International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 44, No. 6, December, 2020, pp. 433-439
Journal homepage: http://iieta.org/journals/acsm

Characteristics of Blended Geopolymer Concrete Using Ultrafine Ground Granulated Blast Furnace Slag and Copper Slag

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https://doi.org/10.18280/acsm.440610

Received: 6 July 2020
Accepted: 24 November 2020

Keywords:
geopolymer concrete, copper slag, fly ash, ultrafine ground granulated blast furnace slag

ABSTRACT

This paper presents the properties of blended geopolymer concrete manufactured using fly ash and ultrafine Ground Granulated Blast Furnace Slag (UFGGBFS), along with the copper slag (CPS) as replacement of fine aggregate (crushed stone sand). Various parameters considered in this study include different sodium hydroxide concentrations (10M, 12M and 14M); 0.35 as alkaline liquid to binder ratio; 2.5 as sodium silicate to sodium hydroxide ratio and cured in ambient curing condition. Further, geopolymer concrete was manufactured using fly ash as the prime source material which is replaced with UFGGBFS (0%, 5%, 10% and 15%). Copper slag has been used as replacement of fine aggregate in this study. Properties of the fresh manufactured geopolymer concrete were studied by slump test. Compressive strength of the manufactured geopolymer concrete was tested and recorded after curing for 3, 7 and 28 days. Microstructure Characterization of Geopolymer concrete specimens was done by Scanning Electron Microscope (SEM) analysis. Experimental results revealed that the addition of UFGGBFS resulted in an increased strength performance of geopolymer concrete. Also, this study demonstrated that the strength of geopolymer concrete increased with an increase in sodium hydroxide concentration. SEM results revealed that the addition of UFGGBFS resulted in a dense structure.

1. INTRODUCTION

Concrete is the second largest used material in the world, next to water [1]. Each material used to make concrete increases the concern for durability [2]. Portland Cement is the main ingredient to make concrete. The manufacture of OPC releases approximately 5% to 7% of the total greenhouse gases (mainly CO_2) into the atmosphere [3]. In addition, the demand for concrete is increasing every day. With regard to sustainability and increasing demand, the search for an alternative binding material is necessary. One such alternate to conventional concrete is geopolymer concrete which is manufactured by the alkali activation of aluminosilicate materials. Geopolymer is obtained from the polymerization of aluminosilicate rich source materials/by-product materials by an activator solution (alkaline). The most commonly used alkaline activator solution is a blend of sodium silicate solution (Na_2SiO_3) and sodium hydroxide solution (NaOH) or potassium silicate solution (K_2SiO_3) and potassium hydroxide solution (KOH). An extensive variety of industrial by-products like fly ash [4, 5]; ground granulated blast furnace slag [6]; rice husk ash [7, 8], red mud [8], metakaolin [9], etc. can be used as raw materials that have reactive silica and alumina.

Jawahar et al. [10] stated that geopolymer concrete made with fly ash as the prime source material showed poor results when cured in ambient temperature. Studies by various researchers [11, 12] stated that the addition of GGBFS enabled ambient curing of geopolymer concrete along with strength and stability. The conventional use of natural river sand as a fine aggregate to manufacture concrete is very high and constant increase in its demand due to infrastructure developments results in decreased availability of natural river sand in the near future. To overcome this problem, an alternative fine aggregate is essential. Researchers throughout the world have studied the use of slag [13], quarry dust [14], granite fines [15-18], copper slag [19, 20], etc. as replacement of conventionally used natural sand as fine aggregate for the manufacture of concrete. Studies by Mahendran and Arunachalam [21] on GPC manufactured using copper slag as fine aggregate showed better results in terms of compressive strength. Studies by Neethu Susan [22] revealed that limited replacement of copper slag in GPC affects the mechanical strength as well as durability properties. Further, they stated that the addition of up to 40% copper slag as partial replacement of natural sand to GPC showed better results as compared to that of GPC manufactured only with natural sand as fine aggregate.

At present, several studies have been carried out on the performance of copper slag as an alternative to natural sand as fine aggregate in the manufacture of conventionally used Portland cement-based concrete, but there are limited studies on the behaviour of copper slag as an alternative to natural sand or crushed stone sand as fine aggregate in the manufacture of GPC and its strength performance, etc.

Based on the understanding of literatures, the present investigation is focused on the manufacture of ambient cured Geopolymer Concrete (GPC) using fly ash and ultrafine ground granulated blast furnace slag as the aluminosilicate source materials along with copper slag as a replacement of fine aggregate. Use of copper slag as fine aggregate will pave way to manufacture a more sustainable and environmentally friendly geopolymer concrete. Further, Sodium hydroxide and Sodium Silicate combinedly have been considered as the alkaline activator solution. Three numbers of geopolymer concrete specimens for each mix is considered for this study and their average is taken to understand the behaviour of geopolymer concrete.

2. EXPERIMENTAL STUDY

2.1 Materials used

In this study, class F Fly ash with a specific gravity of 2.64 procured from Mettur Thermal Power Plant, INDIA and confirming to IS 3812 (1) - 2013 [23] has been used as the prime source material. The chemical composition of class F fly ash used is given in Table 1. Ultrafine ground granulated blast furnace slag (UFGGBFS) having material size between 4 to 6 microns, specific surface area 12,000 cm^2/gm, specific gravity of 2.72 has been used. The chemical composition of UFGGBFS is given in Table 1. Well-graded aggregate of size 12.5 mm with a specific gravity of 2.83 and confirming to IS 383-1970 [24] has been used as coarse aggregate. Copper slag, a black colored glassy granular particle as per IS: 2386 (Part I)-1963 [25] with a specific gravity of 3.50 has been used to replace fine aggregate in this study. The chemical composition of copper slag used in presented in Table 1. Naphthalene sulfonate-based superplasticizer has been used to improve workability as per IS 9130: 1999 [26].

A combination of sodium silicate solution and sodium hydroxide solution in the ratio of 2.5 has been used as alkaline activator. Commercial grade NaOH in pellet form and liquid Na_2SiO_3 (Na_2O = 16.38%, SiO_2 = 37.02, water = 46.59) has been used.

2.2 Preparation of geopolymer concrete specimen

NaOH solution has been prepared for 10M (314 grams of NaOH / 1 lit of NaOH solution), 12M (361 grams of NaOH / 1 lit of NaOH solution) and 14M (404 grams of NaOH / 1 lit of NaOH Solution) concentrations. Preparation of NaOH was done at room temperature and kept to cool at room temperature. After 24 hours, Na_2SiO_3 was mixed along with the NaOH solution in the ratio of 2.5. All the geopolymer constituent materials were dry mixed in the laboratory before they were mixed with the alkaline liquid (along with superplasticizer). Mixed Geopolymer concrete specimens were being cast in cube specimen of size 150 mm x 150 mm x 150 mm to determine the compressive strength after 3 days, 7 days and 28 days of curing.

Table 1. Chemical composition of Class F fly ash, UFGGBFS and Copper slag

Material	Chemical composition (w/w)								
	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CaO	Na_2O	K_2O	MgO	LOI
Class F Fly ash	61.30	26.62	4.55	0.28	1.20	0.22	1.32	0.50	0.55
UFGGBFS	33.00	22.40	1.70	-	34.20	-	-	6.00	-
Copper Slag	31.20	2.42	55.00	1.92	5.37	0.25	0.66	1.54	-

Table 2. Mixture proportioning of geopolymer concrete using UFGGBFS and Copper Slag

Mix Designation	NaOH concentration	Fly ash (kg/m^3)	UFGGBFS (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate		Alkaline activator solution	
					Crushed stone sand (kg/m^3)	Copper Slag (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)
M11	10M	408	0	1257	592	0	42	105
M12		388	20		592	0	42	105
M13		367	41		592	0	42	105
M14		347	61		592	0	42	105
M21		408	0	1257	0	592	42	105
M22		388	20		0	592	42	105
M23		367	41		0	592	42	105
M24		347	61		0	592	42	105
M11	12M	408	0	1257	592	0	42	105
M12		388	20		592	0	42	105
M13		367	41		592	0	42	105
M14		347	61		592	0	42	105
M21		408	0	1257	0	592	42	105
M22		388	20		0	592	42	105
M23		367	41		0	592	42	105
M24		347	61		0	592	42	105
M11	14M	408	0	1257	592	0	42	105
M12		388	20		592	0	42	105
M13		367	41		592	0	42	105
M14		347	61		592	0	42	105
M21		408	0	1257	0	592	42	105
M22		388	20		0	592	42	105
M23		367	41		0	592	42	105
M24		347	61		0	592	42	105

Curing of geopolymer concrete specimens has been done by two ways. In the first case, where Fly ash has been used alone as a binder, curing in an oven at 60° has been adopted [27]. In the second case, where fly ash has been replaced by 5%, 10%

and 15% UFGGBFS, ambient temperature curing of geopolymer concrete specimens has been adopted. Then, the specimens were cured and kept in the laboratory until the time of testing. The mix proportioning of geopolymer concrete is given in Table 2. Overall, mix designations M11, M12, M13 and M14 represent geopolymer concrete mix with 100% crushed stone sand as the fine aggregate and Mix designations M21, M22, M23 and M24 represent geopolymer concrete mix having 100% copper slag used as replacement of crushed stone sand. Further, the mix designation M11 and M21 represent the geopolymer mix with 100% fly ash as the binding material; M12 and M22 represent the geopolymer mix with 95% fly ash as the binding material along with 5% UFGGBFS; M13 and M23 represent the geopolymer mix with 90% fly ash as the binding material along with 10% UFGGBFS; and M14 and M24 represent the geopolymer mix with 85% fly ash as the binding material along with 15% UFGGBFS.

2.3 Testing

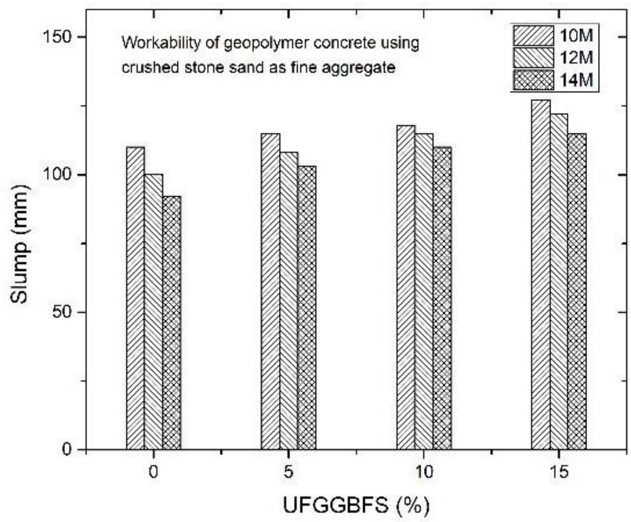
Slump test [28] has been used to determine the workability of geopolymer concrete in a fresh state. Compressive strength of geopolymer concrete specimens has been performed on cube specimens having size of 150mm x 150mm x 150mm per mix according to IS: 516-1959 [29]. The reported values represent an average of measurement on three cube specimens.

3. RESULTS AND DISCUSSION

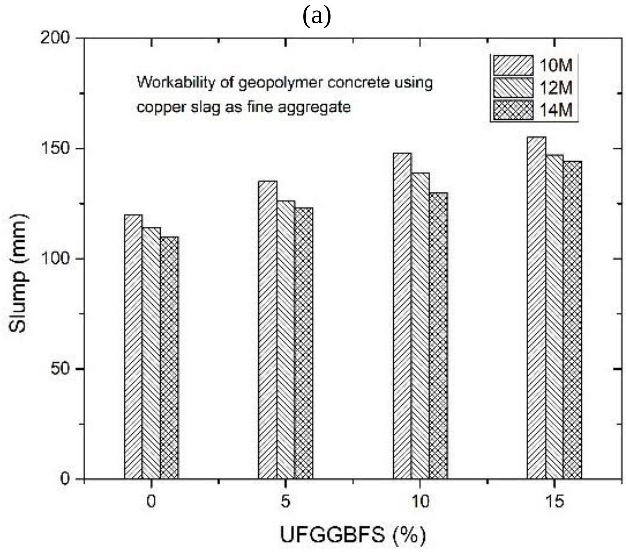
3.1 Properties of geopolymer concrete in fresh state

The workability of fresh geopolymer concrete has been determined by slump test and the corresponding experimental results are plotted graphically in Figure 1.

From Figure 1, it is to be seen that the workability of fresh geopolymer concrete decreases with increase in NaOH concentration. It can be inferred from Figure 1 (a) that for Mix M14 having 15% UFGGBFS as replacement of fly ash content, the slump decreases by 16.35% from 110mm (10M NaOH concentration) to 92mm (14M NaOH concentration). A similar tendency of decreased workability in fresh state with an increase in NaOH concentration is seen for geopolymer concrete manufactured using copper slag as fine aggregate. The reason behind this decrease may be the high viscous nature of alkaline activator solution used to manufacture geopolymer concrete. Further, from Figure 1 (a) and Figure 1 (b), it is clear that adding UFGGBFS to geopolymer concrete as limited replacement of fly ash increases the slump value. For instance, from Figure 1 (b) it is to be seen that addition of 15% UFGGBFS to geopolymer concrete having 12M NaOH concentration increases the slump value by 28.95% from 114mm (100% fly ash – mix M21) to 147mm (15% UFGGBFS – mix M24). This may be attributed to the reason that UFGGBFS acts as a filler material thus increasing workability [30]. Also, it is evident from Figure 1 (a) and Figure 1 (b) that the replacement of crushed stone sand by using copper slag as fine aggregate enhances the workability of geopolymer concrete in fresh state. For instance, for geopolymer concrete with 10% UFGGBFS as replacement of fly ash having 14 M NaOH concentrations, the slump increases by 18.18% from 110mm (mix M13) to 130mm (mix M23). This increase in workability with the addition of copper slag as replacement of fine aggregate may be credited to the low water absorption characteristics of copper slag [31].



(a)



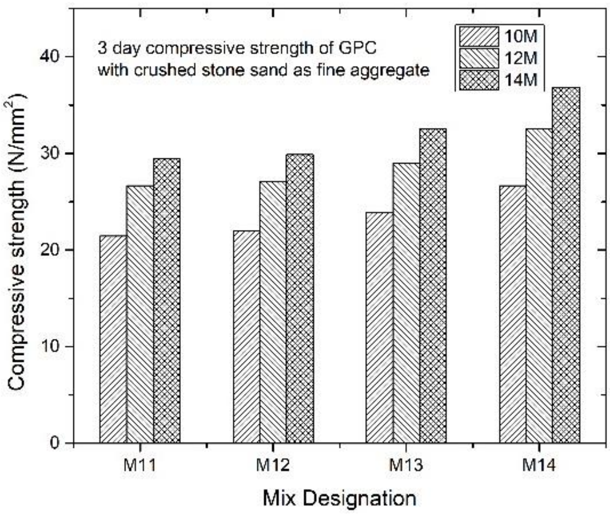
(b)

Figure 1. Workability of geopolymer concrete using (a) crushed stone sand as fine aggregate (b) copper slag as fine aggregate

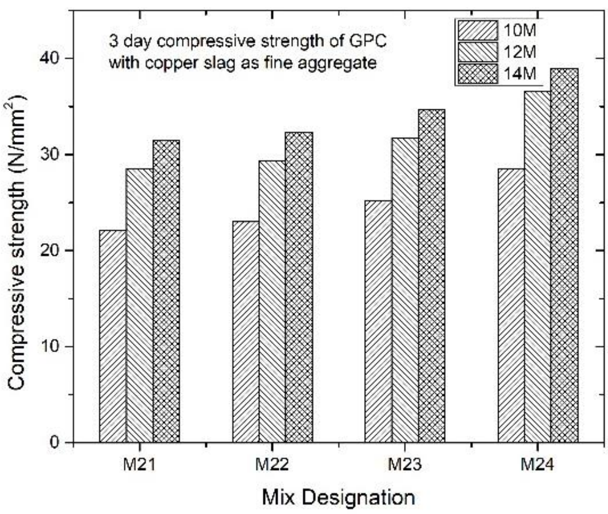
3.2 Properties of geopolymer concrete in hardened state

Properties of geopolymer concrete in hardened state has been done to assess the compressive strength of cube specimens having a size 150mm x 150mm x 150mm. The cast, cured geopolymer concrete cube specimens were tested for compressive strength at 3 days, 7 days and 28 days of curing and its corresponding results have been plotted graphically. Figure 2 (a) illustrates the compressive strength of geopolymer concrete manufactured using crushed stone sand as fine aggregate after 3 days of curing and Figure 2 (b) shows the compressive strength of geopolymer concrete manufactured using copper slag as fine aggregate after 3 days of curing.

From Figure 2, it is inferred that the compressive strength of geopolymer concrete increases with increase in NaOH concentration. It can also be inferred from Figure 2 (a) that the 3-day compressive strength of geopolymer concrete mix M14 having 15% UFGGBFS content as replacement of fly ash and crushed stone sand as fine aggregate increases by 22.01% from 26.67 N/mm^2 (10M NaOH concentration) to 32.54 N/mm^2 (12M NaOH concentration). Further, the increase in NaOH concentration, increases the 3-day compressive strength of geopolymer concrete by 13.05% from 32.54 N/mm^2 (12M NaOH concentration) to 36.81 N/mm^2 (14M NaOH concentration). A similar trend of increase in 3-day compressive strength is seen for geopolymer concrete using copper slag as replacement to fine aggregate. This may be attributed to the fact that rise in alkali concentration boosted the geopolymerization process thereby resulting in an increased compressive strength. Further, it can be seen from Figure 2 (a) that the 3-day compressive strength of geopolymer concrete having 14M NaOH concentration increases marginally from 29.45 N/mm^2 (for mix M11 with fly ash as the prime source material cured at 60°C) to 29.89 N/mm^2 (for mix M12 with 5% UFGGBFS as replacement of fly ash cured at ambient temperature). Strength improvement of fly ash based geopolymer concrete cured in oven at high temperatures may be attributed to the fact that curing temperatures play a vital role in accelerating the reaction mechanism [32, 33].



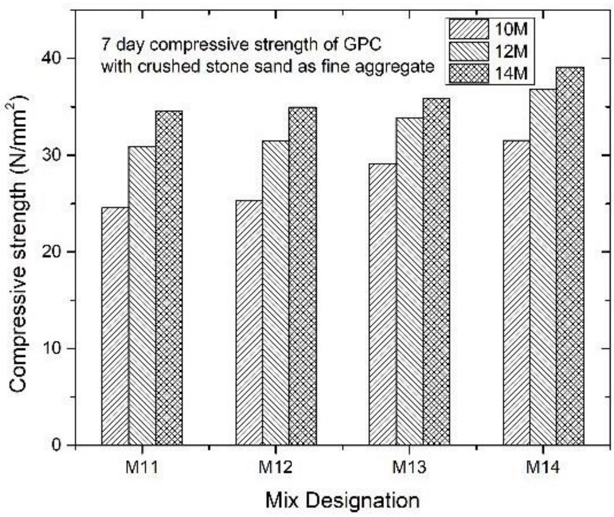
(a)



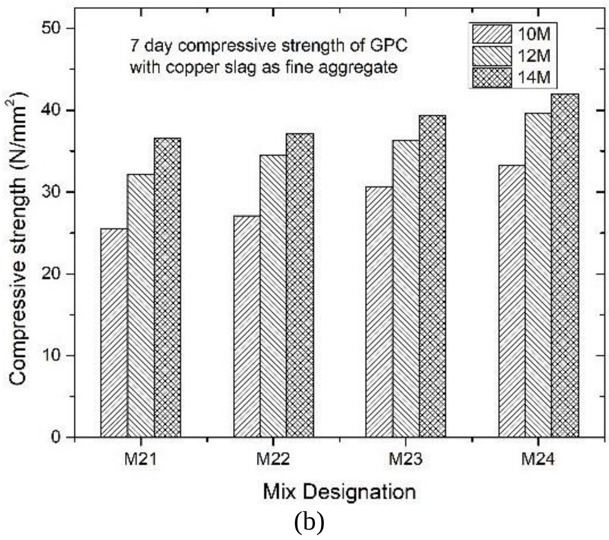
(b)

Figure 2. 3-day compressive strength of geopolymer concrete using (a) crushed stone sand as fine aggregate (b) copper slag as fine aggregate

Also, it can be remarked from Figure 2 (a) that the 3-day compressive strength of geopolymer concrete cured at ambient temperature increases with increase in UFGGBFS as limited replacement of fly ash. For instance, it can be understood from Figure 2 (a) that the 3-day compressive strength of geopolymer concrete with crushed stone sand as fine aggregate and having 12M NaOH concentration increases by 6.71% from 27.13 N/mm^2 (mix M12 having 5% UFGGBFS) to 28.95 N/mm^2 (mix M13 having 10% UFGGBFS). Further increase in UFGGBFS content from 10% to 15% resulted in an increased compressive strength by 12.40%. A similar trend of increased results has been seen for geopolymer concrete using copper slag as a replacement to fine aggregate. This increasing trend may be due to the presence of CaO in UFGGBFS that aids in ambient curing of geopolymer concrete but also enhances the initial strength gain. It can be noted from Figure 2 (b) that the compressive strength of geopolymer concrete increases with copper slag as fine aggregate as compared to that of the geopolymer concrete manufactured using crushed stone sand as fine aggregate. For instance, it can be inferred from Figure 2(a) and Figure 2 (b) that the 3-day compressive strength of geopolymer concrete mix having 15% UFGGBFS and 12M NaOH concentration increases from 32.54 N/mm^2 for geopolymer concrete with crushed stone sand as fine aggregate to 36.56 N/mm^2 for geopolymer concrete with copper slag as fine aggregate. This may be due to the amorphous nature of copper slag that aids in geopolymerization process [34].



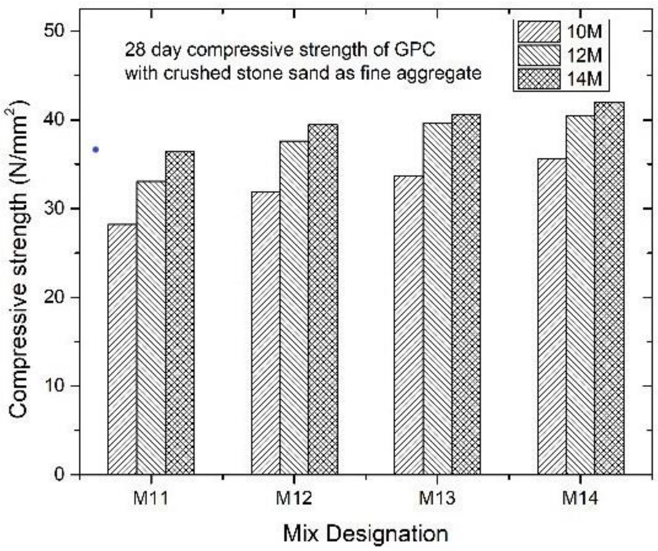
(a)



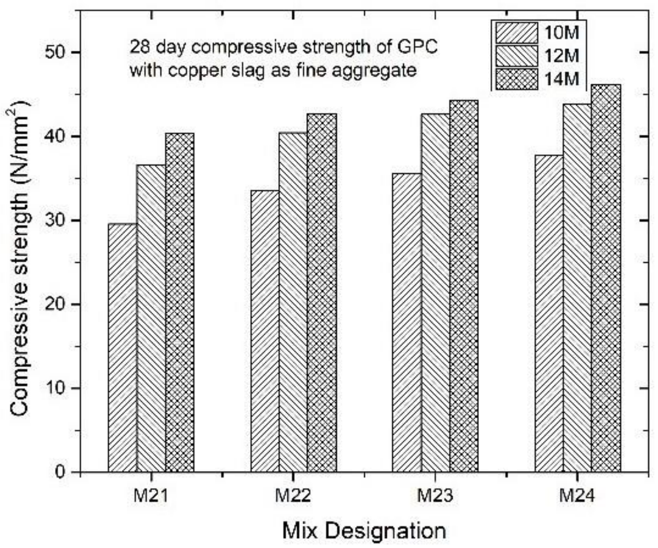
(b)

Figure 3. 7-day compressive strength of geopolymer concrete using (a) crushed stone sand as fine aggregate (b) copper slag as fine aggregate

Figure 3 (a) shows the 7-day compressive strength of geopolymer concrete with crushed stone sand as fine aggregate and Figure 3 (b) shows the 7-day compressive strength of geopolymer concrete with copper slag as fine aggregate. From Figure 3 (a) and Figure 3 (b), it is to be noted that the 7-day compressive strength of geopolymer concrete increases with increase in NaOH concentration. Further, it can be noted from Figure 3 (a) and Figure 3 (b) that addition of UFGGBFS to the mix increased the compressive strength. Also, it can be seen from Figure 3 (b) that addition of copper slag as replacement to fine aggregate resulted in an increased compressive strength of geopolymer concrete as compared to that of crushed stone sand. Maximum 7-day compressive strength of 39.13 N/mm^2 and 41.97 N/mm^2 were yielded for geopolymer concrete mix with 15% UFGGBFS content having 14M NaOH concentration both without and with replacement of crushed stone sand by copper slag, respectively.



(a)



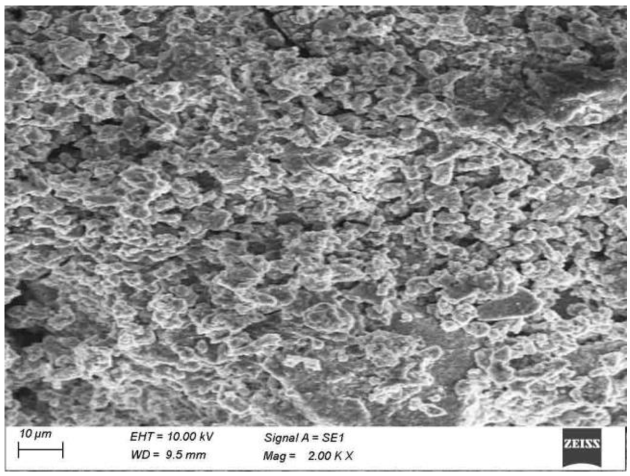
(b)

Figure 4. 28-day compressive strength of geopolymer concrete using (a) crushed stone sand as fine aggregate (b) copper slag as fine aggregate

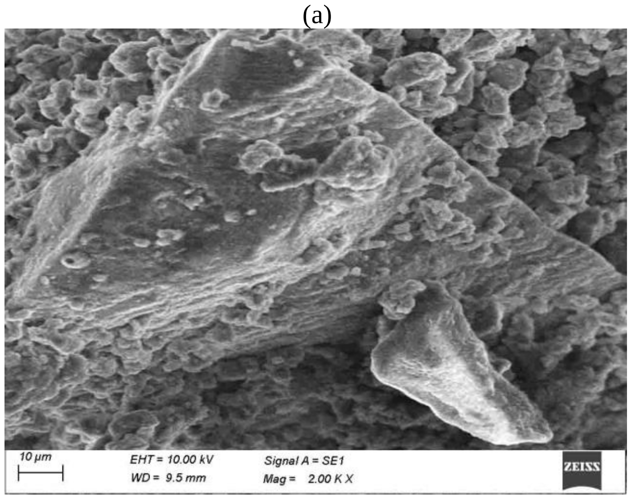
Figure 4 (a) displays the 28-day compressive strength of geopolymer concrete with crushed stone sand being used as fine aggregate and Figure 4 (b) shows the 28-day compressive strength of geopolymer concrete with copper slag used as fine aggregate. Also, it is clear that geopolymer concrete follows the similar trend of an increase in compressive strength with an increase in NaOH concentration as well as increase in UFGGBFS content. It can further be highlighted that adding copper slag resulted in an enhanced compressive strength of geopolymer concrete, irrespective of the NaOH concentration or UFGGBFS content. Maximum 28-day compressive strength of 42.00 N/mm^2 and 46.15 N/mm^2 were yielded for geopolymer concrete mix with 15% UFGGBFS content having 14M NaOH concentration both without and with replacement of crushed stone sand by copper slag, respectively.

4. SEM ANALYSIS

Geopolymer concrete mix M14 and M24 with 15% UFGGBFS content having 14 M NaOH concentration was chosen for Scanning Electron Microscopy analysis. Figure 5 (a) illustrates the SEM image of geopolymer concrete with crushed stone sand as fine aggregate and Figure 5 (b) depicts the SEM image of geopolymer concrete with copper slag as fine aggregate.



(a)



(b)

Figure 5. Microstructure of geopolymer concrete using (a) crushed stone sand as fine aggregate (b) copper slag as fine aggregate

It can be seen from Figure 5 (a) and Figure 5 (b) that adding UFGGBFS to geopolymer concrete as a replacement to fly ash resulted in an enhanced and dense microstructure. This may be due to the presence of CaO in the mix resulting in heat generation that in turn helps the fly ash particles experience geopolymerization [35, 36]. Also, it must be seen from Figure 5 (b) that adding copper slag suggestively improves the microstructure of geopolymer concrete and the formed geopolymeric gel reduces cracks and voids, and also fills the space between aggregates [21].

Overall, it is clear from the experimental study that the strength of geopolymer concrete increases with addition of UFGGBFS as replacement to fly ash. Maximum strength was yielded for the geopolymer concrete mix with 15% UFGGBFS content. Addition of UFGGBFS resulted in a dense microstructure that may be due to the presence of CaO resulting in effective geopolymerization. Further, addition of copper slag to the mix results in reduced cracks in the mix. Also, it is evident that the strength of geopolymer concrete increased with the increase in NaOH concentration.

5. CONCLUSIONS

Based on the experimental studies on geopolymer concrete using UFGGBFS as replacement of fly ash and copper slag as fine aggregate instead of crushed stone sand, the following conclusions are drawn:

- Addition of UFGGBFS enables ambient curing of geopolymer concrete.
- 14M NaOH concentration yields the maximum compressive strength for geopolymer concrete.
- Increase in UFGGBFS content by 5%, 10% and 15% results in an increased compressive strength of geopolymer concrete at 3, 7 and 28 days of curing.
- Replacement of crushed stone sand by using copper slag as fine aggregate resulted in an enhanced compressive strength.
- Geopolymer concrete manufactured with UFGGBFS as replacement and copper slag as fine aggregate resulted in an enhanced and dense microstructure.
- Overall, geopolymer concrete made with UFGGBFS as replacement to fly ash and copper slag as replacement to crushed stone sand can be used in cast-in-situ applications and for the manufacture of retaining walls, pavements, railway sleepers, etc.

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NOMENCLATURE

GPC	Geopolymer Concrete
M	Molarity
SEM	Scanning Electron Microscope