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EFFECTS OF POZZOLANAS AND FIBERS ON MECHANICAL PROPERTIES OF MORTARS IN HISTORICAL BUILDINGS

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ABSTRACT

In our country there are many historic buildings built in different type of construction systems like masonry, timber frame and composite structures. The conservation, restoration and strengthening studies of these historical buildings are very important as the conservation of cultural heritage. In the determination studies it is proved that in the historical masonry buildings lime mortars are used and also puzzolanic materials like brick powder, casein (milk), egg white, linseed oil, fresh blood, wax, keratin, animal fat are mixed so as to increase the durability and strengthening of the mortar.
In this study, broken brick (max. 8 mm) is used as an aggregate, lime as a binding material, silica fume, fly ash, blast furnace, brick powder as puzzolanas and polymer fibre is used. According to the TS EN 196-1 standard, in 10 groups 126 pieces of 40 × 40 × 160 mm dimensioned samples are produced with four different puzzolans. Determination of the mechanical properties of mortars produced with fibers or without fibers one group of samples kept for one year in the laboratory conditions and the other group of samples is left in the atmosphere for the investigation of the durability of the effects of the atmospheric conditions. The effects of laboratory and atmospheric conditions to the mechanical properties of mortar samples are investigated with control experiments.

Keywords: *Historical buildings, Lime mortars, Puzzolanas, Silica fume, Fly ash, Blast furnace slag, Brick powder, Polymer fibers*

1. INTRODUCTION

1.1. General information

Lime, sand and crashed brick are the most important binding materials used for historical mortars and plasters. Lime was used in building constructions in Ancient Greek and Roma period till the cement material were discovered. The binding property of lime was discovered at various different places of the world independently, however, its indusrial production has been possible in the XIV th century [1, 2].
Determination of lime mortar characteristics for conservation works of historic buildings became an important task in the second half of the 20th century due to the extensive damage of cement mortars used in historic buildings [3]. The most important thing to be considered in the conservation works of the ancient materials is that intervention materials should be compatible with the original material and should not do any damage in the long term. This requires knowing about the properties of original materials as well as the problems of deterioration. Use of wrong materials in the conservation works of ancient materials leads to rapid deterioration, causing lost of their historical, documental and esthetical values [2, 4].
Plasters were often used in ancient architecture as a majör expressive tool besides that of a simple sacrifice layer, hence they strongly contribute to the façades' architectural image and their repair and conservation are key points in architectural restoration. Many analytical techniques and procedures for the characterisation of ancient mortars and plaster can be used most of them concern the nature of the binder and aggregates [5].

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Analysis of Early Byzantine mortars indicates a slow chemical reaction between the hydrated lime mortar and the crushed brick aggregate and brick dust that resulted in material of concrete-like hardness. Scientists refer to this reaction as "pozzolanic" – that is, comparable to what occurred during the setting of Roman concrete. The brick fragments seem to have strengthened and stiffened the mortar in addition to giving them a special compactness. Pozzolanic mortars are composed of slaked lime, pozzolana and water. These mortars are also hardened in damp conditions and under water, maintaining their quality for centuries. Pozzolanic mortars can be also obtained using a kind of artificial pozzolana obtained by heating pulverized tiles or old bricks (cocciopesto); this type of mortar, although requiring a longer time to reach full strength, is of good quality and was often used when pozzolana was not available, as in the building of Hagia Sophia [6].

The addition of pozzolana to any lime mortar (hydraulic or non-hydraulic) will modify its characteristics. Depending on the type of pozzolan chosen, the density and compressive strength of the mortar may be increased or porosity reduced. In general, the softer pozzolanic materials (such as dust brick from clay bricks fired at less than 950°C) will produce permeable and flexible mortars whilst the hard-burned materials, will tend to produce a harder mortar, closer in its characteristics to cement [7].

Through the centuries historical mortars have proved to be well compatible with the historic structural units and long lasting under severe mechanical and environmental loads, the design of restoration materials should be approached by simulating the historic materials. However during the last decades the industrial production of building materials has changed significantly. Traditional building materials and techniques have been replaced by cement technology which displaced traditional binding materials resulting to the loss of traditional practice and building empiricism. Therefore, there is a demand for proper restoration mortars and building materials compatible with the original structures [8].

Silica fume is a byproduct of producing silicon metal or ferrosilicon alloys. The smoke that results from furnace operation is collected and sold as silica fume. Fly ash is typically precipi-tated electro statically in coal-fired power stations; blast furnace slag is a waste by-product from the production of pig iron. Therefore, utilization of silica fume, fly ash and slag in the construction industry, besides being of strength and durability benefit, has environmental positive fea-tures. Silica fume, fly ash and slag were reported to enhance the properties of fresh and hard-ened concrete with confirmed contribution to long-term strength and durability [9]. And also in the experimental studies it is pointed that the polymer fibres as an admixture material are decreases the micro-cracks, plastic shrinkages, increases the flow (workability) of fresh mortar and decreases the pouring in the application process of plastering. And also it is seen that a very limited percentage of polymer fibres added in the lime mortar mixture significantly increases the bending stress of mortars.

Experimental study was carried out on lime mortars with the aim of material selection convenient to the original material for lime mortars used in conservation, restoration and strengthening of historical buildings. Broken brick, lime, silica fume, fly ash, blast furnace slag, brick powder and polymer fibers are used to prepare mortar samples with different properties.

2. EXPERIMENTAL STUDY

2.1. Materials and methods

With the aim of material selection convenient to the original mortars used in conservation, restoration and strengthening of historical buildings, an experimental study was carried out on mortars. During the preparation process, the workability of fresh mortar was taken into account. Water/binding material ratio is defined with pre-tests than the specimens are prepared according to this ratio. Experimental study as brick aggregate and brick powder is prepared, water/binding material ratio is defined, pozzolanic activity is determined by investigating the preliminary experiments and the production of mortar samples, to cure and control experiments carried out in four phases and was completed in a year. Crashed brick aggregate (B) was prepared in 8 mm max particle size as seen in Figure 1. For the preparation of brick powder used as pozzolan material in the production of mortar crushed brick is broken with the Disc Grinder, 90 µ'luk sieve sifted powder passing through the bottom sieve, are used as additives.

Crashed brick and the materials given in Table 1 were used for the mortar mixtures. As a binding material slaked lime, silica fume, flays ash, blast furnace slag and brick powder were used as pozzonalic materials and were replaced 30% of lime. Pozzolanic activity of them was determined according to the Turkish standard (TS 25/T1, 2011). According to the standard, mortar mixture containing lime, siliceous sand, water and one of the materials mentioned before was prepared, and the mortar was cast into the prismatic moulds. The specimens are kept in laboratory conditions for 24 hours and in an oven at 55 ± 2°C for 6 days. Flexural and compressive strength tests were performed on the 7th day on three specimens of one material according to the TS EN 196-1 (2002).

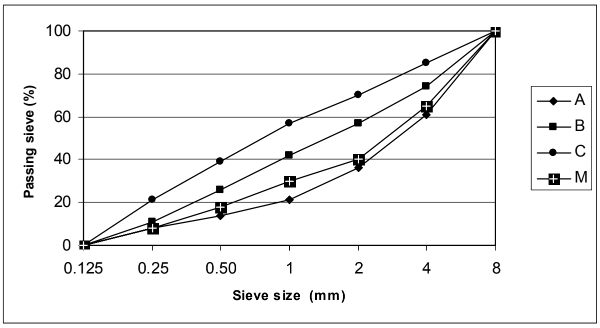

Fig. 1 Granulation of crashed brick aggregate

In a series of mortars, polypropylene fibers which has length 12 mm, diameter 18 μ, slenderness ratio of approximately 670, specific gravity 0.91 g/cm^3, tensile strength 700 N/mm^2 and 3500 N/mm^2 the modulus of elasticity which (ASTM C: 1116 Type III)% by weight of 0.1 percent are used.

Table 1 The physical properties and chemical analyses of materials

	Physical Properties		**Chemical Analyses**	**%**
Lime	Retained on 630 μm sieve	%0.5	CaO	61 min.
	Retained on 90 μm sieve	%10 max.	$Ca(OH)_2$	80 min.
	Density	0.50 kg/dm	MgO	0.5 max.
	Color	White	R_2O_3	0.5
	Specific gravity	2,50 kg/dm^3		
Silica Fume	Particle size (typical)	<10∝m	Cr_2O_3	1-4
	Bulk density as produced	0,15-0,25 g/cm^3	SiO_2	70-85
	Bulk density slurry	1,1 g/cm^3	Fe_2O_3	1-2,5
	Bulk density densified	0,500-0,700 g/cm^3	Al_2O_3	2-5
	Surface area (BET)	12300-31000m^2/kg	CaO	1-2
	Specific gravity	2.20 g/cm^3	MgO	4-8
			A.K.	1-3,5
			C	1-1,5
			S	0,5-1,3
Fly Ash	Specific gravity	2.38 g/cm^3	Loss in ignition	3.775
			Cl	0.016
			SO_3	1.067
			CaO	0.412
Blast Furnace Slag	Surface area	118 m^2/kg	SiO	38,99
	Specific gravity	2,89 g/cm^3	Al_2O_3	11,58
			Fe_2O_3	0,23
			CaO	35,97
			MgO	9,12
			MnO	1,20
			K_2O	0,95
			S	0,72
			Ti_2O	0,57
Brick Powder	Specific gravity	2,78 g/cm^3	CaO	0.330
			Al_2O	15.705
			SiO_2	62.313
			Fe_2O_3	5.993
			MgO	1.903
			Na_2O	1.670
			K_2O	3.210
			SO_3	0.075
			Impurity	8.753
			Total	99.95

10 groups 126 pieces of 40 × 40 × 160 mm prismatic specimens were prepared with different puzzolanas for 7th, 28th and 365th day tests. Specimens were demoulded from casts after 48 hours and one group stored in laboratory conditions with average of 20 ± 2°C temperature and 60% ± 5 humidity without wind and other group on YTÜ Campus at atmospheric conditions to the defined test dates. Specimens are grouped and coded as seen in Table 3 according to the aggregate as crashed brick (B), control group (C), and pozzolanic materials as silica füme (SF), blast furnace slag (BF), fly ash (FA), brick powder (BP) and polimer fiber (f).

Table 2 Codes of the specimen-materials ratio

Code	Explanation	ratio
BC	Crashed brick + Lime + Water (kontrol)	3:1:0,97
BSF	Crashed brick + Lime + Silica fume + Water	3:0,77: 0,23:0,80
BFA	Crashed brick + Lime + Fly ash + Water	3:0,77: 0,23:0,72
BBF	Crashed brick + Lime + Furnace slag + Water	3:0,77: 0,23:0,72
BBP	Crashed brick + Lime + brick powder + Water	3:0,77: 0,23:0,70
BCf	Crashed brick + Lime + Water (kontrol) + polimer fiber	3:1:0,75: 0,01
BSFf	Crashed brick + Lime + Silica fume + Water + polimer fiber	3:0,77:0,23:0,82: 0,01
BFAf	Crashed brick + Lime + Fly ash + Water + polimer fiber	3:0,77:0,23:0,74: 0,01
BBFf	Crashed brick + Lime + Furnace slag + Water + polimer fiber	3:0,77:0,23:0,75: 0,01
BBPf	Crashed brick + Lime + brick powder + Water + polimer fiber	3:0,77:0,23:0,72: 0,01

Flexural and compressive strength test were caried on 7th, 28th, 365th days according to the TS EN 196-1. The flexural strength tests was carried out on each 40 × 40 × 160 mm prismatic specimens and during the flexural strength test each specimen broken into two pieces then compressive strength test conducted on one piece specimen. During compressive strength test load was increased on 2400 ±200 N/s speed till the specimens are broken.

2.2. Investigation of Atmospheric Conditions as Damage Factor

Samples are left in the YTU Central Campus in atmospheric conditions to determine the atmospheric conditions between October 2005 and January 2006, meteorological information between those dates, were obtained from Kireçburnu (Sarıyer) Meteorological Station which is closest to campus For determination of the atmospheric conditions as a damage factor and repetition numbers (n_t), the study of Aköz (1989) who developed the boundary values are used.

According to this study from the meteorological events, temperature, precipitation and relative humidity values, with certain assumptions, wetting-drying, freeze-thaw and wetting-drying up to a certain degree of moisture are determined as damage factor number of repetitions (n_t).

Wetting-drying event has two-phase, for wetting phase relative humidity is high and / or to be rainfall, for drying phase increased temperature, relative humidity falls is based. Also similar approach is based in the case of wetting-drying in certain humidity; for the phase of relative humidity is high and / or to be rainfall, a partial drying phase increased temperature and the relative humidity remain between the specific values. In these two damage cases; in the case of wetting and drying wetting rainfall for the day to be at least 0.1 mm, for drying temperature at least 25°C and relative humidity is less than 90%, wetting and drying up the specific humidity of 70-80% of incident conditions were sought.

For the freeze-thaw phase the freezing temperature must be below 0°C, for thawing phase the temperature must be 0°C or above. For the two-phase, water existence in the external environment isn't necessary. However, the material has absorbed water is more effective than in case of the event. High temperature or rain in the high temperature must be for the phase of thaw. The case of freeze-thaw; the freezing temperature at least –0.1°C, for dissolution the temperature at least 5°C, rainfall at least 0.1 mm., of incident conditions were sought.

For wetting-drying, wetting-drying in certain humidity, freezing-thaw cases specified conditions number of days provided at the same time are examined and the minimum value has been recognized as the number of repetitions for that month. Samples exposed to atmospheric conditions between 2005 and January 2006 temperature, rainfall and relative humidity factors using the assumptions above are determined and the damage factor numbers of repetitions are given in Table 4.

Between these dates damage factor number of repetitions for wetting-drying and wetting-drying in certain humidity environment is 12 and 6 repetition numbers for the freeze-thaw [10].

Table 3 Days provides the limit values and damage factor repetition numbers (Jan. 2005 – Jan. 2006)

DATE		Days provides the limit values						Repetition numbers								
		Temperature			Rainfall	Relative Humidity		Wetting-Drying Repetition number			Wetting- Drying in specific humıdıty Repetition number			Freeze-Thaw Repetition number		
								Wetting	Drying		Wetting	Drying		Freeze	Thaw	
		ort. ≥5 °C	min ≤-0,1 °C	max. ≥25° C	≥0,1 mm	70-80 %RH	<90 %RH	≥0,1mm	≥25 °C	<90 %RH	≥0,1mm	≥25°C	70-80 %RH	≤-0,1°C	≥0,1 mm	ort. ≥5°C
2005	Jan.	25	*	*	22	6	25	22	*	25	22	*	6	*	22	25
	Fe.	14	3	*	21	5	22	21	*	22	21	*	5	3	21	14
	Mar.	19	1	*	16	4	27	16	*	27	16	*	4	1	16	19
	April	29	*	*	10	8	29	10	*	29	10	*	8	*	10	29
	May	31	*	*	5	6	30	5	*	30	5	*	6	*	5	31
	June	30	*	*	6	15	29	6	*	29	6	*	15	*	6	30
	July	28	*	3	3	13	30	3	3	30	3	3	13	*	3	28
	Aug.	22	*	9	8	18	31	8	9	31	8	9	18	*	8	22
	Sep.	29	*	1	15	9	29	15	1	29	15	1	9	*	15	29
	Oct.	31	*	*	14	8	30	14	*	30	14	*	8	*	14	31
	Nov.	27	*	*	20	13	27	20	*	27	20	*	13	*	20	27
	Dec.	23	*	*	21	10	29	21	*	29	21	*	10	*	21	23
2006	Jan.	7	2	*	20	7	30	20	*	30	20	*	7	2	20	7
								n_t 3+8+1=12			n_t 3+8+1=12			n_t 3+1+2=6		

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The mechanical properties of all studied lime-pozzolana mortar specimens were significantly improved in comparison with the control group of lime mortar. Pozzolans react with $Ca(OH)_2$ and the result is additional CSH gel. This transformation leads to an increase in the resistance of the material. The positive effect of the applied pozzolanic admixtures was observed not only in 28-days tests but also in 365 days tests. The results of the long term (365 days) tests showed that in the time when the negative aging effects on the control group lime mortar have appeared, the increase of strengths of lime pozzolana mortars continued in 365 days. These achieved 1,5-6 times higher strengths than after 28 days. The pozzolanic reaction of silica fume, fly ash, blast furnace slag and brick powder was reported to have a significant effect on strength development when long-term strength rather than short-term strength is of concern. Therefore, the characteristic 28 day mortar strength does not necessarily reflect the long-term behavior of pozzolanic materials mortar because of the long term required for the pozzolanic reaction to be completed.

Flexural and compressive sthrength tests results of mortar specimens with pozzolanic materials and polymer fibers examined in 7 th, 28^{th} and 365 th days are presented below.

Table 4 The mechanical test results of the specimens

Code	Flexural Strength (MPa)				Compressive Strength(MPa)			
	7 days	28 days	LAB 365 days	ATM 365 days	7 days	28 days	LAB 365 days	ATM 365 days
BC	~0	0,3	0,86	0,54	0,71	1,46	3,4	1,5
BSF	0,85	1,46	2,07	0,52	3,71	7,25	9,9	9,2
BFA	0,16	0,57	1,11	1,77	0,96	1,79	4,8	5,3
BBF	0,79	1	2,1	3,13	2,6	3,63	7,3	11,5
BBP	0,34	0,53	0,85	1,41	1,29	2,25	4,3	5,6
BCf	~0	~0	0,36	0,23	0,83	1,29	1,92	1,33
BSFf	0,41	1,24	1,38	1,49	2,88	5,96	7,92	9,5
BFAf	~0	0,29	0,55	1,23	0,88	1,63	2,33	4,79
BBFf	0,41	0,52	0,84	2,38	1,75	2,21	4,17	7,83
BBPf	0,36	0,49	0,8	1,27	1,63	2,17	4,08	5,33

3.1 Flexural Strength

Flexural strength of the samples by addition pozzolanic materials increased over time, at the end of a year in the laboratory conditions achieved 2.0 MPa, and 3.0 MPa in the atmospheric environment. Although the samples effected in the atmospheric environment 12 times of wetting-drying, wetting-drying in certain humidity and 6 times freeze-thaw cases the flexural strength have increased about 3-4 times.

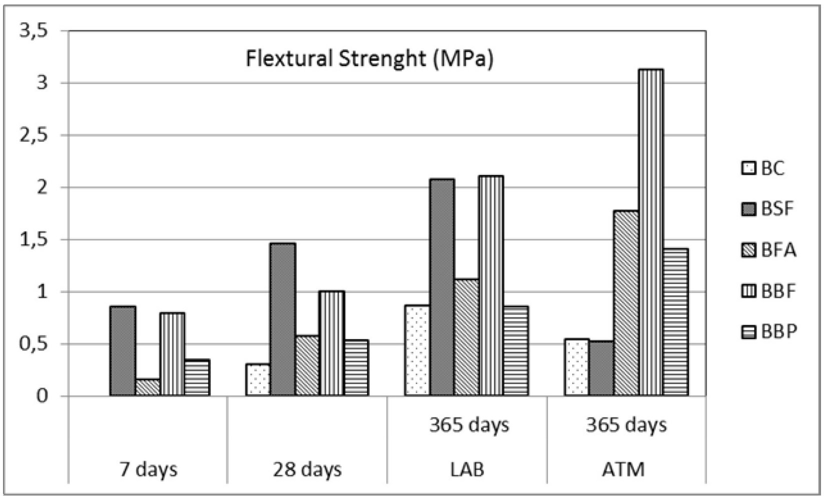

Fig. 2 Effect of pozzolanas on flexural strength of mortars at laboratory and atmospheric conditions

Fiber addition to the samples decreased the flexural strength (Table 5). Cause of decline, can be related with the largest grain size of 8mm brick aggregates is close to a 12-mm length of fiber and surface properties brick aggregate.

In a similar study conducted by Drdácký (2003); 12 mm in length polypropylene fiber added in ratio of 0.3% 0.1% 0.5% to the lime mortar, samples stored in the laboratory 90 days, and then the mechanical and physical experiments have been examined. According to the test results the samples added 0,1% ratio has 0,5 Mpa flextural strenght, 0,3% ratio has 0,6 Mpa flextural strenght, compressive strenght values have been approxiametly 2,0 ≈ 2,5 Mpa. [11].

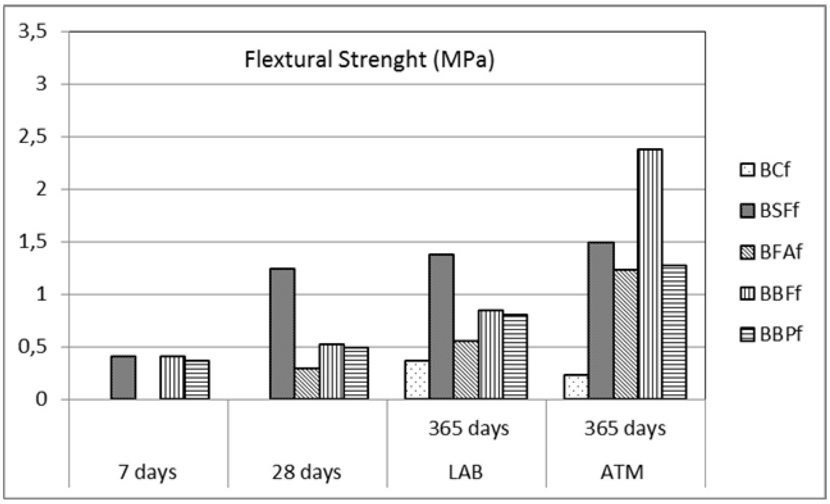

Fig. 3 Effect of pozzolanas on flexural strength of with fiber mortars at laboratory and atmospheric conditions

3.2 Compressive Strength

Compressive strength of the samples by addition pozzolanic materials increased like the flexural strength over time.In the laboratory conditions the compressive strenght of control group (BC) achieved 3,4 MPa; silica fume added mortars are achieved 10 MPa. The compressive strength of mortars in the same mixture ratio left in the atmospheric environment for a year, as shown in Figure 4 has higher values than the samples stored in laboratory conditions. In the atmospheric environment the compressive strength of blast furnace (BBF) has been effective, and reached 11.5 MPa.

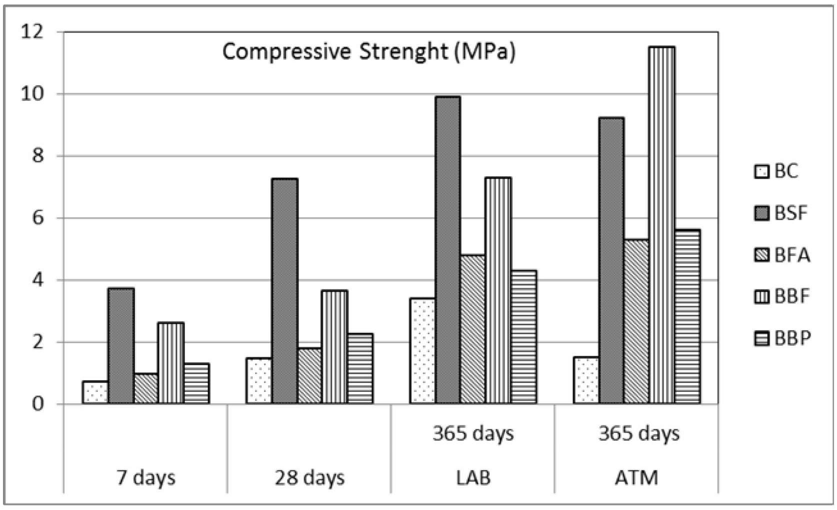

Fig. 4 Effect of pozzolanas on compressive strength of mortars at laboratory and atmospheric conditions

The compressive strength of fiber added samples have similar behaviors like the flexural strength, fiber addition to the samples caused a slight decrease in compressive strength.As it is mentioned above the relationship between fiber length with the aggregate maximum grain size should be considered

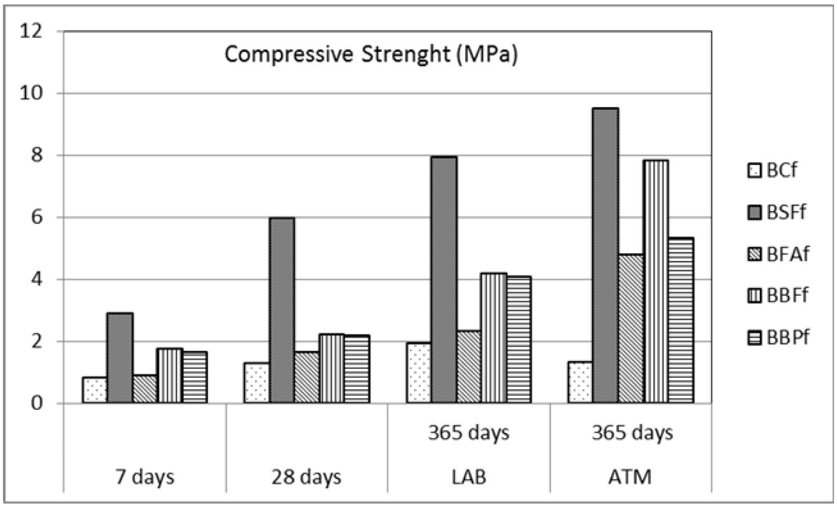

Fig. 5 Effect of pozzolanas on compressive strength of with fiber mortars at laboratory and atmospheric conditions

4. CONCLUSIONS

According to the results of the experimental study that was carried out on lime mortars with the aim of material selection convenient to the original material for lime mortars used in conservation, restoration and strengthening of historical buildings; Flexural and compressive sthrength tests results of mortar specimens with pozzolanic materials and polymer fibers examined in 7th, 28th and 365th days are presented below.

- Pozzolanas as silica fume, blast furnace slag, fly ash as industrial waste products and brick powder obtained from brick waste product increased the flexural and compressive strength of lime mortars in laboratory and atmopheric conditions. Care must be taken in the treatment conditions in order for the puzzolanic activity to continue and for it to beneficially effect the mortar characteristics.
- The results of the long term (365 days) tests showed that in the time when the negative aging effects on the control group lime mortar have appeared, the increase of strengths of lime pozzolana mortars continued in 365 days. These achieved 1,5-6 times higher strengths than after 28 days.
- Flexural and compressive strength of fiber added samples are decreased. This may be caused by the mismatch between fiber length and the aggregate maximum grain size.

Consequently, in the production of lime mortars used in restoration studies of historical buildings, besides brick powder, the industrial waste products such as silica fume, fly ash and blast furnace slag can be employed. However, before the application congruities of these materials with the original mortars must be examined and besides the mechanical properties the color harmony must be taken into account in an aesthetical point of view.

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