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Developing geopolymer concrete by using cold-bonded fly ash aggregate, nano-silica, and steel fiber

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HIGHLIGHTS

- GPCs have been synthesized using cold-bonded fly ash aggregate (CFA).
- No elevated temperatures have been used in this study.
- The dosage of superplasticizer to achieve the target slump value is reduced by the use of CFA.
- The pore structure of GPC incorporated permeable aggregate is significantly improved by the utilization of nano-silica (NS).
- Better performance of GPC is achieved by the use of 1% steel fiber and 2% NS.

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ABSTRACT

This experimental study presents the effect of nano-silica and steel fiber on the transport properties and compressive strength of alkali-activated slag/fly ash concrete incorporated cold-bonded fly ash aggregate. In order to reduce energy consumption and provide environmental impact, the cold-bonded process was used to manufacture cold-bonded fly ash aggregate. Twenty four geopolymer concrete mixtures incorporated cold-bonded fly ash aggregate, nano-silica, and steel fiber were produced with sodium hydroxide concentration of 12 M and cured at ambient temperature. Transport properties of geopolymers were examined through water penetration, water sorptivity, and gas permeability at 28 and 90 days. Results indicate that geopolymer concrete incorporated cold-bonded fly ash aggregate can be produced with compressive strength as high as 28.23 and 36.62 at 28 and 90 days, respectively. However, 2% nano-silica and 1% steel fiber volume fraction were the most significant parameters that caused remarkable improvement of investigated properties. Moreover, the incorporation of waste materials in aggregate and geopolymer concrete production can alleviate environmental problems.

1. Introduction

As in most of the industrialized countries, Turkey generates large amounts of waste materials. The annual production of Fly Ash (FA) and blast furnace slag in Turkey reach about 15 million tons and 600,000 tons, respectively. The disposal process of waste materials has been one of the most challenging matters in our country and worldwide [1]. Employing of solid waste materials in the construction industry are commonly used nowadays as it introduces usable construction materials.

Concrete technology can introduce suggestions for recycling industrial wastes like FA and Ground Granulated Blast Furnace Slag (GGBFS). The scientific investigators reengineered some types of solid wastes in the production of artificial aggregate [2–4]. Several advantages of producing artificial aggregate from waste materials such as a promising an alternative to recycle waste materials, reducing the consumption of non-renewable natural resources, and producing lighter weight aggregate compared to the natural ones [5,6]. Three common different procedures used for manufacturing artificial aggregate; cold bonding, autoclaving, and sintering. Using of these methods form spherical shape aggregates with a relatively smooth surface which are preferred because they more readily flow past each other as the low specific surface area needs less binder and water in the design of concrete [7,8]. In addition, comparing to autoclaving or sintering method, the cold-bonding process method is the lowest energy consumption and has the least detrimental environmental impact [9,10].

Studies conducted recently by several authors with the use of Cold-bonded FA aggregate (CFA) in conventional concrete have revealed the performance of them to be satisfactory comparing to natural aggregate [9–13]. The studies reported the CFA to have

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improved the fresh properties on account of its spherical shape, and smooth texture [11,14]. Also, the studies reported that the incorporation of CFA in conventional concrete led to reduce strength and increase susceptibility to suffer drying shrinkage as compared to natural aggregates [9,11,14]. For example, the replacement of natural aggregate by CFA reduced compressive strength and increased drying shrinkage of ordinary Portland Cement (PC) concrete by about 25% and 50%, respectively [14]. However, water to binder (w/b) ratio, binder content, and Nano-Silica (NS) were used as effective factors by Güneyisi et al. [11] to avoid the negative side effect of CFA on concrete properties.

Considering the production of PC, the environmental impact associated with its activities includes: discharging of a considerable amount of greenhouse gases, e.g. carbon dioxide (CO_2) emissions, depleting of fossil fuels as nearly 40% of the cost of production of PC is energy-related, and exploiting of natural resource [15,16]. Also, the recognition of long-term problems in PC structures has acted as an impetus to develop a novel generation of cement with durability and environmental sustainability [15,17].

The high performance of GeoPolymer Concrete (GPC) in terms of its high durability, high sustainability, and adequate strength can be considered the key motivation for lessening the use of PC in construction projects. In addition, geopolymerization reaction is an environmentally-friendly process and can significantly account for reducing global CO_2 emissions [18–20]. In this reaction, the use of alkali silicate solution to reactivate raw aluminosilicate materials such as FA, GGBFS, red mud, mine waste, etc., at ambient or slightly high temperatures, allows the creation of cementitious gel [21]. Xu and Deventer [22] reported that the most reasonable aluminosilicate source is FA due to its low cost, availability, and greater potential for producing geopolymers. It was found that calcium oxide (CaO) in FA forms calcium silicate hydrate which was believed to have a significant influence on the hardened properties of FA based GPC [23].

Reports in literature recommended using heat or steam cured geopolymer in an aggressive environment because of their low effective porosity [24–28]. However, a lesser strength is obtained when FA GPC is cured at an ambient temperature of 25 °C [27,28]. In this context, some researchers recently sought to improve the quality of geopolymer-based FA cured at ambient temperature. Phoo-ngernkham et al. [29] developed high calcium FA geopolymer incorporated with 1%, 2%, and 3% NS and nano-aluminum. Nath et al. [30] partially replaced FA with GGBFS, PC, and calcium hydroxide. The results of the study revealed that workability was optimal with a binder for the FA geopolymer blended with these additives.

Steel Fiber (SF) reinforced concrete sections are of interest in some construction applications. For this, some studies are used SF for reinforcing geopolymers. Bernal et al. [15] observed that the water absorption and porosity in alkali-activated slag concrete reinforced with SF were reduced by about 20% in comparison to the mixes without fibers. Aydın and Baradan [31] reported the workability and drying shrinkage of alkali-activated slag/silica fume mortars decreased with the inclusion of SF. However, as there are few references concerning the influence of fibers on the transport properties of GGBFS/FA based geopolymer, it is of importance to discover capabilities of geopolymers, when they are reinforced by fibers. Furthermore and to the knowledge of the authors, no investigation had been made up to date to study the performance of CFA in alkali-activated binder concrete cured at ambient or oven temperature. Therefore there is a necessity for further researches to be performed in this regard.

The main motivation of the paper is to produce and evaluate the transport properties of highly sustainable green concrete through the use of CFA to synthesize low calcium FA-blended GGBFS geopolymer, incorporated with SF and NS. FA is used as a sustainable precursor for manufacturing artificial aggregate through the cold-bonded process. It has long been established that concrete durability is significantly influenced by pore structure. Thus, the present investigation focuses on the compressive strength, water permeability, sorptivity, and gas permeability.

2. Experimental details and methodology

2.1. Materials

In this investigation, the mineral oxides used as an aluminosilicate source to produce GPC were low calcium FA, GGBFS, and NS. Class-F FA was utilized with a specific gravity of 2.25 and specific surface area of 379 m^2/kg conforming to ASTM C 618. Locally available high calcium precursor GGBFS was provided by a cement production factory with the specific gravity of 2.88 and specific surface area of 575 m^2/kg. NS has a specific surface area of 170–230 m^2/g. Tests of the particle size distribution and microstructure properties of dry powdered precursors (FA, GGBFS, NS) were conducted with a dry-dispersion laser diffraction (Sympatec RODOS T4.1 Particle Size Analyzer) and image analysis using Scanning Electron Microscopy (SEM). The chemical and physical properties of the raw powder materials are presented in Table 1. Fig. 1 depicts the microstructure images of FA, GGBFS, and NS. Fig. 2 shows the particle size distribution curves of FA and GGBFS.

The alkaline activator used for the geopolymerization process was a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. In this study, potable water was used to dissolve pure NaOH pellets to prepare an aqueous compound with the desired concentration. The chemical composition of water glass as provided by the supplier refers to the presence of 14.7% Na_2O, 29.4% SiO_2, and the rest is water. superplasticizer based on polycarboxylic-ether formulation with a specific gravity of 1.08 ± 0.02 and PH-value of 7 ± 1 was used in all mixes to attain the required slump value for fresh GPC.

In this research, hooked-end SF with a yield strength 1500 N/mm, young modulus E = 200 GPa, density ρ = 7850 kg/m^3, length L = 30 mm, and aspect ratio l/d = 54.55 was utilized. Fig. 3 shows the SF used in the production of GPC.

Two types of coarse aggregate were used to manufacture GPC, viz., natural river and CFA. The maximum size, fineness modulus, and specific gravity of natural coarse aggregate were calculated as 16 mm, 5.7%, and 2.7, respectively. Regarding the production of CFA, This research based on previous studies concentrating on the use of CFA in conventional concrete [32,33]. For this, the same type of FA as used in geopolymer production was utilized in the pelletizing process. CFA was produced in the construction laboratory through the agglomeration of 90% FA and 10% cement by

Table 1
Chemical composition and physical properties of fly ash, slag, and nano-silica.

Item, %	Fly ash	Slag	Nano-silica
CaO	4.24	34.19	–
SiO_2	57.2	40.42	>99.8
Al_2O_3	24.4	10.6	–
Fe_2O_3	7.1	1.28	–
MgO	2.4	7.63	–
SO_3	0.29	0.68	–
K_2O	3.37	–	–
Na_2O	0.38	–	–
Cl	–	0.0128	–
Loss of ignition (1000 °C)	1.58	2.74	<1.5
Specific gravity	2.25	2.88	2.2
Blaine fineness, m^2/kg	379	575	–
Surface-volume ratio, m^2/g	–	–	170–230