Sustainable Geopolymer Concrete: Optimizing Fly Ash And SCBA For Eco-Friendly Construction

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ABSTRACT

The rising concerns of global warming and greenhouse gas emissions necessitate sustainable alternatives in the construction industry, particularly in cement production, a major contributor to CO_2 emissions. India, as the second-largest cement producer, plays a crucial role in addressing this issue. This study explores an eco-friendly approach by replacing cement entirely with fly ash and partially substituting fly ash with Sugar Cane Bagasse Ash (SCBA) in geopolymer concrete. The research investigates the mechanical properties of SCBA-based geopolymer concrete under different curing conditions: heat curing at 60°C and 80°C, and ambient curing for 7, 14, and 28 days. Various replacement levels of fly ash with SCBA (2.5%, 5.0%, 7.5%, and 10.0%) were examined to assess their impact on compressive strength. Experimental results indicate that geopolymer concrete with up to 5.0% SCBA replacement achieves the highest compressive strength after 28 days of ambient curing. This study highlights the feasibility of using SCBA-based geopolymer concrete as a sustainable alternative, reducing cement dependency and lowering CO_2 emissions, thereby contributing to environmental conservation and sustainable construction practices.

Key words: Bottom ash, Pozzolanic materials, Eco-friendly concrete, Alternative binders

1. INTRODUCTION

Concrete is a widely used building material, with cement being a key component that provides binding properties. However, the rapid growth of cement production has led to significant CO_2 emissions, contributing to global warming. Cement industries account for approximately 8% of total greenhouse gas emissions, making it crucial to explore sustainable alternatives. Geopolymer concrete presents an eco-friendly solution by utilizing industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binders, eliminating the need for cement. India, a major producer of coal-based power, generates large quantities of fly ash and bottom ash, much of which remains unutilized, leading to environmental concerns. Additionally, the excessive extraction of river sand for construction depletes natural resources. This research investigates the feasibility of replacing cement with fly ash and substituting river sand with M-Sand and bottom ash in geopolymer concrete. By incorporating these industrial by-products, this study aims to develop a sustainable alternative to conventional concrete, reducing environmental impact while ensuring structural efficiency.

2. LITERATURE SURVEY

Davidovits (1994) theorized that an alkaline liquid had the potential to react with the aluminium (Al) and silicon (Si) located in a source material of geological origin or in by-product materials such as fly ash and blast furnace slag to create binders. This reaction of alkaline liquid with aluminium and silicon is termed as polymerization process. These alumino-silicate polymers with an amorphous microstructure, which are formed in alkaline environment, are termed as geopolymers. The activation mechanism of alumino-silicate materials was proposed by Glukhovsky in 1959. This mechanism was broadly divided into three steps: (a) destruction–coagulation, (b) coagulation–condensation, and (c) condensation–crystallization.

In 1979, Davidovits proposed geopolymer chemistry concept, and the properties of this new binder material. The term poly (sialate) was also suggested by him, wherein sialate is an abbreviation form for silicon-oxo- aluminate (Davidovits 2008). The chemical structure of polysialates which exists in three different features based on silicon and aluminum proportions is shown in Figure 2.1. The poly (sialate) network consists of Si+4 and Al+3 ions in IV-fold coordination, sharing oxygen ions and ranges from amorphous to semi-crystalline (Davidovits 1989, Sakulich 2011). Poly (sialate) has an empirical formula of: Mn (-(SiO2)z –AlO2)n, wH2O, where „M" is the alkali element that is used; „n" is the degree of polymerization, „z" value lies in between 1and 3 depending on the chemistry of the reaction, and „w" depends on the extent of hydration reaction completed. As mentioned earlier the geopolymerization, which is similar to hydration process in case of OPC, involves alumino-silicate oxides (Si2O5 and Al2O3) reacts with polysilicates, results in three dimensional polymeric bonds (Si-O-Al-O) under highly alkaline conditions. Sodium or potassium silicates which are available either in crystalline or non-crystalline forms are more commonly used as poly-silicates. (Davidovits 1991, Wallah and Rangan 2006). Significant contribution was made by the scientists Fernandez – Jimenez et al. (2009), Van Deventer et al. (2009) in developing different theories to explain the mechanism of geopolymerization and they have proposed a reaction mechanism for geopolymerization. They have presented a conceptual model which describes various sequential stages of geopolymerization. In summary the above schematic representation can be explained in three steps as follows (Davidovits 1999; Xu and Van Deventer 2000). 1. Dissolution of Si and Al atoms from the source material through the action of hydroxide ions in the alkali solution. 2. Transportation or orientation or condensation of precursor ions into monomers. 3. Setting or polycondensation/polymerization of monomers into polymeric structures in presence of heat media. According to Davidovits (1999), Van Jaarsveld et al. (1997) the schematic formation of geopolymer material can be understood by the following equations.

Fly ash is a by-product of coal fired power plants. This is used as fuel in the generation of electricity. Before they are discharged into the atmosphere, a dust collection system removes the fly ash, as a fine particulate residue. In general, anthracite and bituminous coals possess high content of silica and produce low calcium fly ash, whereas, lignite or sub-bituminous coals possess high CaO content and low content of silica and alumina. Fly ash with high CaO content exhibits pozzolanic and cementitious properties, whereas the low calcium fly ash exhibits mainly pozzolanic properties. ASTM categorized the low calcium and high calcium fly ash as Class F and Class C, respectively. Class C fly ash, because of its possessing high calcium content when used in concrete works very quickly forms the hydration products as the rate of reaction is highly accelerated by the presence of high calcium. Chemical requirements of Class C and Class F according to ASTM . In general, in fly ash the silica content varies between 40 and 60% and the alumina content varies in between 20 and 30% (Khale and Chaudhary 2007). From the point of view of maintaining longer workability and setting time for the concrete Class C fly ash is not suitable for its use in producing mass concrete. Class F fly ash possesses high content of amorphous alumino-silicate phases and less than 10% CaO content (Hardjito and Rangan 2005). With Class F fly ash, it is possible to maintain longer workability (Sindhunata 2006a). For these fly ashes heat media is necessary to accelerate the pozzolanic reaction. Hence it was preferred by many researchers (Katz 1998, Van Jaarsveld et al. 1997, Palomo et al. 1999, Swanepoel and Strydom 2002, Fernandez-Jimenez and Palomo 2003, Rangan and Hardjito 2005, 2008) in their experimental investigations in producing geopolymers. Few researchers investigated on the activation of high-calcium fly ash (Chindaprasirt et al. 2007).

Hardjito and Rangan (2005) were the foremost researchers who have published a work report, where the complete mixture proportions and have investigated the effect of various synthesizing parameters on fly ash based geopolymer concrete. They have determined the short-term properties of low-calcium fly ash-based geopolymer concrete by altering all the possible parameters which influence the mechanical properties. Numerous batches of geopolymer concrete were prepared using Class F fly ash as source material and mixture of sodium silicate solution-to-sodium hydroxide solution as the activator solution. Locally available aggregates were taken in different sizes ranging from 7 to 20 mm. Uncrushed material from sand dunes was used as fine aggregate. Similar to OPC the volume of aggregates in the concrete was taken about 75 to 80% of the total mass. Specimens used for testing were of size of 10 x 20 cm cylinders. Concentrations of NaOH used in this investigation were in the range of 8 molar to 16 molar. The ratio of sodium silicate solution-to-sodium hydroxide solution, by mass, varies from 0.4 to 2.5. Water to geopolymer solids by mass of the specimens were varied in the range of 0.16-0.25. Specimens were cured in the temperature range of 30 to 60oC for a duration varying from 4 to 96 hours.

The authors replaced 100% cement and sand by Class F fly ash and manufactured - sand respectively. Sodium silicate and sodium hydroxide solutions were used as alkaline activators. The ratio of alkaline liquid to fly ash was taken as 0.61. Curing temperature and duration were kept as 600 C and 48 hours respectively.

The compressive strength of geopolymer concrete is a function of many parameters, hence clear understanding of the influences of various synthesizing parameters is essential in preparing the geopolymers. Hardjito et al. (2005) conducted a detailed investigation about the influences of these parameters on compressive strength of geopolymer concrete (GPC). According to Van Jaarsveld et al. (2003), molarity of the sodium hydroxide is a major influential aspect that determines the compressive strength of geopolymer concrete. From the experimental results Hardjito et al. (2005) have concluded that higher concentrations of NaOH yielded in higher compressive strength of geopolymer concrete (Lloyd and Rangan 2010). The reason was attributed to increased dissolution of aluminosilicates which results in formation of stronger bonds. As shown in Table 2.4 from mixtures 1 and 3, it can be observed that at a constant ratio of sodium silicate to sodium hydroxide with the increase in the concentration of NaOH, there was a significant increase in the compressive strength of concrete. Abdulkadir et al. (2014) investigated various pozzolanic activities index of SCBA for M25 mix at 28 days. The total of SiO2, Al2O3 and Fe2O3 of SCBA used in the study was 80.55%. The highest Pozzolanic Activity Index (PAI) of 83.2% was achieved by burning the sugarcane bagasse at 700°C, then sieving it through 425 micro meter sieve and further grinding to 45 micro meter sieve. However, the optimum compressive strength reported even with such high PAI was less than that of the normal concrete.

3. PROPOSED SYSTEM

The proposed system aims to develop an eco-friendly geopolymer concrete by replacing cement with fly ash and utilizing bottom ash and M-Sand as substitutes for river sand. This approach seeks to reduce CO_2 emissions, minimize the over-exploitation of natural resources, and provide an efficient way to utilize industrial by-products.

Key Components of the Proposed System

1. **Material Selection and Preparation**
   - Fly ash is used as the primary binder instead of cement.
   - Bottom ash and M-Sand replace river sand as fine aggregates.
   - Alkaline activators (Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3)) are used to initiate the geopolymerization reaction.
2. **Mix Proportions and Optimization**
   - Various mix proportions of fly ash, bottom ash, and M-Sand are tested to identify the optimal combination.
   - Different molarities (M) of **NaOH solution (10M, 12M, etc.)** are examined to enhance the geopolymerization process.
3. **Curing Techniques**
   - Geopolymer concrete specimens are subjected to **heat curing (60°C & 80°C)** and **ambient curing (7, 14, and 28 days)** to evaluate performance.
4. **Mechanical and Durability Testing**
   - **Compressive strength, tensile strength, and flexural strength** tests are conducted to assess the structural integrity of geopolymer concrete.
   - Durability tests such as **water absorption and sulfate resistance** are performed to ensure long-term sustainability.
5. **Comparative Analysis**
   - Performance comparisons between geopolymer concrete and conventional cement-based concrete are conducted.
   - The CO_2 emissions reduction potential and cost efficiency are analyzed.

Expected Outcomes

- Development of a **sustainable and eco-friendly** geopolymer concrete.
- Significant reduction in **cement dependency** and **CO_2 emissions**.
- Effective utilization of **industrial waste materials**, reducing environmental pollution.
- High-performance concrete with improved **strength and durability**.

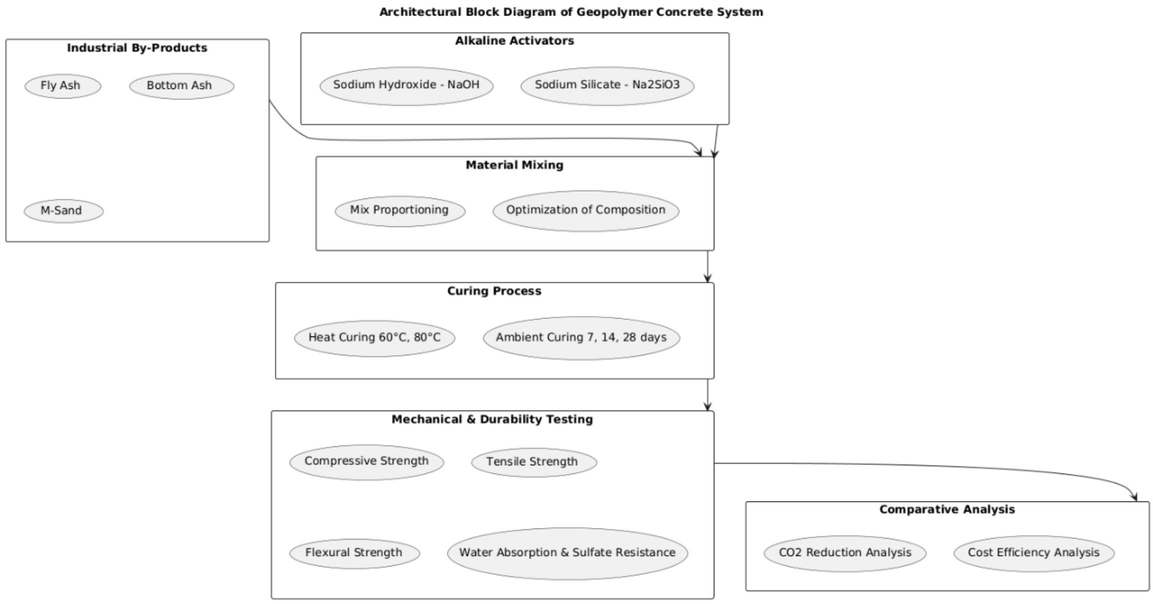

Figure 1 Presents the Block Diagram of Proposed System.

4. RESULTS AND DISCUSSIONS

This chapter presents the results obtained from the tests (discussed in Chapter 4) conducted on geopolymer concrete specimens and their composites. First of all, the results of mechanical properties of GPC (100% fly ash) and GPC with Fly ash replacing with SCBA ($F_{100}S_0$, $F_{97.5}S_{2.5}$, $F_{95}S_5$, $F_{92.5}S_{7.5}$ & $F_{90}S_{10}$) specimens on mechanical properties and physical properties was presented.

5.1 Physical properties of Geopolymer concrete

Table 5.1 Physical properties of GPC cubes

Mix No.	RS - QD (%)	Shape and size test	Colour test	Structure test
M1	$F_{100}S_0$	For all cubes are cube shaped with sharp edges and size of 15 cm x 15 cm x 15 cm	All the cubes having the uniform colour for entire structure	There are no flaws, cracks or holes present on that broken face then that is a good quality
M2	$F_{97.5}S_{2.5}$			
M3	$F_{95}S_5$			
M4	$F_{92.5}S_{7.5}$			
M5	$F_{90}S_{10}$			

4.2 Fresh properties of Geopolymer concrete

The Slump cone test results of the Geopolymer concrete for the replacement of fly ash with SCBA by 0, 2.5, 5.0, 7.5 and 10.0 % are shown in table 5.2 and graphically represented in Fig 5.1.

Table 4.2 Slump cone test results

Mix No.	Fly ash - SCBA (%)	Slump value (mm)
M1	$F_{100}S_0$	85
M2	$F_{97.5}S_{2.5}$	90
M3	$F_{95}S_5$	94
M4	$F_{92.5}S_{7.5}$	100
M5	$F_{90}S_{10}$	104

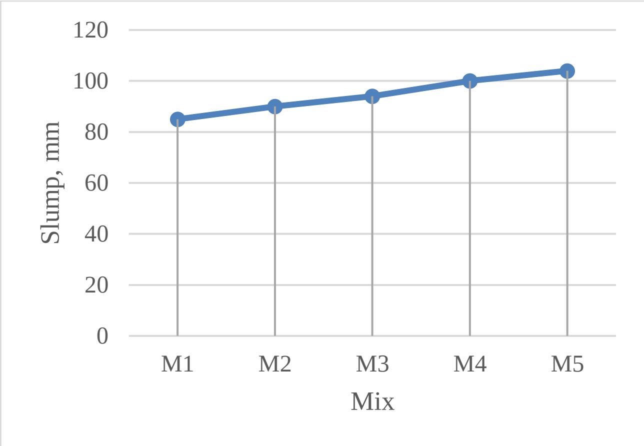

Figure 4.1 Slump test results graph

It is observed that there is increase in the workability of the Geopolymer concrete when the fly ash is replaced with SCBA. Based on the observations, all of the slump values are in the low to medium workability range.

4.3 Harden properties of Geopolymer concrete

4.3.1 Oven curing

The compressive strength by oven curing under 60^0c and 80^0c results of the Geopolymer concrete for the replacement of fly ash with SCBA by 0, 2.5, 5.0, 7.5 and 10.0 % are shown in table 5.3 and graphically represented in Fig 5.2.

Table 4.3 Compressive strength test results (Oven curing)

Mix No.	Fly ash - SCBA (%)	Average Compressive strength (Mpa)	
		60^0c	80^0c
M1	$F_{100}S_0$	22.4	35
M2	$F_{97.5}S_{2.5}$	24	37.5
M3	$F_{95}S_5$	26	39.2
M4	$F_{92.5}S_{7.5}$	20.5	34.1
M5	$F_{90}S_{10}$	18	30.2

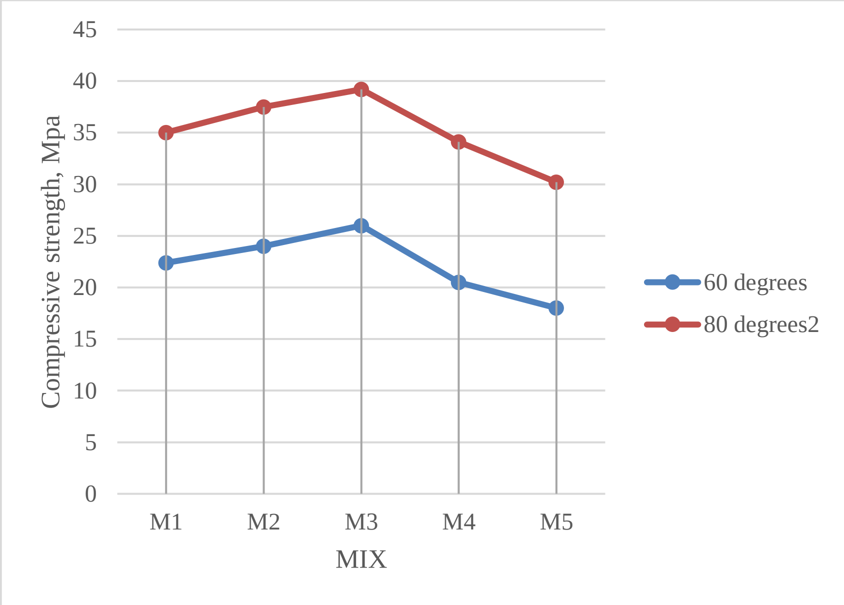

Figure 4.2 Compressive strength test results graph (Oven curing)

It is observed that there is increase in the compressive strength of the geopolymer concrete when the Flyash was replaced with SCBA. Based on the observations, all of the compressive strength values are higher for SCBA replacement. The highest compressive strength gains for 80^0c as compare to the 60^0c. The optimum dosage of Fly ash replacement in SCBA was 5.0%.

4.3.2 Ambient curing

The compressive strength by ambient curing under 7, 14 and 28 days results of the Geopolymer concrete for the replacement of fly ash with SCBA by 0, 2.5, 5.0, 7.5 and 10.0 % are shown in table 5.4 and graphically represented in Fig 5.3.

Table 4.4 Compressive strength test results (Ambient curing)

Mix No.	Fly ash - SCBA (%)	Average Compressive strength (Mpa)		
		7days	14 days	28 days
M1	$F_{100}S_0$	28.5	38.9	45
M2	$F_{97.5}S_{2.5}$	27.5	43	47.4
M3	$F_{95}S_5$	28	42.24	48.6
M4	$F_{92.5}S_{7.5}$	27.54	40	46.3
M5	$F_{90}S_{10}$	25.2	38.6	45.2

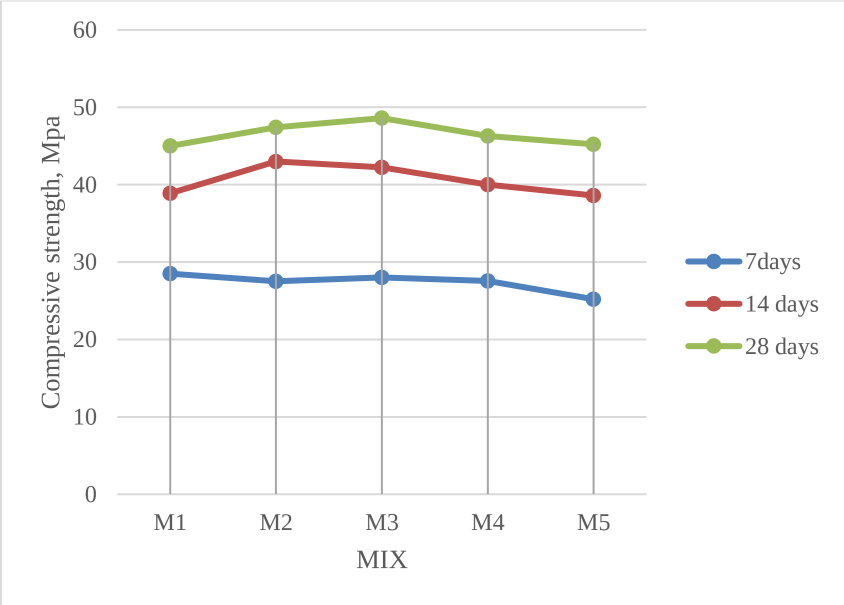

Figure 4.3 Compressive strength test results graph (Ambient curing)

It is observed that there is increase in the compressive strength of the geopolymer concrete when the fly ash was replaced with SCBA. Based on the observations, all of the compressive strength values are higher for SCBA replacement. The optimum dosage of Fly ash replacement in SCBA was 5.0%.

4.3.3 Comparison of curing based strength

It is observed that there is increase in the compressive strength of the geopolymer concrete when the fly ash was replaced with SCBA. Based on the comparison of oven and ambient curing, the compressive strength higher for 28days ambient curing as compare to the oven curing.

For 28days ambient curing of geopolymer concrete, the percentage increase of compressive strength value for 2.0%, 5.0%, 7.5% and 10.0% replacement of fly ash with SCBA was 5.5%, 8%, 2.83% and 0.44%respectively.

Table 5.5 Compressive strength test results comparison

Mix No.	Fly ash - SCBA (%)	Average Compressive strength (Mpa)		
		60^0c	80^0c	28 days
M1	$F_{100}S_0$	22.4	35	45
M2	$F_{97.5}S_{2.5}$	24	37.5	47.4
M3	$F_{95}S_5$	26	39.2	48.6
M4	$F_{92.5}S_{7.5}$	20.5	34.1	46.3
M5	$F_{90}S_{10}$	18	30.2	45.2

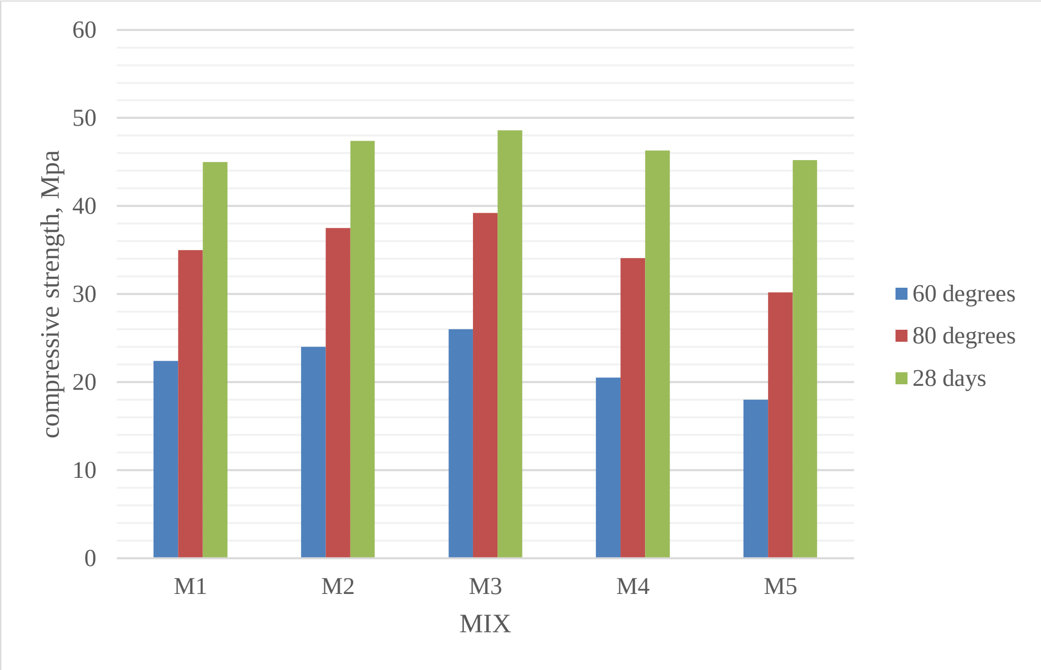

Figure 4.4 Compressive strength test results comparison graph

4.4 Indirect strength of Geopolymer concrete

Table 4.6 Indirect strength from compressive strength

Mix No.	Fly ash - SCBA (%)	Strength (Mpa)				
		28 days ambient cured cube compressive strength	Indirect Tensile strength	Direct tensile strength	Shear strength	Flexural strength
M1	$F_{100}S_0$	45	4.5	3.825	5.4	7.2
M2	$F_{97.5}S_{2.5}$	47.4	4.74	4.029	5.688	7.58
M3	$F_{95}S_5$	48.6	4.86	4.131	5.832	7.77
M4	$F_{92.5}S_{7.5}$	46.3	4.63	3.9355	5.556	7.408
M5	$F_{90}S_{10}$	45.2	4.52	3.842	5.424	7.232

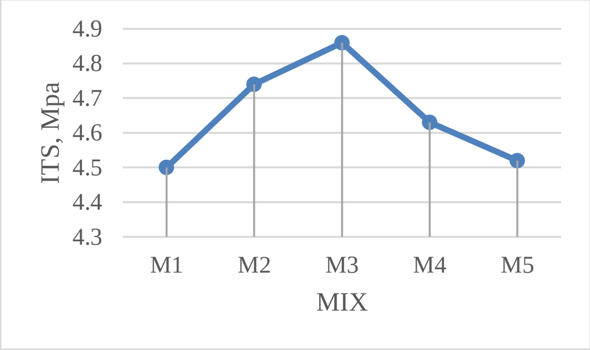

Figure 4.5 Indirect tensile strength test result graph

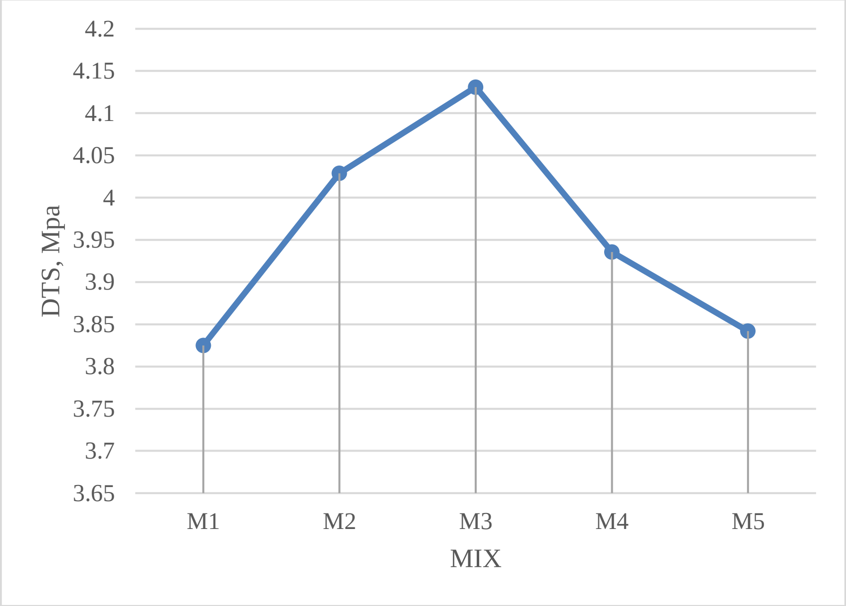

Figure 4.6 Direct tensile strength test results graph

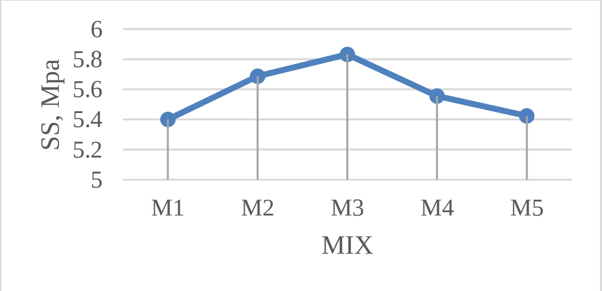

Figure 4.7 Shear strength test results graph

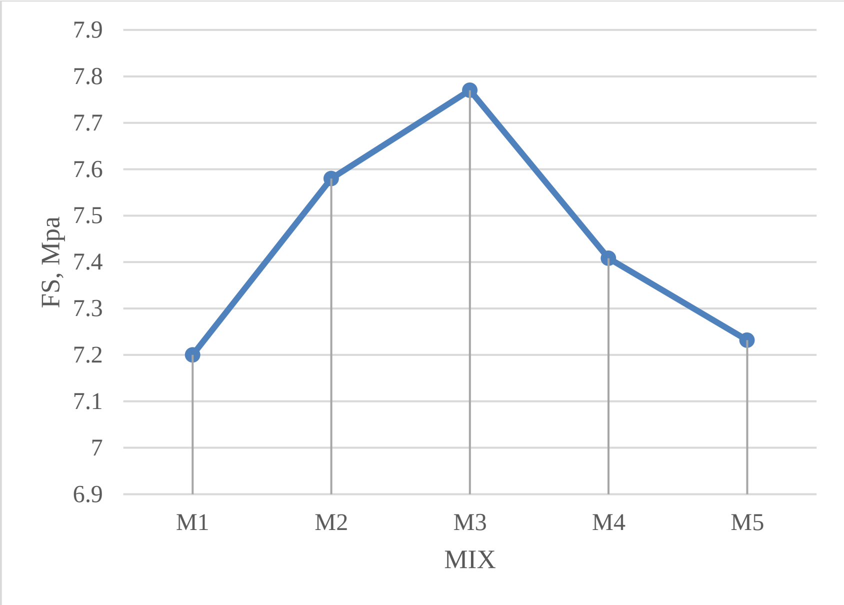

Figure 4.8 Flexural strength test results graph

It is observed that there is increase in the indirect tensile strength, direct tensile strength, shear strength and flexural or bending strength of the geopolymer concrete when the fly ash was replaced with SCBA. Based on the observations, all of the strength values are higher for SCBA replacement. The optimum dosage of SCBA replacement in Fly ash was 5.0%.

5. CONCLUSIONS

This study evaluated the mechanical properties of geopolymer concrete with partial replacement of fly ash with Sugar Cane Bagasse Ash (SCBA) under ambient and oven curing conditions. The results indicate that increasing SCBA content improves workability from low to medium slump and enhances compressive strength. Geopolymer concrete with 5.0% SCBA replacement exhibited the highest compressive strength after 28 days of ambient curing, outperforming oven-cured samples. The strength increment for 2.5%, 5.0%, 7.5%, and 10.0% SCBA replacements was 5.5%, 8%, 2.83%, and 0.44%, respectively, confirming 5.0% as the optimal SCBA dosage for G30-based geopolymer concrete.

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