

Effect of Slag Fineness and Curing Conditions on the Mechanical Properties of Alkali-Activated Blast Furnace Slag Mortars

Hasan Biricik*, Işıl Sanrı Karapinar*‡

* Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Maltepe University, Istanbul, Turkey

(hasanbiricik43@gmail.com, isilkarapinar@maltepe.edu.tr)

‡Işıl Sanrı Karapinar, Maltepe University, Istanbul, Turkey
Tel: +90 216 626 10 50, isilkarapinar@maltepe.edu.tr

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Abstract- The main objective of this experimental study was to investigate the effect of the slag fineness on the compressive and flexural strengths of ground granulated alkali-activated blast furnace slag mortars. Two types of alkali-activated mortar mixtures were produced using blast furnace slags having the Blaine fineness of 400 m²/kg and 600 m²/kg. Three curing methods; water curing, air curing and outdoor conditions, were applied to the samples. Compressive strengths and flexural strengths of the mixtures were determined at various ages and capillary water absorption tests were also performed. Test results confirm that increasing the fineness of slag had an important effect on the properties obtained. The curing method is also an important factor affecting the results.

Keywords- Blast furnace slag; alkali activation; fineness; curing conditions; mechanical strength; capillary water absorption.

1.Introduction

Alkali-activated materials have received much attention in the past decade due to their promising potential of replacing Portland cement. As is well known, the cement industry is one of the major producers of CO₂ emissions. Since the manufacturing process of Portland cement contributes considerably to CO₂ emissions, with the purpose of reducing the carbon footprint, many attempts have been made to find alternative binders to decrease the amount of cement used. Alkali-activated binders have been considered to be more environment-friendly due to the fact that the CO₂ emission is less compared to Portland cement[1, 2]. Aluminosilicates which are mostly reused industrial by-products and wastes are used as precursors in the production of alkali-activated binders. Many pozzolanic by-products are being used in cement as an alkali-activated binder, however, blast furnace slag is one of the most reused materials for this process resembling the Portland cement in chemical composition[3]. A growing body of literature has been investigated the mechanical and microstructural properties of alkali-activated cementitious composites blended by blast furnace slag[4-9]. The studies have shown that as the amount of blast furnace slag increases, an improvement in compressive strength occurs. On the other hand, it was reported that the dosages of the slag affect the workability and setting time of the cementitious composites[10, 11]. Also, the fineness and the curing conditions significantly affect the fresh and hardened

properties as well[12]. In a study, it was noted that increasing the fineness of blast furnace slag resulted in the development of the strength of the binder by 50% [13]. Also, slags having two different blaine fineness were used for the alkali-activated binder and the development in strength due to the increase in blaine fineness was reported[14]. The use of blast furnace slag in cementitious composites is detailed by three grades in ASTM C 989 showing its potential as supplementary cementitious material[15]. The grinding process has an important effect on the particle size of the blast furnace slag. The relationship between the particle size and the specific surface area has significant implications in terms of the pozzolanic activity of the granulated blast furnace slag[16]. As stated, there has been an enhancement in strength due to the increase in fineness of the blast furnace slag. This observed increase in strength is explained by the increase in the specific surface area inducing an improvement in the reactivity of the blast furnace slag. Also, in recent studies, cementitious composites including granulated blast furnace slag activated with sodium carbonate and sodium silicate were compared and the changes in mechanical strength and setting time were discussed[17, 18]. Also, another study has used sodium carbonate and sodium silicate (waterglass) as activators to investigate the mechanical strength of alkali-activated blast furnace slag and waste of ceramic bricks and concluded that the axial compressive strength has improved for the

cementitious composites in which sodium silicate was used as the activator[19].

In this experimental study, blast furnace slag-based geopolymer mortars having different particle sizes were prepared using both sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) as activators and the effect of blast furnace slag fineness on compressive and flexural strength of alkali-activated mortars was investigated under different curing conditions.

2. Experimental Study

2.1. Materials

Blast furnace slags having two fineness values were used. Same ground blast furnace slag was used and was grounded in a laboratory ball mill. The initial Blaine fineness of the slag was 400 m²/kg and was increased to 600 m²/kg after the grinding. Chemical compositions of the slags are shown in Table 1 and some of their physical properties are given in Table 2.

Table 1. Chemical compositions of the blast furnace slags.

Oxide Composition (%)	Slag BSA: 400 m ² /kg	Slag BSA: 600 m ² /kg
SiO ₂	38.41	37.78
Al ₂ O ₃	10.22	10.07
Fe ₂ O ₃	1.53	1.58
CaO	37.71	37.56
MgO	7.88	8.08
SO ₃	0.63	0.65
Cl ⁻	0.0381	0.256
Na ₂ O	0.33	0.32
K ₂ O	0.82	0.82
Loss on ignition	2.05	2.62

Table 2. Some physical properties of the blast furnace slag.

Property	Slag BSA: 400 m ² /kg	Slag BSA: 600 m ² /kg
Density	2.88	2.88
Blaine surface area (m ² /kg)	400	600
Retained on 200 μm sieve (%)	0.0	0.0
Retained on 90 μm sieve (%)	0.0	0.0
Retained on 45 μm sieve (%)	1.0	0.4

Figure 1 demonstrates that the average particle size decreases by grinding of the slag. The initial average particle was 45 μm, which was reduced to 8 μm after grinding.

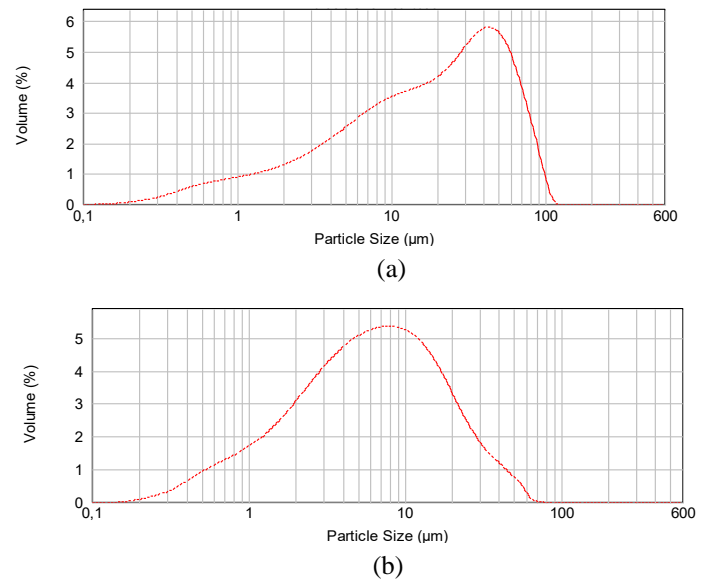


Figure 1. Particle size distributions of blast furnace slags (a) before grinding (b) after grinding.

In order to activate the ground granulated blast furnace slag, two different alkaline materials; sodium hydroxide and sodium silicate were utilized. Both of the activators were classified as the technical grade. Sodium hydroxide was in solid form and was dissolved in distilled water before using in the mixtures. Sodium silicate and sodium hydroxide solutions were used together for the activation of the blast furnace slags. The amounts of these activators in the solution by weight were 8% and 27%, respectively. The modulus of sodium silicate was 3. The density of the sodium hydroxide was ranging from 0.93 g/cm³ whereas the density of sodium silicate solution was 1.33 g/cm³. The same siliceous natural sand with a maximum particle size of 4 mm and a specific gravity of 2.563 g/cm³ was used in the study.

2.2. Mixtures

Two mortar mixtures were produced in the experimental work. The mixture proportions are given in Table 3. The mixtures were designated as BFS4 and BFS6 where BFS indicates blast furnace slag and the numbers following BFS show the fineness of the slag. For instance, BFS4 shows that the mixture was produced with slag having the Blaine fineness of 400 m²/kg. Both of the mixtures were stirred in a laboratory mixer. 160 x 40 x 40 mm steel molds were used for casting of all specimen series and were unmolded after 24 hours.

2.3. Curing Conditions

After demolding, three different curing conditions were applied;

- i) Standard water curing at 20°C, or
- ii) Laboratory air curing at 20±3°C and 60% relative humidity, or

iii) Outdoor conditions with an average temperature of $15\pm 5^{\circ}\text{C}$ and varying humidity (such as rain). These curing conditions were applied until testing.

The flexural strengths of the mixtures are given in Table 4. In this table, the letters O, L and W represent the curing conditions

Table 3. Mixture proportions.

Mixture code	Blast furnace slag (kg/m ³)	Water (kg/m ³)	Na(OH) (kg/m ³)	Na ₂ SiO ₂ (kg/m ³)	Sand (kg/m ³)	Unit weight (kg/m ³)
BFS4	466	233	32.6	79.2	1398	2209
BFS6	468	208	32.8	79.6	1404	2192

2.4. Testing

Bending tests of the samples were made according to TS EN 196-1[20]. After this bending test, the compressive strength tests were conducted on the prism halves having a 40 x 40 mm cross-section. The compressive strengths of the specimens were also obtained with respect to TS EN 196-1. The mechanical properties of the specimens were tested at the ages of 3, 7, 28 and 56 days. To determine the permeability properties, capillary water absorption tests were made on the mixtures at the age of 56 days according to the requirements of TS EN 480-5 [21].

3. Results and Discussion

3.1. Flexural Strengths

where O denotes the outdoor curing, L indicates laboratory air curing and W stands for water curing.

Figures 2 and 3 illustrate the flexural strengths of the mixtures produced with slag of 400 and 600 m²/kg fineness, respectively. As presented in these figures, water curing resulted in higher strengths. The flexural strength of the water cured samples were approximately 65 to 80% higher than the outdoor conditions. These results confirm that water is essential for the continuation of the hydration reactions. The 28-day and 56-day strengths obtained for the outdoor exposed specimens containing 600 m²/kg slag (BFS 6O), were lower than 7-day strengths. This may be due to the fluctuations in the humidity of the outdoor conditions. Reductions in humidity might have caused possible damages, such as micro-cracks at aggregate–paste interfaces, which may reduce the strength.

Table 4. Flexural strengths of the mixtures.

Testing Age (Days)	Flexural strength (MPa)					
	BFS 4O	BFS 4L	BFS 4W	BFS 6O	BFS 6L	BFS 6W
3	0.8	1.0	2.8	4.6	4.8	5.7
7	2.8	2.1	4.3	4.8	5.7	5.8
28	3.2	3.0	5.8	4.1	5.5	6.8
56	3.3	4.1	6.5	4.6	5.9	7.0

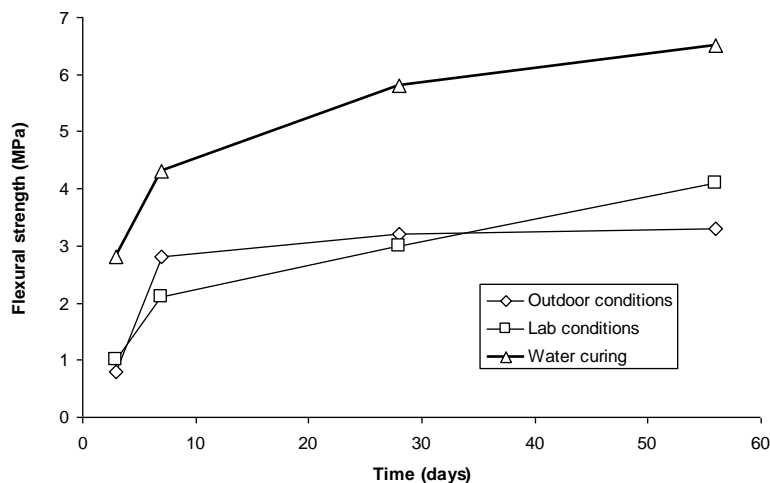


Figure 2. Flexural strengths of the mixtures produced with slag of 400 m²/kg fineness.

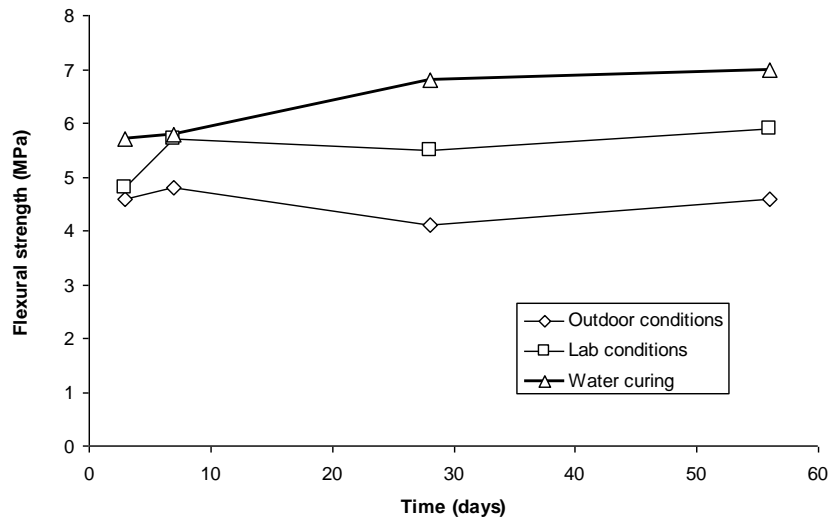


Figure 3. Flexural strengths of the mixtures produced with slag of 600 m²/kg fineness.

When the effect of slag fineness is compared, it can be seen that the mixtures containing finer slag had higher strength values.

3.2. Compressive Strengths

Compressive strengths of the mixtures are shown in Table 5, and also in Figures 4 and 5. Similar to the flexural test results, the water-cured specimens achieved higher compressive strengths, as expected. Depending on these findings, it may be

deduced that the effect of curing conditions for alkali-activated mixtures is similar to those for normal concretes.

Increasing the fineness of slag from 400 m²/kg to 600 m²/kg resulted in higher compressive strength. For example, after 28 days of water curing; the compressive strength of the mixture produced with 400 m²/kg was 38 MPa, but that with 600 m²/kg was 60.3 MPa, which corresponds to a strength increase of approximately 60%. This strength increase was more

Table 5. Compressive strengths of the mixtures.

Testing Age (Days)	Compressive strength (MPa)					
	BFS 4O	BFS 4L	BFS 4W	BFS 6O	BFS 6L	BFS 6W
3	4.5	6.9	12.2	25.1	25.9	27.5
7	16.1	14.8	21.1	33.7	43.1	47.7
28	18.8	26.6	38.0	38.7	54.6	60.3
56	46.9	50.5	58.5	40.5	58.7	63.6

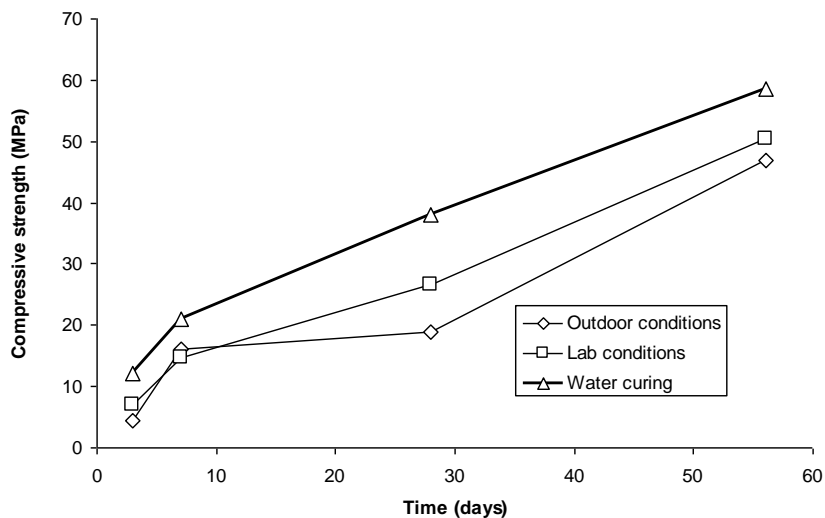


Figure 4. Compressive strengths of the mixtures produced with slag of 600 m²/kg fineness.

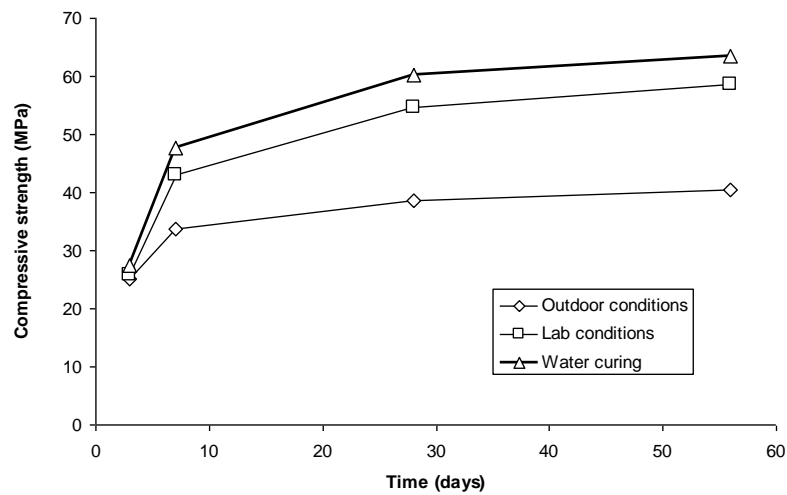


Figure 5. Compressive strengths of the mixtures produced with slag of 600 m²/kg fineness.

significant for early ages. Similar strength increases were obtained also for the other curing methods.

3.3. Capillary Water Absorption

Table 6 displays the results of the capillary water absorption test carried out with respect to TS EN 480-5. These tests were performed only at the age of 56 days. As seen in Figure 6, the fineness of slag had a significant effect on the capillary water absorption, especially for laboratory air curing and water curing. The reduction in capillarity was more than 60% for these two curing methods.

Table 6. Capillary water absorption of the mixtures.

Fineness of slag (m ² /kg)	Capillary coefficient (cm ² /s)		
	Outdoor conditions	Laboratory air curing	Water curing
400	8.6	7.4	5.8

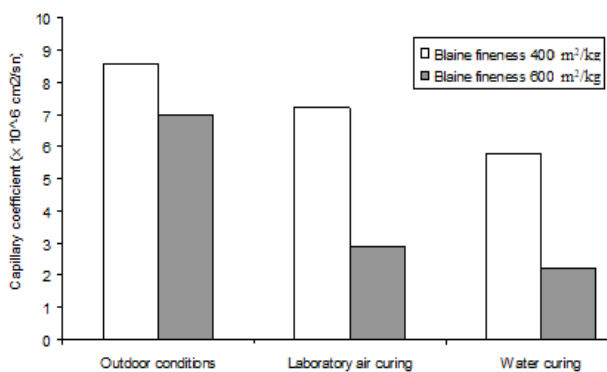


Figure 6. Capillary water absorption of the mixtures.

4. Conclusion

This experimental study has investigated the effect of slag fineness and type of curing on the mechanical properties of alkali-activated blast furnace slag mortar. Two different blaine fineness of 400 m²/kg and 600 m²/kg for the blast furnace slag were used and three kinds of curing methods, namely, water curing, air curing and outdoor conditions, were applied to the mortar samples. They were alkali-activated by both sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). In conclusion, the compressive strength of the alkali-activated mortar increased significantly as the fineness of the blast furnace slag was increased. Also, higher flexural strengths were obtained by using a finely ground slag. It is observed that the fineness of slag also affected the capillary water absorption of the mixtures. The reduction in capillarity was more than 60% for laboratory air curing and water curing. On the other hand, according to all the test results obtained, the water-cured samples achieved the best results.

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