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# Geopolymer Self Compacting Concrete

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***Abstract* -** The increasing environmental concerns associated with Ordinary Portland Cement (OPC), particularly its high carbon dioxide emissions, have encouraged the development of sustainable alternatives in concrete technology. This study investigates the performance of Geopolymer Self-Compacting Concrete (GPC-SCC) as an eco-friendly substitute for conventional Normal Self-Compacting Concrete (N-SCC). In the experimental program, fly ash and Ground Granulated Blast Furnace Slag (GGBS) were used as geopolymer binders, while steel slag was incorporated as a partial replacement for natural fine aggregate to improve sustainability. Two GPC-SCC mixes were prepared: one with 100% natural sand and another with 50% steel slag replacement, and their fresh and hardened properties were compared with N-SCC of M50 grade. Fresh-state performance was evaluated using Slump Cone, J-Ring, L-Box, and V-Funnel tests, while hardened-state performance was assessed through compressive strength tests under oven curing and ambient curing conditions. The study concludes that GPC-SCC with steel slag is a viable and sustainable alternative to conventional SCC, offering reduced environmental impact while maintaining adequate fresh and hardened performance for structural applications.

***Keywords - Geopolymer Concrete, Self-Compacting Concrete, Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Steel Slag, Sustainable Construction, Compressive Strength, Workability, Alkali Activation, Eco-Friendly Concrete.***

## INTRODUCTION

Concrete is the most widely used construction material in the world due to its versatility, durability, and cost-effectiveness. The primary binding ingredient in conventional concrete is **Ordinary Portland Cement (OPC)**, which significantly contributes to global carbon dioxide emissions during its manufacturing process. It is estimated that the production of one ton of OPC releases nearly one ton of $CO_2$ into the atmosphere, making the cement industry one of the major contributors to greenhouse gas emissions. With the growing demand for infrastructure development and the urgent need to reduce environmental impacts, the construction industry is increasingly focusing on sustainable alternatives to traditional cement-based concrete.[1]

One of the most promising alternatives is **geopolymer concrete**, which eliminates the use of OPC by utilizing industrial by-products such as **fly ash** and **Ground Granulated Blast Furnace Slag (GGBS)** as binder materials. These aluminosilicate-rich materials react with alkaline activators such as **sodium hydroxide (NaOH)** and **sodium silicate ($Na_2SiO_3$)** to form a geopolymeric binder through a process called **geopolymerization**. This process significantly reduces carbon emissions compared to OPC production while also promoting the beneficial reuse of industrial waste materials. As a result, geopolymer concrete offers both environmental and technical advantages, including lower embodied energy, improved durability, and enhanced resistance to aggressive chemical environments. [2]

Another important sustainability challenge in concrete production is the excessive consumption of natural river sand as fine aggregate. The rapid depletion of natural sand resources and the environmental degradation caused by sand mining have encouraged researchers to explore alternative fine aggregate materials. **Steel slag**, a by-product generated during steel manufacturing, has emerged as a potential substitute due to its favorable physical properties, including higher density, rough surface texture, and good mechanical strength. Utilizing steel slag as partial replacement for natural sand not only reduces industrial waste disposal problems but also contributes to the conservation of natural resources. [3]

The main objective of this research is to determine whether GPC-SCC with steel slag can achieve the workability and compressive strength required for structural applications while reducing the environmental burden associated with OPC and natural sand usage. By integrating **industrial by-products as binder and aggregate materials**, the study aims to contribute to the development of **sustainable and high-performance concrete** suitable for future construction needs. [4]

## MATERIALS AND METHODS

### A. *Materials*

The materials used in this study were selected to produce both **Normal Self-Compacting Concrete (N-SCC)** and **Geopolymer Self-Compacting Concrete (GPC-SCC)** with adequate fresh and hardened properties. For the normal SCC mix, **Ordinary Portland Cement (OPC) 53 Grade** was used as the primary binder. The cement conformed to the relevant Indian standards and exhibited suitable physical properties such as a specific gravity of 3.15 and adequate compressive strength. OPC served as the control binder material against which the geopolymer concrete mixes were evaluated. Natural river sand is used as fine aggregate with particle size ranging from 75 microns to 2.36 mm. The sand provides bulk to the mix and helps in maintaining dimensional stability. Its grading and particle size distribution influence the workability and packing of the plaster.

For the geopolymer concrete mixes, **Class F Fly Ash** and **Ground Granulated Blast Furnace Slag (GGBS)** were used as the binder materials. Fly ash is a by-product of coal combustion and is rich in silica and alumina, making it suitable for geopolymerization. GGBS, a by-product of the steel industry, was incorporated to improve early-age strength and enhance the reaction kinetics of the geopolymer matrix. In this study, the binder composition consisted of **70% fly ash and 30% GGBS**, which provided a balance between workability and strength development.[5]

To activate the geopolymer binder, an alkaline activator solution consisting of **sodium hydroxide (NaOH)** and **sodium silicate ($Na_2SiO_3$)** was prepared. A **10 molar NaOH solution** was used, and the mass ratio of sodium silicate to sodium hydroxide was maintained at approximately **2:1**. The alkaline solution initiated the geopolymerization process by dissolving silica and alumina from the fly ash and GGBS, resulting in the formation of a hardened geopolymer matrix. The activator solution was prepared at least 24 hours prior to mixing to ensure temperature stabilization and complete dissolution.

In addition, a **polycarboxylate ether-based superplasticizer** was added to improve the flowability and self-compacting properties of the concrete. The superplasticizer dosage was adjusted to achieve the required workability without segregation, ensuring that both normal SCC and geopolymer SCC satisfied the fresh-state performance criteria.

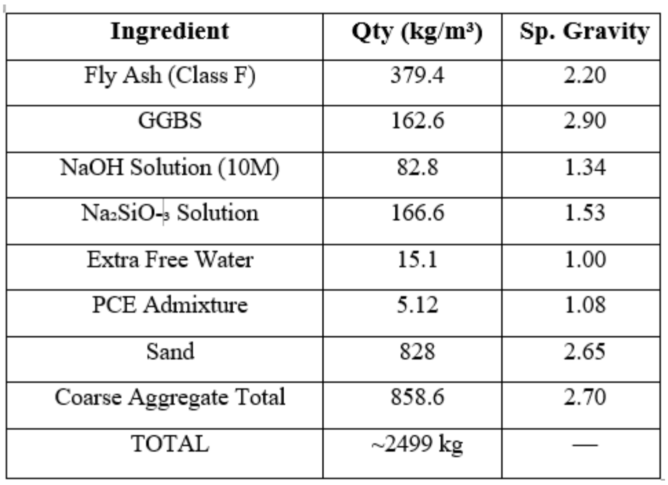
### B. *Methodology*

The experimental methodology involved preparing and testing **one Normal SCC mix** and **two Geopolymer SCC mixes**. The Normal SCC mix was designed for **M50 grade concrete** using conventional mix design procedures, whereas the geopolymer SCC mixes were developed using **fly ash and GGBS as complete cement replacement**. Two geopolymer mixes were prepared: one with **100% natural sand** and another with **50% steel slag as fine aggregate replacement**.

**Table 1: Mix Proportion**

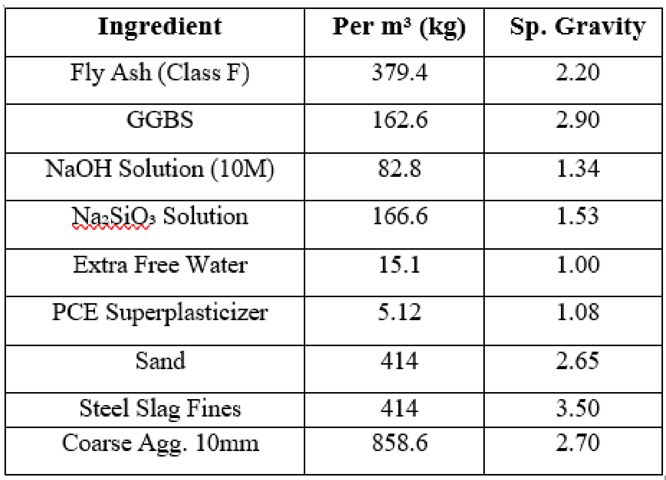
| OPC (kg) | Fine Agg. (kg) | Coarse Agg. (kg) | PCE (kg) | VMA (kg) | w/c ratio | Water (kg) |
|---|---|---|---|---|---|---|
| 542 | 828 | 858.6 | 5.97 | 0.54 | 0.35 | 190 |

**Table 2: Mix Proportion GPC_SCC (100% natural Sand)**



| Ingredient | Qty (kg/m³) | Sp. Gravity |
|---|---|---|
| Fly Ash (Class F) | 379.4 | 2.20 |
| GGBS | 162.6 | 2.90 |
| NaOH Solution (10M) | 82.8 | 1.34 |
| $Na_2SiO_3$ Solution | 166.6 | 1.53 |
| Extra Free Water | 15.1 | 1.00 |
| PCE Admixture | 5.12 | 1.08 |
| Sand | 828 | 2.65 |
| Coarse Aggregate Total | 858.6 | 2.70 |
| TOTAL | ~2499 kg | — |

**Table 3: Mix Proportion GPC_SCC (50% Steel Slag)**



| Ingredient | Per m³ (kg) | Sp. Gravity |
|---|---|---|
| Fly Ash (Class F) | 379.4 | 2.20 |
| GGBS | 162.6 | 2.90 |
| NaOH Solution (10M) | 82.8 | 1.34 |
| $Na_2SiO_3$ Solution | 166.6 | 1.53 |
| Extra Free Water | 15.1 | 1.00 |
| PCE Superplasticizer | 5.12 | 1.08 |
| Sand | 414 | 2.65 |
| Steel Slag Fines | 414 | 3.50 |
| Coarse Agg. 10mm | 858.6 | 2.70 |

The dry materials, including binder materials and aggregates, were first mixed thoroughly to ensure uniform distribution. In the geopolymer mixes, the pre-prepared alkaline activator solution was then added gradually along with the superplasticizer. Mixing was continued until a homogeneous and workable concrete mix was obtained. Care was taken to complete the casting process within the workable time of the geopolymer mix to avoid premature setting.

To evaluate the fresh properties of the concrete, **Slump Cone, J-Ring, L-Box, and V-Funnel tests** were conducted immediately after mixing. These tests were performed to determine the flowability, passing ability, and viscosity of the self-compacting concrete mixes. The results were compared with the standard acceptance limits to confirm whether the mixes qualified as self-compacting concrete.

For hardened-state testing, **150 mm × 150 mm × 150 mm cube specimens** were cast for each mix. The Normal SCC specimens were water-cured at room temperature and tested for compressive strength at **7, 14, and 28 days**. For the geopolymer SCC specimens, two curing methods were adopted: **oven curing at 70°C for 24 hours** and **ambient curing at room temperature for 28 days**. This allowed comparison of strength development under different curing conditions.

After the curing period, the specimens were tested for **compressive strength** using a compression testing machine. The maximum load at failure was recorded, and the compressive strength was calculated. The fresh and hardened test results of the geopolymer mixes were then compared with the control SCC mix to assess the feasibility of using **steel slag and geopolymer binders** in self-compacting concrete for sustainable construction applications.

## RESULTS AND DISCUSSION

The SCC mixture demonstrates satisfactory fresh-state performance, with Slump Flow (9 s), J-Ring (13 s), L-Box (8 s), and V-Funnel (11 s) all complying with EFNARC (2005) limits. The results indicate adequate filling ability, passing ability, and viscosity. However, compared to optimized GPC-SCC mixes, slightly higher flow times suggest increased internal resistance, likely due to conventional binder composition and reduced particle-level lubrication.

**Table 4: Normal SCC: Fresh Property Test Results**

| SCC | Slump flow (s) | J-Ring (s) | L-Box (s) | V-Funnel (s) | Remarks |
|---|---|---|---|---|---|
| SCC | 9 | 13 | 8 | 11 | All values well within limits |

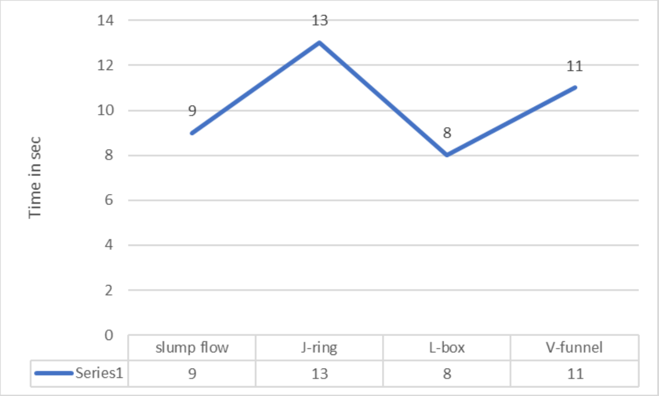


**Figure 1 N-SCC fresh Test results**

The N-SCC mixture exhibits a typical strength development pattern, with 7-day strength of 33.0 MPa, a slight dip at 14 days (32.8 MPa), and a significant increase to 45.0 MPa at 28 days. The minor reduction at 14 days may reflect normal variability or delayed hydration effects. The substantial 28-day gain indicates continued cement hydration and microstructure densification, leading to improved load-bearing capacity. This trend is consistent with conventional Portland cement systems, where strength develops progressively over time. Overall, the results confirm that the N-SCC mix achieves adequate compressive strength for structural applications while maintaining expected performance characteristics.

**Table 5: Compressive Strength Results N-SCC**

| Case | Avg.7d (MPa) | Avg.14d (MPa) | Avg.28d (MPa) |
|---|---|---|---|
| N-SCC | 33.0 | 32.8 | 45.0 |

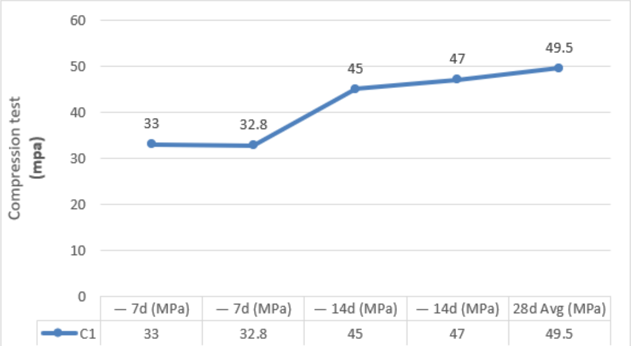


**Figure 2: N-SCC Compressive Strength Results**

Both GPC-SCC cases show superior fresh-state performance, with values well below EFNARC (2005) limits compared to Normal SCC. Case 1 records Slump = 8 s, J-Ring = 9 s, L-Box = 6 s, and V-Funnel = 10 s, indicating excellent flowability. This is due to alkaline activator dispersion using Sodium Hydroxide and Sodium Silicate, which reduces particle interaction, and the spherical morphology of Class F Fly Ash that enhances flow.

With 50% Steel Slag (Case 2), flow times increase slightly due to higher density and angularity, raising internal friction. However, all values remain within EFNARC limits, confirming maintained self-compactability.

**Table 6: GPC-SCC: Fresh Property Test Results Case 1**

| Test | EFNARC Limit | Case 1 (Sand) | Case 1 Status |
|---|---|---|---|
| Slump flow (s) | < 30 s | 8 s | Pass |
| J-Ring (s) | < 25 s | 9 s | Pass |
| L-Box (s) | < 60 s | 6 s | Pass |
| V-Funnel (s) | < 25 s | 10 s | Pass |
| L-Box $h_2/h_1$ | ≥ 0.80 | ≈ 0.87 | Pass |

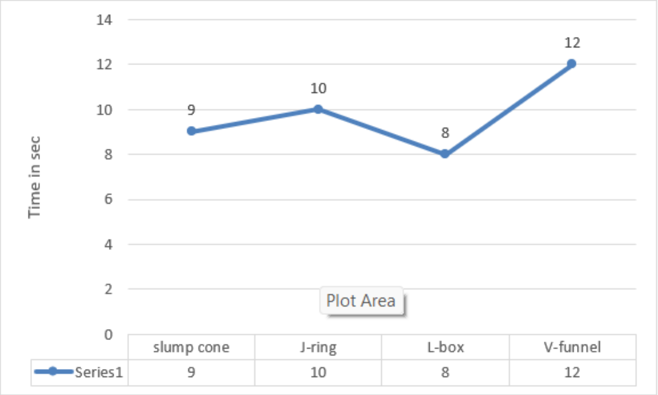


Figure 3: GPC-SCC Case 1 fresh Test results

Table 7: GPC-SCC: Fresh Property Test Results Case 2

| Test | EFNARC Limit | Case 2 (Steel Slag) | Case 2 Status |
|---|---|---|---|
| Slump flow (s) | < 30 s | 9 s | Pass |
| J-Ring (s) | < 25 s | 10 s | Pass |
| L-Box (s) | < 60 s | 8 s | Pass |
| V-Funnel (s) | < 25 s | 12 s | Pass |
| L-Box $h_2/h_1$ | ≥ 0.80 | ≈ 0.84 | Pass |

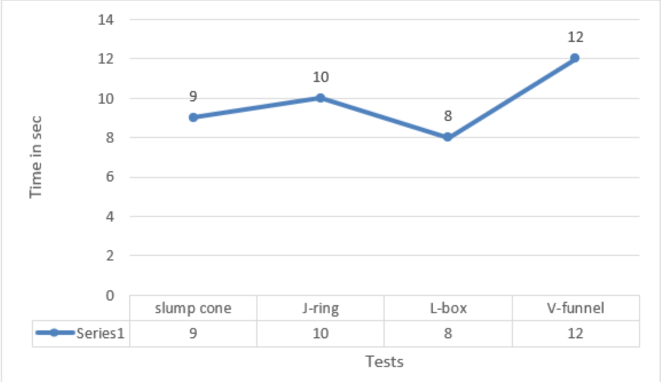


Figure 4: GPC-SCC Case 2 fresh Test results

Both GPC-SCC mixtures exhibit superior fresh-state performance compared to Normal SCC, with all values well below EFNARC (2005) limits. Case 1 shows Slump = 8 s (27%), J-Ring = 9 s (36%), L-Box ≈ 0.94, and V-Funnel = 10 s (40%), outperforming Normal SCC (C6: 11.9 s, 40%). This is attributed to alkaline activator dispersion using Sodium Hydroxide and Sodium Silicate, which reduces particle flocculation and yield stress, and the spherical morphology of Class F Fly Ash, producing a ball-bearing effect that enhances flowability. With 50% Steel Slag (Case 2), test times increase slightly (1–2 s) due to higher density and angular texture, which increase friction and paste demand. However, all values remain within EFNARC limits, confirming maintained self-compactability.

Table 8: Compressive Strength Results GPC-SCC Case 1

| Cube | Curing Condition | Load (kN) | Area (mm²) | CS (MPa) | Avg CS (Mpa) |
|---|---|---|---|---|---|
| 1 | Oven 70°C/24h | 1050 | 22,500 | 46.66 | 45.03 |
| 2 | Oven 70°C/24h | 1000 | 22,500 | 44.44 | |
| 3 | Oven 70°C/24h | 990 | 22,500 | 44.00 | |
| 4 | Oven 70°C/24h | 1050 | 22,500 | 46.66 | 45.55 |
| 5 | Oven 70°C/24h | 1030 | 22,500 | 45.77 | |
| 6 | Oven 70°C/24h | 995 | 22,500 | 44.22 | |
| 7 | Ambient 27°C/28d | 995 | 22,500 | 44.22 | 45.23 |
| 8 | Ambient 27°C/28d | 1000 | 22,500 | 45.33 | |
| 9 | Ambient 27°C/28d | 1040 | 22,500 | 46.22 | |

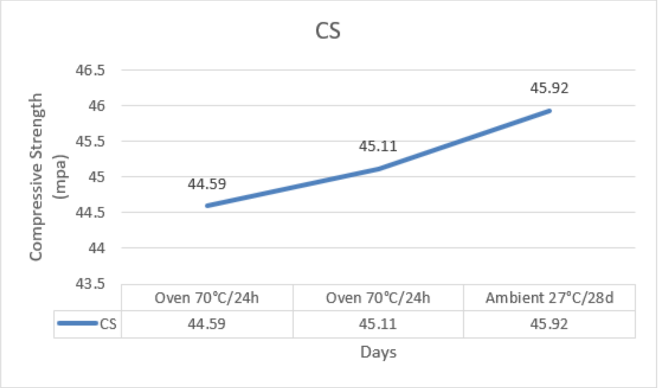


Figure 5: GPC-SCC Case 1 Compressive Strength Results

The results show consistent compressive strength for both curing regimes, with oven curing (70°C/24 h) achieving averages of 45.03–45.55 MPa, slightly higher than ambient curing (27°C/28 d) at ~45.23 MPa. Oven curing accelerates geopolymerization, leading to early strength gain, while ambient curing achieves comparable strength over longer periods. The minimal variation indicates stable mix performance and effective binder reaction under both curing conditions, confirming reliability of the geopolymer SCC system.

*Table 9: Compressive Strength Results GPC-SCC Case 2*

| Cube | Curing Condition | Load (kN) | Area (mm²) | CS (MPa) | Avg CS (Mpa |
|---|---|---|---|---|---|
| 1 | Oven 70°C/24h | 990 | 22,500 | 44 | 44.59 |
| 2 | Oven 70°C/24h | 1020 | 22,500 | 45.33 | |
| 3 | Oven 70°C/24h | 1000 | 22,500 | 44.44 | |
| 4 | Oven 70°C/24h | 1070 | 22,500 | 47.56 | 45.11 |
| 5 | Oven 70°C/24h | 990 | 22,500 | 44 | |
| 6 | Oven 70°C/24h | 985 | 22,500 | 43.77 | |
| 7 | Ambient 27°C/28d | 1030 | 22,500 | 45.77 | 45.92 |
| 8 | Ambient 27°C/28d | 1040 | 22,500 | 46.22 | |
| 9 | Ambient 27°C/28d | 1030 | 22,500 | 45.77 | |

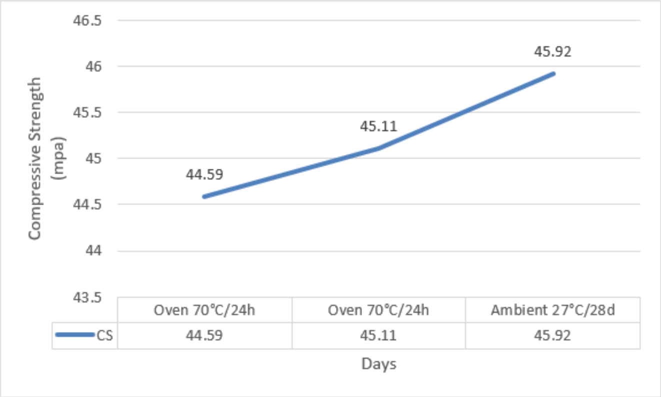


Figure 6: GPC-SCC Case 2 Compressive Strength Results

The results show consistent compressive strength across both curing regimes. Oven curing (70°C/24 h) produces average strengths of 44.59 MPa and 45.11 MPa, indicating effective early geopolymerization and rapid strength gain. Ambient curing (27°C/28 d) yields a slightly higher average of 45.92 MPa, suggesting continued reaction and gradual microstructure development over time. The small variation between curing methods confirms that while heat curing accelerates strength development, ambient curing can achieve comparable or marginally higher ultimate strength, demonstrating the stability and reliability of the GPC-SCC mix under different curing conditions.

A comparative assessment including N-SCC shows clear differences in strength development. The GPC-SCC mix under oven curing (70°C/24 h) achieves 44.59–45.11 MPa, indicating rapid early geopolymerization, while ambient curing (27°C/28 d) gives a slightly higher 45.92 MPa due to continued reaction. In comparison, N-SCC reaches 45.0 MPa at 28 days, showing a slower, hydration-controlled strength gain. The results highlight that GPC-SCC can match or slightly exceed N-SCC strength, with the added advantage of accelerated early strength under heat curing, confirming its efficiency and reliability.

## CONCLUSION

This study investigated the performance of **Geopolymer Self-Compacting Concrete (GPC-SCC)** incorporating **steel slag as a partial replacement for natural fine aggregate**, and compared its properties with those of **Normal Self-Compacting Concrete (N-SCC)**. The experimental results demonstrated that both geopolymer concrete mixes achieved satisfactory self-compacting properties, meeting the standard requirements for flowability, passing ability, and viscosity. The fresh-state test results confirmed that the use of fly ash, GGBS, and alkaline activators can successfully produce self-compacting concrete with adequate workability, while the inclusion of steel slag caused only a slight reduction in flow performance due to its rough surface texture and higher specific gravity.

In terms of hardened properties, the geopolymer concrete mixes developed compressive strengths comparable to the conventional SCC mix. The geopolymer mix with **100% natural sand** achieved compressive strengths of **45.55 MPa under oven curing** and **45.23 MPa under ambient curing**, while the mix containing **50% steel slag** attained strengths of **45.11 MPa** and **45.92 MPa**, respectively. Although these values were slightly lower than the compressive strength of the normal SCC mix, the difference remained within acceptable structural limits. The results also indicated that the use of steel slag as a fine aggregate replacement did not adversely affect the compressive strength, proving its effectiveness as a sustainable construction material.

Overall, the findings of this study confirm that **Geopolymer Self-Compacting Concrete with steel slag** is a feasible and sustainable alternative to conventional self-compacting concrete. The combined use of **industrial by-products such as fly ash, GGBS, and steel slag** reduces the dependence on Ordinary Portland Cement and natural river sand, thereby minimizing environmental impact and promoting resource conservation. This research highlights the potential of geopolymer technology in the development of eco-friendly construction materials capable of delivering satisfactory fresh and hardened properties for structural applications. Further studies on long-term durability and large-scale implementation can strengthen the practical applicability of this sustainable concrete system.

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