Influence of steel slag on strength properties of fly ash-based geopolymer concrete

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***Abstract*—Geopolymer concrete (GPC) is a novel construction material with diverse chemical compositions and reactions, utilizing pozzolanic materials such as fly ash, GGBFS, and rice husk ash as binding agents due to their high silica and alumina content. GPC offers economic benefits, low energy consumption, thermal stability, easy workability, eco-friendliness, and durability. By leveraging industrial waste like slag, fly ash, and rice husk ash, GPC reduces carbon footprints significantly compared to traditional cement production, thereby contributing to environmental sustainability. It serves as a promising alternative to Portland cement concrete, offering comparable physical, mechanical, and durability properties while addressing the need for sustainable development in the Indian construction sector. It can be concluded from the investigation that the geopolymer samples have shown better outcomes compared to conventional concrete samples. Higher mechanical values were observed at a mix proportion of 70% of FA and 30% of GGBFS-based geopolymer concrete.**

***Index Terms*—Geopolymer Concrete; Fly ash; Ground Granulated Blast Furnace Slag; Mechanical Properties**

I. INTRODUCTION

Iron, steel-making, and power generation industries generate a substantial volume of industrial waste, including materials like blast furnace slag and fly ash [1-4]. Disposing of this waste safely poses a significant challenge. Extensive research has been undertaken to address this issue and find effective ways to manage and utilize the waste generated by these industries [5-7]. As a result, geopolymer concrete composite has emerged as a promising material with the potential to efficiently utilize industrial waste in concrete development. Geopolymer concrete offers an environmentally friendly alternative by reducing or eliminating the need for Portland cement [8-10].

These aluminosilicates can transform into a binder through alkaline activation. Davidovits first introduced the concept of geopolymer in 1978, defining it as an inorganic polymer formed from the poly-condensation reaction of alumina–silicate source materials such as fly ash, rice husk ash, and metakaolin [11]. This reaction yields three-dimensional tecto-aluminosilicate frameworks. The resulting Ca-Al-Si-H2O and Na-Al-Si-H2O gels, developed through poly-condensation, provide structural integrity to the geopolymer composite [12-15]. The curing conditions significantly influence geopolymerization reactions; optimal conditions are typically around 35 °C to 85 °C temperature and approximately 95% humidity, which facilitate better curing of geopolymer concrete. Consequently, the properties of the final product are heavily influenced by various processing parameters and their ingredients [16-20].

The geopolymer concrete composite generally possess almost similar or improved strength and resistance to the environmental agencies [21,22]. Various researchers have concluded that the geopolymer concrete made of GGBS and Fly Ash have better resistance to the acid and sulphate attack [23]. A number of research works have been conducted that focuses on the use of domestic and industrial waste as aggregates in conventional as well as in geopolymer concrete [24,25]. Few researchers have reported that geopolymer concrete made of GGBS and Fly ash possesses good chloride resistance as well as good weathering resistance [26]. Limited research has been conducted on the diverse factors influencing optimal geopolymer preparation under various curing conditions, with particularly scarce information on geopolymerization reaction mechanisms. Notably, achieving high mechanical properties in specialized concrete is crucial for enhancing geopolymers' mechanical attributes [27].

II. RESEARCH SIGNIFICANCE

This paper aims to present the influence of steel slag on fly ash-based geopolymer concrete under ambient curing conditions. On the other hand, the mechanical properties were studied at different proportion levels of steel slag. The mechanical properties such as compressive strength and split tensile strength were determined to know the influence of steel slag in fly ash-based geopolymer concrete.

III. MATERIALS AND MIX PROPORTIONS

The prepared samples primarily consisted of precursors (FA and GGBFS), sourced from UltraTech Cements Limited in Vijayawada, Andhra Pradesh, India. An alkaline activator solution, comprising sodium-based solutions such as sodium silicate and sodium hydroxide, was employed to bind the raw materials. The sodium silicate solution had 28.6% SiO2, 9% Na2O, and 62.4% water, utilizing NaOH pellets of over 99% purity. All GC samples were produced using an 8-molarity NaOH solution. For the sodium hydroxide solution, NaOH pellets were dissolved in water to create a 10-molar solution. The NaOH to Na2SiO3 ratio was maintained at 1:2 for all GC mixtures, with an alkaline liquid-to-binder ratio (S/B ratio) set at 0.4. The activator solution was prepared by mixing NaOH and Na2SiO3 solutions 24 hours prior to GC synthesis and stored for prolonged use. Locally available natural River sand served as fine aggregates, while coarse aggregates comprised granite rock pieces in the manufacturing process of GC.

Figure 1: Raw fly ash and ground granulated blast furnace slag

Table 1 Chemical composition of raw materials used in this paper

Material	SiO_2	MgO	Al_2O_3	Na_2O	Fe_2O_3	TiO_2	CaO	SO_3	MnO	K_2O	P_2O_5	LOI
Slag	31.16	3.62	12.27	0.91	1.3	-	46.51	0.76	2.05	-	-	1.42
FA	59.13	1.18	24.11	0.38	5.06	0.72	2.55	1.25	2.76	0.91	0.31	1.64

Initially, a solution comprising sodium silicate, sodium hydroxide, and water with the appropriate modulus was prepared. After stirring and dissolving, the process, which was exothermic, was sealed and left to cool at room temperature for 24 hours. Subsequently, FA and GGBFS were introduced into the stirring pot and mixed for 2 minutes at low speed to ensure thorough integration of the solid raw materials. Following this, the alkaline activator was added to the stirring pot and stirred for a total of 6 minutes, including 2 minutes at low speed and 4 minutes at high speed. The freshly prepared geopolymer paste was then cast into 150 mm cubes and 150 x 300 mm cylinders for compression and tensile strength testing. To minimize the formation of bubbles and fluid irregularities during casting, the mold was placed on a vibrating table and subjected to low-frequency vibrations for 30 seconds. Finally, the surface of the specimens was leveled using a steel ruler.

This study investigated six mixtures, including one control mix, to assess the desired properties. The variables examined were the addition of steel slag content and the ratios of sodium silicate to sodium hydroxide in the GPC mixtures. The concrete mix designs are outlined in Table 2. Steel slag was utilized to replace fly ash in the geopolymer mixtures, with four alternative replacement ratios (0%, 10%, 20%, and 30% by weight of fly ash) for each method. The objective of the replacement was to determine the maximum amount of steel slag that could be incorporated without compromising the mechanical and physical properties of the geopolymers based on FA. The specimens were labeled as CM, GM1, GM2, GM3, and GM4, corresponding to the amount of FA replaced with steel slag and variations in alkaline ratios. For comparison with the geopolymer samples, the control mix (CM) was prepared using OPC.

Table 2: Mix proportions of GPC and control samples

Mix Lable	Binder			Aggregate		NaOH: Na2SiO3
	Cement	GGBFS	FA	Coarse	Fine	
CM	360	-	-	1217	610	1:1
GM1	-	36	324	1217	610	1:1
GM2	-	72	288	1217	610	1:1
GM3	-	108	252	1217	610	1:1
GM4	-	144	216	1217	610	1:1

IV. TEST METHODS

The workability of a geopolymer concrete mixture is measured by using the Slump cone test. This test is carried out with a mould called a slump cone whose top diameter is 10cm, bottom diameter is 20 cm and height is 30 cm. The test may be performed in the following steps: 1. Place the slump mould on a smooth flat and non-absorbent surface. 2. Mix the dry ingredients of the concrete thoroughly till a uniform color is obtained and then add the required quantity of water. 3. Place the mixed concrete in the mould to about one-fourth of its height. When the settlement of concrete stops, measure the subsidence of the concrete in millimeters which is the required slump of the concrete. Mechanical properties such as compressive strength and split tensile strength properties were tested using a compression testing machine with 300 kN capacity. Compressive strength is the capacity of concrete to withstand applied loads on its surface without exhibiting cracks or deformations. When subjected to compression, materials tend to decrease in size, whereas tension forces cause elongation. The compressive strength formula for any material is the load applied at the point of failure to the cross-section area of the face on which the load was applied. A compression testing machine, often referred to as a compressive strength testing machine, is an essential apparatus used to determine the compressive strength of materials, particularly concrete and other construction materials. This machine applies axial loads to test specimens in a controlled and gradual manner to assess their ability to withstand compression forces without failing or deforming. It plays a crucial role in quality control and design in construction and material industries, ensuring that structures and materials meet the required strength standards.

Compressive Strength = Load / Cross-sectional AreaEq. (1)

Figure 2: Compression testing machine

Figure 3: Workability of geopolymer and conventional concrete

The tensile strength of concrete is one of the basic and important properties that greatly affect the extent and size of cracking in structures. Moreover, the concrete is very weak in tension due to its brittle nature. Hence. it is not expected to resist the direct tension. So, concrete develops cracks when tensile forces exceed its tensile strength. Therefore, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack. Furthermore, splitting tensile strength test on concrete cylinder is a method to determine the tensile strength of concrete. Apply loads at a constant rate within the range 0.7 to 1.4 MPa/min (1.2 to 2.4 MPa/min based on IS 5816-1999) splitting tensile stress until the specimen fails.

V. RESULT AND DISCUSSION

5.1 Workability

The workability of geopolymer concrete can be determined by using various test methods, but in this paper slump cone method is used to find the workability. From the experimental results, it was clear that the increase in the GGBFS content the workability of GPC is reduced. However, a higher slump value is found in conventional concrete samples compared to GPC samples. The workability of various samples used in this paper is 74, 92, 84, 71 and 58 for the mixes of CM, GM1, GM2, GM3, and GM4 respectively. The greater workability value is observed in the 100% fly ash-based GPC sample compared to all other mixes. Similarly, a lower workability value was observed in the mixture 30% GGBFS and 70% FA-based GPC sample compared to the remaining samples. On the other hand, increase in the GGBFS content the workability values were reduced

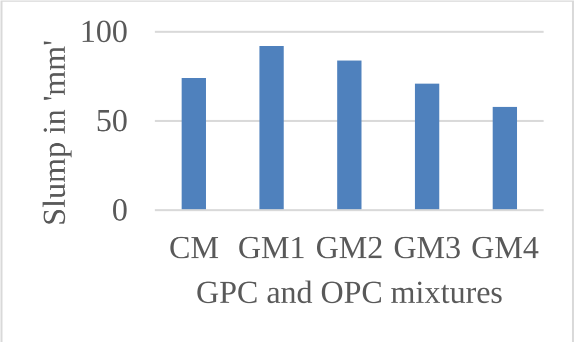

Figure 4: Workability of GPC and Conventional samples

5.2 Compressive Strength

A compression testing machine was used to find the compressive strength of geopolymer and conventional concrete samples. Conventional concrete samples were cured under the traditional curing method and GPC samples were cured under ambient temperature for 14 days and 28 days. However, 150 mm cube moulds were used to find the compressive strength of concrete. It was clearly observed that with the increase in the GGBFS content in FA-based GPC samples, the compressive strength was also increased under ambient curing for both 14 and 28 days. On the other hand, increased in the curing period the strength properties were also increased.

The higher compressive strength properties were found in the mixture GM4 for both 14 days and 28 days of curing and the values are 32.47 MPa and 44.36 MPa respectively. Similarly, the lower compressive strength values were observed in the mixture GM1, this mix is prepared with 100% fly ash. The compressive strength values for this particular mixture is 20.5 MPa and 28.34 MPa for 14 days and 28 days of ambient curing respectively. However, it was also clear that the geopolymer samples were shown enhanced compressive strength values compared to conventional concrete samples. At the same time, lower strength values were observed in pure fly ash based geopolymer mixture GM1.

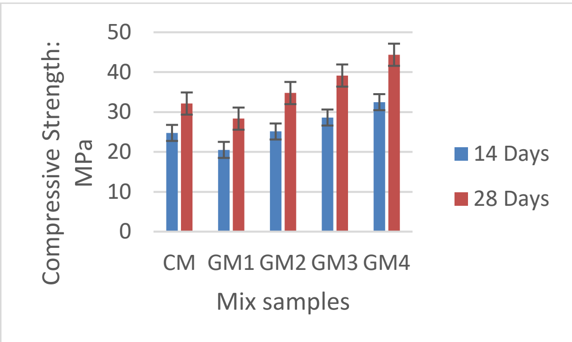

Figure 5: Compressive strength of geopolymer and control mixes

5.3 Split Tensile Strength

To determine the split tensile strength of both geopolymer and conventional concrete samples, a compression testing machine was employed. While conventional concrete samples underwent curing using the traditional method, GPC samples were subjected to ambient temperature curing for a duration of 28 days. The split tensile strength of the concrete was assessed using cylindrical molds measuring 150 x 300 mm.

Upon analysis, it was evident that an increase in GGBFS content in FA-based GPC samples corresponded to an increase in split tensile strength under ambient curing conditions for 28 days. This observation suggests a positive correlation between GGBFS content and split tensile strength in GPC samples over the specified curing period.

The mixture GM4 exhibited notably higher split tensile strength properties after 28 days of curing, with a recorded value of 6.54 MPa. This indicates superior performance in terms of tensile strength compared to other mixtures tested. Conversely, lower compressive strength values were observed in the mixture GM1, which consisted solely of fly ash as its primary constituent. This suggests that the absence of additional materials or additives in GM1 led to decreased compressive strength compared to other mixtures. For this specific mixture, the split tensile strength value after 28 days of ambient curing was determined to be 3.28 MPa. Notably, the geopolymer samples exhibited superior split tensile strength values in comparison to conventional concrete samples, indicating enhanced performance. Conversely, the pure fly ash-based geopolymer mixture GM1 displayed lower split tensile strength values.

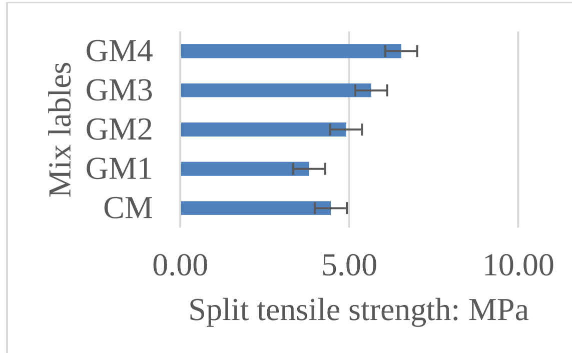

Figure 6: Split tensile strength of geopolymer and control mixes

5.4 Interfacial Transition Zone (ITZ)

The Interfacial Transition Zone (ITZ) exhibits a unique reaction mechanism compared to the matrix. Initially, numerous voids form within the ITZ due to its water content, but these voids are filled by hydration products post-hydration. Identifying differences between the microstructures of the matrix and ITZ becomes challenging post-reaction. EDS analysis reveals higher K/Al and Si/Al content in the ITZ compared to the bulk matrix, with the ITZ exhibiting a sponge-like amorphous gel without well-developed crystallinity. Good ITZ properties are observed in sodium silicate-activated mortar, featuring low porosity at the interface and thermal activation contributing to early strength, even with delayed reaction times. A strong ITZ bond between siliceous aggregate and fly ash requires a high concentration of alkaline solution. SEM and Nano-indentation analysis shows no ITZ bond between old cement paste and geopolymer matrix. ITZ thickness directly impacts concrete compressive strength, with a decrease leading to a strength increase and vice versa. The presence of soluble silicate in the mix is crucial for developing ITZ in GPC, with low quantities leading to weaker compressive strength compared to higher dosages. Chloride in the mix can cause debonding between aggregate and paste by crystallizing at ITZ.

VI. CONCLUSIONS

The following conclusions were drawn from the experimental investigation on FA-GGBFS-based geopolymer concrete samples under ambient curing conditions for 7 and 28 days.

1. Geopolymer concrete samples showed promise in the protection of the environment by reducing the effect of CO2 emissions in the production of cement.
2. The compressive strength of geopolymer concrete is shown enhanced value i.e. 44.36 MPa at a proportion of 30% GGBFS and 70% fly ash at 28 days of ambient curing.
3. The mix GM4 has shown enhanced split tensile strength as 6.54 MPa under 28 days of ambient curing with a replacement of 30% GGBFS in an FA-based geopolymer mixture.
4. In geopolymer samples better bonding was observed in between geopolymer paste and aggregates, it was clearly observed through ITZ.

As a result of these outstanding properties, geopolymer has been utilized as an alternative to Portland cement composites in various specialized applications such as fire-resistant coats, fiber-reinforced composites, and waste immobilization.

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