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Effects of Pozzolanas on Mechanical Properties of Mortars in Historical Buildings

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ABSTRACT: In restoration and strengthening studies of historical buildings, the historic, authentic and identity values of the building must preserved, and all restorations, strengthening works must be done by minimum interference to the original construction techniques and materials. In this study, siliceous sand, crashed brick as aggregate, lime and silica fume, fly ash, blast furnace slag, brick powder as puzzolanas were mixed to develop contemporary mortars for use in restoration works of historical buildings. The effects of puzzolanas on mechanical properties were examined with the tests performed in 7th, 28th and 365th days. Test results show that the effects of puzzolan material on flexural strength, compressive strength are increased in the long term and pozzolanic materials decreased the capillarity and reduced the porozite of the mortars.

1 INTRODUCTION

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 was discovered.

Among the binders, the historical development of lime is interesting. The binding property of lime was discovered at various different places of the world independently, however, its industrial production has been possible in the XIV th century. It can be argued that the making of fire in lime stone caves lead to the discovery of lime. This supposition dates the discovery of lime back to times before Neolithic Age. It is reported that the Babylonians had lime kilns. Although the making of mortar by mixing lime with sand and water is claimed to be found in Hellenistic age, it has been also observed in Neolithic communities who were in Anatolia before the Hellens. (Akman 1997, Böke 2004)

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 (Croci 1998).

Pozzolanas vary in reactivity, and historically include naturally occurring volcanic Italian pozzolana and Santorini earth as well as artificial forms including brick and tile powder. 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. (Croci 1998).

The addition of pozzolana to any lime mortar (hydraulic or non- hydraulic) will modify its characteristics. Pozzolanic materials can combine with uncarbonated lime (calcium hydroxide) to form stable compounds, thus reducing the risk of early leaching or frost damage and increasing the potential durability of the mortar. 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 (Gibbons 1997).

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 precipitated 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 features. Silica fume, fly ash and slag were reported to enhance the properties of fresh and hardened concrete with confirmed contribution to long-term strength and durability (Reda Taha and Shrive 2001)

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 (Moropoulou et al. 2005).

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. Siliceous sand according to the Rilem guidelines, broken brick, lime, silica fume, fly ash, blast furnace slag, brick powder are used to prepare mortar samples with different properties.

2 MATERIALS AND METHODS

In this experimental study on lime mortars with the aim of material selection convenient to the original material for lime mortars used in restoration and strengthening of historical buildings, 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. Pozzonalic materials replaced %30 of lime. Specimens are grouped and coded as seen in Table 1 according to the aggregates and pozzolanic materials as siliceous sand (S), crashed brick (B), control group (C), silica fume(SF), blast furnace slag (BF), fly ash (FA), brick powder (BP). According to the TS EN 196-1 in 10 groups 90 pieces of 40x40x160 mm prismatic specimens are prepared with different puzzolanas for 7^{th}, 28^{th} and 365^{th} day tests. Specimens are demoulded from casts after 48 hours and stored in laboratory conditions with average of 20±2˚C temperature and %60±5 humidity without wind to the defined test dates.

Table 1 : Codes of the specimen

Aggregate	Code	Explanation
SAND	SC	Sand (rilem)+ Lime + Water
	SSF	Sand (rilem) + Lime + Silica fume + Water
	SFA	Sand (rilem) + Lime + Fly ash + Water
	SBF	Sand (rilem) + Lime + Furnace slag + Water
	SBP	Sand (rilem) + Lime + brick powder + Water
CRASHED BRICK	BC	Crashed brick + Lime + Water
	BSF	Crashed brick + Lime + Silica fume + Water
	BFA	Crashed brick + Lime + Fly ash + Water
	BBF	Crashed brick + Lime + Furnace slag + Water
	BBP	Crashed brick + Lime + brick powder + Water

- Aggregates

Siliceous sand (S), according to the Rilem Guideline max.2mm particle sizes and crashed brick (B) in max 8mm particle sizes were used in mortar mixtures. Crashed brick aggregate was prepared in 8 mm max particle size as seen in Fig. 1 by using the bricks obtained from market. In the preparation process so as to achieve the proper granulation the crashed bricks sifted, grouped and weighted and than the crashed brick aggregate mixture with 1,51g/cm^2 unit weight and 2,50g/cm^2 specific weight was prepared.

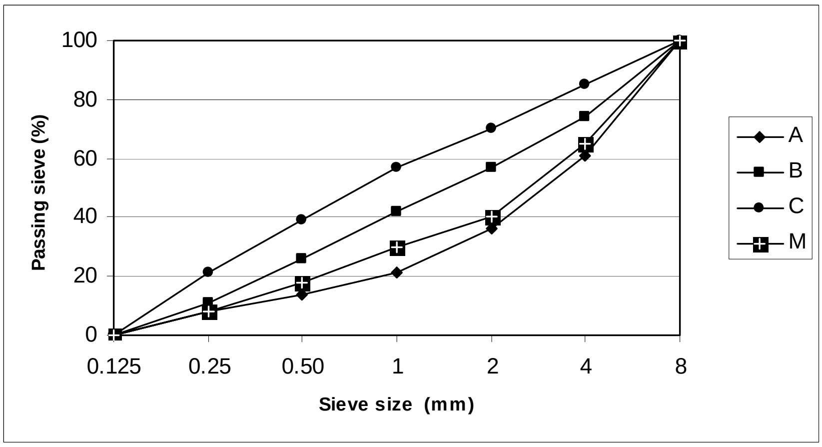

Figure 1 : Granulation of crashed brick aggregate

- Binder and pozzolanas

Pozzolanic activity of silica fume, fly ash, blast furnace slag and brick powder was determined according to the Turkish standard (TS25).Pozzolanas are materials containing reactive silica and/or alumina which on their own have little or no binding property but, when mixed with lime in the presence of water, will set and harden like a cement. So according to the standard (TS25), 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. So as to analyze the pozzolanic activity flexural and compressive strength tests were performed on the 7th day on three specimens of one material. Mean values of the test results for silica fume, fly ash, blast furnace slag and brick powder and the standard values are presented in Table 2.

Table 2 : Pozzolanic activity test results

Material	Flexural strength f_e (MPa)	Compression strength f_b (MPa)
Standard values (TS25)	1	4
Silica Fume	3,77	26,33
Brick powder	1,11	4,04
Blast furnace slag	1,93	6,13
Fly ash	2,11	7,96

Crashed brick, siliceous sand and the materials given in Table 3 were used for the mortar mixtures. As a binding material slaked lime, silica fume from silicoferrochrome shaft fume, flay ash from Iskenderun power station, blast furnace slag; 118m^2/kg fine grinded and brick powder achieved by grinding the crashed bricks were used as pozzolanas. Brick powder sifted from 10 µm size sieve and passing was taken as mixture material.

Table 3 : The physical properties and chemical analyses of lime, silica fume, fly ash, blast furnace slag and brick powder

	Physical Properties		Chemical Analyses	%
Lime	Retained on 63 µm sieve	%0.5	CaO	61 min.
	Retained on 90µm 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)	<10µm	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

The flexural and compressive strength test and capillary water absorptions were measured on 7th 28th, 365th days. The flexural strength tests was carried out on each 40x40x160mm prismatic specimens and during the flexural strength test each specimen broken into two pieces then compressive strength test conducted on tone piece and capillary water absorption test conducted with the other piece of specimen. During compressive strength test load was increased on 2400 ± 200N/s speed till the specimens are broken. Prior to capillary water absorption testing, specimens were dried in the oven at 105 ± 2˚C until constant mass was achieved and then cooled in desiccators. For the capillary water absorption test upper face 40x40 mm dimensions was brought in contact with water in a tray. Environmental temperature was 20 ±1˚C and relative humidity was % 65±5 during the test. Absorbed water was measured at different intervals. Initial slope of the curve of absorbed water-square root of time was calculated representing the capillary water absorption coefficient.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

Flexural, compressive and capillary water absorption tests results of mortar specimens with different aggregate and pozzolanic materials examined in 7 th, 28th and 365 th days are presented below.

- Flexural Strength

Flexural strength of both aggregates increased in long term as seen in Fig. 2 and 3. Flexural strength of silica fume added lime mortars with siliceous sand and crashed brick aggregate were higher at 7th, 28th and 365th days. Silica fume increased the strength in lime mortars such as in cement mortars. Flexural strength of SC and SBP mortars were lower at 7th day while SSF mortar was higher by 0,6MPa value. SSF mortar was the higher flexural strength by 2, 3 MPa at 28th day however there were no significant change up to 365th days. After silica fume, blast furnace slag mortars had the highest flexural strength. Fly ash and brick powder mortars achieved similar values to the control group at all days.

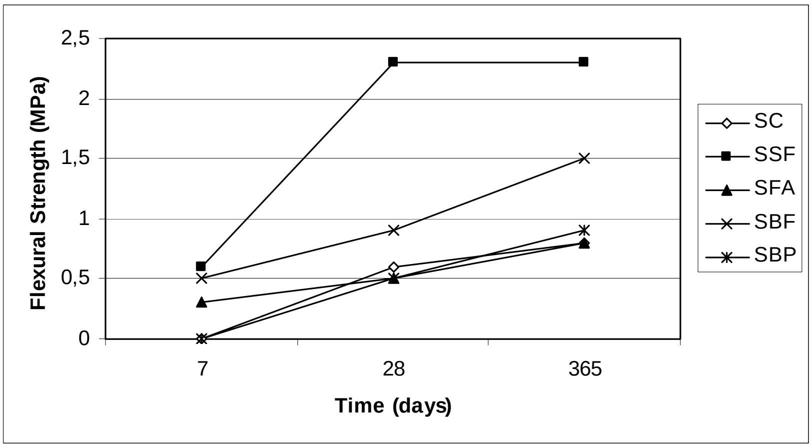

Figure 2 : Effect of time on flexural strength for siliceous sand aggregate mortars with pozzolanas

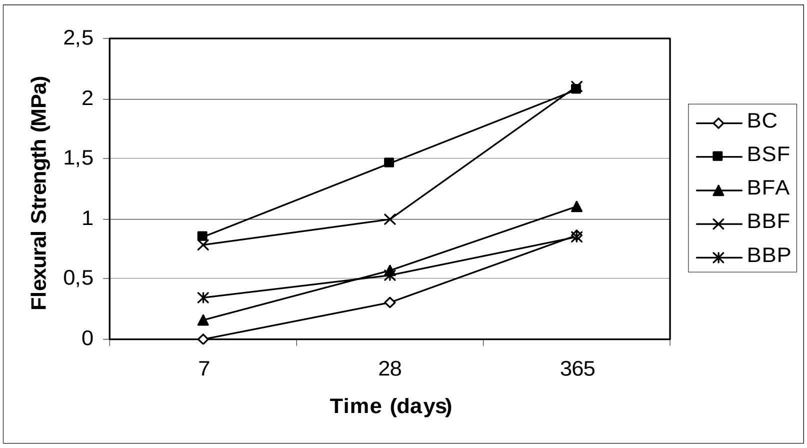

Figure 3 : Effect of time on flexural strength for crashed brick aggregate mortars with pozzolanas

Flexural strength of crashed brick aggregate mortars was higher by long term similarly siliceous sand aggregate mortars. BSF mortars achieved highest flexural strength by 0,85 MPa at 7th day. Flexural strength of BSF and BBF mortars achieved same values as 2,0MPa at 365th days.

- Compressive Strength

In the result of compressive strength test as well as flexural strength test, silica fume added mortars were the higher compressive strength at 7th, 28th and 365th days

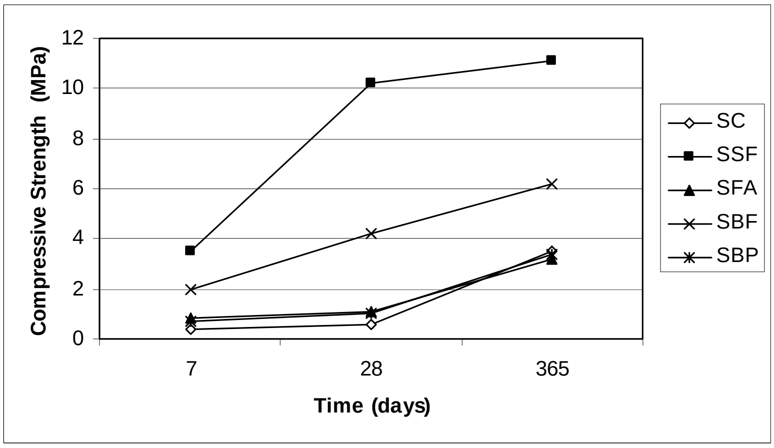

Figure 4 : Effect of time on compressive strength for siliceous sand aggregate mortars with pozzolanas

SSF mortars achieved 11,1 MPa compressive strength value at 365th days that is considerably similar to the cement mortars. Compressive strength of fly ash and brick powder mortars were almost same at all days.

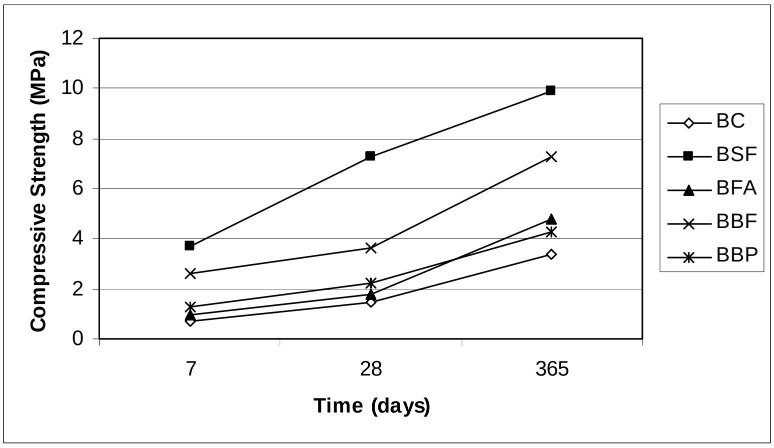

Figure 5 : Effect of time on compressive strength for crashed brick aggregate mortars with pozzolanas

Compressive strength of crashed brick aggregate mortars was increased by long term as well as siliceous sand aggregate mortars. Compressive strength of silica fume mortars with crashed brick aggregate were higher with 9,9 MPa at 7th, 28th and 365th days. After silica fume, blast furnace slag mortars had the highest by achieving 7,3 MPa compressive strength test result. Fly ash, brick powder and control group mortars achieved similar values at all days (Fig. 5).

- Capillary Water Absorption

Capillary water absorption of pozzolanas mortars in both aggregate groups was lower than the control group without any pozolana. Capillary water absorption of crashed brick aggregate mortars was higher than the siliceous sand aggregate mortars (Figs.6-7).

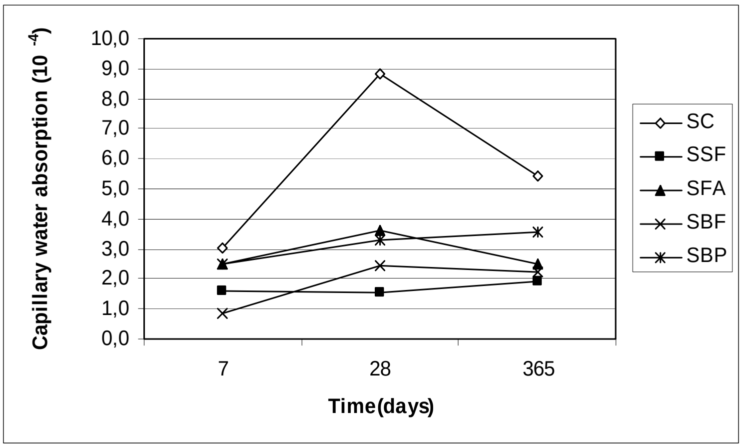

Figure 6 : Effect of time on capillary water absorption for siliceous sand aggregate mortars with Pozzolanas

Capillary water absorption of siliceous sand aggregate mortars, SSF mortars were the lowest, this result confirm the flexural and compressive strength. As the pozzolanic activity of silica fume is high it composes silicate (CSH) gel, and also as its particle size is fine enough to infuse the spaces in the mixture.

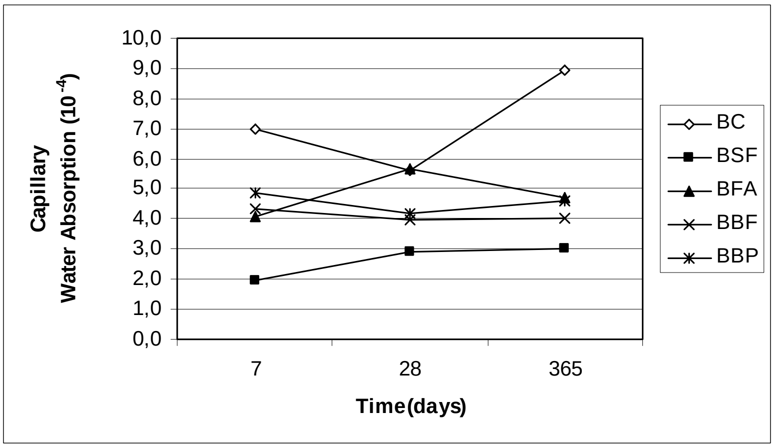

Figure 7 : Effect of time on capillary water absorption for crashed brick aggregate mortars with Pozzolanas

The lowest capillary water absorption value achieved by BSF mortars in crashed brick aggregate mortar groups. Brick powder and fly ash showed similar capillary water absorption effect as well as in mechanical properties.

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 mechanical properties of all studied lime-pozzolana mortar specimens were significantly improved in comparison with the control group of lime mortar. 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.

The effect of silica fume fly ash or slag on hardened concrete is attributed to its pozzolanic activity, by which the pozzolans chemically convert the weak CH crystals to strong CSH fibrous gel. The pozzolanic activity depends mainly on the chemical composition and the fineness of the pozzolans.

Table 4 : The physical and mechanical test results of the specimens

	Code	Bendıng strength (MPa)			Compression strength (MPa)			Capillary Coefficient E-04 (cm^2/sec)		
		7	28	365	7	28	365	7	28	365
SAND AGREGATE	SC	0,1	0,6	0,8	0,4	0,6	3,5	3,03	8,80	5,42
	SSF	0,6	2,3	2,3	3,5	10,2	11,1	1,61	1,53	1,94
	SFA	0,3	0,5	0,8	0,8	1,1	3,2	2,50	3,63	2,48
	SBF	0,5	0,9	1,5	2	4,2	6,2	0,85	2,43	2,26
	SBP	0,1	0,5	0,9	0,7	1	3,4	2,51	3,32	3,55
CRASHED BRICK AGREGATE	BC	0,1	0,3	0,86	0,71	1,46	3,4	7,00	5,61	8,94
	BSF	0,85	1,46	2,07	3,71	7,25	9,9	1,98	2,91	2,99
	BFA	0,16	0,57	1,11	0,96	1,79	4,8	4,09	5,66	4,73
	BBF	0,79	1	2,1	2,6	3,63	7,3	4,34	3,98	4,02
	BBP	0,34	0,53	0,85	1,29	2,25	4,3	4,88	4,21	4,60

3 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;

- 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 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.
- As these pozzolanic materials decrease the water absorption of mortar, it is suggested that reduction of water absorption increased performance and the durability of mortars.

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. And also using the industrial waste products in construction not only improves the properties of mortars but also contributes to reducing the harmful effects to the environment.

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