Compressive Strength Development of Slag-Based Geopolymer Paste Reinforced with Fibers Cured at Ambient Condition

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Abstract

Geopolymer mixtures (such as concrete, mortar, and paste) were used as sustainable alternatives to Portland cement, and enhancement the mechanical properties by addition fibers, due to their great potential in reducing environmental pollution and reducing consumption of raw materials. In this paper, verified the effect of different fibers added to slag based geopolymer paste, on compressive strength development. Ten mixes were preparing and curing at ambient condition. The variables included; type of fibers added (i.e. micro steel fiber, carbon fiber, or polypropylene fiber), and volumetric ratio of fibers included, (1%, 2%, or 3%) of micro steel fiber, and (0.2%, 0.4%, or 0.6%) of carbon fiber and polypropylene fiber. The alkaline solution was combination of sodium silicate (Na$_2$SiO$_3$), and sodium hydroxide (NaOH) with concentrically 10 molar. The results were found that the addition of fibers led to improving significant of the compressive strength. Generally, the development of compression was estimate by about (30% and 23%) at ages (7 and 28) days, respectively. Finally, the slag based geopolymer paste is more suitable to use in construction sites as alternative sustainable of Portland cement.

Keywords: slag, geopolymer paste, fibers, compressive strength, and ambient curing.

1. Introduction

In recent years, the increasing demand for infrastructure has led to an increase in the consumption of raw materials, mainly Portland cement. Thus, cement production in large quantities causes high energy consumption. Cement is the second highest consumption of water in the world. One ton of cement produces approximately one ton of carbon dioxide, which is released into the atmosphere [1]. Therefore, the Portland cement manufacturing process contributes 6-8% of greenhouse gases [2]. Thus, the problem of global warming has become a concern of researchers. In order to reduce the proportion of greenhouse gases in the atmosphere, the researchers resorted to using alternative materials of Portland cement, and at the same time the recycling of solid waste or by-product materials produced from iron manufacturing plants or power plants. Such as the geopolymer materials that are rich in silicate and aluminate, e.g. fly ash, ground granulated blast furnace slag, rice husk ash, silica fume, and metakoline [3]. Where, contributes greatly to the sustainable green buildings, which are considered one of the most important promises to reduce environmental pollution and the depletion of raw materials. Geopolymer materials are inert materials until they are activated by alkaline solutions through a process called polymerization, which results in substances material with good mechanical properties that depend mainly on the chemical composition (silicate and aluminate ratio) [4, 5]. Previous studies have reported that the polymerization process for the production of geopolymer concrete based on fly ash requires a high temperature to cured, in order to accelerate the development of resistance in early ages [6]. Noushini et al. [7] also reported that the optimum heat curing for fly ash based geopolymer is 18 hours at 75°C. Although geopolymer concrete based on fly ash provided high compressive strength, but it caused decreasing in creep and shrinkage [8, 9]. Consequently, the heat curing system limits the utilization of geopolymer in construction sites and considered an inefficient system. To overcome these defects, the addition of steel fibers has been reported with a different aspect ratio and volume fraction, to the composite geopolymer concrete, that cured at ambient conditions, to improve its mechanical properties. The results were it indicates the
development of compression and tensile strength as the percentage of fiber addition and aspect ratio increased [10]. Also, Yan and Sagoe-Crenstsil [11] used calcined waste residues (wastepaper-sludge) in the production of geopolymer slurry based on fly ash, to accelerate the polymerization process in ambient conditions (cured under ambient conditions). The results indicated a significant increase in compressive strength but caused a decrease in flowability and setting time. Likewise, many previous studies have shown that the formation of calcium-silicate hydrate (C-S-H) gel and sodium-aluminum-silicate hydrate (N-A-S-H) gel as compounds resulting from the hydration and polymerization processes respectively, for geopolymer mixtures consisting of fly ash and slag, gave superior properties in terms of compressive strength, acid and sulfate attack, corrosion and fire resistance [12, 13,14, 15, 16]. While El-Hassan, and Ismail, N. [17] reported a significant increase in compressive strength with increase the ratio of slag in the slurry of geopolymer formed from blended fly ash and slag, but it reduces the flowability and accelerates the setting time, then, it was improved the mechanical performance of geopolymer mixtures by adding a superplasticizers (Sp.), and found that the processor system By heat, it is less important for geopolymer mixtures that the proportion of slag is more than 50%, therefore, geopolymer mixtures with high content of slag that about 100% are more suitable for cured with ambient condition and use in construction sites. To this date, there has been no published research on the compressive strength development of slag-based geopolymer paste reinforced with different types of fibers, cured at ambient condition. Accordingly, this study aims to verify the effect of added fibers (i.e. steel fiber, carbon fiber, and polypropylene fiber), and volume fraction ratio of these fibers, where was added by (1%, 2%, or 3%) of micro steel fiber (SF), and (0.2%, 0.4, or 0.6%) of carbon fiber (CF) and polypropylene fiber (PPF) respectively, on the development compressive strength of slag-based geopolymer paste, which was examined through the compression test. This work presents the first study using slag alone in the production of geopolymer paste to indicate the possibility of using geopolymer mixtures in construction sites as sustainable and environmentally friendly alternatives for Portland cement.

2. The Experimental Scheme

2.1 The materials

Totally sixty samples of geopolymer paste with standard mold (50×50×50) mm were prepared. In this study the geopolymer paste is based on slag as a binder, which supplied from iron production plants by-product in Turkey. Table 1 shows the chemical composition of slag through X-Ray Fluorescence (XRF).

| Chemical analyze | SiO$_2$ | Al$_2$O$_3$ | CaO | Fe$_2$O$_3$ | MgO | SO$_3$ | K$_2$O | Na$_2$O | LOI | Specific gravity |
|-----------------|--------|-------------|-----|------------|-----|--------|-------|---------|-----|-----------------|
| GGBFS (wt. %)   | 9.81   | 1.31        | 25.35 | 0.90       | 0.36 | 0.42   | 0.69  | < 0.39  | 1.64 | 2.79            |

ggbfs wt. %: compound weight ratio of slag.

Whereas, sodium hydroxide (NaOH) solution with a concentration of 10 molarity and a purity of 97-98%, that depended on previous studies, and sodium silicate (Na$_2$SiO$_3$) solution that have chemical composition provided from local source (Na$_2$O:13.1-13.4%, SiO$_2$ 28-33%, specific gravity 1.53-1.548 and viscosity 625-1175), were used in the production of alkaline solution. Figure 1 shows the material that utilized to prepare the geopolymer paste. Superplasticizer (Sp.) used in this study to improve the flowability and setting time of geopolymer paste mixes, type of Sika ViscoCrete 5930.
Fibers have been used more recently in concrete mixtures (i.e. concrete, mortar, and binder), due to their ability to improve the compressive strength of mixtures, and have superior properties such as highly tensile strength, depressed thermic expansion, and lower risk to corrosion and good chemical resistance. Therefore, three different types of fibers were used in geopolymer paste mixes, included; micro steel fiber (SF), carbon fiber (CF), and polypropylene fiber (PPF). Which have properties (length, aspect ratio, tensile strength, young's modulus, and density) represented by (6mm, approximately 30, 2500MPa, 200GPa, and 7850kg/m3), (8mm, 7±2 micron, 1140, 3500 MPa, 230 GPa, and 1.75 g/cm3), and (12mm, 20±2 micron, about 600, 300-400 MPa, and 0.91 g/cm3) respectively. The types of fibers used in this study are shown in Figure 2.

2.2 Mix preparation and design of samples

Ten-mixes of geopolymer pastes were prepared and cured at ambient condition, divided into four groups, the first includes mixes of geopolymer paste reference (GP-R), the second, third, and fourth groups included geopolymer paste mixes that micro steel fiber (SF), carbon fiber (CF), and polypropylene fiber (PPF) were added respectively.

The volumetric ratio of fibers added included; (1%, 2%, and 3%) of micro steel fiber, and (0.2%, 0.4%, and 0.6%) of carbon fiber and polypropylene fiber. Where prepared every three samples with identical configuration that casting into 50 mm standard cubes ASTM C109 [18], and tested at 7 and 28 days.
For the purpose of preparing the alkaline solution, was dissolved the flakes with pure water at a concentration of 10 molar, to prepare the sodium hydroxide (NaOH) solution, then mixed with sodium silicate (Na$_2$SiO$_3$) solution in a (SH/SS) ratio of 1:2, respectively, prior 24 hours from casting [19, 20, 21]. Fluid to binder ratio 0.55 was utilized. The details of geopolymer paste mixes were illustrated in Table 2.

The mixes process included that, placed the dry material (slag) in the electric mixer followed by the addition of the alkali solution and superplasticizer then mixed for 5-minutes. After that, the fibers are gradually added to the mixes and mixed again for 4-minutes to ensure homogeneity of the mixture [10]. Subsequently, the mixture is placed in two batches in the mold, and then the vibrating table is used for 20-second for every batch to get rid of air bubbles. Then demolded samples after 24 hours, and stored at laboratory until the testing day.

| Mixes       | Binder  | Fibers  | Solution  |
|-------------|---------|---------|-----------|
|             | GGBFS%  | SF%     | CF%       | PPF%     | F/b | Sp.% |
| GP-R        | 100     | -       | -         | -        | 0.55 | 0.0  |
| *GP-SF1%    | 100     | 1       | -         | -        | 0.55 | 1.7  |
| GP-SF2%     | 100     | 2       | -         | -        | 0.55 | 2.6  |
| GP-SF3%     | 100     | 3       | -         | -        | 0.55 | 3.5  |
| GP-CF0.2%   | 100     | -       | 0.2       | -        | 0.55 | 0.0  |
| GP-CF0.4%   | 100     | -       | 0.4       | -        | 0.55 | 1.7  |
| GP-CF0.6%   | 100     | -       | 0.6       | -        | 0.55 | 2.6  |
| GP-PPF0.2%  | 100     | -       | -         | 0.2      | 0.55 | 0.0  |
| GP-PPF0.4%  | 100     | -       | -         | 0.4      | 0.55 | 1.7  |
| GP-PPF0.6%  | 100     | -       | -         | 0.6      | 0.55 | 2.6  |

Note: *GP-SF1% represents the geopolymer paste mix having volume fraction of steel fiber 1%, GGBFS means ground granulated blast furnace slag, (SF, CF, PPF) represents to micro steel fiber, carbon fiber, and polypropylene fiber respectively, F/b means that fluid to binder ratio, Sp.% means superplasticizer ratio of binder.

3. Results and discussion

Development of compressive strength

This study focuses on verification the strength development of geopolymer paste mixes through compression test since the compressive strength considered benchmark of all other mechanical properties. Where, three cubes were examined for each mix at age of (7 and 28) days. Figure 3 shows the compressive strength of geopolymer paste mixes.
a) Compressive strength chart of GP-R and geopolymer paste mixes with addition micro steel fiber.

b) Compressive strength curves of GP-R and geopolymer paste mixes with addition micro steel fiber.

c) Compressive strength chart of GP-R and geopolymer paste mixes with addition carbon fiber.

d) Compressive strength curves of GP-R and geopolymer paste mixes with addition carbon fiber.
Compressive strength chart of GP-R and geopolymer paste mixes with addition polypropylene fiber.

Compressive strength curves of GP-R and geopolymer paste mixes with addition polypropylene fiber.

Figure 3: Compressive strength of geopolymer paste mixes.

From Figure 3 illustrated that, the high strength of geopolymer paste reference (GP-R) is return to the calcium-silicate hydrate (C-S-H) gel and sodium-aluminum-silicate hydrate (N-A-S-H) gel as compounds that resulting from the hydration and polymerization processes. Because the slag was used as a binder, that have been high content of calcium oxides, which consider the compound responsible of strength.

The addition of fibers led to improving the compressive strength of geopolymer paste reference (GP-R). Generally, that development estimated by about (30% and 23%) at ages (7 and 28) days, respectively. The micro steel fiber, carbon fiber, and polypropylene fiber caused increasing of the compressive strength at age 7 days about (21, 30, or 25), (25, 20, or 12), and (13, 22, or 18) respectively. While, caused increasing of the compressive strength at age 28 days about (10, 23, or 13), (18, 12, or 7), and (6, 14, or 10) respectively. This is because of the fibers act to bridge cracks, and distribute the stresses applied regularly in the samples during a compression test. Also, observed that the compressive strength development ratio at 7 days has been a higher trend than the 28 days, due to formation sufficient amount of gels that caused higher microstructure denser at early age.

The results indicate that, the optimal added volume fractions of micro steel fiber is 2%, while 0.2% of carbon fiber, and 0.4% of polypropylene fiber where gave the significant increase of compressive strength compared with the geopolymer paste reference (GP-R).
4. Conclusions

In this study was verified that, the effect of three type varying fibers added to slag based geopolymer paste mixes, on compressive strength development. The variables included type of fiber added and volume fractions. The geopolymer paste samples were cured at ambient condition and examined at (7 and 28) days. The results can be summarized in the following points;

- Slag based geopolymer paste as a binder, develops a high compressive strength of about 116.5 MPa.
- The addition of fibers improved the compressive strength. The highest development of compression resulting from the addition of micro steel fibers is estimated at 30% and 23% at the age of (7 and 28) days, respectively, with the optimum volumetric ratio being 2%.
- The addition of carbon fiber resulted to development of compressive strength, which that the highest development is estimated at (25% and 18%) at the age of (7 and 28) days, respectively, with the optimum volumetric ratio being 0.2%.
- Polypropylene fiber addition resulted to development of compressive strength, with the highest developed estimated at (22% and 14%) at the age of (7 and 28) days, respectively, with the optimum volumetric ratio being 0.4%.
- The compressive strength development ratio at 7 days has been a higher trend than the 28 days.
- Finally, the slag based geopolymer paste is more suitable to use in construction sites as alternative sustainable of Portland cement, since to have superior properties represented on compressive strength and ambient curing system.

Further studies is needed to evaluate the other mechanical properties development of slag based geopolymer paste such as, flowability, setting time, flexural and tensile strength, when fibers added.

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