



# Article A Comprehensive Study on the Factors Affecting the Workability and Mechanical Properties of Ambient Cured Fly Ash and Slag Based Geopolymer Concrete

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Abstract: Geopolymer concrete (GPC), also known as an earth friendly concrete, has been under continuous study due to its environmental benefits and potential as a sustainable alternative to conventional concrete construction. However, there is still a lack of comprehensive studies focusing on the influence of all the design mix variables on the fresh and strength properties of GPC. GPC is still a relatively new material in terms of field application and has yet to secure international acceptance as a construction material. Therefore, it is important that comprehensive studies be carried out to collect more reliable information to expand this relatively new material technology to field and site applications. This research work aims to provide a comprehensive study on the factors affecting the fresh and hardened properties of ambient cured fly ash and slag based geopolymer concrete (FS-GPC). Industrial by-products, fly ash from thermal power plants, and ground granulated blast furnace slag from steel industries were utilized to produce ambient cured FS-GPC. A series of experiments were conducted to study the effect of various parameters, i.e., slag content (10%, 20%, 30%, and 50%), amount of alkaline activator solution (AAS) (35% and 40%), sodium silicate (SS) to sodium hydroxide (SH) ratio (SS/SH = 2.0, 2.5 and 3.0), sodium hydroxide concentration (10 M, 12 M, and 14 M) and addition of extra water on fresh and mechanical properties of FS-GPC. The workability of the fresh FS-GPC mixes was measured by the slump cone test. The mechanical properties of the mixes were evaluated by compressive strength, split tensile strength, flexure strength, and static modulus tests. The results revealed that workability of FS-GPC is greatly reduced by increasing slag content, molarity of NaOH solution, and SS/SH ratio. The compressive strength was improved with an increase in the molarity of NaOH solution and slag content and a decrease in AAS content from 40% to 35%. However, the influence of SS/SH ratio on mechanical properties of FS-GPC has a varying effect. The addition of extra water to enhance the workability of GPC matrix caused a decrease in the compressive strength. The validity of the equations suggested by previous studies to estimate the tensile and flexural strength and elastic modulus of FS-GPC mixes were also evaluated. Based on the test results of this study, empirical equations are proposed to predict the splitting tensile strength, flexural strength, and elastic modulus of ambient cured FS-GPC. The optimal mixtures of FS-GPC in terms of workability and mechanical properties were also proposed for the field applications.

**Keywords:** geopolymer; NaOH molarity; NaOH to Na<sub>2</sub>SiO<sub>3</sub> ratio; alkaline to binder ratio; mechanical properties



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## 1. Introduction

Over the last two decades, constructional activities have been growing rapidly around the globe due to increased infrastructure demand. It cannot be ignored that cement is the most widely used material in all the construction activities. According to an estimate, about 2 billion tons of cement is produced each year worldwide [1]. The production of cement causes serious damage to the environment due to green-house gas (GHG) emissions. Hence, the manufacturing industries of cement are responsible for huge amounts of  $CO_2$ emissions into the atmosphere due to the consumption of energy, i.e., the fuel and raw material conversion. According to a study, 1.6 tons of raw materials are consumed for the production of one ton of cement that will result in the liberation of 1 ton of  $CO_2$ in the atmosphere [2]. The cement industry alone is emitting about 7–8% of the total greenhouse gas emissions. Therefore, serious environmental concerns have been raised on the production of ordinary Portland cement (OPC) in recent times. Consequently, researchers are making efforts to replace the traditional OPC with environment friendly material with properties like OPC.

Apart from greenhouse gas emissions, there has been significant increase in the generation of by-products and waste materials from industries, such as fly ash (FA), molten slag (SG), silica powders, lime stone dust, and ceramic wastes [3,4]. For example, fly ash is a fine powder that is a by-product of burning pulverized coal in electric generation power plants [5]. However, in most of the cases, the end product of fly ash is a waste material that is dumped into landfill sites because utilization rate of fly ash in most of the developing countries is not 100%. For instance, the average comprehensive utilization rate of fly ash in China is 70%, which is mainly used in building materials [4]. There are different problems related to fly ash like requirement of large area of land for disposal. Similarly, slag is a by-product of steel and iron industries, produced in the process of iron and steel smelting, and its emission is about 15% by weight of crude steel output. However, in most of the data released by the World Iron and Steel Association, China's crude steel output in 2019 was 996 million tons, which meant that the emission of steel slag is not 100% as high as 100 million tons, while the comprehensive utilization rate of steel slag in China was only about 25% [6].

This has become a challenging task for the environmentalists and researchers to dispose of or manage these wastes and develop alternatives to traditional OPC [2]. The usual popular approach is to develop better and viable solutions that can utilize these products to create binder materials like ordinary Portland cement (OPC). This will help to resolve the issues associated with the management of these products, preserving the natural resources and simultaneously reducing the global warming effects. One of the solutions to fully avoid the usage of cement and promote efficient use of these products concurrently is geopolymer concrete (GPC) [7–9].

There is no doubt about the sustainability benefits of using geopolymer concrete as compared to conventional concrete because it indirectly negates the CO<sub>2</sub> emissions during cement production [10,11]. However, the environmental benefits and outcome of life cycle assessment (LCA) of GPC depend on a number of parameters and vary from location to location. There are a number of studies that conclude that geopolymer concrete yields environmental benefits [7,8,12]. Recently, Meshram and Kumar (2021) conducted the comparative LCA of GPC manufacturing with OPC in the Indian context. It is reported that the geopolymer cement produced from FA and SG reduces the global warming potential by 70% as compared to OPC [12].

GPC is also recognized as the earth friendly concrete (EFC) and can be produced by activating the source material rich in alumina and silica by alkaline activator solution (AAS) [13–16]. The utilization of GPC causes reduction in energy consumption, CO<sub>2</sub> emissions, and overall budget due to the effective consumption of by-products/waste materials, thus making it an environment friendly material [7,13,17,18].

However, these emissions vary for different location and mixes, and depend on several factors such as location, curing, transportation distance of source materials, and

the production of the activator solution. For the sake of comparison, the contribution to CO<sub>2</sub> emissions as a percentage of each of the ingredient/activity, from sourcing of raw materials to the curing of 1 m<sup>3</sup> of concrete, for GPC and OPC/conventional concrete is summarized in Figure 1 [8]. This is one of the typical cases of  $CO_2$  emissions for a specific mix design and location. The reported calculations were based on the activities associated with production of 1 m<sup>3</sup> of Grade 40 concrete (i.e., compressive strength of 40 MPa) which comprises locally available materials, manufacturing, and construction methods in the Melbourne Metropolitan area in Australia. The OPC is by far the most significant contributor to emissions, contributing 76.4% of CO<sub>2</sub> emissions in conventional concrete. On the other hand, the contribution of the geopolymer binder (fly ash + sodium silicate (SS) +sodium hydroxide (SH)) towards total emissions is 63% in the GPC. By weight comparison reveals 201 kg of  $CO_2$  emissions from the geopolymer binder which is 25% less than the OPC binder (269 kg of  $CO_2$  emissions) in the conventional concrete. The alkali activators required for the production of GPC expend significant energy. The total emissions for all the ingredients/activities from sourcing to curing of the OPC/conventional concrete and the GPC are estimated as 354 kg and 320 kg of CO<sub>2</sub> respectively [8]. A significant difference between emissions during the curing processes of both the concretes is due to the high temperature (40–80  $^{\circ}$ C) curing of the GPC for at least 6 h to achieve strength comparable to the OPC concrete. However, the  $CO_2$  emissions during the curing operations can be reduced to less than 1 kg by promoting ambient curing conditions in the GPC construction. If ambient curing conditions are considered, then the total  $CO_2$  emissions for the GPC construction would reduce to 281 kg, i.e., 21% less than the CO<sub>2</sub> emissions of the conventional concrete (for each cubic meter) for this specific case.

It is reported that GPC can achieve better strength and durability properties than the OPC concrete if heat curing is performed at a temperature of 60–100 °C [19,20]. Wallah and Rangan (2006) stated that the heat curing of GPC at elevated temperature results in higher compressive strength than the ambient curing [21]. The heat curing of GPC may practically be possible to manufacture precast concrete elements. However, such curing conditions may be challenging for in situ application of GPC. To make GPC application possible for in situ construction, material containing high calcium content like slag can be incorporated to increase reactivity of FA. By the addition of slag in FA based GPC, geopolymeric gel is produced along with the formation of calcium silicate hydrate (C-S-H). These hydrates help GPC to set at ambient temperature and improve its mechanical properties [22].

A number of studies have been carried out on GPC with FA and SG being the source materials [19–23]. Okoye et al. (2015) used silica fume in different dosages in combination with fly ash and metakaolin to improve the mechanical properties and concluded that the elevated temperature curing is the most suitable option to produce a stronger GPC [23]. Lee et al. have developed the marble-based geopolymer concrete and examined its physical/mechanical properties [24]. It was found that marble-based geopolymer concrete is an excellent material to be used in engineering applications.

Hadi et al. (2019) have studied the effects of different parameters on the compressive strength, setting time, and workability of geopolymer pastes [25]. Based on the test results of compressive strength, setting time, and workability, the optimum mix design of geopolymer paste was found to have SG content of 40% and AAs content of 50%. The main limitation of this research is that it was carried out on the geopolymer cement pastes to find out the optimum mix. Furthermore, different concentrations of alkaline activating solution were not considered. The effect of slag content on the properties of ambient cured FS-GPC paste mixes may be affected by different molarities of NaOH solution. Aliabdo et al. (2019) have studied the influence of different parameters on the mechanical properties of alkali activated blast furnace slag concrete [26]. The main limitation of this research is that heat curing method was adopted for the specimens. The results of this study may be different to those of ambient cured specimens. Furthermore, the results of this study do not apply to the alkali activated fly ash and slag blended geopolymer concrete since only slag was used as a source material to produce GPC. Bellum et al. (2019) also explored the mechanical

properties of fly ash and slag based alkali-activated geopolymer concrete [27]. It was found that GPC mixtures developed with 30% fly ash and 70% slag have better properties at 14 M of NaOH when cured in an oven for 24 h at 70 °C. However, it should be noted that the ambient curing conditions were not considered in selecting the optimal slag content and NaOH molarity. Furthermore, the optimal mixtures should also include alkaline activating solution content and SS/SH ratio in alkaline solution. It is therefore important to have comprehensive studies like the present study which should focus on the influence of all important parameters on fresh and mechanical properties of GPC to enhance the already available knowledge base.



(**b**) Conventional/OPC Concrete

Figure 1. The contribution of each ingredient/activity in  $CO_2$  emissions as a percentage in the production of a cubic meter of GPC and OPC concrete.

The workability and compressive strength are the two internationally accepted criteria for designing the OPC concrete mixes. However, the mix proportion of GPC is not that similar to OPC. There are more constituents involved in the production of GPC that makes its mix design process more complex. In OPC concrete, the strength of the mix is dependent, in general, on the ratio between cement, fine and coarse aggregates, water-cement ratio, fineness of cement, aggregates gradations, etc. The strength of GPC mix is dependent generally on various ingredients and their ratios, i.e., type of source materials like FA, SG, and alkaline activators, activating solution content, curing methods, mixing procedure, concentration of alkaline solution etc.; this makes it challenging to design it against a specified target strength. GPC is still a relatively new material in terms of field application and has yet to secure international acceptance as a construction material.

In order to effectively substitute the OPC concrete, GPC has yet to reach to a point where the constituents of the GPC mix with a specified target strength can be calculated confidently before mixing. However, this is only possible through a complete understanding of the parameters of the GPC mix. The fresh and hardened properties of GPC mix and the parameters affecting it must be thoroughly understood before its practical application to make sure that reliable and acceptable mixes can be proportioned with confidence. Thus, it is important that comprehensive studies taking the all-important parameters be carried out to collect a significant amount of information about the material and to expand this relatively new material technology to field and site applications.

This research work aims to provide a comprehensive study on the main factors affecting the workability and mechanical properties of fly ash and slag based geopolymer concrete (FS-GPC). The mechanical properties studied herein were compressive strength, tensile strength, flexural strength, and modulus of elasticity. There were five parameters/factors considered in this study viz. the effect of ground granulated blast furnace slag (SG) content (10%, 20%, 30%, and 50%), amount of alkaline activator solution (35% and 40%), sodium silicate to sodium hydroxide ratio (SS/SH = 2.0, 2.5 and 3.0), sodium hydroxide molarity (10 M, 12 M, and 14 M), and additional water to improve workability. The optimal mixtures of FS-GPC were proposed for the general concreting applications, i.e., columns, beams, and foundations. The data from this research can be utilized to design a mix of FA and SG blended GPC with a specified strength. The influence of all mix design parameters can be utilized to control the desired fresh and strength properties of FS-GPC. This study will help construction practitioners to achieve the desired fresh and mechanical properties of FS-GPC by controlling different mix design parameters. Further, mathematical equations based on the compressive strength were also proposed to predict the splitting tensile strength, flexural strength, and static modulus of elasticity of ambient cured FS-GPC. These equations can be used to provide prediction of tensile, flexural strengths, and modulus of elasticity of FS-GPC mixes having 28 days compressive strength in the range of 30-60 MPa.

#### 2. Experimental Program

The experimental work in this research is designed to study the effect of five main parameters on the workability and mechanical properties of geopolymer concrete mixtures. The optimal range of studied parameters for mixture proportions were selected from the previous studies available in the literature [25,26,28–33].

The industrial by-products, i.e., FA from thermal power plants and SG from steel industries, were used to produce the ambient cured FS-GPC. A total of twenty trial mixes were designed by varying different mix variables viz. slag content (10%, 20%, 30%, and 50%), amount of alkaline activator solution (35% and 40%), sodium silicate to sodium hydroxide ratio (SS/SH = 2.0, 2.5 and 3.0), sodium hydroxide concentration (10 M, 12 M, and 14 M) and addition of extra water. A series of tests were conducted to study the effect of these mix parameters on the fresh and mechanical properties. The workability of the fresh FS-GPC mixes was measured by the slump cone test, whereas the mechanical

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properties were evaluated by the compressive, split tensile, flexural strengths, and the static modulus tests.

# 2.1. Materials Specifications

The fresh and hardened properties of GPC not only vary with the constituents but also changes with chemical composition of the source materials. The procedure of geopolymerization starts when source materials (FA and SG) react with the alkaline activators. This process is primarily based on the proportions of silica and alumina present in the source materials. It was made sure that industrial by-products, FA and SG, for all the mixes were obtained from the same source (power plant and steel industry respectively) to avoid error in results due to the variation in source materials. In this study, FA and SG were utilized as the source materials to produce geopolymer binder and FA was replaced by SG in different proportions to promote ambient curing conditions. The FA and SG used in the study are shown in Figures 2 and 3. The chemical composition and physical properties of FA and SG are shown in Table 1.

The solutions of SH and SS were mixed in predetermined ratios to make alkaline activator solution (AAS). The solution of SH of required molarity was prepared by mixing 98–99% pure pellets of SH (with a specific gravity of 2.10) in water. The mass of SH pellets to prepare 1000 mL of solution depends on the molarity of solution stated in Molar, M. It was prepared 24 h before mixing with SS solution due to heat evolution resulting from exothermic reaction. The SS solution with a ratio of SiO<sub>2</sub> to Na<sub>2</sub>O = 2.0, was used. It was composed of Na<sub>2</sub>O, SiO<sub>2</sub>, and H<sub>2</sub>O in 15.06%, 29.95%, and 54.99% by mass respectively. The properties of SS solution are shown in Table 2.



Figure 2. Pictures of slag used in the study.







Figure 3. Pictures of fly ash used in the study.

Oxides	FA (%)	SG (%)
SiO <sub>2</sub>	54.55	34.2
$Al_2O_3$	31.93	14.2
$Fe_2O_3$	3.12	0.76
Na <sub>2</sub> O	0.25	0.3
CaO	4.65	44.95
SO <sub>3</sub>	0.4	1.75
K <sub>2</sub> O	0.7	0.5
$P_2O_5$	0.45	0.05
MgO	1.42	0.95
TiO <sub>2</sub>	1.15	0.5
LOI	0.95	1.6
Specific Surface Area $(m^2/kg)$	320.7	405
Specific Gravity	2.1	2.8

Table 1. The chemical composition and physical properties of FA and SG.

Table 2. The properties of SS solution.

Entity	Specification
Color	Colorless
Density, kg/m <sup>3</sup>	1460
Total solid content	48 (% mass)

The coarse aggregates (CA) with a maximum size of 20 mm were taken from the Margallah quarry source in Pakistan. They were prepared to surface dry condition conforming to ASTM C127-15 (2015). The natural river sand from Lawrencepur in Pakistan was used as fine aggregates in surface dry condition (SSD) conforming to ASTM C128-15. The properties of CA and sand are shown in Table 3.

Table 3. The physical properties of CA and sand.

Entity	Sand	CA
Relative Density	2.64	2.70
Bulk Density $(kg/m^3)$	1688.4	1644.5
Fineness Modulus (kg/m <sup>3</sup> )	2.50	7.65
Water Absorption (% mass)	1.40	1.20

Since GPC mix is more cohesive and viscous due to high viscosity of SS and SH solutions [28], a naphthalene based superplasticizer (SP) was used to increase workability of the fresh mix.

## 2.2. Mix Proportions

The process of finding the proportions of GPC mix is different than the OPC concrete mix. In the OPC concrete mix design, the quantity of water and cement are calculated first, after which the quantity of aggregates (CA and sand) is worked out. However, the mix design process of GPC involves more parameters, i.e., source materials, AAS content, SS/SH ratio, curing temperature, molarity of SH, etc. Therefore, it is relatively challenging to proportion such a mix appropriately against a specified target strength. In the present study, twenty trial design mixes have been considered with the aim to study the influence of various parameters on the fresh and hardened properties of FS-GPC cured at ambient temperature.

The literature on mix design of GPC, in which quantities and ratios of the constituents can be calculated to get the specific properties, i.e., slump or strength, etc., is scarce. Therefore, each mix in the present study was prepared by allotting the specific percentages by mass to all the individual constituents. The optimal ranges of all the constituents are

selected from the previous studies available in the literature [25,26,28–33]. A number of FA and SG based GPC mixes with different slag content, AAS content, SH concentration, SS/SH ratio, and water content were prepared and tested. The mixes were divided into five groups, A, B, C, D, and E, as shown in Table 4. The mixes were devised by varying one parameter while the others were kept constant to investigate the influence of a certain mix design parameter on the engineering properties of geopolymer matrix. In group A, the mixes were prepared with different FA/SG ratios, i.e., 90/10, 80/20, 70/30, and 50/50; with a varying slag content, i.e., 10%, 20%, 30%, and 50% respectively; while all the other parameters were kept constant, i.e., molarity of SH solution (M = 10), SS/SH = 2.0, and AAS content as 40%. In group B, the mixes were prepared with two different molarities of the SH solution (i.e., 12 M and 14 M) and were compared with 10 M mixes of group A, to study the influence of SH concentration. The AAS content was varied from 40% (group A and B mixes) to 35% in group C mixes to study the influence of AAS content, keeping all the other parameters same as group A. In group D, the mixes were prepared using two different SS/SH ratios (2.5 and 3.0) and compared to the respective mixes of group A (SS/SH = 2.0) to investigate the effect of different SS/SH ratios. Lastly, in group E, the mixes were prepared with extra water  $(12 \text{ kg/m}^3)$ , keeping all the other parameters same as group C to investigate the consequence of addition of extra water on the properties of geopolymer matrix. All the mixes were named based on the group and amount of slag content. For instance, B2-S20 denotes the second GPC mix (B2) of group B with slag content (S20) as 20% of the total binder material. The proportions for all the mixes were prepared for one cubic meter volume of concrete. The quantity of the binder (400 kg/m<sup>3</sup>) was kept same for all the mixes; therefore, the binder materials (FA and SG) were calculated as per their mass ratio in the mix. The details of mix proportions are shown in Table 4.

Table 4. The detail of proportions and quantities of design mixes.

		Mix Proportions							Mix Quantities (kg/m <sup>3</sup> )						
Group	Mix No.	Mix ID	SG:FA	AAS Content	SS/SH Ratio	М	Sand	CA	SG	FA	Total AAS	NaOH	Na <sub>2</sub> SiO <sub>3</sub>	SP	Extra Water
A	1 2 3 4	A1-S10 A2-S20 A3-S30 A4-S50	10:90 20:80 30:70 50:50	40% 40% 40% 40%	2 2 2 2	10 10 10 10	640 643 646 652	1201 1206 1212 1220	40 80 120 200	360 320 280 200	160 160 160 160	53 53 53 53	107 107 107 107	6 6 6	- - -
В	5 6 7 8	B1-S20 B2-S30 B3-S20 B4-S30	20:80 30:70 20:80 30:70	40% 40% 40% 40%	2 2 2 2	12 12 14 14	643 646 644 647	1206 1212 1208 1214	80 120 80 120	320 280 320 280	160 160 160 160	53 53 53 53	107 107 107 107	6 6 6	- - -
С	9 10 11 12	C1-S10 C2-S20 C3-S30 C4-S50	10:90 20:80 30:70 50:50	35% 35% 35% 35%	2 2 2 2	10 10 10 10	644 646 649 655	1205 1212 1216 1225	40 80 120 200	360 320 280 200	$140 \\ 140 \\ 140 \\ 140 \\ 140$	53 53 53 53	107 107 107 107	6 6 6	
D	13 14 15 16	D1-S20 D2-S30 D3-S20 D4-S30	20:80 30:70 20:80 30:70	$40\% \\ 40\% \\ 40\% \\ 40\% \\ 40\%$	2.5 2.5 3 3	10 10 10 10	644 648 645 650	1208 1215 1209 1218	80 120 80 120	320 280 320 280	160 160 160 160	46 46 40 40 40	114 114 120 120	6 6 6	- - -
E	17 18 19 20	E1-S10 E2-S20 E3-S30 E4-S50	10:90 20:80 30:70 50:50	35% 35% 35% 35%	2 2 2 2	10 10 10 10	644 646 649 655	1206 1210 1216 1225	40 80 120 200	360 320 280 200	$140 \\ 140 \\ 140 \\ 140 \\ 140$	53 53 53 53	107 107 107 107	6 6 6	12 12 12 12

## 2.3. Preparation of Specimens

All the mixes were prepared in a drum mixer. The aggregates were prepared to surface dry condition conforming to ASTM standards before the mixing operation. The alkaline activators SH and SS were mixed in predetermined ratios to make the solution, one hour before the mixing operation due to heat evolution resulting from exothermic reaction. The mixing procedure and time of mixing was kept same for all the mixes. All the dry ingredients were added first to the mixer. The sand was added at the start followed by binder materials and coarse aggregates. After 2 min of dry mixing, AAS was added to the premixed dry ingredients. Then water and superplasticizer were added if required and mixing was continued for another 3 min to ensure homogeneity. Then freshly mixed geopolymer concrete was poured into the molds of specimens. The compaction

of specimens was carried out by the internal vibrator during casting. The specimens were demolded after 24 h. After demolding, the specimens were placed under ambient environment with temperature of  $25 \pm 2$  °C and  $70 \pm 5\%$  relative humidity till testing age. Figure 4. shows the curing of specimens at ambient temperature.



Figure 4. The curing of specimens at ambient temperature.

## 2.4. Testing Procedures

The workability of the fresh FS-GPC mixes was measured by the slump cone test as per ASTM C143/C143M-12. The mechanical properties of the mixes were evaluated by compressive, split tensile, and flexure strengths, and static modulus tests. The compressive strength test was performed on  $150 \times 150 \times 150$  mm cubes following BS EN 12390-3:2009 at the age of 3, 7, 14, 28, 56, and 90 days as shown in Figure 5. The split tensile strength tests were performed on  $150 \times 300$  mm cylinders according to ASTM C496/C496M-11 at the age of 28 days as shown in Figure 6. The flexural strength test was performed on  $100 \times 100 \times 400$  mm prisms after 28 days of curing following the ASTM C78/C78M-16 as shown in Figure 7. The static modulus of FS-GPC mixes was determined by conducting the tests on  $150 \times 300$  mm cylindrical specimens according to ASTM C469/C469M-10 at the age of 28 days as shown in Figure 8.



Figure 5. The testing setup for compressive strength test.



Figure 6. The testing setup for splitting tensile strength test.



Figure 7. The testing setup for flexural strength test.



Figure 8. The testing setup for modulus of elasticity test.

### 3. Results and Discussions

# 3.1. Workability

The workability of the fresh concrete mix is defined as the ease with which the concrete can be handled, placed, compacted, and finished. There are different methods available to measure the workability of concrete. However, the method that is commonly used at the site is slump cone test. The workability of FS-GPC mixes was observed by performing slump cone test following the ASTM C143/C143M-12 soon after mixing of concrete was completed. The results of slump cone test are presented in Figure 2 and Table 5.

Generally, the workability of GPC is lower than the conventional concrete due to sticky characteristics of the alkaline activator solution. However, it can be compacted well by using mechanical compaction methods. Although the sphere-shaped particles of FA provide lubricating effect to the freshly mixed GPC, the SS and SH solutions used in GPC mix have more viscosity as compared to water, which gives it more cohesion and stickiness than the conventional concrete.

#### 3.1.1. Influence of Slag Content

Figure 2 illustrates the slump values of various GPC mixes with different proportions of slag. It can be noted that the slump values are influenced by varying the amount of slag in the mixes. The slump values show similar trends for different slag content in all the mix groups. The workability of the freshly mixed GPC was reduced gradually by increasing the slag replacement levels (10% to 50%) in the mixes.

_	Mix	Mix — ID	Mix Proportions			Slumn	Compressive Strength (MPa)						
Group	No.		SG: FA	Alkaline Content	SS/SH Ratio	М	(mm)	3 Day	7 Days	14 Days	28 Days	56 Days	90 Days
A	1 2 3 4	A1-S10 A2-S20 A3-S30 A4-S50	10:90 20:80 30:70 50:50	$\begin{array}{c} 40\% \\ 40\% \\ 40\% \\ 40\% \end{array}$	2 2 2 2	10 10 10 10	130 120 100 90	5 11 15 20	12 22 32 42	16 32 45 55	20 40 54 61	23 43 58 64	25 45 62 69
В	5 6 7 8	B1-S20 B2-S30 B3-S20 B4-S30	20:80 30:70 20:80 30:70	$\begin{array}{c} 40\% \\ 40\% \\ 40\% \\ 40\% \end{array}$	2 2 2 2	12 12 14 14	80 45 60 30	15 20 18 24	29 38 33 43	40 54 44 57	48 63 53 61	52 67 58 66	54 69 59 69
С	9 10 11 12	C1-S10 C2-S20 C3-S30 C4-S50	10:90 20:80 30:70 50:50	35% 35% 35% 35%	2 2 2 2	10 10 10 10	70 60 45 35	9 14 19 24	17 27 38 46	22 38 51 60	26 46 59 69	28 49 64 74	29 50 67 76
D	13 14 15 16	D1-S20 D2-S30 D3-S20 D4-S30	20:80 30:70 20:80 30:70	40% 40% 40%	2.5 2.5 3 3	10 10 10 10	110 85 75 60	13 18 10 14	26 38 21 30	37 52 30 42	46 63 37 49	49 68 41 54	50 70 42 55
Е	17 18 19 20	E1-S10 E2-S20 E3-S30 E4-S50	10:90 20:80 30:70 50:50	35% 35% 35% 35%	2 2 2 2	10 10 10 10	150 135 115 100	5 11 17 22	10 21 32 41	14 30 43 54	17 36 51 63	19 39 56 67	20 41 59 69

Table 5. The mix design parameters, slump values, and compressive strengths of FS-GPC mixes.

This decreasing trend of slump values against increasing slag content is also consistent with the previous studies [28,31,34]. This is due to the angular shaped particles of slag as compared to spherical shaped particles of FA that makes the concrete more flowable. However, this effect was not the same for different quantities of slag. In group A, the mix A1-S10 having 10% slag content gives highest slump value of 130 mm as compared to other mixes with higher slag content in this group. The slump values were decreased by 8%, 23%, and 31% for mixes A2-S20, A3-S30, and A4-S50, with 20%, 30%, and 50% slag content respectively, when compared to A1-S10 (10% slag content).

In group B, the mixes were prepared with two different molarities of NaOH, i.e., 12 M, and 14 M. The decrease in slump value for 12 M mixes is 44% by increasing the slag content from 20% (B1-S20) to 30% (B2-S30), whereas for 14 M mixes, the slump value was decreased by 50% by increasing the slag content from 20% (B3-S20) to 30% (B4-S30). It can be concluded, therefore, that higher molarity will further lower the workability of the FS-GPC mix.

In group C, the slump of the mixes C2-S20, C3-S30, and C4-S50 was reduced by 15%, 31%, and 39% respectively as compared to mix C1-S10. For group D mixes, the slump value of the mix D2-S30 (SS/SH = 2.0) was reduced by 23% as compared to D1-S20 (SS/SH = 2.0). In the same group, the slump value of mix D4-S30 was 20% less than D3-S20 mix, both having SS/SH ratio of 3.0. In the last group E, where extra water was added to all the mixes, the similar trend was observed for slump values. The slump values of mixes E2-S20, E3-S30, and E4-S50 were reduced by 10%, 23%, and 33% respectively as compared to mix E1-S10.

The influence of slag on slump values for mixes with 30% replacement levels seemed more prominent than 10%, 20%, or 50% levels. Furthermore, it was observed that slag content has substantial influence on slump values at higher molarity of NaOH solution (i.e., M = 14), lower AAS content (35%), and lower SS/SH ratio (2.0).

#### 3.1.2. Influence of Molarity of NaOH Solution

As illustrated in Table 4, the mixes of group B were prepared with 12 M and 14 M molarity NaOH solution in comparison with group A mixes of 10 M. It can be observed from the Figure 9 that group A mixes exhibited higher slump values as compared to the respective mixes of group B. The slump values of 10 M mixes in group A are in the range of 90–130 mm, while the slump values of 12 M and 14 M mixes vary from 30–80 mm. The workability of the mixes was decreased by increasing the concentration of NaOH solution.

The lower slump values of the mixes can be attributed to the increased viscous nature of the mix solution due to higher molarity; this, consequently, resulted in stickier and less workable concrete [34,35]. Furthermore, the increase in NaOH solution concentration led to rapid solidification of the mix due to quick reaction of calcium present in the FA and slag, thus causing a decrease in the slump values of the mix [36,37].



Figure 9. Influence of mix design variables on slump values of GPC mixes.

However, the influence of NaOH solution concentration was not uniform for different slag replacement levels. The slump values of the 12 M mix B1-S20 (80 mm) and 14 M mix B3-S20 (60 mm) were decreased by 33% and 50% respectively as compared to 10 M mix A2-S20 (120 mm) for the same slag replacement level of 20%. For 30% slag replacement level, the slump value of 12 M mix B2-S30 (45 mm) and 14 M mix B4-S30 (30 mm) was reduced by 55% and 70% respectively, compared to the 10 M mix A3-S30 (100 mm). Therefore, it can be inferred that the influence of NaOH solution concentration was pronounced for the mixes with higher slag content.

## 3.1.3. Influence of AAS Content

The slump values of group A and C were compared to study the influence of AAS content on workability of FS-GPC mixes. In groups A and C, the mixes were prepared with 40% and 35% AAS content respectively. The workability of the group C mixes (35% AAS) were observed to be much lower than the group A mixes (40% AAS). The slump values of the group A mixes are between 90–130 mm, whereas the group C mixes are between 35–70 mm.

Furthermore, the influence of AAS content can be noted in mixes with different slag replacement levels. The slump values of group C mixes, C1-S10, C2-S20, C3-S30, and C4-S50 were decreased by 46%, 50%, 55%, and 61% respectively as compared to their counterparts of group A, i.e., A1-S10, A2-S20, A3-S30, and A4-S50. These lower slump values can be attributed to the decreased consistency of the mix due to reduced alkaline activator content. It can be concluded, therefore, that workability of FS-GPC mixes is strongly affected by AAS content, in agreement with the previous studies [28,34,36].

## 3.1.4. Influence of SS/SH Ratio

The slump values of group D mixes (SS/SH = 2.5 and 3.0) and group A mixes (SS/SH = 2.0) were compared to study the influence of SS/SH ratio on workability. The slump values of group A mixes were observed to be higher than the corresponding mixes

of group D (having higher SS/SH ratio). The slump values of D1-S20 (SS/SH = 2.5) and D3-S20 (SS/SH = 3.0) were decreased by 10% and 38% respectively when compared to the corresponding group A mix, A2-S20 (SS/SH = 2.0). Similarly, for D2-S30 (SS/SH = 2.5) and D4-S30 (SS/SH = 3.0), the slump values were decreased by 15% and 40% respectively as compared to A3-S30 (SS/SH = 2.0). It can be observed from Figure 2 that A2-S20 (SS/SH = 2.0) has the highest slump value of 120 mm when compared to D1-S20 (SS/SH = 2.5) and D3-S20 (SS/SH = 3.0) with slump values of 110 mm and 75 mm respectively. Similarly, A3-S30 (SS/SH = 2.0) has the highest slump values of 100 mm as compared to D2-S30 (SS/SH = 2.5) and D4-S30 (SS/SH = 3.0) with slump values of 85 mm and 60 mm respectively. It shows that workability of FS-GPC mixes decreases significantly by increasing the SS/SH ratio. Since sodium silicate has more viscosity than sodium hydroxide in AAS, higher SS/SH ratio led to more viscous AAS which resulted in lower slump values of FS-GPC mixes [28].

#### 3.1.5. Influence of Extra Water

The mixes of group C, with 35% AAS content, exhibited poor workability characteristics when compared with their counterparts in group A (40% AAS content). To improve the workability with the same AAS content, the group E mixes were prepared with additional water (12 kg/m<sup>3</sup>). As shown in Figure 2, all the mixes of group E have higher slump values as compared to the corresponding mixes of group C. The slump values of E1-S10 (150 mm), E2-S20 (135 mm), E3-S30 (115 mm), and E4-S50 (100 mm) were increased by 53%, 56%, 61%, and 65% respectively as compared to C1-S10 (70 mm), C2-S20 (60 mm), C3-S30 (45 mm), and C4-S50 (35 mm). Hence, additional water can be used to improve the workability of GPC mix in situations where high workable mixes are desired. However, the effect of the extra water on the mechanical properties needs to be studied as well.

## 3.2. Compressive Strength

Compressive strength is one of the important mechanical properties that are related to other characteristics of concrete as well. In this study, compressive strength tests were conducted on  $150 \times 150 \times 150$  mm cubes in a universal testing machine according to BS EN 12390-3:2009 (2009). The tests were conducted on three identical specimens at 3, 7, 14, 28, 56, and 90 days for each mix. The mean values of the results from three samples after the tests are shown in Table 5.

## 3.2.1. Influence of Slag Content

The compressive strengths of group A mixes with varying slag content are shown in Figure 3. It can be seen that the increase of slag content from 10 to 50% resulted in a significant improvement of the compressive strength of GPC mix. The compressive strength of all the mixes in group A increased at a faster rate till the age of 28 days, after which this rate of strength gain slowed down. It can also be observed that the rate of development of strength is significantly dependent on the slag content. The compressive strength of specimen A4-S50 (50% slag content) was more than two times that of A1-S10 (10% slag content) at 28 days. The 28 days compressive strength of A2-S20 (40 MPa), A3-S30 (54 MPa), A4-S50 (64 MPa) was 100%, 170%, and 225% higher respectively than A1-S10 (20 MPa). The 90 days compressive strength of A2-S20 (45 MPa), A3-S30 (62 MPa), and A4-S50 (69 MPa) was 80%, 150%, and 190% higher respectively than A1-S10 (25 MPa).

The increase in the compressive strength by the addition of slag is due to the development of C-S-H gel in combination with geopolymeric gel, which is produced when slag reacts with the AAS. The C-S-H gel helps GPC matrix to harden at room temperature and reduce the porosity, thus providing more compact and denser microstructure [38,39]. The C-S-H gel present in the fresh GPC matrix also provides more nucleation sites, consequently activating the geopolymer gel formation at ambient temperature, which leads to the rapid solidification and hardening process. Therefore, an explanation for the increased strength by increasing the slag content is the enhanced production of C-S-H gel during the hardening process. Hence, the more the slag content in the mix, the more amount of C-S-H gel would be available in the matrix, resulting in a higher compressive strength of the specimens.

### 3.2.2. Influence of Molarity of NaOH Solution

The concentration of NaOH solution is considered an important parameter in the geopolymerization process of GPC, since OH ions help to dissolve the aluminosilicates in the dissolution process of raw materials. Therefore, it is important to ensure that the geopolymer matrix has a sufficient amount of OH ions for the geopolymerization process. It can also be inferred that compressive strength of geopolymer matrix is dependent on the molarity of NaOH solution [40,41].

The influence of NaOH solution molarity on the compressive strength development of GPC mixes can be observed in Figure 4. It can be noticed that the compressive strength has been significantly increased as the molarity of NaOH solution was increased from 10 M (group A) to 12 M and 14 M (group B). The compressive strength of 12 M mixes, i.e., B1-S20 (48 MPa) and B2-S30 (62 MPa), has been increased by 20% and 17% respectively compared to their counterparts in 10 M mixes, i.e., A2-S20 (40 MPa) and A3-S30 (54 MPa). Similarly, the strength of 14 M mixes, i.e., B3-S20 (53 MPa) and B4-S30 (67 MPa), has been 33% and 28% higher respectively than the corresponding mixes of 10 M.

The reason for increase in strength is the quick reaction of the internal Si, Al, and Ca components present in the source materials. The high alkalinity of NaOH solution due to increased molarity leads to rapid breaking of internal bonds, i.e., Si-O or Al-O, and Ca-O or Si-O, in FA and SG respectively. Furthermore, due to increased concentration of NaOH solution, more aluminosilicates can be dissolved quickly resulting in formation of stronger bonds [42].

#### 3.2.3. Influence of AAS Content

Alkaline activator solution content is a vital parameter of GPC since it starts the dissolution of aluminosilicate in source raw materials. A sufficient quantity of aluminosilicate materials needs to be available in the matrix to confirm that adequate Si, Al, and Ca ions are present to take part in the dissolution process. Therefore, it is essential to ensure that the proportion of AAS content and binder materials must be adequate to provide an effective dissolution process. In the previous section, it is observed that the workability of mixes with reduced alkaline content (35%) was much lower than the mixes with higher alkaline activator content (i.e., 40%). Hence, an optimal alkaline activator content must be determined that should provide workable mix with acceptable compressive strength. The comparison of the compressive strength of GPC mixes with different AAS content (35%) and 40%) is shown in Figure 5.

It can be observed that the compressive strength of group C mixes (35% AAS content) was higher than the corresponding mixes of Group A (40% AAS content). Therefore, it can be inferred that the compressive strength of FS-GPC is increased by decreasing the amount of alkaline activator content from 40 to 35%. The 28 days strength of Group C mixes, C1-S10 (26 MPa), C2-S20 (46 MPa), C3-S30 (61 MPa), and C4-S50 (68 MPa) was increased by 30%, 15%, 13%, and 11% respectively compared to A1-S10 (20 MPa), A2-S20 (40 MPa), A3-S30 (54 MPa), and A4-S50 (62 MPa) of Group A mixes. The influence of alkaline activator content is observed to be more pronounced at lower level of slag content. Hence, as the slag content is increased, the difference between compressive strengths becomes smaller. It was also observed that the influence of alkaline activator content was more noticeable at the early age strength of GPC up to 14 days, with little or no effect on 90 days strength. The difference between 14 days compressive strength of group A and C mixes was 44% (A1-S10 vs. C1-S10), 31% (A2-S20 vs. C2-S20), 20% (A3-S30 vs. C3-S30) and 18% (A4-S50 vs. C4-S50) respectively. However, this difference tends to decrease after the age of 14 days and becomes negligible for both groups at 90 days. This can be attributed to the decreased consistency of the mix due to reduced alkaline activator content [34,41]. At early age, the speedy alkaline activation process accelerates the dissolution process of FA and SG, enhancing reaction products formation, thereby increasing the rate of development of compressive strength at the early age.

### 3.2.4. Influence of SS/SH Ratio

The AAS is prepared by mixing SH and SS in predetermined ratios. The SS is added to increase the silica content of the geopolymer matrix and SH is essential for dissolution process. In case the geopolymer matrix has a high silica content, more SH is then needed to achieve an affective geopolymerization process. Furthermore, the dissolution process will not be effective if the matrix has not enough of SH [43,44]. It is, therefore, important to find the optimum ratio of SH and SS in the AAS. Figure 6 illustrates the effect of the SS/SH ratios (2, 2.5, and 3.0) on the development of compressive strength of GPC. It can be observed that there is an increase in compressive strength as the SS/SH ratio increases from 2.0 to 2.5, while it decreased from 2.5 to 3.0. The compressive strength of the mixes with 20% and 30% slag content was increased by 15% and 17% respectively by the rise of SS/SH from 2.0 to 2.5. However, when this ratio was further increased to 3.0, a decrease in strength was observed by 7% and 10% respectively for mixes having 20% and 30% slag content. The enhancement in strength can be credited to the modification in microstructure of the geopolymer matrix due to the increased quantity of SS. However, when the ratio is increased to 3.0, the adequate quantity of SH may not be available in the matrix that is required for the completion of dissolution process during the development of geopolymer which resulted in a drop of strength of the GPC mix.

## 3.2.5. Influence of Extra Water

The preliminary mixes of group C with 35% AAS content exhibited poor workability characteristics showing slump values from 70 mm to 35 mm when compared to mixes of group A (40% AAS content). In group E (35% AAS), additional water ( $12 \text{ kg/m}^3$ ) was used to enhance the workability of GPC mixes. The influence of additional water on the strength properties of FS-GPC has not been broadly stated yet. Thus, the influence of extra water in the mix was studied to find whether it can be used to enhance the workability of GPC mixes with an acceptable strength.

As illustrated in Figure 7, the compressive strength of all mixes of group E was reduced as compared to their counterparts of group C due to the extra water. However, the influence of extra water was observed to be less prominent on mixes with high slag content. The 28 days compressive strength of group E mixes, E1-S10 (17 MPa), E2-S20 (36 MPa), E3-S30 (51 MPa), and E4-S50 (63 MPa) was reduced by 34%, 22%, 14%, and 8% respectively as compared to their corresponding mixes of group C viz. C1-S10 (26 MPa), C2-S20 (46 MPa), C3-S30 (59 MPa), and C4-S50 (69 MPa). Figure 10 shows the influence of extra water on compressive strength of geopolymer concrete mixes (Group C vs. Group E).

When AAS content was reduced to 35% and extra water was used to improve the workability of the mix, then the concentration of the AAS decreased; as a result, fewer SH ions were available in the mix to dissolve the aluminosilicates. The compressive strength of the mix containing 50% slag content as binder was least influenced (8% strength reduction) by the addition of extra water. The presence of slag in the mix led to the formation of C-S-H gel in the matrix along with the geo-polymeric gel. This gel leads to substantial increase in strength; consequently, if the amount of slag in the mix is increased then more C-S-H gel will be formed. Thus, if the amount of AAS is reduced and extra water is added to the mix containing higher slag content, there still will be enough OH ions present in the matrix to form enough C-S-H gel. Hence, the result is the strength comparable to the mixes without the extra water.



Figure 10. The influence of extra water on compressive strength of geopolymer concrete mixes (Group C vs. Group E).

#### 3.3. Tensile Strength

Tensile strength is one of the important mechanical properties and is utilized in various design aspects of concrete structures such as those associated with the initiation and propagation of cracks, shear, and anchorage of steel reinforcement in concrete [45]. The indirect tensile strength tests were performed on 150 mm  $\times$  300 mm cylinders after 28 days of casting according to ASTM C496/C496M-11. The effect of different mix design variables on indirect tensile strength is shown in Figure 8. It can be observed from the results of groups A and C that tensile strength of FS-GPC mixes increased by increasing the amount of slag and decreasing the AAS. As shown in Figure 8, mixes of group A designed with 10 M molarity NaOH solution exhibited lower tensile strengths as compared to the corresponding mixes of group B with higher molarity NaOH solution (12 M and 14 M). The tensile strength of FS-GPC was also increased by increasing the concentration of NaOH solution. Furthermore, it can be noted from the results of groups A and D that tensile strength of GPC mix increased significantly by varying SS/SH ratio from 2.0 to 2.5, while a decrease in strength was observed when the ratio was further increased from 2.5 to 3.0. The trends observed for the tensile strength results are the same as were observed for the compressive strength. The tensile strength of group E mixes prepared with reduced AAS content (35%) and additional water content (12 kg/m<sup>3</sup>) was decreased as compared to group C mixes with similar AAS and no additional water. This result is also identical to the compressive strength results discussed earlier.

In conventional concrete design, the compressive strength is often used to estimate the tensile strength since a correlation exists between the two. The correlation is generally represented by a simple equation which is used to estimate uniaxial or split tensile strength. For example, the Equations (1)–(3) are recommended by the ACI 318-14, Eurocode BS EN 1992-1-1:2004 and Australian standard AS 3600, 2009 respectively to predict the tensile strength of OPC mixes.

$$f_{ct} = 0.56 \sqrt{f_c'} \tag{1}$$

$$f_{ct} = 0.30 (f_c)^{2/3} \text{ for } f_c \le 50 \text{ MPa}$$
 (2)

$$f_{ct} = 0.36 \sqrt{f_c'}$$
 (3)

where  $f_{ct}$  = mean split tensile strength (MPa),  $f'_c$  = characteristic compressive strength (MPa), and  $f_c$  = average compressive strength (MPa). Figure 11 shows the influence of mix design variables on tensile strength of FS-GPC at the age of 28 days.



Figure 11. The influence of mix design variables on tensile strength of FS-GPC at the age of 28 days.

Lee and Lee (2013) and Sofi et al. (2007) have used the equations recommended by ACI 318-08 (Equation (1)) and Eurocode (Equation (2)) respectively to estimate the tensile strength of GPC mixes [30,46]. They have found that the estimated strength values were higher than the measured values. By using the experimental results, the Equations (4) and (5) were proposed by Lee and Lee (2013) and Sofi et al. (2007) respectively to predict the split tensile strength of FA and SG based GPC.

$$f_{ct} = 0.45 \sqrt{f_c'} \tag{4}$$

$$f_{ct} = 0.48 \sqrt{f_c'} \tag{5}$$

In the present study, Equation (4) (Lee and Lee (2013)) and Equation (5) (Sofi et al. (2007)) were used to estimate the tensile strength of GPC mixes based on their compressive strength [30,46]. The calculated values from these equations along with the test values from the present study are presented in Table 6 and Figure 9. The comparison between predicted and measured values showed that the test values of the present study are lower as compared to the values predicted by the models of Sofi et al. (2007) (Equation (5)) and Lee and Lee (2014) (Equation (4)).

It is worth mentioning that the relationship between the tensile strength and compressive strength of GPC is significantly influenced by several factors, i.e., type of source materials, chemical composition of the source materials, curing techniques, type of alkaline activators, and composition of activating solution. Considering the mixing procedure, curing method, testing age, and chemical composition of the source materials were similar for Lee and Lee (2013), Sofi et al. (2007), and the present study, the variation in the predicted and the measured values can be due to the difference in composition of the activating solution and the mix proportions. Lee and Lee (2013) used the AAS content as 56% of the total binder and NaOH solution with 4 M and 6 M molarity, whereas, in the present study, AAS contents were 40% and 35% of the total binder with molarity of NaOH solution as 10 M, 12 M, and 14 M. Sofi et al. (2007) used sodium silicate and potassium hydroxide to prepare the AAS. The sodium silicate and potassium hydroxide were mixed in a predetermined ratio of 1.5. However, in the present study, sodium silicate and sodium hydroxide were used to prepare the activating solution with their ratio as 2, 2.5, and 3.0. These variations might have resulted in different correlations for predicting the values of splitting tensile strengths. Nevertheless, the present study can be considered as an effort to propose a

relatively more suitable empirical relationship (Equation (6)), based on the existing data and the observations from the present study, for predicting the splitting tensile strength of ambient cured FS-GPC.

$$f_{ct} = 0.40 \ (f_c)^{1/2} \tag{6}$$

where,  $f_{ct}$  = mean split tensile strength (MPa), and  $f_c$  = average compressive strength measured on cubes (MPa). Figure 12 shows the comparison of the test and estimated values of indirect tensile strength of GPC mixes specimens at the age of 28 days.

Tensile Strength,  $f_{ct}$  (MPa) Compressive Mix ID Strength,  $f_{cm}$  (MPa) Test Lee & Lee Sofi et al. Test/Lee & Lee Test/Sofi et al. 1.9 2.0 2.1 0.94 0.89 A1-S10 20.0 0.88 A2-S20 40.0 2.5 2.8 3.0 0.82 A3-S30 54.0 2.9 3.3 3.5 0.88 0.82 A4-S50 3.4 3.9 0.94 65.0 3.6 0.88 B1-S20 48.0 2.8 3.1 3.3 0.90 0.84 B2-S30 3.3 0.92 63.0 3.6 3.8 0.87 B3-S20 53.0 2.9 3.3 3.5 0.89 0.83 B4-S30 69.0 3.5 3.7 4.0 0.94 0.88 C1-S10 26.0 2.3 2.3 2.4 1.00 0.94 C2-S20 46.0 3.1 3.1 3.3 1.02 0.95 C3-S30 59.0 3.3 3.5 3.7 0.95 0.90 3.7 3.7 C4-S50 69.0 4.0 0.99 0.93 D1-S20 2.9 3.1 0.95 46.0 3.3 0.89 D2-S30 3.3 3.6 3.8 0.92 0.87 63.0 2.7 D3-S20 37.0 2.5 2.9 0.91 0.86 D4-S30 49.0 2.9 3.2 0.92 0.86 3.4 E1-S10 17.0 1.7 1.9 2.0 0.92 0.86 2.7 E2-S20 36.0 2.2 2.9 0.81 0.76 E3-S30 51.0 2.7 3.2 0.79 3.4 0.84 E4-S50 63.0 3.1 3.6 3.8 0.87 0.81





**Figure 12.** The comparison of the test and estimated values of indirect tensile strength of GPC mixes specimens at the age of 28 days.

#### 3.4. Flexural Strength

The flexural strength tests were performed on  $100 \times 100 \times 400$  mm prisms after 28 days of curing following the ASTM C78/78M-16. The flexural strength values of GPC along with the compressive strength values are presented in Table 7. The effect of NaOH solution concentration, slag content, alkaline activator content, SS/SH ratio, and inclusion of extra water on flexural strength were studied. The influence of these mix design variables on 28 days flexural strength of FS-GPC is shown in Figure 10. It can be observed that the results of flexural strengths for all mixes follow the trends similar to that of the compressive and split tensile strength results. The comparison between groups A and C (Figure 10) showed that the flexural strength of GPC mixes increased by increasing the slag replacement levels (10% to 50%) and decreasing the amount of AAS content (40% to 35%). The specimens of group B prepared with 12 M and 14 M NaOH solution showed higher flexural strength in comparison to the corresponding specimens of group A (10 M NaOH solution). It can be observed from the results of groups A and D that the GPC mix showed increase in flexural strength by increasing SS/SH ratio from 2.0 to 2.5, while a decrease in strength was observed by increasing this ratio from 2.5 to 3.0. The flexural strength of group E specimens prepared with reduced AAS content (35%) and additional water content (12 kg/m<sup>3</sup>) was decreased as compared to the group C mixes with similar AAS content and without extra water. Figure 13 shows the compressive strength variations of group A mixes with different slag content.

Mix ID	Commenceirre	Flexural Strength, $f_{ct,f}$ (MPa)							
	Strength, $f_{cm}$ (MPa)	Test	Diaz-Loya et al.	Nath and Sarkar	Test/Diaz-Loya et al.	Test/Nath and Sarkar			
A1-S10	20.0	2.2	3.1	4.2	0.71	0.53			
A2-S20	40.0	3.1	4.4	5.9	0.71	0.53			
A3-S30	54.0	3.7	5.1	6.8	0.73	0.54			
A4-S50	65.0	4.1	5.6	7.5	0.74	0.55			
B1-S20	48.0	3.6	4.8	6.4	0.75	0.56			
B2-S30	63.0	4.2	5.5	7.4	0.77	0.57			
B3-S20	53.0	3.9	5.0	6.8	0.78	0.58			
B4-S30	69.0	4.5	5.7	7.7	0.79	0.58			
C1-S10	26.0	2.7	3.5	4.7	0.77	0.57			
C2-S20	46.0	3.7	4.7	6.3	0.79	0.59			
C3-S30	59.0	4.3	5.3	7.1	0.81	0.60			
C4-S50	69.0	4.9	5.7	7.7	0.85	0.63			
D1-S20	46.0	3.5	4.7	6.3	0.75	0.55			
D2-S30	63.0	4.1	5.5	7.4	0.75	0.56			
D3-S20	37.0	3.0	4.2	5.7	0.71	0.53			
D4-S30	49.0	3.5	4.8	6.5	0.72	0.54			
E1-S10	17.0	1.8	2.8	3.8	0.63	0.47			
E2-S20	36.0	2.7	4.1	5.6	0.65	0.48			
E3-S30	51.0	3.4	4.9	6.6	0.69	0.51			
E4-S50	63.0	3.9	5.5	7.4	0.71	0.53			

Table 7. The measured and predicted values of flexural strength.



Figure 13. The compressive strength variations of group A mixes with different slag content.

Generally, a strong relationship between flexural and compressive strengths of conventional concrete exists. Therefore, the flexural strength of conventional concrete can be predicted from the correlations suggested by the design codes and studies. ACI 318-14 and AS 3600, 2009 provide simple equations (Equations (7) and (8) respectively) to estimate the flexural strength of the OPC mixes. However, there is a need to validate the use of these equations for estimating flexural strength of GPC mixes.

$$f_{ct,f} = 0.62 \sqrt{f_c'}$$
 (7)

$$f_{ct.f} = 0.60 \sqrt{f_c'} \tag{8}$$

where,  $f_{ct.f}$  = characteristic flexural tensile strength of concrete. Figure 14 shows the influence of mix design variables on flexural strength of FS-GPC specimens at the age of 28 days.



Figure 14. The influence of mix design variables on flexural strength of FS-GPC specimens at the age of 28 days.

$$f_{ct.f} = 0.69 \sqrt{f_c} \tag{9}$$

Nath and Sarker (2017) used ACI 318-14 (Equation (7)), AS 3600 (Equation (8)), and Diaz-Loya et al. (Equation (9)) relationships to predict the flexural strength of ambient cured fly-ash based GPC [48]. It was observed that their measured values were higher than the predicted values. However, the estimated values provided by AS 3600 (Equation (8)) were closer to their measured values than the values predicted by the other equations. Nath and Sarkar (2017) also proposed an empirical relationship (Equation (10)) based on their experimental test data to best fit their results, given by:

$$f_{ct.f} = 0.93 \sqrt{f_c} \tag{10}$$

In the present study, the flexural strengths of all GPC mixes were estimated by the relationships proposed by Diaz-Loya et al. (2011) (Equation (9)) and Nath and Sarker (2017) (Equation (10)). The estimated values of flexural strength from these equations along with the test values from the present study are presented in Table 7 and Figure 15. Figure 16 shows the comparison of the measured and estimated values of flexural strength of GPC mixes specimens at the age of 28 days.



Figure 15. The compressive strength variations of groups A and B mixes with molarity of NaOH solution.



**Figure 16.** The comparison of the measured and estimated values of flexural strength of GPC mixes specimens at the age of 28 days.

As shown in Figure 11, the expressions suggested by Diaz-Loya et al. (Equation (9)) and Nath and Sarker (Equation (10)) have overestimated the flexural strength of ambient cured GPC mixes. The values predicted by Diaz-Loya et al. (2011) and Nath and Sarkar (2017) relationships were about 60% and 100% higher respectively than the measured values of this study. The mixing procedure, AAS content, and SS/SH ratio were almost the same in both the above studies. They have used low-calcium fly ash to produce the geopolymer concrete. However, the source material used to produce the geopolymer binder was different than the present study. Nath and Sarkar (2017) have used the ambient curing conditions; whereas, heat curing was adopted by Diaz-Loya et al. (2011). Hence, Diaz-Loya et al. (Equation (9)) and Nath and Sarkar (Equation (10)) relationships were proposed for heat cured and ambient cured fly ash based geopolymer concrete respectively. For the sake of comparison and to develop a more suitable relationship, these proposed equations were used to predict the flexural strength of ambient cured FS-GPC of the present study. Therefore, the marginal difference in the predicted and the measured values can be attributed to the difference in the source materials and the curing techniques. From the test results of this study, a more appropriate expression to estimate the flexural strength of ambient cured FS-GPC was proposed using regression analysis and given by:

$$f_{ct,f} = 0.25 \left( f_c \right)^{2/3} \tag{11}$$

where,  $f_{ct}$  = characteristic flexural strength of concrete (MPa), and  $f_c$  = average compressive strength measured on cubes (MPa).

## 3.5. Elastic Modulus

Modulus of elasticity is a mechanical property of concrete that is used in design aspects of structural members, i.e., columns, beams, and slabs. It determines the resistance of concrete members to elastic deformation against the applied load. The static modulus of FS-GPC mixes was measured by conducting tests on  $150 \times 300$  mm cylindrical specimens according to ASTM C469/C469M-10 at the age of 28 days. For each mix, three identical specimens were tested, and mean values of results obtained from the tests are presented in Table 8. The effect of different mix design parameters on the measured elastic modulus is presented in Figure 12.

		Elastic Modulus, $E_c$ (GPa)									
Mix ID	Strength, $f_{cm}$ (MPa)	Test	Lee & Lee	Diaz-Loya	Nath & Sarkar	Test/Lee & Lee	Test/Diaz- Loya	Test/Nath & Sarkar			
A1-S10	20.0	15.4	14.2	18.8	15.7	1.08	0.82	0.98			
A2-S20	40.0	21.8	17.9	26.7	22.2	1.22	0.82	0.98			
A3-S30	54.0	26.6	19.8	31.2	25.8	1.35	0.85	1.03			
A4-S50	65.0	30.3	21.0	34.8	28.3	1.44	0.87	1.07			
B1-S20	48.0	24.1	19.0	29.4	24.3	1.27	0.82	0.99			
B2-S30	63.0	30.1	20.8	33.8	27.9	1.45	0.89	1.08			
B3-S20	53.0	27.8	19.6	30.9	25.6	1.42	0.90	1.09			
B4-S30	69.0	31.2	21.4	35.5	29.2	1.46	0.88	1.07			
C1-S10	26.0	19.0	15.5	21.3	17.9	1.22	0.89	1.06			
C2-S20	46.0	24.8	18.7	28.4	23.8	1.32	0.87	1.04			
C3-S30	59.0	29.0	20.4	32.2	27.0	1.42	0.90	1.08			
C4-S50	69.0	30.9	21.4	35.1	29.2	1.44	0.88	1.06			
D1-S20	46.0	22.1	18.7	28.8	23.8	1.18	0.77	0.93			
D2-S30	63.0	27.2	20.8	33.8	27.9	1.31	0.80	0.98			
D3-S20	37.0	20.6	17.4	26.0	21.4	1.18	0.79	0.96			
D4-S30	49.0	24.2	19.1	30.2	24.6	1.26	0.80	0.98			
E1-S10	17.0	14.5	13.5	17.0	14.5	1.07	0.85	1.00			
E2-S20	36.0	20.4	17.3	24.9	21.1	1.18	0.82	0.97			
E3-S30	51.0	24.6	19.4	29.7	25.1	1.27	0.83	0.98			
E4-S50	63.0	29.8	20.8	33.2	27.9	1.43	0.90	1.07			

Table 8. The predicted and test values of elastic modulus.

It is evident from Figure 12 and the results of groups A, C, and E that the elastic modulus of FS-GPC mixes increased steadily by increasing the slag content from 10% to 50%. The elastic modulus of group B mixes, designed with 12 M and 14 M molarity of NaOH solution, was higher than the corresponding mixes of group A prepared with 10 M NaOH solution. Furthermore, decrease of AAS content from 40% (group A) to 35% (group C) also led to increase in elastic modulus of GPC mixes. The trends are similar to that of the compressive strength results. However, the influence of SS/SH ratio on static modulus was not the same as that of the compressive strength results. It can be observed from the results of groups A and D that increase of SS/SH ratio from 2.0 to 2.5 has no effect on static modulus while a decrease in static modulus was observed when it was further increased from 2.5 to 3.0. The effect of additional water on elastic modulus was also like that of the compressive strength results as discussed earlier. Generally, the modulus of elasticity of conventional concrete varies with the compressive strength. By comparing the results of compressive strength and elastic modulus of all the groups, it was observed that the elastic modulus of FS-GPC mixes increased with the increase in compressive strength. Therefore, it can be inferred that the increase of elastic modulus of FS-GPC mix is attributed to the increase in compressive strength due to the variation in mix design parameters [48]. Figure 17 shows the compressive strength variations of groups A and C mixes with alkaline activator content. Furthermore, Figure 18 indicates the influence of mix design variables on elastic modulus of FS-GPC mix specimens at the age of 28 days.



Figure 17. The compressive strength variations of groups A and C mixes with alkaline activator content.





The elastic modulus of FS-GPC mixes was predicted by the empirical relationships suggested by different studies. According to ACI 318-14, the static modulus of normal density ( $1500-2500 \text{ kg/m}^3$ ) OPC concrete can be estimated by the following equation (Equation (12)):

$$E_c = 0.043 \times \rho^{1.5} \times \sqrt{f_c'} \tag{12}$$

Another relationship (Equation (13)) suggested by CEB-FIP Model Code 90 (1993) for static modulus of normal density concrete is given by:

$$Ec = 0.85 \times 2.15 \times 10^4 \times \left(\frac{f'_c}{10}\right)^{0.33}$$
 (13)

where  $E_c$  = elastic modulus of concrete (MPa),  $\rho$  = density of concrete (kg/m<sup>3</sup>), and  $f'_c$  = characteristic compressive strength (MPa).

Diaz-Loya et al. (2011) proposed Equation (14) based on their test results to calculate the elastic modulus of FA based geopolymer concrete mixes cured at elevated temperature [47].

$$E_c = 2707 \times \sqrt{f_c + 5300}$$
(14)

where,  $E_c$  is the elastic modulus of concrete (MPa) and  $f_c$  is the compressive strength of concrete at the age of 3 days. The heat cured geopolymer concrete achieved compressive strength close to the ultimate strength during the initial curing period. However, the ambient cured geopolymer concrete develops strength gradually over time. Therefore, the strength after 28 days of curing has been used to calculate the elastic modulus in the present study.

Lee and Lee (2013) analyzed the data obtained from their experimental study on ambient cured FS-GPC specimens and proposed the Equation (15) to estimate the elastic modulus [30].

$$Ec = 5300 \times (f_c)^{\frac{1}{3}} \tag{15}$$

Nath and Sarkar (2017) also suggested a relationship (Equation (16)) based on their experimental results to predict the elastic modulus of ambient cured blended low calcium FA based GPC mixes [48].

$$E_{cj.a} = 3510 \times \sqrt{f_c} \tag{16}$$

where,  $E_{cj,a}$  is the elastic modulus of ambient cured FA based GPC in MPa.

Table 8 and Figure 13 show the comparison between the values of elastic modulus measured from the tests of the present study and predicted from the proposed equations of previous studies. It can be observed from the Figure 13 that the values of the ambient cured FS-GPC mixes predicted by Diaz-Loya et al. (2011) model (Equation (14)) are higher than the test values. The equation proposed by Diaz-Loya et al. was developed for heat cured fly-ash based geopolymer concrete. The elastic modulus of heat cured GPC are generally found to be lesser when compared to modulus of OPC mixes. The values predicted by Lee and Lee (2013) relationship (Equation (15)) were observed to be lower than the measured values of this study. The predicted values of Lee and Lee model were about 25-30% lesser than the present study. The reason of this difference may be due to the composition of source materials (FA and SG), variation in mix proportions, difference in activating solution and curing techniques. Lee and Lee (2013) used high alkaline solution to binder ratio (0.56), low molarity of alkaline solution (4 M and 6 M NaOH), and lower sodium silicate to sodium hydroxide ratio (SS/SH = 0.5 and 1), which resulted in difference between predicted and measured values of strength and elastic modulus. It can be observed that the predictions by Nath and Sarkar (2017) relationship are the closest to the measured values of the present study, i.e., ambient cured FS-GPC mixes, while the equations proposed by Lee and Lee (2013) and Diaz-Loya et al. (2011) yield lower and higher values respectively than the present study. The source materials, curing method, alkaline activating solution, and mix proportions vary for the above-mentioned studies, which affects the predicted values of elastic moduli. Figure 19 shows the compressive strength variations of groups A and D mixes with different SS/SH ratios. Moreover, Figure 20 shows the comparison of test and estimated values of elastic modulus of GPC mixes specimens at the age of 28 days. Based on the experimental test data of this study, Equation (17) was proposed to predict the elastic modulus of ambient cured FS-GPC, given by:

$$Ec = 2.5 \times (f_c)^{\frac{3}{5}} \tag{17}$$

where Ec = elastic modulus of concrete (GPa) and  $f_c$  = average compressive strength measured on cubes (MPa). Figure 20 shows the comparison of test and estimated values of elastic modulus of GPC mixes specimens at the age of 28 days.



Figure 19. The compressive strength variations of groups A and D mixes with different SS/SH ratios.



Figure 20. The comparison of test and estimated values of elastic modulus of GPC mixes specimens at the age of 28 days.

# 4. Concluding Remarks

This paper presented the results of an experimental program conducted to evaluate the influence of five main parameters of ambient cured FS-GPC on fresh and hardened properties. The following key conclusions have been drawn from this study:

• Increasing the slag replacement levels and decreasing the alkaline activator content resulted in a reduction of workability for all FS-GPC mixes. The slag contents have substantial influence on the slump values at higher molarity of NaOH solution M = 14, lower AAS content (35%), and lower value of SS/SH ration (2.0). The workability of FS-GPC mixes was also decreased by increasing the molarity (10 M to 12 M and 14 M) of NaOH solution. The influence of NaOH solution concentration was more noticeable for the mixes with higher slag content. Increasing the sodium silicate content (SS/SH = 2.0 to 2.5 or 3.0) in AAS also led to a decrease in workability of the mix. The additional water can be used to enhance the workability of FS-GPC mixes in situations where high workable (100 mm to 150 mm) concrete mixes are desired, keeping in view the strength requirements.

- The increase in the slag contents from 10% to 50% resulted in an increase in the compressive strength for the mixes at a rapid rate till the age of 28 days, after which the rate of development of strength slowed down. The compressive strength of FS-GPC mixes was also increased by increasing the molarity (10 M to 12 M, and 14 M) of NaOH solution and lowering the AAS content to 35%. The influence of amount of alkaline activator seems to be more pronounced at lower levels of slag contents. The influence of alkaline activator was more noticeable at early age of GPC mixes, i.e., 7 to 14 days, with little or no effect at 90 days strength. The mixes showed increase in compressive strength by increasing SS/SH ratio from 2.0 to 2.5, whereas beyond 2.5 it decreased. The strength of FS-GPC mixes decreased with the addition of extra water (excluding that used for preparing AAS).
- The practicable mix for FS-GPC, with slump value in the range of 60–100 mm and 28 days compressive strength values in the range of 30–50 MPa, suitable for various concreting applications, i.e., columns, beams, and foundations, can be obtained by limiting the slag content to 20% or 30%, SS/SH ratio to 2.0 or 2.5, molarity of NaOH solution to 10 M or 12 M, and alkaline content to 40%.
- The tensile and flexural strength of FS-GPC mixes showed similar trends to that of the compressive strength. The tensile and flexural strength of FS-GPC increased by increasing the slag replacement levels, molarity of NaOH solution, and SS/SH ratio (2.0 to 2.5) and decreasing the alkaline activator content (40% to 35%). The influence of slag content, molarity of NaOH solution, and AAS content on the elastic modulus of FS-GPC mixes was also similar to that of the compressive strength. However, the influence of SS/SH ratio on the static modulus was different than the compressive strength. Increasing the SS/SH ratio from 2.0 to 2.5 had no effect on the elastic modulus, while a decrease was observed when it was increased from 2.5 to 3.0.
- The expressions provided by Diaz-Loya et al. and Nath and Sarkar have overestimated the values of flexural strength as compared to the present study. The values of tensile strength predicted by Sofi et al. were much higher than the experimentally measured values of this study. The values of elastic modulus predicted by Diaz-Loya et al. were higher, whereas those predicted by Lee and Lee were much lower than the present study. From the test results of the present study, Equations (6), (11), and (17) are proposed to predict the tensile strength, flexural strength, and static modulus of ambient cured FS-GPC mixes, respectively. The schematic illustration of the proposed relationship is shown in Figure 21.
- The study proposed empirical equations which are valid for ambient cured FS-GPC mixes with slag contents 10% to 50% of total binder; AAS content 35% to 40% of total binder; molarity of NaOH solution 10 M to 14 M, and SS/SH ratio 2.0 to 3.0. These equations can be used to provide prediction of tensile strength, flexural strength, and modulus of elasticity of FS-GPC mixes with 28 days compressive strengths in the range of 30–60 MPa.



**Figure 21.** The schematic illustration of proposed relationships for specified mixture proportions of fly ash and slag based geopolymer concrete.

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