Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Investigation of Mortar Mixtures to be used in Repair of Historical Structures

S.E. Pusat
Yildiz Technical University, Dept. of Architecture, Structural Systems Division, Istanbul, Turkey

F. Aköz
Yildiz Technical University, Dept.t of Civil Engineering, Structural Materials Division, Istanbul, Turkey

ABSTRACT: The different types of mortars used in historical masonry structures do not have the same properties. Therefore one cannot define a single type of mortar suitable for use in repair and strengthening of historical structures. The properties of the mortar have to be investigated through physical, mechanical and chemical experiments to be conducted in-situ and in the laboratory for each structure separately. The mortar should be produced and implemented with materials resembling the original the most. Otherwise, the structure will be harmed instead of benefiting due to arising dissonance.
It is known that natural pozzolanas and brick powder are added to the mortars of masonry structures. In this study, the use of blast furnace slag, which is a type of industrial waste pozzolana, has been used as mineral admixture in the experiments and the results are compared to the brick powder. It has been observed that the blast furnace slag is increasing the flexural and compressive strength of the lime mortar and decreasing porosity.

1 INTRODUCTION

Preservation and maintenance of the existing historical heritage is a cultural imperative. Aging, exposure to aggressive environmental factors and increasing loads often result in deterioration of many culturally valuable and potentially functional structures. The preservation process which should keep the structure’s original and authentic message requires accurate evaluation procedures and efficient repair methods.

Most historic buildings were constructed of stone and brick masonry bonded with mortar. Knowledge of the mechanical and physical properties of these construction materials is necessary in conservation interventions.

The results of the material analysis of the building to be restored are specific only to this building. Therefore it is wrong to make a generalization with only a few experiments with the composite materials such as mortar particularly. It would be better if a great number of different mixtures using todays material had been prepared and compared with the original samples when the historical building is subject of repair and strengthening.

With this aim in mind, an experimental study preparing different mortar mixtures has been carried out. In this study, in order to investigate the change in the mechanical and physical properties of the mortars, depending on time, the pozzolanic activities of the blast furnace slag and brick powder are tested. Lime was replaced by blast furnace slag and brick powder 10%, 20%, 30% and 40% by weight. Siliceous sand according to the RILEM guidelines was used as aggregate. This method is used to define 9 series of mixtures. The specimens of mortar mixtures are prepared according to these series. In order to carry out mechanical and physical experiments on the 14th, 28th, 56th and 90th days, three specimens of each serie, making in total 108 specimens with 40x40x160mm dimensions, have been produced.

The fresh mortars, on which flow test and unit weight are measured, were taken out of the mould 48 hours after the production. The specimens were stored in laboratory conditions with average of 50±5% relative humidity and 20±3°C temperature until the experiments were performed.

First, the unit weight of the specimens was weighed, then, sound transition time was measured using ultrasonic test apparatus, dynamic modulus of elasticity was calculated and the unit weights were compared. Later, the compression and bending experiments were made on the specimens. At the end of the experiment, it is observed that the series with higher percentage of blast furnace slag have more compressive strength and higher dynamic modulus of elasticity. In contrast, the series with higher percentage of brick powder as pozzolana resulted to have less compressive strength and lower dynamic modulus of elasticity.

In this paper, mortars with different mixtures and properties will be examined using the experiments' results

2 EXPERIMENTAL STUDIES

In the experimental study, the effect of blast furnace slag and brick powder added in various ratios to the lime mortar was investigated under curing conditions lasting 90 days.

Siliceous sand

Siliceous sand according to the RILEM guidelines was used as aggregates. The unit weight of the siliceous sand is determined as 2.01 gr/cm^3.

Lime

In the experiments, "powder limestone lime", which has specific weight of 2.38gr/cm^3 and which has been put out in accordance with TS EN 459-1:2005 has been used. (TS EN 459-1:2005; TS 32 EN 459-2:2005; TS EN 998-2:2003).

Blast furnace slag

Blast furnace slag used in the production is obtained from Iskenderun Iron and Steel Factory. It has a specific weight of 2.89 gr/cm^3 and specific surface area of 1180 cm^2/gr.

Brick powder

The brick powder which contributes to the Horasan mortar with its pozzolanic characteristics is obtained by crushing and grinding the crushed the bricks that are in accordance with TS EN 771-1:2005, with dimensions of 290x190x135mm, having vertical holes and obtained from the market. Brick powder was sifted from 300 µm size sieve by conducting a sieve analysis and its surface area has been approximated to that of the blast furnace slag. The specific weight of brick powder is determined to be 2.5 gr/cm^3.

2.1 Production

9 series of mortar whose mixture ratios are provided in Table 1 are produced by using the materials whose properties are given. The amount of water to be used in the preparation of mortar is determined with a flow test done as pre-test. During each production, the flow test is conducted to test the workability of the fresh mortar. The unit weight of the fresh mortar is determined and the results are provided in Table 2. The specimens are demoulded from casts after 48 hours and stored in laboratory conditions with average of 20±3°C temperature and %50±5 relative humidity until the 14th, 28th, 56th and 90th test days.

Table 1 : Codes of the specimens and material mixture ratios by weight

Specimen code		Aggregate	Binding Material	Puzzolana		Water / Lime
		Fine Aggregate / Lime	Lime / Lime	BFS / Lime	Brick Powder / Lime	
L	S + L	3.00	1.00	-	-	0.76
BFS 10	S + L + BFS 10%	3.00	0.90	0.10	-	0.76
BFS 20	S + L + BFS 20%	3.00	0.80	0.20	-	0.76
BFS 30	S + L + BFS 30%	3.00	0.70	0.30	-	0.76
BFS 40	S + L + BFS 40%	3.00	0.60	0.40	-	0.76
BP 10	S + L +BP 10%	3.00	0.90	-	0.10	0.76
BP 20	S + L +BP 20%	3.00	0.80	-	0.20	0.76
BP 30	S + L +BP 30%	3.00	0.70	-	0.30	0.76
BP 40	S + L +BP 40%	3.00	0.60	-	0.40	0.76

S: Siliceous sand ; L: Lime ; BFS: Blast Furnace Slag; BP: Brick Powder

Two series made up of 9 groups of mortar mixtures are prepared by adding brick powder and blast furnace slag 0% (control group) 10%, 20%, 30% and 40% by weight These mixtures were used in producing 108 specimens in total, with 40^{mm}x40^{mm} x160^{mm} dimensions. As seen in Table 1, specimens are coded as siliceous sand (S), lime (L), blast furnace slag (BSF), brick powder (BP) and the ratios are coded as 10% (10), 20% (20), 30% (30) and 40% (40). The real amount of materials for 1m^3 mortar is determined through the unit weight of the fresh mortar and provided at Table 2.

Table 2 : Unit weight and real amounts of materials in fresh mortar

Specimen code	Unit weight (β) (kg/m^3)	Real dosage of lime (kg/m^3)	The real amounts of materials needed for mortar (kg/m^3)				
			Water	Lime	Siliceous sand	Blast Furnace Slag	Brick Powder
L	2020	425.4	323.28	425.37	1276.10	0.00	0.00
BFS 10	2070	434.9	330.55	391.45	1304.82	43.49	0.00
BFS 20	2060	433.2	329.25	346.58	1299.69	86.65	0.00
BFS 30	2060	432.6	328.74	302.78	1297.64	129.76	0.00
BFS 40	2080	438.0	332.89	262.81	1314.05	175.21	0.00
BP 10	2050	431.5	327.96	388.37	1294.56	0.00	43.15
BP 20	2060	432.6	328.74	346.04	1297.64	0.00	86.51
BP 30	2060	432.2	328.48	302.54	1296.61	0.00	129.66
BP 40	2070	435.6	331.07	261.37	1306.87	0.00	174.25

3 TEST RESULTS AND DISCUSSION

On the 14th, 28th, 56th and 90th test days, unit weight, ultrasonic pulse velocity, bending and compression tests were performed on the specimens stored in laboratory air conditions.

Unit weight

Before the mechanical tests, the specimens have been weighed by an electronic weighing device sensitive for 0.1 g and with a capacity of 4000 g. The unit weight is obtained by dividing the specimens' weight to their volume a. The average unit weight of both series was found to be between 1720 and 1810 kg/m^3. These values are close to the values determined in the experimental study conducted by Penelis (1995).

Table 3 : Unit weight and amounts of materials in fresh mortar (Penelis 1995)

Specimen code	The real amounts of materials needed for mortar (kg/m^3)							Unit weight (β) (kg/m^3)
	Lime	Puzzolana	Sand Max size 2mm	Sand Max size 6mm	Crushed Brick Max size 2mm	Crushed Brick Max size 6mm	Water	
K1	1	1	6		-	-	2,24	1860
K2	1	1	3		3	-	2,70	1880
K3	1	1	3		-	3	2,42	1870
K4	1	1		6	-	-	1,92	1940
K5	1	1		6	-	-	1,86	1930
K6	1	1	3		-	3	2,20	1840
K7	1	1		5	-	1	1,97	1900
K8	1	1		3	-	3	2,24	1860
K18	1	1	6		-	-	2,17	1940
K19	1	1		6	-	-	1,67	2020

Ultrasonic test

Before destructive experiments were conducted on the specimens, ultrasonic transition time (t,μsn) is measured according to BS 1881 Part 203 (1986) and the ultrasonic pulse velocity (v,km/sec) is determined by dividing the specimen's length to the arrival time. Effect of time on the calculated ultrasonic pulse velocity is provided in Fig. 1 for the blast furnace slag replaced specimens and in Fig. 2 for brick powder replaced specimens.

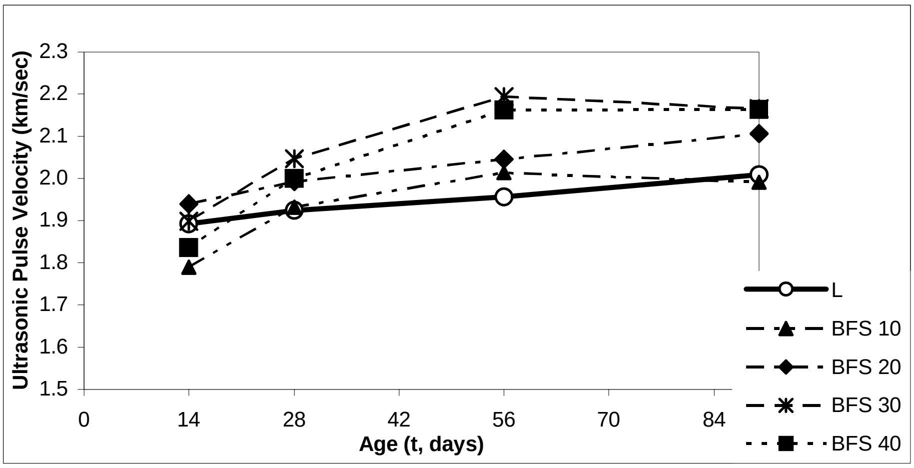

Figure 1: Effect of time on ultrasonic pulse velocity of the mortars with the blast furnace slag

In the control (L) group and the slag replaced specimens, the ultrasonic pulse velocity has increased depending on time and the slag's replacement ratio. The ultrasonic pulse velocity of slag replaced specimens is lower than the control group on 14th day but higher in the following days, see Fig.1. At the end of 90 days the increase in the control group is 6.4%, while the increase in BFS40 is 17.4%. The slag added to the lime increased the pozzolanic activity and decreased the porosity by forming silicathydrate (CSH).

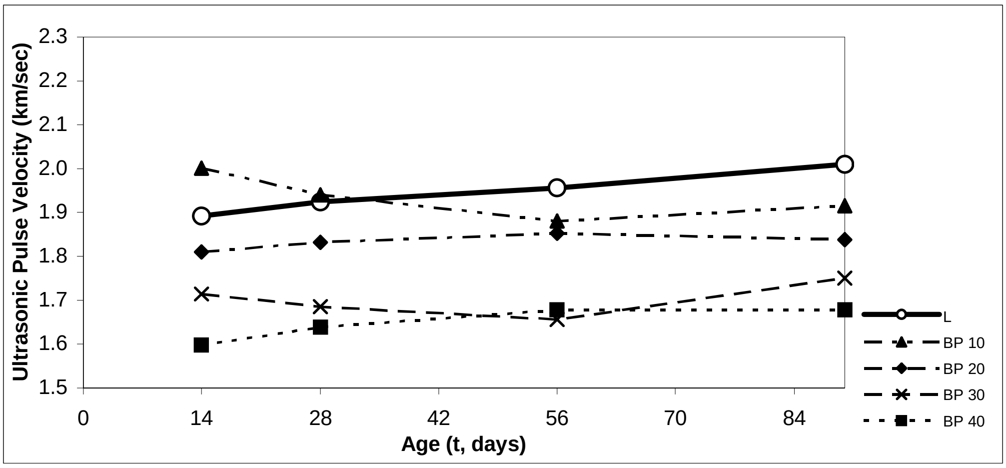

Figure 2 : Effect of time on ultrasonic pulse velocity of the mortars with the brick powder

The ultrasonic pulse velocity of all groups, except BP10, was lower than the control group at 14^{th} day. The ultrasonic pulse velocity decreases as the ratio of the brick powder added to the specimens increases (Fig. 2). Nevertheless, the ultrasonic pulse velocity of the brick powder replaced group has increased in time but this increase was very modest (%2 - %5). Therefore it can be concluded that the brick powder has no effect on porosity.

Calculation of the dynamic modulus of elasticity

The dynamic modulus of elasticity (E_d, MPa) of the mortar specimens is calculated by using the unit weight (Δ), the ultrasonic pulse velocity (v, km/sec) values as seen in Eq.(1). The Poisson ratio of the mortar (μ) is taken as 0.20 in the calculation. The effect of time on the dynamic modulus of elasticity can be seen in Fig. 3 and Fig. 4.

$$E_d = \frac{\Delta v^2 (1+\mu)(1-2\mu)}{1\text{-}\mu} \tag{1}$$

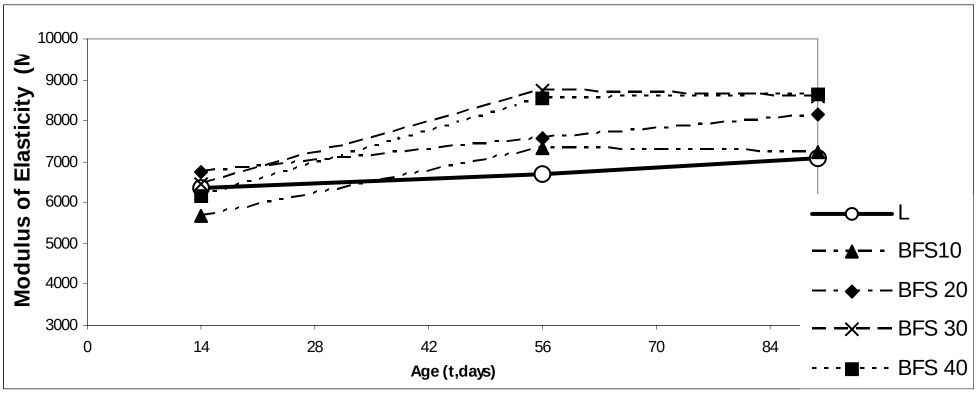

Figure 3 : The effect of time on the dynamic modulus of elasticity of the mortars with the Blast furnace slag

Because the unit weights are close to each other, the dynamic modulus of elasticity of the slag replaced (BFS) specimens is higher than the control group (L). Therefore the ultrasonic pulse velocity is dominant on dynamic modulus of elasticity. The dynamic modulus of elasticity increases as the amount of slag increase, see Fig. 3). The ratio of the increase is 11.5% in the control group and 40.3% in the BFS40 group.

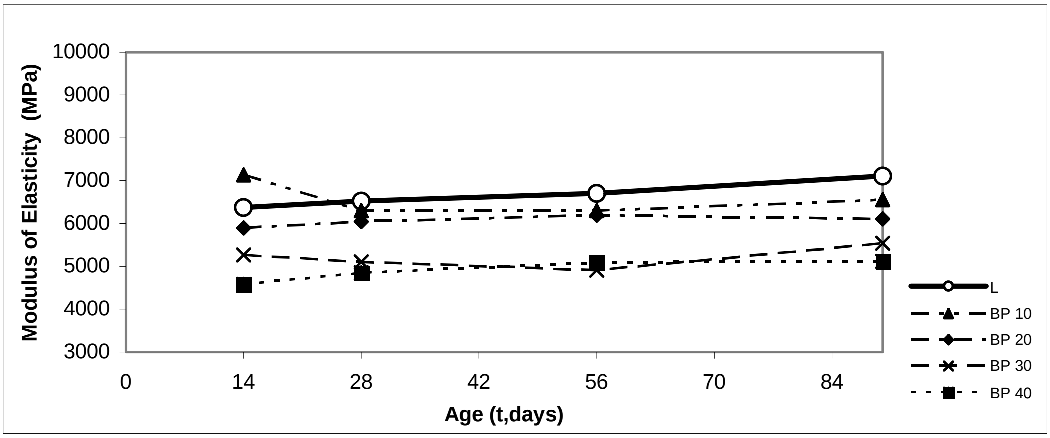

Figure 4 : The effect of time on the dynamic modulus of elasticity of the mortars with the brick powder

The dynamic modulus of elasticity of the brick powder replaced specimens is lower than the control group (L) and the slag replaced group (BFS). The dynamic modulus of elasticity decreases as the amount of brick powder increase, see Fig. 4. The dynamic modulus of elasticity of the brick powder replaced group increases in time, although in very modest amounts (%3 - %11). A decrease of 8% has been noticed for BP10.

Bending test

Bending test has been conducted according to TS EN 196-1. The specimens were broken from their mid length with a loading speed of 50±10 N/sec. then the bending failure load is determined (P_b, N). The flexural strength (f_f, MPa) is calculated by using the results obtained from the tests. The effect of time on the flexural strength can be seen in Fig.5 and 6.

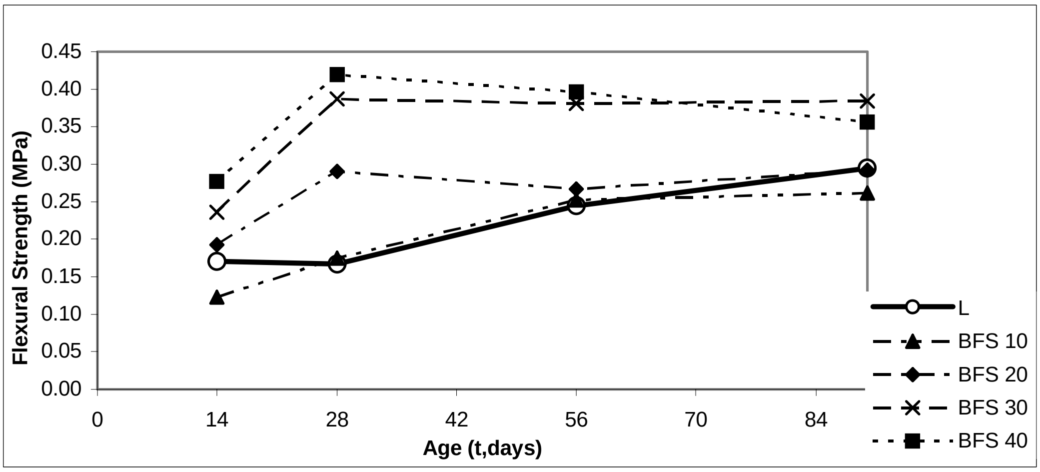

Figure 5 : The effect of time on the flexural strength of the mortars with the blast furnace slag

The flexural strength of all slag replaced groups including the control group has increased by time, see Fig.5. The increase in the flexural strength has been rapid until 28th day and the rate of increase has decreased in time. The flexural strength of the slag replaced specimens are higher than the control group except BSF10 group. The increase ratio at 90th day is 113% for BSF10 group, 52% for BSF20 group, 63% for BSF30 group and 51% for BSF40 group.

The flexural strength of the control mortar has increased regularly depending on time. The increase ratio at 90th day is 73%. The flexural strength of the control group has increased from 0.17 MPa at 14th day to 0.30 MPa with a 76% increase. The flexural strength of the 40% slag replaced %40 BSF40 group at 28th day has been recorded as 0.43 MPa. This flexural strength is higher than the one obtained by Penelis in the study done by the mortar produced from the pozzalana of Santorini.

Table 4 : Test Results (Penelis,1995)

Specimen Code	Unit weight (β) (kg/m^3)	Flexural strength (MPa)	Compressive strength (MPa)
K1	1590	0,166	0,410
K2	1470	0,234	0,859
K3	1510	0,261	1,318
K4	1680	0,421	0,697
K5	1590	0,258	0,928
K6	1540	0,214	0,770
K7	1630	0,194	0,784
K8	1510	0,269	1,249
K18	1600	0,193	0,336
K19	1740	0,142	0,652

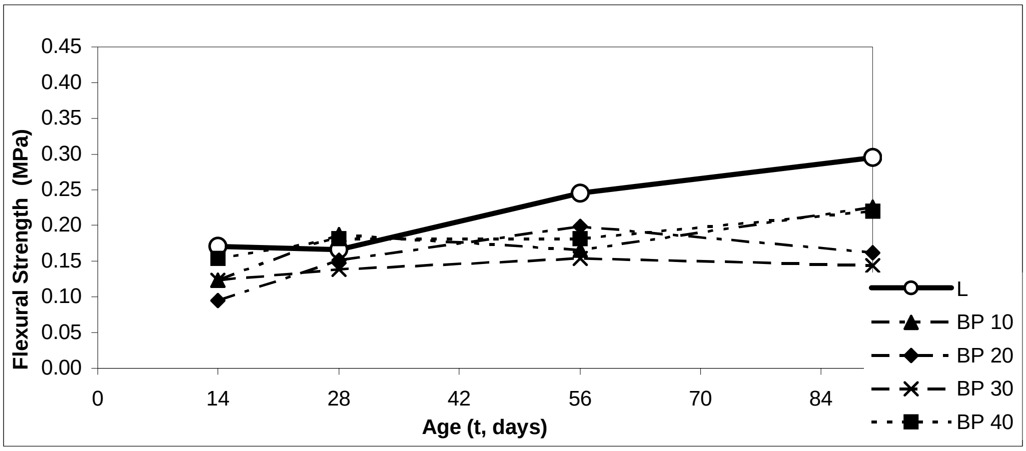

Figure 6 : The effect of time on the flexural strength of the mortars with the brick powder

In the brick powder groups (BP), the flexural strength is lower than that of the control group (L), see Fig. 6. As it did for the other groups, this group's flexural strength has also increased in time. The rate of increase at 90th day is 84% for BP10 group, 71% for BP20 group, 17% for BP30 group and 44% for BP40 group.

Compression test

The compression test has been conducted on the pieces that were broken into two in the bending test. The effects of time on the compression strength of the specimens are shown in Fig. 7 and. 8.

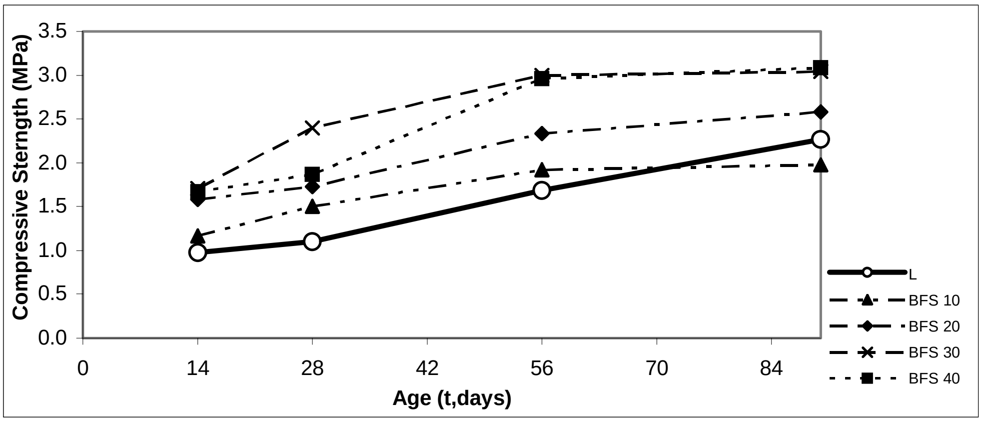

Figure 7 : The effect of time on the compression strength of the mortars with the blast furnace slag

The compressive strength of the control group (L) is higher than the slag replaced (BSF) group, as the rate of blast furnace slag increases. 1,6MPa compressive strength of BSF30 and BSF40 groups on 14^{th} day equalized in 56^{th} day increased 85% and became 3,0MPa. The increase rate of the control group on 90^{th} day is 132%.

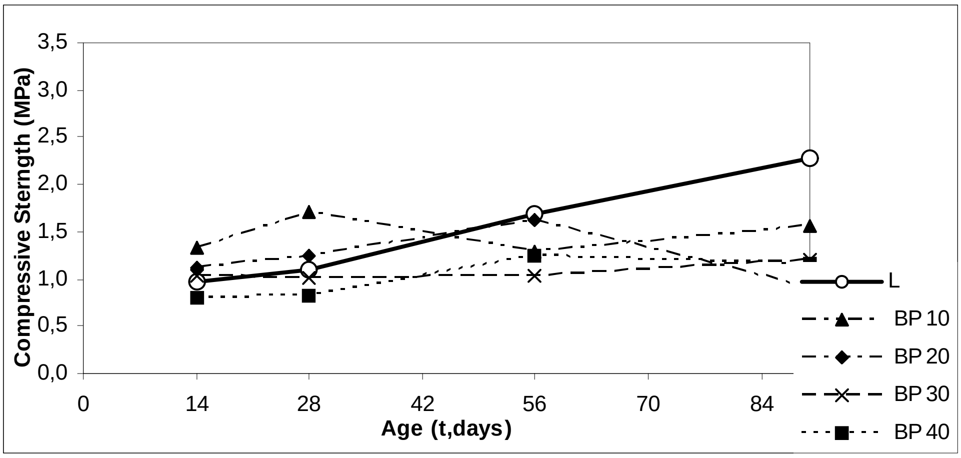

Figure 8 : The effect of time on the compression strength of the mortars with the brick powder

Though the inconsistence observed in brick powder replaced (BP) groups, the compressive strength of all the specimens have increased by time. The compressive strength of brick powder replaced (BP) group is less than slag replaced (BFS) group. As the brick powder ratio increases, the strength decreases.

The fact that the effect of brick powder being less than the slag shows that the puzzolanic activity of brick powder is less.

4 CONCLUSIONS

According to the results of the long term experiments conducted by mixing blast furnace slag and brick powder in different ratios to the lime mortar with siliceous sand:

- Slag replacement and increasing of its ratio have increased the ultrasonic pulse velocity, flexural strength and compressive strength and decreased the porosity.
- Brick powder replacement has increased the porosity and decreased the ultrasonic pulse velocity, flexural strength and compressive strength.

If it is necessary to increase the flexural and compression strength of the mortar to be used in repair and strengthening of historical structures, ground blast furnace slag can be added to mortar for required strength.

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