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Mechanical and microstructural characterization of fiber reinforced fly ash based geopolymer composites

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HIGHLIGHTS

- Steel, polypropylene and polyvinyl alcohol fibers were used in geopolymer mixtures.
- Strength properties, abrasion resistance and drying shrinkage were measured.
- SEM and CT analyses were carried out to inspect the fiber-matrix bonding.
- Use of fibers improved toughness, abrasion resistance and shrinkage behavior.

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ABSTRACT

In this paper, an experimental investigation was carried out to study some mechanical and microstructural characteristics of fly ash based geopolymer mortars reinforced with three different fiber types. Steel, polypropylene, and polyvinyl alcohol fibers were used and the effect of their addition on the geopolymer composites behavior regarding strength properties, abrasion resistance, and drying shrinkage was studied, furthermore, a microstructural analysis was carried out to understand the geopolymeric matrix composition and its bonding to the fibers. Results showed that the addition of fibers improved the strength characteristics of the geopolymer composites, for instance, the existence of Steel and polyvinyl alcohol fibers increased the flexural strength of the geopolymer composite 31.45% and 39.84% respectively with respect to control sample. Moreover, all fiber reinforced geopolymer composites yielded a drying shrinkage of less than 400 microstrains and an abrasion resistance of less than 1 g. Microstructural analysis of the non-fibrous geopolymer control sample revealed a good degree of geopolymerization and the fibers yielded an acceptable interfacial bonding with the geopolymeric binder.

1. Introduction

The worldwide inevitable increasing use of Portland cement in construction industry leads to major problems concerning greenhouse gas emissions which requires serious precautions to be made especially by researchers, thus, the development of non-cementitious materials has reached a good level of research and application because of the need for eco-friendly alternative binders and due to the existence of so many waste materials and by-products that are disposed to landfill stations [1–4].

Geopolymers, as one of the promising future alternatives, have drawn the attention of many researchers worldwide due to its remarkable strength and durability characteristics [5–7]. Geopolymerization is a feasible technology for waste management and greenhouse gas emissions reduction. In future, geopolymer technology is expected to be a major step towards the sustainable use of the by-product materials sector. The main components to form a geopolymer binder are an active silica-alumina source and the alkaline solutions to start the formation of the polymeric bonds (Si-O-Al-O), then, geopolymer resin is mixed with a filler to produce the geopolymer binder [8].

Since SiO_2 and Al_2O_3 are the main oxides in the geopolymer processing, industrial waste materials such as fly ash, blast furnace slag, copper and zinc slag can be used as an aluminosilicate source in geopolymer synthesis. Fly ash is considered as one of the most pozzolanic by-product materials which can be used in construction section due to its availability worldwide and because it contributes to producing binders with good properties, therefore, it was studied by many geopolymer researchers regarding its mechanical characteristics, durability aspects and microstructural composition [9–19].

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Table 1
Chemical composition of Fly Ash and Ground Granulated Blast Furnace Slag (%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	Free CaO	Cl^-	LOI
FA	54.08	26.08	6.681	2.002	2.676	0.735	0.79	0.11	0.092	1.36
GGBS	40.55	12.83	1.10	35.58	5.87	0.18	0.79	–	0.0143	0.03

Table 2
Properties of investigated fibers.

Fiber Type	Length (mm)	Diameter (mm)	Specific Gravity	Nominal Tensile Strength (MPa)	Aspect ratio
PVA	8	0.04	1.3	1620	200
PP	12	0.0075	0.91	750	1600
STEEL	6	0.17	7.85	2100	35.29

On the other hand, an addition of fibers can improve the strength properties of the resulting product. Various studies were carried out using different types and different amounts of fibers in order to examine their effect on the behavior of the binder by conducting the common mechanical and durability tests.

Alengaram et al. [20] examined the effect of steel fiber on the mechanical properties and impact resistance of lightweight geopolymer concrete. Their results revealed that fibers addition enhanced the splitting tensile and flexural strength by 19%–38% and 13%–44%, respectively with respect to the plain samples, also, all fiber reinforced samples showed higher impact resistance when compared to the plain samples.

Ganesan et al. [21] carried out an investigation to study the durability properties of plain and fiber reinforced geopolymer concrete compared to Portland cement concrete. They concluded that in general plain and fiber reinforced geopolymer concrete yielded better results when compared to the conventional concrete, furthermore, addition of fibers led to a better improvement concerning durability properties.

Borges et al. [22] studied the flexural behavior of fly ash based geopolymer composites reinforced with steel and polypropylene fibers. Results showed that heat curing improves the strength properties for the macro fiber reinforced geopolymer composite, also, polypropylene fibers did not exhibit a significant improvement regarding compressive strength but achieved a little development in terms of indirect tensile and flexural strength.

Moreover, a considerable amount of research has been made with regard to polyvinyl alcohol fibers, by way of illustration, Xu et al. [23] performed an investigation about the mix design and mechanical properties of polyvinyl alcohol fiber reinforced fly ash based geopolymer composites by using two different lengths of those fibers. The results revealed that compressive strength, flexural and tensile strength increase with a larger trend when compared to the strength properties of control samples. Also, they concluded that the resulting properties of geopolymers with longer fibers exhibited better toughness and strength characteristics.

In the same field of research, Tanyildizi and Yonar [24] studied the effect of high temperature on the mechanical properties of polyvinyl alcohol fibers fiber reinforced geopolymer concrete. The research findings showed that the increasing fiber ratio can improve the compressive and the flexural strengths of the concrete. In addition to that, the samples exposed to high temperatures yielded fewer strength reductions with respect to the control sample.

The aim of this paper is to examine some mechanical and microstructural characteristics of fly ash based geopolymer composites reinforced with three different fibers, therefore, a comparative investigation will be made using steel, polypropylene, and polyvinyl alcohol fibers to study the effect of their addition with different ratios on the compressive and flexural strength, development of ultrasonic pulse velocity, abrasion resistance and drying shrinkage of fly ash based geopolymer mortars. Moreover, flexural toughness factors will be calculated to investigate the fibers capability of absorbing energy due to applied loads. Concerning microstructural analysis, scanning electron microscopy (SEM) and micro-computed tomography (CT) will be conducted to understand the interaction between the fibers and the geopolymeric matrix and to scrutinize the microstructural composition of the manufactured geopolymer mortars.

2. Materials characterization

Fly ash (class F) which is correspondent to specific standard ASTM C618 [27] was provided from Cates electrical production Inc., Catalagzi/Zonguldak, a thermal power plant located in a northern city in Turkey whereas Ground Granulated Blast Furnace Slag (GGBS) was obtained from Bolu cement Company. The chemical composition of fly ash and GGBS are detailed in Table 1. The chemical solution was a mix of sodium silicate and sodium hydroxide (12 M). Sodium silicate contained 8.2% Na_2O, 27% SiO_2 and a modulus of 3.29 while the purity of the used sodium hydroxide was higher than 99%. Both chemicals were provided by Merck Group Chemicals Company. Standard sand which is correspondent to BS EN 196-1 [32] and Rilem Cembureau standard was used in this study. Details of polypropylene, polyvinyl alcohol, and straight steel fibers are presented in Table 2.

3. Experimental procedure

Mortars were prepared according to the mixing procedure shown in Fig. 1 and fibers were added as a volume fraction ratio of 0.4%, 0.8% and 1.2% for every type of fibers. Mixtures notation was ST for steel, PP for polypropylene and PVA for polyvinyl alcohol fibers followed then by the fibers ratio number. Fiber volume fraction ratios were selected depending on the laboratory trial experiments and the in accordance with the previous literature [21–25] in order to inspect the effect of similar ratios of different fibers on the behavior of geopolymer composites under the conducted tests. A total of ten mixes were prepared and the mix proportions are detailed in Table 3.

After mixing process, 50 mm side cubes, 40 × 40 × 160 prisms, Φ10 mm × 7.5 mm cylinders and 25 × 25 × 285 mm prisms were cast for performing compressive strength, flexural strength, abrasion resistance and drying shrinkage tests. All the specimens were heat cured with 80 °C for 24 h. After heat curing, the specimens were kept in laboratory conditions and scheduled for the intended tests. Compressive strength test was carried out after 7 and 28 days using the 50 mm side cubes, the test procedure was done according to ASTM C 109 [28]. Flexural strength test was also conducted after 7