-	-
	28-day	3	-	-
	90-day	3	-	-
PM	7-day	-	2	1
	28-day	-	3	-
	90-day	-	3	-
PM30F	7-day	-	2	1
	28-day	-	3	-
	90-day	-	3	-
PM2N	7-day	-	3	-
	28-day	-	3	-
	90-day	-	3	-
PM30F2N	7-day	-	3	-
	28-day	-	3	-
	90-day	-	3	-

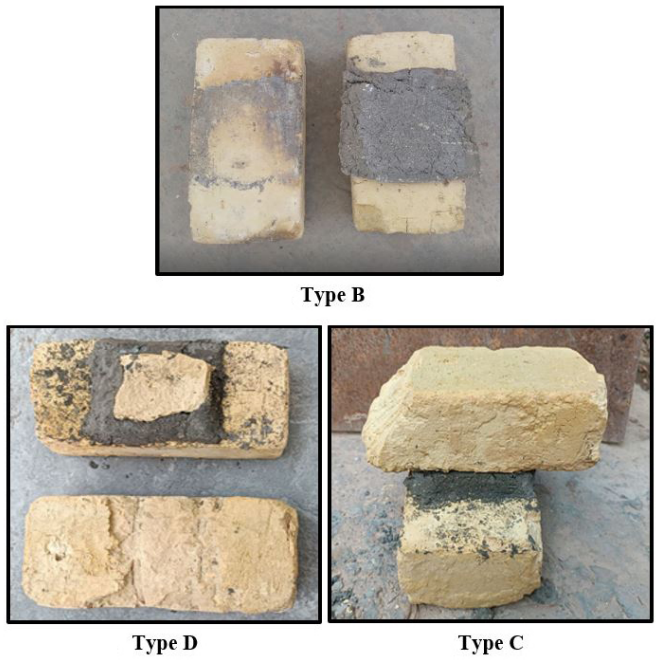

Figure 10. Classes of failures pattern noticed in bond test.

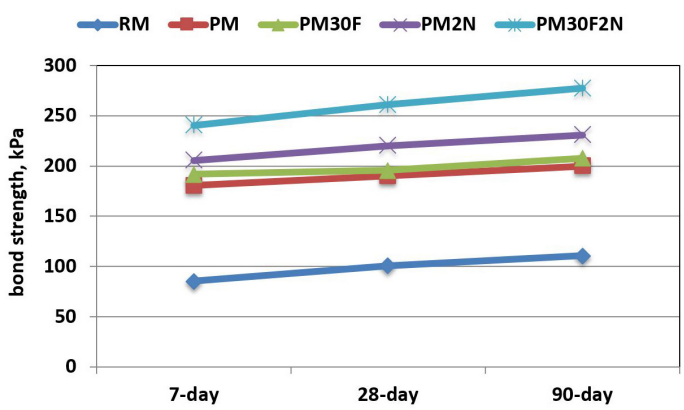

Figure 11. Bond strength of masonry couplets.

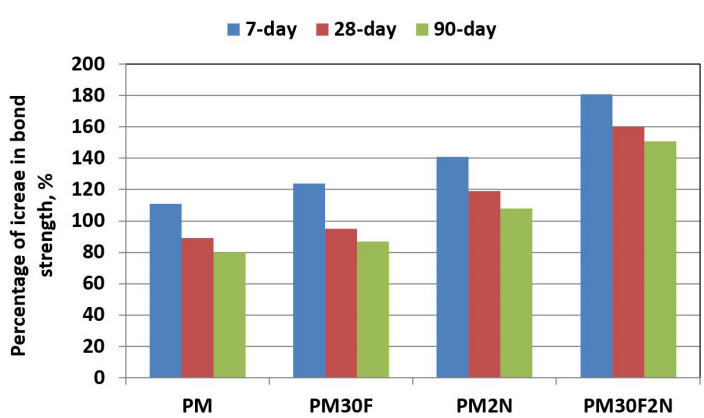

Figure 12. Efficiency of polyurethane mortars used in increasing the bond strength of masonry couplets with respect to masonry couplets made with reference mortar.

Conclusions

In the present study, the mechanical properties of brick masonry using polyurethane foam mortar with blended cement were investigated. The test results showed that:

Polyurethane mortar with supplementary cementitious materials does have a substantial influence on the mechanical properties of masonry bricks. Partial replacement of cement by fly ash and nano silica together in the binding mortar of brick masonry will improve the compressive strength, shear strength and bond strength significantly.

Poor bond was observed of brick masonry made with reference cement mortar. Therefore; the shear failure of masonry triplets and the bond failure of masonry couplets occurred in the interface between brick and binding mortar failure pattern at different ages of the test.

Interesting results were achieved for masonry triplets and couplets made with polyurethane mortars. A strong bonding between polyurethane mortar and brick interface has been shown and caused failure in the brick only for most of the masonry specimens.

Polyurethane masonry triplets and couplets made with PM30F2N and PM2N mortars seem to have a higher shear and bond strength than the other ones.

The percentage of increase in shear strength was reaching up to 79% and 61% at 28-day for PM30F2N and PM2N, respectively. The percentage of increase in bond strength was reaching up to 160% and 119% at 28-day for PM30F2N and PM2N, respectively.

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- Ethics approval/This study does not contain any studies with human participants or animals performed by any of the authors.
- Consent to participate (This study does not contain any studies with human participants or animals performed by any of the authors).
- Consent for publication (This study does not contain any studies with human participants or animals performed by any of the authors).
- Availability of data and material/ All data generated or analysed during this study are included in this article.

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