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Research Article

Investigation of mechanical and microstructural performance of alkali activated electrical arc furnace slag mortars

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ABSTRACT

The production of Portland cement, resulting in the release of CO_2 gas, excessive energy and natural resource consumption, has led to search for alternative materials with similar physical and mechanical properties to the Portland cement of the scientific community. Geopolymers as alternative to conventional cement have a great potential for use in terms of their mechanical and durability properties. For this reason, it is necessary to investigate the usability of a new material alternative to cement, to reduce the environmental impact and for the disposal of Electric Arc Furnace Slag (EAFS), which is produced in large quantities in the primary target world and in Turkey and which causes storage space bottleneck. For this purpose, the mechanical and microstructure of the activated EAFS exposed to different curing conditions at three different sodium concentrations with a silicate module was investigated. When the results are examined, it is obvious that the strength increases with the increase of the sodium concentration. In addition, the literature on which alkali activation of EAFS has been added for the first time.

1. Introduction

Cement based materials are the most used materials in the construction sector. The need for cement increased as the need for construction increased. Hence, harmony with nature has been among the priorities of scientists. The release of CO_2 gas, excess energy and natural resource consumption resulting in the production of Portland cement led to the search for alternative materials with similar physical and mechanical properties to the Portland cement of the scientific community [1]. One of the ways of producing eco-friendly concrete or mortar has been proposed by researchers to reduce the use of Portland cement and the active use of by-products pozzolan [2].

Geopolymers or alkali activated Cementituos alkenes are the products of the reactions between solutions with high alkalinities and aluminum silicates [3]. Activated geopolymers have a great potential for use as an alternative to conventional cement in terms of their mechanical and durability properties. In particular, they exhibited against harsh environmental conditions and have increased their usefulness and environmental benefits as well as their resistance against fire and acid attack. For this reason, aluminum silicates such as metakaolin, slag, fly ash and clay, and pozzolans such as zeolite have been extensively studied as different forms of geopolymers.

Development of compressive strength in the alkali activated blast-furnace slags is possible and the same process can be applied in different additives lime, fly ash and sodium sulphate. Douglas expressed that compressive strength test values of slag mortars showed the slag is potential as a replacement material for ordinary cement concrete [4].

Hydration mechanism and strength gain mechanism of alkali activation of ground granulated blast furnace slag with sodium silicate forms clinker-free binders, with high and early strength development. Due to alkali compound

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of solution setting times were shorter than ordinary cement binder. Three important stages are exist and determined by using isothermal calorimetry. These stages are wetting, gelation of activator and bulk reaction between slag and alkali activator. When looking at the results of X-ray diffraction analysis it is seen that no crystalline products occurred. Also hydration mechanism was investigated by scanning electron microscopy and it is specified that a gel structure filled the initially water-filled space, and gradually make the structure denser as reaction proceeded [5,6].

The primary objective of this study is to develop an alternative method for disposal of slag to use of an alternative material for a new environmental impact reduction and cement material which is produced in large quantities in the world and Turkey, EAFS, causing a huge storage problem. For this purpose, mortar specimens are produced to investigate the mechanical and microstructure of the activated EAFS cement subjected to different curing conditions in three different sodium concentrations in a silicate module.

2. Experimental Study

2.1. Materials

EAFS, Sodium hydroxide (NaOH), Sodium silicate (Na_2SiO_3) solution and fine natural crushed stone aggregate were used for alkali activated EAFS mortars. The Na_2SiO_3 solution contained 8.52% Na_2O, 27.09% SiO_2 and 64.39% H_2O. The properties of the sodium silicate and sodium hydroxide are given in Tables 1 and 2. The maximum particle size distribution of the agglomerate used is 4 mm, fineness modulus and specific gravity are 2.65 and 2.6 g/cm^3, respectively.

Table 1. Chemical and physical properties of sodium silicate

Chemical and physical properties	Analysis (%)
(SiO_2/Na_2O)	3.19
Be (at 20 °C)	39.4
Specific gravity (20 °C g/cm^3)	1.373
Na_2O (%)	8.52
SiO_2 (%)	27.09

Table 2. Chemical and physical properties of sodium silicate

Chemical and physical properties	Unit	Analysis (%)
(NaOH)	g/kg	≥ 990
(Na_2CO_3)	g/kg	≤ 4
(Na_2SO_4)	mg/kg	≤ 80
(NaCl)	mg/kg	≤ 200
(Fe)	mg/kg	≤ 10
(Hg)	mg/kg	≤ 0.1
(Pb)	mg/kg	≤ 0.5
(Sb)	mg/kg	≤ 5
(Se)	mg/kg	≤ 5
(Ni)	mg/kg	≤ 2

The used EAFS is taken from Iskenderun Tosçelik Corporation. 500 kg EAFS is grinded through steel mills until reaching grain size of -45 μm. After grinding, the metals were separated from the product using magnetic separators (around 150 kg of metal was drawn from 500 kg of product). The final product has a specific gravity of 3.98 g/cm^3, a blaine value of 2600 g/cm^2, and also chemical analysis result is shown in Table 3.

Table 3. Chemical composition of EAFS

Component	FeO	Fe_2O_3	SiO_2	CaO	Al_2O_3
%	14.22	17.02	17.04	33.42	11.573
Component	MgO	MnO	K_2O	TiO_2	Na_2O
%	7.62	2.45	0.03	0.04	0.18

2.2. Mix Design

Twelve different test specimens were prepared to determine if EAFS cement was to be activated;

- The silicate module (SM) is selected as 1.
- The curing temperature (CT) is 40 ° C.
- Cure time (CTm) is 6 and 12 hours.
- Cured atmospheric moisture (AM) is 48% and 98%.
- Sodium concentrations (SC) are 4%, 6% and 8%.
- Samples were tested 28 days after curing.

In all test samples, the EAFS : Alkali solution: Aggregate ratio was kept constant at 1: 2.75: 0.485 by mass. Table 4 gives the mix design details. A gradually accelerating concrete mixer was used for the mixture. Mixing fine aggregate and EAFS was poured and dry mixing started, followed by dissolving sodium hydroxide in sodium silicate solution. Since the solution is exothermic, after waiting for cooling, the solution is poured in water and mixing process is continued. After a certain flowability is observed, the mixture is poured into prism molds (40x40x160 mm^3).

Table 4. Design parameters of alkali activated EAFS mortar

SM.	CT (°C)	SC	AM (%)	CTm (h)	Comp. str. (MPa)	Mix No
1	40	4	45	6	1,38	M1
				12	1,56	M2
			98	6	1,24	M3
				12	3,06	M4
		6	45	6	10,75	M5
				12	10,38	M6
			98	6	9,55	M7
				12	9,84	M8
		8	45	6	8,86	M9
				12	7,50	M10
			98	6	6,75	M11
				12	10,19	M12

After 24 hours the molds were demolded, the samples were removed and stayed at room temperature for 28 days after curing for 6 and 12 hours at 48 and 98% humidity with the help of climatic test cabinet, at 40 ° C. Mechanical tests were applied and then the microstructure analysis were examined.

2.3. Test Method

Compressive strength tests were carried out on 40x40x40 mm^3 cubic samples with a press machine with a pressure capacity of 2500 kN. The test procedure was carried out in accordance with ASTM C349.

JEOL JSM-5610LV model equipment was used for Scanning Electron Microscopy (SEM) analysis. Acceleration voltage of the device: 0.1 ~ 30 kV; resolution at high vacuum mode of 5.0 nm; acceleration voltage 30 kV, WD 6 mm; magnification X25 - X300,000; the probe current is from 1 pA to 1 µA.

Mineralogical phase analysis was carried out parallel to the operation of the optical microscope. EAFS material and alkali activated EAFS samples were analyzed using Rigaku SmartLab model equipment. X-ray diffraction (XRD) analyzes were performed using computer controlled Rigaku-SmartLab ranging from 5 ° to 90 ° with Cu Kα radiation (40 kV, 30mA) and 2θ angles.

3. Results and Discussion

In Figure 1, the compressive strength values of different samples are given. As can be seen from the trend in figure 1, the increase in sodium concentration caused an increase in compressive strength. In addition, it can be said that the curing time is increased from 6 hours to 12 hours and the humidity of the environment (RH) is 98% humidity from the room conditions, it has a positive effect on the compressive strength.

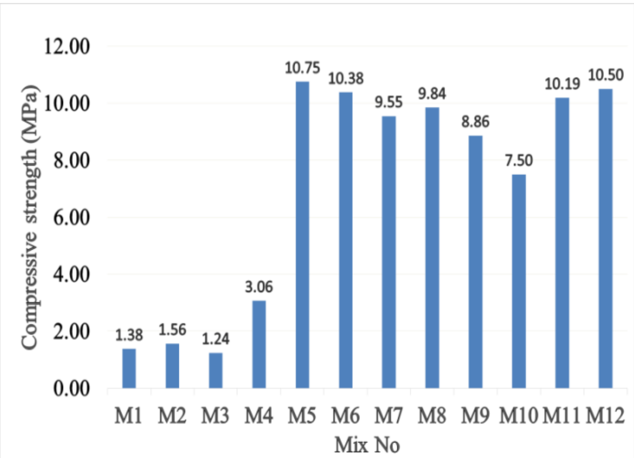
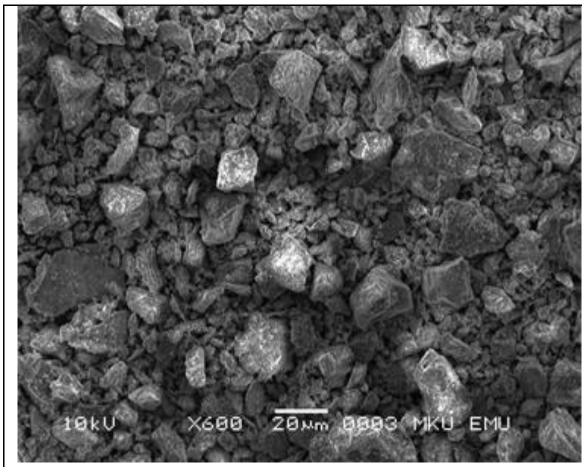
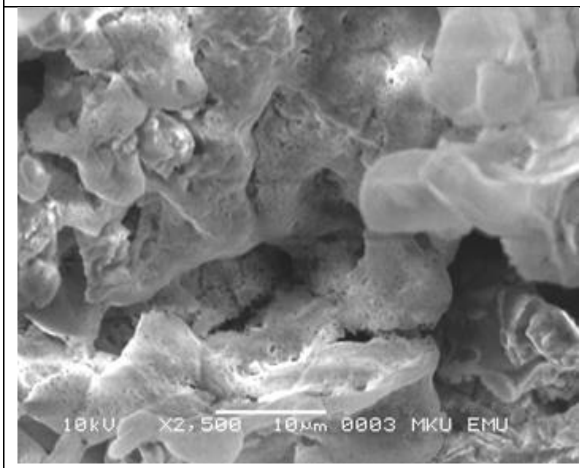


Figure 1. Compressive Strength Values of Alkali Activated EAFS Mortars

Figure 2 shows SEM images of grinded EAFS and activated EAFS (M1). As can be clearly understood, the activation reaction was successfully carried out, and a condensed structure was observed. Figure 3 shows the XRD analysis results of milled EAFS and activated EAFS (M1). When the chemical analysis results are taken into consideration, it is seen that $CaCO_3$ is formed as a significant hydration product. Therefore it is considered that the subsequent formation of Ca^{2+} ions from the EAFS and OH ions from the alkaline activator to form $Ca(OH)_2$ as the reaction result in the formation of $CaCO_3$, which reacts with free CO_2 in the atmosphere.



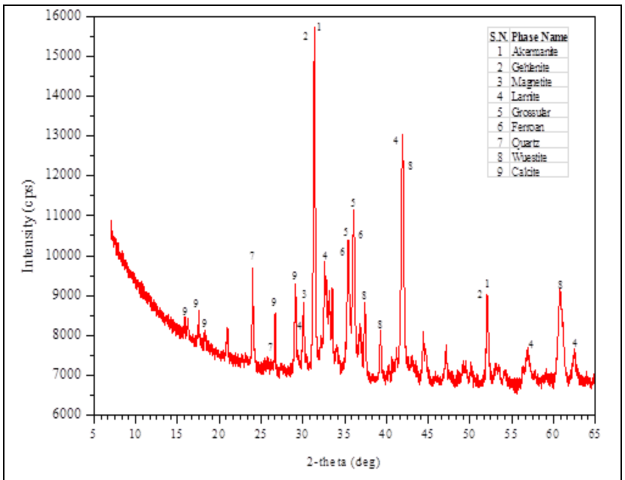
a) SEM image of EAFS



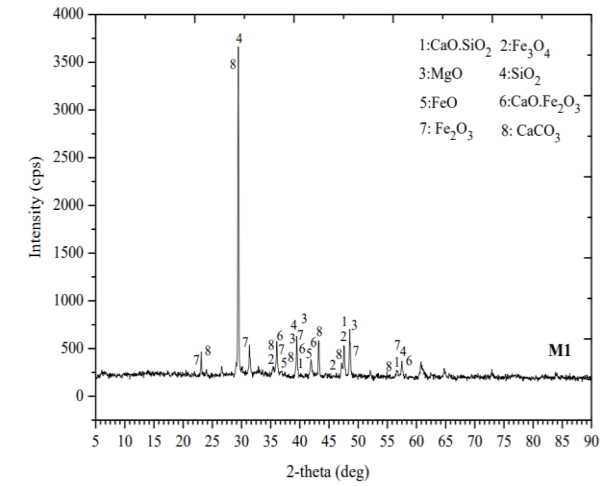
b) SEM image of Alkali activated EAFS mortar

Figure 2. SEM images of EAFS nad alkali activated EAFS mortar

If the concentration of $Na(OH)_2$ in the mixture is low, the strength values are not high enough. Increasing the $Na(OH)_2$ concentration up to a certain level causes an increase in the strength. In Chi's research, the mechanical properties and durability performance of alkali activated slag concrete improved with an increase in the Na_2O dosage and cured at relative humidity of 80% and curing temperature of 60 °C. The specimens has the superior performance with respect to air and saturated limewater curing. Excessive amount of OH^- ion in the mixture causes excessive production of the $Ca(OH)_2$ compound, which surrounds the EAFS and reduces the amount of Ca^{2+} soluble in the sludge. This means that the C-A-S-H gel formed after the reaction with Si^{4+} and Al^{3+} ions is less than necessary. At the end of, there is an internal structure that does not provide the necessary conditions in terms of strength [7,8].



a) XRD analysis of EAFS



b) XRD analysis of alkali activated EAFS mortar

Figure 3. XRD analysis of EAFS and alkali activated EAFS mortar

3. Conclusion

In the present work, EAFS was activated with sodium hydroxide and sodium silicate solutions and mortar samples were produced. Constant silicate modules as 1, and curing temperature (40°C), three different sodium concentrations (4%, 6% and 8%) for this silicate module and curing temperature were used to determine the effect of different parameters on the behavior of the alkali activated mortar samples in two different relative humidity environments (45% and 98%). The samples were cured two different curing times (6 and 12 hours) for each relative humidity value. The samples were leaved in an open atmosphere at room temperature for 28 days in laboratory conditions. The results were observed as follows;

1) The mortar sample, labeled M5, achieved the best strength behavior due to the optimum sodium concentration. The highest compressive strength is obtained with silicate modulus, sodium concentration, relative humidity, curing temperature and duration of cure are respectively; 1, 6%, 45%, 40°C and 6 hours.

2) When microstructure analysis (SEM) is examined, a gel is produced as a product of the chemical reactions between EAFS and alkali activators, and it appears that it forms a denser microstructure which is the main factor that influences the development of strength. In addition, (XRD) showed that amorphous phase structure was observed in alkali activated mortar samples.

3) It is important to mention that the alkali activation of EAFS was carried out for the first time in this study. Thus, a new area of use has been introduced in the literature to use EAFS, which is in a waste material condition, as binding material.

Nomenclature

SM	: Silicate modulus
CT	: Curing temperature
CTm	: Curing time
AM	: Atmospheric moisture
SC	: Sodium concentration
EAFS	: Electrical arc furnace slag

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