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# Sustainable Development And Performance Evaluation Of Geopolymer Concrete (GPC): A Comprehensive Study

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***Abstract***
*GPC presents an environmentally friendly substitute for conventional OPC concrete that makes use of industrial byproducts such fly ash and GGBS to significantly reduce $CO_2$ emissions. This study investigates GPC material properties, mix design, and performance, emphasizing its superior mechanical strength, durability, and environmental benefits. Various GPC mixtures were evaluated using compressive and tensile strength tests, with results indicating enhanced performance with increased sodium hydroxide molarity and the inclusion of GGBS. Effective curing methods, including ambient and oven curing, were employed, demonstrating GPC viability in modern construction. The findings support GPC potential as a robust, eco-friendly building material.*

***Keywords:*** *Fly ash, GGBS, Alkaline Solution, strength, durability.*

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## I. Introduction

GPC emerges as a greener substitute for conventional OPC concrete made of industrial wastes such fly ash and GGBS, and significantly reducing $CO_2$ emissions. It exhibits robust mechanical properties and durability, addressing modern construction needs[1], [2]. Despite annual production exceeding 4.5 billion metric tons, traditional concrete faces challenges like honeycombing and segregation, highlighting the importance of proper consolidation[3], [4].

GPC formation through co-polymerization of alumina silicate species in alkaline conditions offers environmental benefits and robust performance, reducing reliance on calcium-silica-hydrates [3], [4]. Research underscores GPC superior mechanical properties, low permeability, and resistance to chemicals and fire, positioning it as a strong substitute for OPC [5], [6], [7]. With potential to reduce $CO_2$ emissions by up to 80%, GPC offers better durability and lower permeability compared to conventional concrete [8], [9], [10]. Geopolymer binders, derived from waste materials, offer a sustainable solution, with geopolymerization forming a binding gel network from soluble $SiO_4$ and $AlO_4$ species [11], [12].

Incorporating organic polymers enhances compressive strength, while efficient curing methods like self-curing with water soluble polymers are crucial for final properties [11], [12]. GPC exhibits advantages like early strength, fire resistance, and low shrinkage, with better thermal stability compared to PC based systems [11], [12]. GGBS addition, nano additives, and mineral admixtures further enhance GPC mechanical properties and durability, making it cost effective and environmentally friendly [13], [14]. The addition of slaked lime facilitates ambient curing, reducing the need for heat curing, and promoting widespread adoption of GPC in construction projects [13], [14].

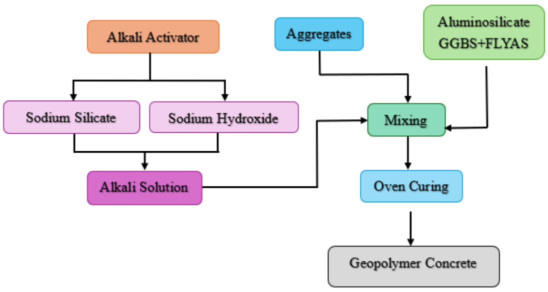


**Fig: 1 Flow chart of development of GPC**

## Materials Used

### Fly ash

Low calcium fly ash with a specific gravity of 2.20 was used in this study. Fly ash, a byproduct of coal burning in industrial power plants, has been used in cement manufacturing for over 100 years [1]. Class F and Class C from were utilized, with properties determined as per IS: 3812-2003[3]. Additionally, Class F fly ash from Khargone, Madhya Pradesh [5], [7] with a specific gravity of 2.32 and 94% fineness, and fly ash from Rajpura, Punjab, with Cao content less than 10%, were used. Both fly ash and GGBS served as precursor materials for GPC preparation[3], [8].

### GGBS

Once molten iron slag is cooled with steam or water, it solidifies into a glassy, granular substance called GGBS. The slag is further dried and finely ground [1], [2], [3] It boasts high levels of calcium-silicate-hydrates, enhancing concrete strength, durability, and appearance[13], [14]. Sourced from JSW Steel Ltd in Ballari, Andhra Pradesh, and Penang, Malaysia, GGBS was utilized in this study with average particle sizes of 138 mm and a specific surface area of 0.106 m²/g, as per IS: 12089 and IS 4031-1988 standards[2], [3]. Its inclusion in GPC promotes faster setting times and higher strength, often optimized at 40-50% of the mix, offering improved quality when combined with fly ash[8], [12].

**Table:1 Chemical composition of Fly ash and GGBS.[39]**

| Composition | $SiO_2$ | Al2O3 | Fe2O3 | $SO_3$ | CaO | MgO | $Na_2O$ | LOI |
|---|---|---|---|---|---|---|---|---|
| Fly ash | 60.1 | 26.52 | 4.24 | 0.34 | 4 | 1.24 | 0.21 | 0.87 |
| GGBS | 34.05 | 20 | 0.8 | 0.89 | 32.5 | 7.88 | NIL | NIL |

### Fine Aggregate & Coarse Aggregate

Used as fine aggregate were river sand and FA with a specific gravity of 2.65 and a size of less than 4.75 mm, as per Zone II of IS 383-1970[14]. With a maximum size of 20 mm and a specific gravity of 2.7, coarse particles were necessary for concrete filler[1], [3]. M-Sand, produced from hard granite boulders, was also used, typically under 4.75 mm in size, Zone II, with coarse aggregates of 20 mm and 12.5 mm sizes[8], [12].. Locally sourced fine sand, conforming to Zone III and free from impurities, was used alongside coarse aggregates ranging from 2 mm to 20 mm, including recycled concrete particles[13].

High class water reducing naphthalene-based superplasticizers should be added to the mixture to improve workability in fresh geopolymer concrete. Superplasticizers improve strength and lower the possibility of segregation[8]. Although overdosing can lead to a standard set, the lack of chloride usually results in an excellent surface finish without affecting fibre reinforcement[8]. Super Plasticizer A, also called Naphthalene Formaldehyde Condensate, was utilized in this experiment at 1% of the binder ingredient. (4 kg/m³). Additionally, a carboxylic superplasticizer from Chemcon Techsys with specifications of 40% solid content, nil chloride content, pH 7.2, and specific gravity 1.13 was utilized[12].

### Alkaline Solution

The alkaline activator solution in this investigation was a combination of SH (NaOH) and SS ($Na_2SiO_3$). To avoid contamination, 98% pure sodium hydroxide[1], [5] was produced as flakes and dissolved in tap water in the laboratory. The NaOH solution was made a day in advance of mixing with the Na2SiO3 solution, which was stored for an additional day before to usage[7], [8]. The chemical composition of the $Na_2SiO_3$ solution was water 55.5% by mass, $SiO_2$ = 9.8%, and Na2O = 14.7%. $Na_2SiO_3$ to NaOH mass ratio was set at 2.5. The mixture was kept at room temperature (27°C) to give the exothermic processes time to cool down[10], [15]. To generate GPC mixes with precise ratios and characteristics for casting specimens, this alkaline activator solution was utilized[11], [12], [13].

### Mix Design

The chapter outlines the mix design, processing, and curing procedures for GPC specimens. Standard concrete blending techniques are adapted for GPC preparation, with dry blending in addition to adding an alkaline solution comprising sodium hydroxide and sodium silicate [1], [15]. Cubes are formed and cured in direct sunlight for specified durations. Alkaline fluid preparation involves mixing Solutions for SH and SS at least one day before usage. Specific mix proportions for GPC, designated as GP1 to GP3 blends, are detailed, with varying molarities of NaOH solutions. Additionally, mix proportions for GGBS and SCBA based GPC mixes are presented, including variations in GGBS,[2], [3] SCBA proportions, and NaOH molarity. Mix design parameters, curing methods, and ages are carefully considered in the experimental setup[7], [11]. The mixing procedure involves dry blending of materials followed by wet mixing with alkaline solution, moulding, and curing under specified conditions. Lastly, the density-based mix design for GPC is elucidated, specifying quantities of alumina-silicate materials, fine aggregate, coarse aggregate, and lime[12], [13], [14].

**Table:2 Mix proportion of GPC (Kg/$m^3$)[2], [3], [4], [5], [7], [9], [10], [15], [16].**

| Designation | GGBS | FLYASH | FA | CA | AS | AS (Kg/$m^3$) | | M |
|---|---|---|---|---|---|---|---|---|
| | (kg/$m^3$) | (kg/$m^3$) | (kg/$m^3$) | (kg/$m^3$) | binder | $Na_2SiO_3$ | NaOH | |
| F70G30 | 165 | 385 | 507 | 0912 | 0.61 | 243 | 097 | 12 |
| F70G30 | 252 | 108 | 774 | 1090 | 0.45 | 097 | 064 | 08 |
| F70G30 | 252 | 108 | 774 | 1090 | 0.50 | 108 | 072 | 08 |
| F70G30 | 252 | 108 | 774 | 1090 | 0.55 | 118 | 079 | 08 |
| F70G30 | 252 | 108 | 774 | 1090 | 0.60 | 129 | 086 | 08 |
| F70G30 | 294 | 126 | 810 | 0966 | 0.45 | 113 | 075 | 08 |
| F70G30 | 294 | 126 | 810 | 0966 | 0.50 | 126 | 084 | 08 |
| F70G30 | 294 | 126 | 810 | 0966 | 0.55 | 138 | 092 | 08 |
| F70G30 | 294 | 126 | 810 | 0966 | 0.60 | 151 | 100 | 08 |
| F70G30 | 315 | 135 | 760 | 0972 | 0.45 | 120 | 082 | 08 |
| F70G30 | 315 | 135 | 760 | 0972 | 0.50 | 135 | 090 | 08 |
| F70G30 | 315 | 135 | 760 | 0972 | 0.55 | 148 | 099 | 08 |
| F70G30 | 315 | 135 | 760 | 0972 | 0.60 | 162 | 108 | 08 |
| G100 | 400 | 000 | 810 | 0990 | 0.50 | 142 | 057 | 08 |
| G95S5 | 380 | 020 | 810 | 0990 | 0.50 | 142. | 057 | 08 |
| G90S10 | 360 | 040 | 810 | 0990 | 0.50 | 142 | 057 | 08 |
| G85S15 | 340 | 060 | 810 | 0990 | 0.50 | 142 | 057 | 08 |
| G80S20 | 320 | 080 | 810 | 0990 | 0.50 | 142 | 057 | 08 |
| G100 | 400 | 000 | 810 | 0990 | 0.50 | 142 | 057 | 10 |
| G95S5 | 380 | 020 | 810 | 0990 | 0.50 | 142 | 057 | 10 |
| G90S10 | 360 | 040 | 810 | 0990 | 0.50 | 142 | 057 | 10 |
| G85S15 | 340 | 060 | 810 | 0990 | 0.50 | 142 | 057 | 10 |
| G80S20 | 320 | 80 | 810 | 0990 | 0.50 | 142 | 057 | 10 |
| G100 | 400 | 000 | 810 | 0990 | 0.50 | 142 | 057 | 12 |
| G95S5 | 380 | 020 | 810 | 0990 | 0.50 | 142 | 057 | 12 |
| G90S10 | 360 | 040 | 810 | 0990 | 0.50 | 142 | 057 | 12 |
| G85S15 | 340 | 060 | 810 | 0990 | 0.50 | 142 | 057 | 12 |
| G80S20 | 320 | 080 | 810 | 0990 | 0.50 | 142 | 057 | 12 |
| F100G0 | 409 | 000 | 554 | 1293 | 0.35 | 102 | 090 | 10 |
| F50G50 | 204 | 204 | 554 | 1293 | 0.35 | 102 | 090 | 10 |
| F0G100 | 000 | 409 | 554 | 1293 | 0.35 | 102 | 090 | 10 |
| F100G0 | 400 | 000 | 584 | 1085 | 0.57 | 137 | 091 | 12 |
| F70G30 | 280 | 280 | 584 | 1085 | 0.57 | 137 | 091 | 12 |
| F100G0 | 408 | 000 | 554 | 1294 | 0.35 | 103 | 041 | 08 |
| F90G10 | 367 | 040 | 554 | 1294 | 0.35 | 103 | 041 | 08 |
| F80G20 | 326 | 081 | 554 | 1294 | 0.35 | 103 | 041 | 08 |
| F70G30 | 285 | 122 | 554 | 1294 | 0.35 | 103 | 041 | 08 |
| F60G40 | 244 | 163 | 554 | 1294 | 0.35 | 103 | 041 | 08 |
| F100G0 | 407 | 000 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F90G10 | 366 | 040 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F80G20 | 325 | 081 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F70G30 | 284 | 122 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F60G40 | 244 | 162 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F50G50 | 203 | 203 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F40G60 | 162 | 244 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| F30G70 | 122 | 284 | 610 | 1221 | 0.40 | 108 | 054 | 08 |
| 90F10S | 382 | 042 | 505 | 1105 | 0.55 | 140 | 093 | 12 |
| 80F20S | 340 | 085 | 505 | 1105 | 0.55 | 140 | 093 | 12 |
| 70F30S | 297 | 127 | 505 | 1105 | 0.55 | 140 | 093 | 12 |
| 60F40S | 255 | 170 | 505 | 1105 | 0.55 | 140 | 093 | 12 |
| 50F50S | 212 | 212 | 505 | 1105 | 0.55 | 140 | 093 | 12 |
| 50F50G | 202 | 202 | 587 | 1283 | 0.35 | 070 | 070 | 14 |
| G9 | 437 | 043 | 740 | 0915 | 0.44 | 171 | 018 | 08 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| G20 | 384 | 096 | 749 | 0926 | 0.44 | 171 | 018 | 08 |
| G27.5 | 348 | 132 | 756 | 0933 | 0.44 | 171 | 018 | 08 |
| G38 | 298 | 182 | 763 | 0943 | 0.44 | 171 | 018 | 08 |
| G43 | 274 | 206 | 767 | 0948 | 0.44 | 171 | 018 | 08 |
| GPC-FG30 | 128 | 298 | 596 | 1108 | 0.50 | 152 | 061 | 12 |
| GPC-FG40 | 170 | 256 | 596 | 1108 | 0.50 | 152 | 061 | 12 |
| GPC-FG50 | 213 | 213 | 596 | 1108 | 0.50 | 152 | 061 | 12 |
| GPC-FG60 | 256 | 170 | 596 | 1108 | 0.50 | 152 | 061 | 12 |

**Note:** G stands for GGBS, F stands for Fly ash and S stands for sugarcane bagasse ash, AS stands for Alkaline Solution, FA stands for Fine Aggregate, CA stands for Coarse Aggregate, and M stands for Molarity.

**Casting and Curing**

GPC casting and curing procedure begins with thorough mixing of precursors, filler materials, and activator solution until achieving a uniform consistency. Subsequently, the freshly prepared to create cubes, cylinders, and beam examples, GPC is poured into moulds, where it is allowed to cure for 24 hours before demoulding [2].

For the specified testing periods (7 and 28 days), the specimens must be exposed to natural circumstances, with temperatures between 25 and 35 °C and a relative humidity of 75%. This process is known as outdoor curing. No humidity or temperature control is required during the six-month trial period. As an alternative, demoulded specimens are cooled to room temperature and then baked for 24 hours at 60 °C. This process is known as oven curing. GPC specimens are tested when they are 7 and 28 days old[3], [5], [7].

Throughout the process, ambient curing in a controlled laboratory environment ensures consistency in temperature [11]. Testing procedures include pullout tests, compressive strength tests, and electrochemical measurements, each performed using specialized equipment and methodologies[9]. These tests ensure a comprehensive evaluation of GPC properties and performance, highlighting the importance of precise mixing, meticulous casting, and controlled curing to obtain reliable results and assess GPC suitability for diverse applications[8].

## II. Result And Discussion

**Compressive Strength**

With increasing SH molarity, the CS of GPC rises. Experiments conducted on cube specimens at 7 and 28 days intervals showed that higher NaOH concentrations resulted in higher CS[1], [7], [8], [9], [12]. Additionally, the study discovered that the strength was impacted by the addition of fly ash, SCBA, and GGBS, with a larger GGBS content producing better results. The test results confirm that a denser microstructure forms over time, enhancing the material's mechanical properties[1], [2], [6], [7], [13], [14].

**Splitting Tensile Strength**

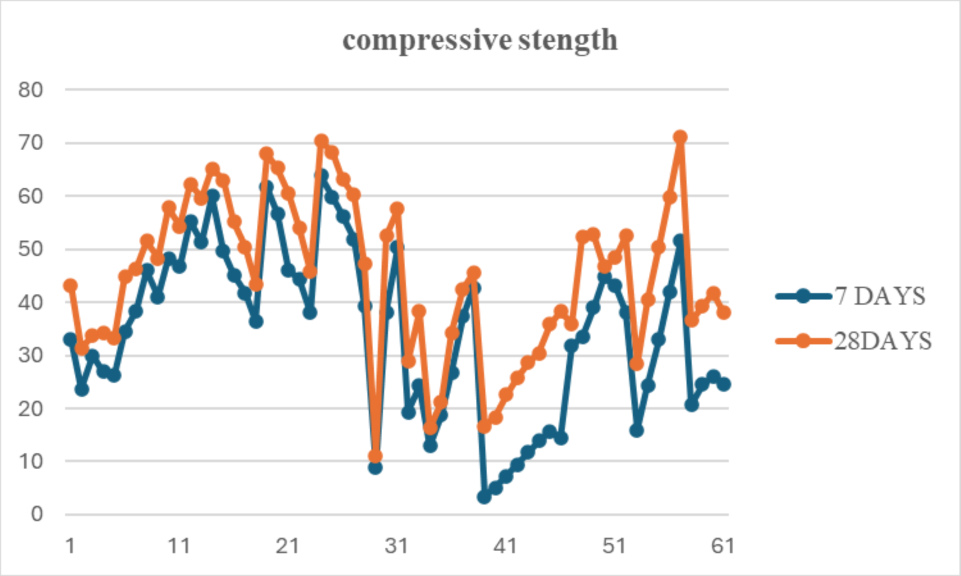
Tests on GPC cylinders were conducted following IS 5816-1970 standards. Test results at 28 days of ambient curing showed that STS increased with higher sodium hydroxide molarity[3], [4], [9], [11], [12]. For example, 8M NaOH solutions resulted in tensile strengths of 6.05 MPa, while 12M solutions achieved 6.65 MPa. However, the STS decreased with increasing SCBA replacement[6], [7], [13], [16]. The source materials, rich in silica, alumina, and calcium oxide, helped develop strong aluminosilicate hydrates enhancing the compactness and bonding in the GPC[7], [10], [13], [14].

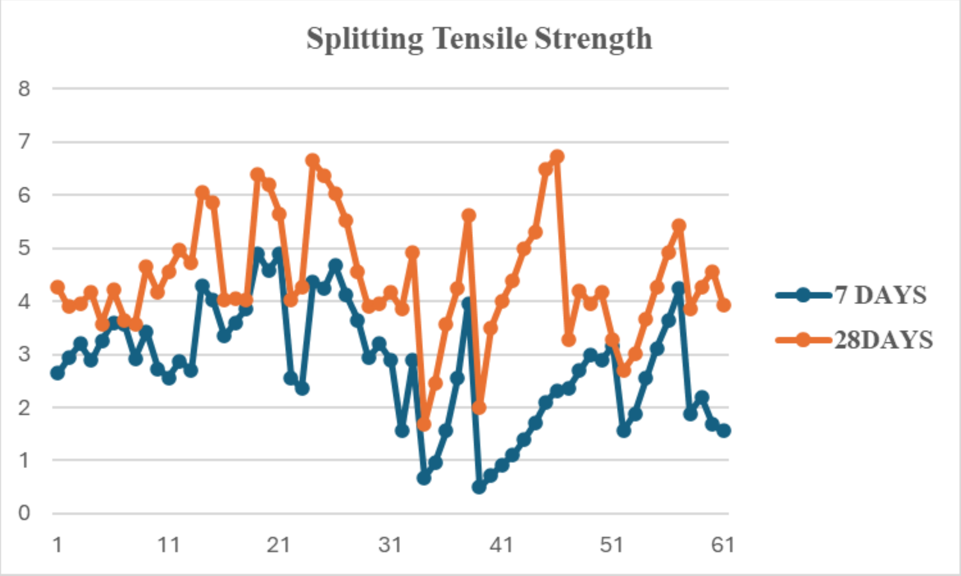
**Table:3 Details of tested specimens of different mixes [2], [3], [4], [5], [7], [9], [10], [15], [16].**

| CS ($N/mm^2$) | | STS ($N/mm^2$) | |
|---|---|---|---|
| **7 DAYS** | **28DAYS** | **7 DAYS** | **28DAYS** |
| 33.06 | 43.25 | 2.65 | 4.26 |
| 23.66 | 31.44 | 2.93 | 3.90 |
| 30.00 | 33.68 | 3.20 | 3.96 |
| 26.88 | 34.25 | 2.89 | 4.16 |
| 26.36 | 33.28 | 3.26 | 3.58 |
| 34.53 | 44.89 | 3.60 | 4.21 |
| 38.41 | 46.35 | 3.56 | 3.65 |
| 46.01 | 51.53 | 2.92 | 3.58 |
| 41.02 | 48.26 | 3.43 | 4.65 |
| 48.25 | 57.84 | 2.73 | 4.16 |

| | | | |
|---|---|---|---|
| 46.78 | 54.32 | 2.56 | 4.56 |
| 55.24 | 62.25 | 2.87 | 4.96 |
| 51.35 | 59.66 | 2.69 | 4.72 |
| 60.05 | 65.21 | 4.30 | 6.05 |
| 49.66 | 63.02 | 4.02 | 5.87 |
| 45.11 | 55.16 | 3.35 | 4.02 |
| 41.84 | 50.45 | 3.60 | 4.05 |
| 36.41 | 43.43 | 3.86 | 4.02 |
| 61.70 | 68.03 | 4.90 | 6.40 |
| 56.74 | 65.34 | 4.58 | 6.20 |
| 46.06 | 60.43 | 4.89 | 5.65 |
| 44.44 | 54.08 | 2.56 | 4.03 |
| 38.04 | 45.75 | 2.36 | 4.27 |
| 63.91 | 70.41 | 4.36 | 6.65 |
| 59.91 | 68.33 | 4.25 | 6.36 |
| 56.31 | 63.12 | 4.68 | 6.04 |
| 51.88 | 60.25 | 4.12 | 5.52 |
| 39.32 | 47.26 | 3.65 | 4.57 |
| 08.79 | 11.08 | 2.93 | 3.90 |
| 38.12 | 52.50 | 3.20 | 3.96 |
| 50.40 | 57.60 | 2.89 | 4.16 |
| 19.32 | 28.92 | 1.56 | 3.85 |
| 24.32 | 38.32 | 2.89 | 4.92 |
| 12.88 | 16.30 | 0.68 | 1.69 |
| 18.67 | 21.11 | 0.96 | 2.46 |
| 26.85 | 34.32 | 1.56 | 3.56 |
| 37.33 | 42.48 | 2.56 | 4.25 |
| 42.77 | 45.55 | 3.96 | 5.62 |
| 03.42 | 16.72 | 0.50 | 2.00 |
| 05.05 | 18.36 | 0.72 | 3.50 |
| 07.28 | 22.54 | 0.92 | 4.00 |
| 09.38 | 25.68 | 1.10 | 4.40 |
| 11.68 | 28.67 | 1.40 | 5.00 |
| 13.92 | 30.48 | 1.70 | 5.30 |
| 15.68 | 35.85 | 2.10 | 6.50 |
| 14.38 | 38.34 | 2.32 | 6.72 |
| 31.85 | 36.00 | 2.35 | 3.27 |
| 33.50 | 52.44 | 2.69 | 4.20 |
| 38.99 | 52.80 | 2.98 | 3.96 |
| 44.74 | 46.67 | 2.89 | 4.16 |
| 43.11 | 48.43 | 3.16 | 3.27 |
| 38.12 | 52.50 | 1.56 | 2.69 |
| 16.00 | 28.33 | 1.88 | 3.01 |
| 24.37 | 40.40 | 2.55 | 3.67 |
| 32.97 | 50.46 | 3.11 | 4.27 |
| 41.94 | 59.90 | 3.63 | 4.93 |
| 51.57 | 71.07 | 4.24 | 5.43 |
| 20.70 | 36.60 | 1.89 | 3.86 |
| 24.50 | 39.20 | 2.20 | 4.28 |
| 26.00 | 41.80 | 1.68 | 4.57 |
| 24.70 | 38.20 | 1.56 | 3.94 |

**Note:** CS stands for compressive strength and STS stands for Splitting Tensile Strength.





## III. Conclusion

GPC demonstrates significant potential as a sustainable alternative to OPC concrete, offering robust mechanical properties and superior durability. The incorporation of industrial by products like fly ash, GGBS, and SCBA not only enhances the compressive and tensile strengths but also promotes environmental sustainability by reducing $CO_2$ emissions. The research findings confirm that higher M of SH and the strategic use of SCM improve the performance of GPC. The optimized mix designs, coupled with efficient curing methods, ensure reliable and consistent results, positioning GPC as a viable and eco-friendly material for diverse construction applications.

## References

[1] G. Jayarajan And S. Arivalagan, "An Experimental Studies Of Geopolymer Concrete Incorporated With Fly-Ash & Ggbs," In Materials Today: Proceedings, Elsevier Ltd, 2020, Pp. 6915–6920. Doi: 10.1016/J.Matpr.2021.01.285.

[2] T. H.M. And S. Unnikrishnan, "Mechanical Strength And Microstructure Of Ggbs-Scba Based Geopolymer Concrete," Journal Of Materials Research And Technology, Vol. 24, Pp. 7816–7831, May 2023, Doi: 10.1016/J.Jmrt.2023.05.051.

[3] K. Pandurangan, M. Thennavan, And A. Muthadhi, "Studies On Effect Of Source Of Flyash On The Bond Strength Of Geopolymer Concrete," 2018. [Online]. Available: Www.Sciencedirect.Comwww.Materialstoday.Com/Proceedings2214-7853.

[4] J. G. S. Van Jaarsveld, J. S. J. Van Deventer, And G. C. Lukey, "The Effect Of Composition And Temperature On The Properties Of Fly Ash-And Kaolinite-Based Geopolymers," 2002.

[5] J. K. Prusty And B. Pradhan, "Effect Of Ggbs And Chloride On Compressive Strength And Corrosion Performance Of Steel In Fly Ash-Ggbs Based Geopolymer Concrete," In Materials Today: Proceedings, Elsevier Ltd, Jan. 2020, Pp. 850–855. Doi: 10.1016/J.Matpr.2020.04.210.

[6] W. H. Lee, J. H. Wang, Y. C. Ding, And T. W. Cheng, "A Study On The Characteristics And Microstructures Of Ggbs/Fa Based Geopolymer Paste And Concrete," Constr Build Mater, Vol. 211, Pp. 807–813, Jun. 2019, Doi: 10.1016/J.Conbuildmat.2019.03.291.

[7] R. P. Singh, K. R. Vanapalli, V. R. S. Cheela, S. R. Peddireddy, H. B. Sharma, And B. Mohanty, “Fly Ash, Ggbs, And Silica Fume Based Geopolymer Concrete With Recycled Aggregates: Properties And Environmental Impacts,” Constr Build Mater, Vol. 378, May 2023, Doi: 10.1016/J.Conbuildmat.2023.131168.

[8] M. Abbass, D. Singh, And G. Singh, “Properties Of Hybrid Geopolymer Concrete Prepared Using Rice Husk Ash, Fly Ash And Ggbs With Coconut Fiber,” In Materials Today: Proceedings, Elsevier Ltd, 2021, Pp. 4964–4970. Doi: 10.1016/J.Matpr.2021.01.390.

[9] R. R. Bellum, K. Muniraj, C. S. R. Indukuri, And S. R. C. Madduru, “Investigation On Performance Enhancement Of Fly Ash-Ggbfs Based Graphene Geopolymer Concrete,” Journal Of Building Engineering, Vol. 32, Nov. 2020, Doi: 10.1016/J.Jobe.2020.101659.

[10] J. Wang, J. Xie, C. Wang, J. Zhao, F. Liu, And C. Fang, “Study On The Optimum Initial Curing Condition For Fly Ash And Ggbs Based Geopolymer Recycled Aggregate Concrete,” Constr Build Mater, Vol. 247, Jun. 2020, Doi: 10.1016/J.Conbuildmat.2020.118540.

[11] Bouaissi, L. Yuan Li, M. M. Al Bakri Abdullah, And Q. B. Bui, “Mechanical Properties And Microstructure Analysis Of Fa-Ggbs-Hmns Based Geopolymer Concrete,” Constr Build Mater, Vol. 210, Pp. 198–209, Jun. 2019, Doi: 10.1016/J.Conbuildmat.2019.03.202.

[12] N. Poornima, D. Katyal, T. Revathi, M. Sivasakthi, And R. Jeyalakshmi, “Effect Of Curing On Mechanical Strength And Microstructure Of Fly Ash Blend Ggbs Geopolymer, Portland Cement Mortar And Its Behavior At Elevated Temperature,” In Materials Today: Proceedings, Elsevier

[13] K. Poloju And K. Srinivasu, “Impact Of Ggbs And Strength Ratio On Mechanical Properties Of Geopolymer Concrete Under Ambient Curing And Oven Curing,” In Materials Today: Proceedings, Elsevier Ltd, 2020, Pp. 962–968. Doi: 10.1016/J.Matpr.2020.11.934.

[14] M. Kalaivani, G. Shyamala, S. Ramesh, K. Angusenthil, And R. Jagadeesan, “Performance Evaluation Of Fly Ash/Slag Based Geopolymer Concrete Beams With Addition Of Lime,” In Materials Today: Proceedings, Elsevier Ltd, Jan. 2020, Pp. 652–656. Doi: 10.1016/J.Matpr.2020.01.596.

[15] R. R. Bellum, K. Muniraj, And S. R. C. Madduru, “Empirical Relationships On Mechanical Properties Of Class-F Fly Ash And Ggbs Based Geopolymer Concrete,” Annales De Chimie: Science Des Materiaux, Vol. 43, No. 3, Pp. 189–197, 2019, Doi: 10.18280/Acsm.430308.

[16] Hassan, M. Arif, And M. Shariq, “Use Of Geopolymer Concrete For A Cleaner And Sustainable Environment – A Review Of Mechanical Properties And Microstructure,” Jun. 20, 2019, Elsevier Ltd. Doi: 10.1016/J.Jclepro.2019.03.051.

[17] S. Paruthi, A. Husain, P. Alam, A. Husain Khan, M. Abul Hasan, And H. M. Magbool, “A Review On Material Mix Proportion And Strength Influence Parameters Of Geopolymer Concrete: Application Of Ann Model For Gpc Strength Prediction,” Nov. 21, 2022, Elsevier Ltd. Doi: 10.1016/J.Conbuildmat.2022.129253.

[18] H. Xu And J. S. J. Van Deventer, “The Geopolymerisation Of Alumino-Silicate Minerals,” 2000. Www.Elsevier.Nlrlocaterijminpro

[19] B. V Rangan Et Al., “Fly Ash-Based Geopolymer Concrete,” Allied Publishers Private Limited, 2010. Https://Www.Researchgate.Net/Publication/230717147

[20] D. Hardjito And B. V Rangan, “Development And Properties Of Low Calcium Fly Ash Based Geopolymer Concrete.”

[21] S. Nagajothi And S. Elavenil, “Effect Of Ggbs Addition On Reactivity And Microstructure Properties Of Ambient Cured Fly Ash Based Geopolymer Concrete,” Silicon, Vol. 13, No. 2, Pp. 507–516, Feb. 2021, Doi: 10.1007/S12633-020-00470-W.

a. Karthik, K. Sudalaimani, And C. T. Vijaya Kumar, “Investigation On Mechanical Properties Of Fly Ash-Ground Granulated Blast Furnace Slag Based Self Curing Bio-Geopolymer Concrete,” Construction Building Materials, Vol. 149, Pp. 338–349, Sep. 2017, Doi: 10.1016/J.Conbuildmat.2017.05.139.

[22] R. Kumar, P. Bhaskar, And S. S. Chaudhary, “Lecture Notes In Civil Engineering Advances In Sustainable Construction Materials.” Http://Www.Springer.Com/Series/15087.

[23] Afsar Ali, Qaiser Uz Zaman Khan, Syed Saqib Mehboob, Aisha Tayyab, Khizar Hayyat, Diyar Khan, Inzimam Ul Haq And Qadir Bux Alias Imran Latif Qureshi “Enhancing Multi-Objective Mix Design For Ggbs-Based Geopolymer Concrete With Natural Mineral Blends Under Ambient Curing: A Taguchi-Grey Relational Optimization,” Ain Shams Engineering Journal, Vol. 15, No. 5, May 2024, Doi: 10.1016/J.Asej.2024.102708.

[24] J. Guru Jawahar And G. Mounika, “Strength Properties Of Fly Ash And Ggbs Based Geo Polymer Concrete,” 2016. Https://Www.Researchgate.Net/Publication/311322715.

[25] Mehta, “Strength And Durability Characteristics Of Fly Ash And Slag Based Geopolymer Concrete,” International Journal Of Civil Engineering And Technology, Vol. 7, No. 5, Pp. 305–314.

[26] M. G. Rao Et Al., “Performance Of Fly Ash And Ggbs Based Geopolymer Concrete Using Single Alkaline Activator Solution And Its Cost Analysis,” In Iop Conference Series: Materials Science And Engineering, Iop Publishing Ltd, Dec. 2020. Doi: 10.1088/1757-899x/998/1/012051.

[27] B. Rajini, A. V. Narasimha Rao, And C. Sashidhar, “Micro-Level Studies Of Fly Ash And Ggbs -Based Geopolymer Concrete Using Fourier Transform Infra-Red,” In Materials Today: Proceedings, Elsevier Ltd, 2021, Pp. 586–589. Doi: 10.1016/J.Matpr.2020.11.291.

[28] Sustainable Solutions In Structural Engineering And Construction. Kawiphat Printers, 19ad.

[29] M. S. Reddy, P. Dinakar, And B. H. Rao, “Mix Design Development Of Fly Ash And Ground Granulated Blast Furnace Slag Based Geopolymer Concrete,” Journal Of Building Engineering, Vol. 20, Pp. 712–722, Nov. 2018, Doi: 10.1016/J.Jobe.2018.09.010.

[30] J. Guru Jawahar, D. Lavanya, And C. Sashidhar, “Ijrsi Volume Iii, Issue Viii,” 2016. Www.Rsisinternational.Org

[31] G. Nagalingam And R. B. Chokkalingam, “Strength Studies On Geopolymer Concrete With Ggbs And Fly Ash,” In Iop Conference Series: Materials Science And Engineering, Institute Of Physics Publishing, Jun. 2020. Doi: 10.1088/1757-899x/872/1/012107.

[32] G. Mallikarjuna Rao And T. D. Gunneswara Rao, “A Quantitative Method Of Approach In Designing The Mix Proportions Of Fly Ash And Ggbs-Based Geopolymer Concrete,” Australian Journal Of Civil Engineering, Vol. 16, No. 1, Pp. 53–63, Jan. 2018, Doi: 10.1080/14488353.2018.1450716.

[33] Pratyush Kumar, Chaitanya Pankar, Divyank Manish And Santhi A.S, Study Of Mechanical And Microstructural Properties Of Geopolymer Concrete With Ggbs And Metakaolin, Materials Today: Proceedings 5 (2018) 28127–28135.

[34] M. Bennet, J. Mathew, M. M. Sudhakar, And C. Natarajan, “Strength, Economic And Sustainability Characteristics Of Coal Ash-Ggbs Based Geopolymer Concrete.”

[35] P. Kathirvel And A. Bhaskar, “Effect Of Replacement Of Slag On The Mechanical Properties Of Fly Ash Based Geopolymer Concrete,” Https://Www.Researchgate.Net/Publication/280021075.

[36] C. Boopalan And N. P. Rajamane, “An Investigation Of Bond Strength Of Reinforcing Bars In Fly Ash And Ggbs Based Geopolymer Concrete.”

[37] P. Vignesh And K. Vivek, “An Experimental Investigation On Strength Parameters Of Fly Ash Based Geopolymer Concrete With Ggbs,” International Research Journal Of Engineering And Technology, 2015. Www.Irjet.Net

[38] P. S. Pithadiya And A. V Nakum, “Experimental Study On Geopolymer Concrete By Using Ggbs”. Http://Www.Ijret.Org

[39] D. Hardijito, S.E. Wallach, B.V. Rangan, Study On Engineering Properties Of Fly Ash- Based Geopolymer Concrete, J. Australas. Ceram. Soc. 38 (1) (2002) 44–47.

[40] D.N. Kumar Abrasion Resistance Of Polypropylene Fiber Reinforced Geopolymer Concrete. J. Emerg. Technol. Innov. Res. Issue 11 Vol: 4 Nov 17.

[41] Specification For Course And Fine Aggregates From The Natural Sources For Concrete, Bureau Of Indian Standards, Is: 383-1970. [4] Method For Physical Tests For Hydrated Cement, Bureau Of Indian Standards, Is: 4031 – 1988.

[42] D.M.J. Sumajouw, D. Hardjito, S.E. Wallah, B.V. Rangan, Fly Ash-Based Geopolymer Concrete: Study Of Slender Reinforced Columns, Springer Science +Business Media, Llc, 2006.

[43] D.S. Vijayan, C. Nivetha, P. Dinesh Kumar, B. Saravanan, V. Gogulnath, "Green Composite Form Of Eco – Friendly Concrete By Adding Pva Fiber", J. Green Eng. (Jge), Volume-10, Issue-6, June 2020. [7] P. Subathra, D.S. Vijayan, R. Abirami, Mebankitbok Kharsati, Geeliberds Soshang, Devrat Kumar Das, Experimental Investigation On Concrete With Marble Dust And Steel Fiber, Aip Conf. Proc. 2271 (2020), Https://Doi.Org/ 10.1063/5.0024779 030016.

[44] Paulmakesh, Material Characteristics Of Geopolymer Concrete Incorporated With Fly-Ash & Ggbs, Int. Res. J. Eng. Technol. (Irjet), Volume: 07 Issue: 03 | Mar 2020. [9] D.S. Vijayan, A. Lema Rose, V. Gokulnath, D. Parthiban, P. Dinesh Kumar, "Experimental Studies On Strength And Durability Of Sustainable Concrete Using Bottom Ash By Replacement Of Fine Aggregate" , Volume-10, Issue-9, Pages: 6938–6949.

[45] N.Manoj Kumar , P.Hanitha, Geopolymer Concrete By Using Fly Ash And Ggbs As A Replacement Of Cement, Iosr J. Mech. Civ. Eng. (Iosr-Jmce), Volume 13, Issue 6 Ver. V (Nov. - Dec. 2016), Pp 85-92.

[46] D.S. Vijayan, A. Leema Rose, P. Dinesh Kumar, V. Gokulnath, D. Parthiban, Sustainable Efficiency Of Hypo Sludge In Concrete, Int. J. Emerg. Trends Eng. Res. (2020).

[47] G. Jayarajan, S. Arivalagan, Geopolymer Concrete By Using Fly Ash, Ggbs, Quarry Dust And 10mm Aggregate, Int. J. Recent Technol. Eng. (Ijrte) Issn: 2277-3878, Volume-8, Issue-6, March 2020.

[48] M. Kalpana, D.S. Vijayan, S.R. Benin, Performance Study About Ductility Behaviour In Electronic Waste Concrete, Mater. Today Proc., Https://Doi.Org/ 10.1016/J.Matpr.2020.07.049.

[49] B. Saravanan, D.S. Vijayan, Status Review On Experimental Investigation On Replacement Of Red-Mud In Cementitious Concrete, Mater. Today, Proc., Https://Doi.Org/10.1016/J.Matpr.2020.05.500. [15] M. Kalpana, C. Vaidevi, D.S. Vijayan Et Al., Benefits Of Metakaolin Over Microsilica In Developing High Performance Concrete, Mater. Today, Proc., Https://Doi.Org/10.1016/J.Matpr.2020.06.566

[50] Tanu Hm, Unnikrishnan S. Utilization Of Industrial And Agricultural Waste Materials For The Development Of Geopolymer Concrete- A Review. Mater Today Proc 2022;65:1290e7. Https://Doi.Org/10.1016/J.Matpr.2022.04.192.

[51] Tanu Hm, Unnikrishnan S. Materials Today : Proceedings Review On Durability Of Geopolymer Concrete Developed With Industrial And Agricultural Byproducts. 2024 Mater Today Proc 2015;1:1e7. Https://Doi.Org/10.1016/J.Matpr.2023.03.335.

[52] Bellum Rr, Venkatesh C, Madduru Src. Influence Of Red Mud On Performance Enhancement Of Fly Ash-Based Geopolymer Concrete. Innov. Infrastruct. Solut. 2021;6:1e9. Https:// Doi.Org/10.1007/S41062-021-00578-X.

[53] Zareei Sa, Ameri F, Bahrami N. Microstructure, Strength, And Durability Of Eco-Friendly Concretes Containing Sugarcane Bagasse Ash. Construct Build Mater 2018;184:258e68. Https:// Doi.Org/10.1016/J.Conbuildmat.2018.06.153.

[54] Sethi H, Bansal Pp, Sharma R. Effect Of Addition Of Ggbs And Glass Powder On The Properties Of Geopolymer Concrete, Iran. J. Sci. Technol. - Trans. Civ. Eng. 2019;43:607e17. Https:// Doi.Org/10.1007/S40996-018-0202-4.

[55] Yadav Al, Sairam V, Srinivasan K, Muruganandam L. Synthesis And Characterization Of Geopolymer From Metakaolin And Sugarcane Bagasse Ash. Construct Build Mater 2020;258:1e15. Https://Doi.Org/10.1016/J.Conbuildmat.2020.119231.

[56] Jain D, Sharma R, Bansal Pp. Potential Use Of Sillimanite Sand In Sustainable Geopolymer Concrete Production. J Mater Civ Eng 2021;33:04021181. Https://Doi.Org/10.1061/(Asce)Mt.1943- 5533.0003826.

[57] Kumar K, Srinivasu K. Materials Today : Proceedings Impact Of Ggbs And Strength Ratio On Mechanical Properties Of Geopolymer Concrete Under Ambient Curing And Oven Curing. Mater Today Proc 2021;42:962e8. Https://Doi.Org/10.1016/ J.Matpr.2020.11.934.

[58] Lee Wh, Wang Jh, Ding Yc, Cheng Tw. A Study On The Characteristics And Microstructures Of Ggbs/Fa Based Geopolymer Paste And Concrete. Construct Build Mater 2019;211:807e13. Https://Doi.Org/10.1016/ J.Conbuildmat.2019.03.291.

[59] Setayesh Gar P, Suresh N, Bindiganavile V. Sugar Cane Bagasse Ash As A Pozzolanic Admixture In Concrete For Resistance To Sustained Elevated Temperatures. Construct Build Mater 2017;153:929e36. Https://Doi.Org/10.1016/ J.Conbuildmat.2017.07.107.

[60] Singh K. Experimental Study On Metakolin And Baggashe Ash Based Geopolymer Concrete. Mater Today Proc 2020;37:3289e95. Https://Doi.Org/10.1016/J.Matpr.2020.09.116.

[61] Saloni Parveen, Pham Tm, Lim Yy, Pradhan Ss, Kumar Jatin, J. Performance Of Rice Husk Ash-Based Sustainable Geopolymer Concrete With Ultra-Fine Slag And Corn Cob Ash. Construct Build Mater 2021;279:122526. Https://Doi.Org/ 10.1016/J.Conbuildmat.2021.122526.

[62] Bellum Rr, Al Khazaleh M, Pilla Rk, Choudhary S, Venkatesh C. Effect Of Slag On Strength, Durability And Microstructural Characteristics Of Fly Ash-Based Geopolymer Concrete. J. Build. Pathol. Rehabil. 2022;7. Https://Doi.Org/ 10.1007/S41024-022-00163-4.

[63] Oyebisi S, Ede A, Olutoge F, Omole D. Geopolymer Concrete Incorporating Agro-Industrial Wastes: Effects On Mechanical Properties, Microstructural Behaviour And Mineralogical Phases. Construct Build Mater 2020;256:119390. Https:// Doi.Org/10.1016/J.Conbuildmat.2020.119390.

[64] Alomayri T, Adesina A, Das S. Influence Of Amorphous Raw Rice Husk Ash As Precursor And Curing Condition On The Performance Of Alkali Activated Concrete. Case Stud Constr Mater 2021;15:E00777. Https://Doi.Org/10.1016/ J.Cscm.2021.E00777.

[65] Saloni Parveen, Lim Y Yan, Pham Tm. Influence Of Portland Cement On Performance Of Fine Rice Husk Ash Geopolymer Concrete: Strength And Permeability Properties. Construct Build Mater 2021;300:124321. Https://Doi.Org/10.1016/ J.Conbuildmat.2021.124321.

[66] Is 4031- Part V, Methods Of Physical Tests For Hydraulic Cement. Part V- Determination Of Initial And Final Setting Times. New Delhi: Bur. Indian Stand.; 1988. Reaffirmed In 2005. [18] Is:383. Specification For Coarse And Fine Aggregates From Natural Sources For Concrete. Indian Stand.; 1970. P. 1e24.

[67] Mallikarjuna Rao G, Gunneswara Rao Td. A Quantitative Method Of Approach In Designing The Mix Proportions Of Fly Ash And Ggbs-Based Geopolymer Concrete. Aust J Civ Eng 2018;16:53e63. Https://Doi.Org/10.1080/ 14488353.2018.1450716. [20] Is 516, Method Of Tests For Strength Of Concrete. Bur. Indian Stand. 1959:1e30. [21] Is 13311 (Part 1), Method Of Non-Destructive Testing Of Concret, Part 1: Ultrasonic Pulse Velocity. Bur. Indian Satandards. 1992:1e7.

[68] Srinivas D, Suresh D, Lakshmi Nh. Experimental Investigation On Bagasse Ash Based Geopolymer Concrete Subjected To Elevated Tempreture. Iop Conf Ser Earth Environ Sci 2021;796. Https://Doi.Org/10.1088/1755-1315/796/ 1/012028.

[69] Amin M, Elsakhawy Y, Abu El-Hassan K, Abdelsalam Ba. Behavior Evaluation Of Sustainable High Strength Geopolymer Concrete Based On Fly Ash, Metakaolin, And Slag. Case Stud Constr Mater 2022;16:E00976. Https://Doi.Org/10.1016/ J.Cscm.2022.E00976.

[70] Shilar Fa, Ganachari Sv, Patil Vb, Neelakanta Reddy I, Shim J. Preparation And Validation Of Sustainable Metakaolin Based Geopolymer Concrete For Structural Application. Construct Build Mater 2023;371:130688. Https://Doi.Org/10.1016/ J.Conbuildmat.2023.130688.

[71] Shilar Fa, Ganachari Sv, Patil Vb. Investigation Of The Effect Of Granite Waste Powder As A Binder For Different Molarity Of Geopolymer Concrete On Fresh And Mechanical Properties. Mater Lett 2022;309:131302. Https://Doi.Org/10.1016/ J.Matlet.2021.131302.

[72] Shilar Fa, Ganachari Sv, Patil Vb, Nisar Ks. Evaluation Of Structural Performances Of Metakaolin Based Geopolymer Concrete. J Mater Res Technol 2022;20:3208e28. Https:// Doi.Org/10.1016/J.Jmrt.2022.08.020.

[73] Shilar Fa, Ganachari Sv, Patil Vb, Khan Tmy, Javed S, Baig Ru. Optimization Of Alkaline Activator On The Strength Properties Of Geopolymer Concrete. Polymers 2022;14. Https:// Doi.Org/10.3390/Polym14122434.

[74] Kanagaraj B, Anand N, Johnson Alengaram U, Samuvel Raj R, Kiran T. Exemplification Of Sustainable Sodium Silicate Waste Sediments As Coarse Aggregates In The Performance Evaluation Of Geopolymer Concrete. Construct Build Mater 2022;330:127135. Https://Doi.Org/10.1016/ J.Conbuildmat.2022.127135. [

[75] Sreenivasulu C, Guru Jawahar J, Sashidhar C. Effect Of Copper Slag On Micro, Macro, And Flexural Characteristics Of Geopolymer Concrete. J Mater Civ Eng 2020;32:04020086. Https://Doi.Org/10.1061/(Asce)Mt.1943-5533.00 03157.

[76] Lloyd Rr, Provis Jl, Van Deventer Jsj. Microscopy And Microanalysis Of Inorganic Polymer Cements. 2: The Gel Binder. J Mater Sci 2009;44:620e31. Https://Doi.Org/10.1007/ S10853-008-3078-Z