



The effect of high temperature on the design of blast furnace slag and coarse fly ash-based geopolymer mortar



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ABSTRACT

In this study, geopolymer mortars were prepared by replacing blast furnace slag (BFS) based mixtures with coarse fly ash (FA) in different proportions. The aim of this study was to build a geopolymer mortar design for high temperatures using constant NaOH molarity (M) and constant curing temperature. In addition to 14 M NaOH solution and BFS as the binder material at a 60 °C curing temperature, double binder mixture ratios were prepared adding 25%, 50% and 75% FA. Geopolymer mortars with a liquid binder (L/B) ratio of 1 were subjected to oven curing for 5, 24, 48, 168 h. After physical and mechanical tests, the samples with the highest compressive strength were determined and six different mixtures with an L/B ratio in the range from 1 to 0.5 were prepared in order to increase the compressive strength of the samples in question. The physical and mechanical tests were repeated for the new samples. After the tests, the mortar sample with the highest compressive strength and its high temperature behavior was determined. For this purpose, the mortar sample with the highest compressive strength was subjected to temperatures of 200, 400, 600, 800 and 1000 °C, and changes in the physical and mechanical properties was analyzed.

As a result of the experiments, the highest flexural strength value (3.6 MPa) was obtained from the mortar samples with a 25% BFS content subjected to curing for 5 h. The highest compressive strength values (27.3 MPa) were obtained from the mortar samples with a 100% BFS content subjected to curing for 48 h. In terms of compressive strength, the optimization of the L/B ratio resulted in a 28% increase (0.7) and this way, 35.1 MPa was achieved. Following the high temperature tests, 400 °C and 600 °C were determined as critical temperatures for changes in mechanical properties and changes in physical properties, respectively. However, the geopolymer mortars lost around 58% of strength at 1000 °C which is the final temperature.

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1. Introduction

Demand for concrete as a building material is increasing day by day. However, the production of cement, which is the raw material of concrete, causes environmental pollution and the amount of limestone, which is also a raw material, decreases. Approximately one ton of CO₂ is released during the production of one ton of Ordinary Portland Cement [1]. The International Energy Agency (IEA) and the World Business Council for Sustainable Development (WBCSD) point out that the current trend in the provision and the use of energy is not sustainable, economic and green for societies and therefore, they have set a course for the replacement of the

current energy system with low-carbon energy technologies in order to reduce CO₂ emissions by half in the cement industry by 2050 [2]. At this point, Geopolymers can be the ideal products as new engineering materials which have the potential to be an important component in the environmentally sustainable construction and building sector [3–5].

Another negative aspect of cementations composites is their lack of sufficient resistance to many external influences [6]. However, geopolymers show high performance against sodium sulfate and magnesium sulfate solutions [7], and high resistance to acid attacks [8], high temperature [9,10] and corrosion [11] as well as high compressive strength [12,13].

Geopolymerization, also referred to as inorganic polymer [14,15] or zeolitic precursor [16] is composed of semi-crystalline polymeric amorphous, Si–O–Al and Si–O–Si bonds of solid aluminosilicate and alkali metal silicate solutions in a high alkaline environment

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and at a low temperature ($<100\text{ }^{\circ}\text{C}$) [17]. Reaction mechanisms of geopolymers are not fully understood. Most proposed mechanisms are dissolution, transportation or orientation and setting or polycondensation/polymerization as well as precipitation [18].

The three most common classes of materials used in the geopolymerization process are calcined clays, coal slag and fly ash [19]. In other words, kaolin clay and volcanic ash, the geological origins of which are in the form of rock, constitute the primary raw material source of geopolymers, while industrial waste or FA and BFS as sub-products constitute the secondary raw material source of geopolymers [20]. Mainly containing metakaolin, calcined clays are not very favorable due to their plate-shaped particles which cause high demand in water and high porosity in concrete production, despite their relatively intensive use in the geopolymer synthesis. Other types of the raw material (slag and fly ash), are more useful for the two-part geopolymer synthesis [19].

FA is an industrial waste with pozzolanic properties obtained from thermal power plants. FA contains a high amount of amorphous silica and alumina content which is dissolved when a soluble alkali solution is used [20]. Activated alkaline solution is very important for the formation of aluminosilicate material with the dissolution of Si and Al atoms. The most commonly used alkaline activators are NaOH and KOH [21]. NaOH has a significant effect on the structure and the compressive strength of geopolymers during geopolymerization. NaOH concentration ensures better coupling of the solid particles in the aqueous phase, as well as in the final structure of the geopolymeric system [22].

During geopolymerization, alumina-silicate powder is first mixed with alkali solution to form a paste and then this paste rapidly turns into solid geopolymer [23]. One factor limiting the use of FA for geopolymerization is its low reactivity. The low reactivity of FA results in low binding and early strength development. Many times, final hardening occurs before the dissolution of FA is achieved [24]. FA based geopolymers gain higher compressive strength when they are subjected to curing between 40 and $85\text{ }^{\circ}\text{C}$ [25]. Activator module and Na_2O dosage have a significant effect on the strength in the activation of FA [26].

The performance of FA in concrete, cement and geopolymer depends on the physical, mineralogical and chemical properties of the FA. The content of the coal used largely determines the mineralogical and chemical composition of the FA. Physical properties, on the other hand, is determined by the differences between the coal sources and the differences in the methods for collecting FA. Combustion conditions of a power plant can also affect the properties of the FA [27,28]. Factors such as combustion temperature and type of coal give rise to differences in size fractions of FA [29]. Therefore, FA with different characteristics can be found in different thermal power plants and it is possible to find FA with different characteristics even in the same thermal power plant over the course of time.

In general, fine FA is considered to exhibit better properties. Fine FA particles have smoother and more spherical surfaces than coarse FA particles when complete combustion is applied. Reduction in water demand due to the high reactivity of fine FA contributes to a higher mortar strength than that achieved using coarse FA [30]. The reactivity of FA depends on the size distribution of particles, the amount of glassy phase and glass phase structure [24]. The reactivity of fine FA depends on the particle size and reactivity rapidly increases with a reduction in the particle size. Change in the reactivity owing to mechanical activation together with the effect of the particle size (increased surface area) change the geopolymerization reaction. Improvements in physical properties are associated with the microstructure improved by geopolymerization [31]. The particle size distribution is a key factor in the geopolymer synthesis process [32,33]. Whatever the nature and the

concentration of the alkali activator, reactivity increases as FA becomes thinner [34]. Classification (removing the fine fraction), grinding or the mechanical activation of FA will significantly increase the reactivity and result in the improvement of geopolymer properties [35,36].

BFS was added to FA-based geopolymer in order to eliminate the disadvantages which appear during the geopolymerization of FA. BFS is an amorphous by-product of hydraulic reactivity which appears during production in the steel industry [37]. When produced using calcium-rich BFS, the compressive strength and setting time of FA-based geopolymers can be improved [38]. FA and BFS mixtures lead to the formation of two different gels (N-A-S-H and C-A-S-H) [39].

There have been many studies conducted on this subject in the literature. FA and BFS were used as binders in different proportions and alkali activation was carried out with sodium silicate solution. The solution was used in different modules and concentrations in the samples cured at $95\text{ }^{\circ}\text{C}$ for 24 h. Considering the setting time, drying shrinkage, mechanical and physical properties, it was determined that the most optimum mixture, activator module and activator concentration were 25% FA-75% BFS, 1.0 and 10%, respectively. The highest compressive strength was obtained from the series of 100% BFS [40]. A study in which granulated blast furnace slag (GBFS) was used in the FA-based geopolymer indicated that hydration heat increased, however, GBFS had a positive effect on the compressive strength and the setting time [38]. A study that investigated the effect of geopolymer concretes on adhesional strength revealed that geopolymer concretes exhibited the same adhesion strength as Portland cement concretes in the early periods, while the former had 10% more adhesion strength than the latter in the later periods [41]. In the geopolymer mortars prepared by mixing FA and BFS in different proportions, it was observed that the compressive strength values of the high pH series increase and that an increase in the depth of carbonation led to a decrease in the compressive strength values. The best compressive strength values (52 MPa) were observed in the series with the 20% FA-80% BFS ratio [42] after supercritical carbonation. In another study in which FA and GBFS were used, the final setting time of the pastes prepared using alkaline activator with different molarity decreased, while the compressive strength increased. It was determined that sodium hydroxide molarity had no effect on the results. An increase in the amount of FA leads to a decrease in the setting time, and an increase in the compressive strength [43].

A mathematical model which is quite consistent with the experimental results was introduced in another study in which the high-temperature performances of the geopolymers were modeled. In addition, the results section of this study suggests that compressive strength, tensile strength, stress-strain relationship, modulus of elasticity, thermal strain and creep stress of geopolymers at different temperatures should be tested [44]. 400 , 600 and $800\text{ }^{\circ}\text{C}$ temperatures were used in a study which investigated the effect of high temperatures on FA-based geopolymer paste, mortar and light-weight aggregate geopolymer concretes. The results revealed that the density and water absorption values of the geopolymer concrete were lower than those of the paste and the mortar. Temperature-dependent mechanical changes were observed the least in the concrete. The changes in the mortars at $800\text{ }^{\circ}\text{C}$ were about 52% [45]. A study which investigated the fire resistance of steel plating made of FA-based geopolymer indicated that the bond strength of the geopolymer was greater than 3.5 MPa and that Si:Al 3.5 mol was the most ideal ratio in terms of fire resistance [46]. Cracks, exfoliation, mass loss and reduction in strength of FA-based geopolymer samples exposed to ISO 834 standard fire up to $1000\text{ }^{\circ}\text{C}$ were examined by comparing them to those of Portland cement concretes. It was observed that the heat

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