# Low-Carbon Geopolymer Concrete with Recycled Fine Aggregates: Mechanical Performance and Eco-Efficiency Assessment

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## Abstract

*The escalating environmental concerns associated with conventional Portland cement production, particularly its contribution to greenhouse gas emissions, necessitate the adoption of sustainable alternatives. Simultaneously, the underutilization of industrial by-products such as fly ash, and the overexploitation of natural river sand for fine aggregates, present significant ecological and resource challenges. In this context, geopolymer concrete (GPC), synthesized through alkali activation of fly ash, offers a promising low-carbon alternative to traditional cementitious systems. This study investigates the mechanical performance and eco-efficiency of GPC incorporating recycled fine aggregates (RFA) as a sustainable substitute for manufactured sand (M-sand). A geopolymer mix was developed using Class F fly ash as the sole binder and an 8M alkaline activator solution. The control mix used 100% M-sand, while subsequent mixes replaced M-sand with RFA at 25%, 50%, 75%, and 100% replacement levels. The influence of RFA on compressive strength, split tensile strength, and flexural strength was experimentally assessed. Results revealed that up to 50% replacement of M-sand with RFA enhanced mechanical performance, achieving strengths comparable to or exceeding the control mix. However, further increase beyond 50% led to marginal reductions in strength, attributed to the porous and angular nature of recycled aggregates. This study demonstrates that partial incorporation of RFA in GPC not only enhances its mechanical properties but also contributes to circular resource utilization and environmental conservation, making it a viable solution for sustainable construction.*

## INTRODUCTION:

Concrete is one of the most extensively utilized construction materials globally, serving as the backbone of infrastructure development. However, the production of conventional Portland cement, a primary binder in concrete, is a major contributor to anthropogenic $CO_2$ emissions—accounting for approximately 7–8% of global greenhouse gas emissions. Additionally, the large-scale extraction of natural aggregates poses significant environmental concerns, including resource depletion and ecological degradation. In light of increasing demand for sustainable construction, there is a pressing need to explore low-carbon alternatives to conventional cementitious systems.

Geopolymer concrete (GPC), developed through the alkali activation of alumino-silicate materials such as fly ash or ground granulated blast furnace slag (GGBS), has emerged as a promising substitute to ordinary Portland cement (OPC) concrete. By leveraging industrial by-products like Class F fly ash, geopolymer binders can significantly reduce the embodied carbon footprint of concrete while simultaneously addressing the waste disposal challenges faced by thermal power plants. The geopolymerization process forms a three-dimensional alumino-silicate network that imparts excellent

mechanical and durability properties to the hardened matrix, often without requiring the high-temperature calcination process inherent to OPC production.

Parallel to the need for binder innovation, the construction industry faces challenges related to fine aggregate consumption. The rapid urbanization and infrastructural expansion have led to excessive mining of river sand and manufactured sand (M-sand), exacerbating environmental concerns. Simultaneously, construction and demolition (C&D) waste has surged, posing serious waste management issues due to limited landfill availability and disposal mechanisms. In India alone, more than 48 million tons of C&D waste are generated annually, with a significant portion being concrete and masonry rubble that remains unrecycled. The reuse of such waste, particularly in the form of recycled fine aggregates (RFA), presents an opportunity for circular economy integration in the concrete value chain.

Despite growing interest in recycled coarse aggregates, the incorporation of recycled fine aggregates in concrete has remained limited due to concerns about increased water absorption, porosity, shrinkage, and reduced workability and durability. These challenges are particularly relevant in high-performance systems such as GPC. Nevertheless, recent studies have indicated that with appropriate mix design and material optimization, RFA can be effectively utilized without significant compromise in performance, especially when used in partial replacement proportions.

In the context of geopolymer technology, fly ash plays a crucial role as the primary alumino-silicate precursor. Class F fly ash, derived from the combustion of anthracite and bituminous coal, is preferred for its pozzolanic characteristics and low calcium oxide content, which make it ideal for geopolymerization. When activated using a combination of alkaline solutions—typically sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$) the resulting binder matrix forms durable, dense geopolymeric gels capable of high early strength development and chemical resistance. The concentration of alkali activator (often expressed in molarity), the $SiO_2/Na_2O$ ratio, and the curing regime play pivotal roles in optimizing the mechanical and microstructural performance of GPC.

This research investigates the synergistic use of fly ash-based GPC and recycled fine aggregates as a sustainable, low-carbon alternative to conventional concrete. The study aims to evaluate the influence of RFA on the mechanical performance of GPC including compressive, split tensile, and flexural strengths at varying replacement levels. Through a comprehensive experimental program, the research seeks to identify the optimal proportion of RFA that achieves desirable strength performance without compromising the eco-efficiency of the mix. The outcomes are expected to contribute to the broader understanding of sustainable material integration in geopolymer concrete systems, aligning with global goals of carbon neutrality and circular resource utilization.

## 2. LITERATURE REVIEW

The integration of recycled aggregates in geopolymer concrete (GPC) has gained increasing attention as a dual solution to environmental concerns: reducing $CO_2$ emissions from cement production and diverting construction and demolition waste (CDW) from landfills. Several researchers have explored the feasibility of replacing natural aggregates with recycled ones and the influence of alkali-activated binders on concrete performance.

Abdollahnejad et al. [1] emphasized that while the incorporation of recycled aggregates (RA) in alkali-activated systems often degrades mechanical performance due to their porous structure, water absorption, and weak interfacial transition zone (ITZ), certain improvements have been observed. These include enhanced internal curing and denser ITZs attributed to unreacted cementitious remnants. Saravanakumar [2] demonstrated that partial substitution of natural aggregates with recycled coarse aggregates (RCA) up to 100% in GPC can yield satisfactory mechanical and durability characteristics when properly proportioned.

Khaleel et al. [3] and Galvin et al. [4] supported the environmental advantages of using RCA in GPC, highlighting its impact on compressive strength and workability. Despite strength reductions at higher RCA content, the values remained within acceptable structural limits. Anuradha et al. [5] and Rathnam et al. [6] studied the combined effects of mix proportioning and alkaline activator concentration, identifying optimal sodium hydroxide molarity and fly ash-to-alkali ratios to maximize compressive strength and workability.

Patankar et al. [7,8,9] focused on the influence of sodium hydroxide molarity, curing temperature, and solution-to-binder ratio on GPC performance. The findings reinforced that Class F fly ash, when activated under suitable alkaline conditions, produces dense alumino-silicate gel structures that enhance strength development. Furthermore, Indian standards (IS 10262) could be adapted for GPC mix design with appropriate modifications.

Yahya et al. [10] and Koushkbaghi et al. [11] extended the investigation to alternative binders such as palm oil boiler ash and metakaolin. They confirmed that increasing the sodium silicate-to-sodium hydroxide ratio improves compressive strength and reduces water absorption, thus enhancing durability. The use of high-molarity alkaline activators (e.g., 14M NaOH) was found to significantly influence early-age strength gain and matrix densification.

Eckert et al. [12] and Kou et al. [13] analyzed the long-term behavior of recycled aggregate concrete (RAC) with fly ash, indicating that while RAC initially lags behind in compressive strength compared to natural aggregate concrete (NAC), it demonstrates progressive strength gains over extended curing periods. Notably, the internal curing provided by recycled aggregates contributed to shrinkage reduction and minimized early-age cracking.

Abdullah et al. [14] and Hu et al. [15] explored the synergistic effects of ground granulated blast furnace slag (GGBFS) and recycled aggregates in GPC. They reported improvements in mechanical performance and microstructural properties when GGBFS was blended with fly ash, particularly under optimized curing conditions. SEM analyses revealed denser matrix formation and reduced porosity, validating the effectiveness of alkali-activated systems in mitigating the drawbacks of recycled aggregate inclusion.

Collectively, these studies affirm that geopolymer concrete incorporating recycled fine or coarse aggregates can serve as a viable low-carbon, sustainable alternative to traditional concrete. However, to fully realize its potential, careful consideration must be given to material selection, mix design parameters, activator chemistry, and curing regimes.

## 3. Objectives of the Study

The primary aim of this study is to evaluate the mechanical and rheological performance of fly ash-based geopolymer concrete (GPC) incorporating recycled fine aggregates (RFA) as a partial or full replacement for manufactured sand (M-sand). The specific objectives are:

1. **Material Characterization**
o        To determine the physical and mechanical properties of fly ash, M-sand, RFA, and coarse aggregates used in geopolymer concrete production.

2. **Fresh State Behavior**
o        To assess the workability characteristics of fresh GPC mixes through standard tests including slump flow, compaction factor, and Vee-Bee consistometer.

3. **Mix Design Optimization**
o        To develop an optimized GPC mix that balances strength, durability, and fresh-state rheological performance using fly ash as the binder and an alkaline activator.

4. **Influence of Alkali Activator**
o        To investigate the effect of varying concentrations of alkaline activator solution on the mechanical strength of hardened GPC.

5. **Recycled Fine Aggregate Substitution**
o        To examine the impact of substituting M-sand with varying proportions of RFA on the mechanical properties and durability of GPC.
o        To evaluate changes in rheological parameters resulting from RFA incorporation.

6. **Curing Regime Sensitivity**
o        To study the influence of curing temperature on strength development and matrix performance of GPC.

7. **Sustainability and Waste Valorization**
o        To explore the potential of RFA utilization as a circular solution for mitigating construction and demolition waste challenges in developing economies and reducing pressure on natural resources and landfill capacity.

## 4. MATERIALS AND MIX DESIGN

### 4.1 Materials

The experimental study was conducted using the following constituents to develop fly ash-based geopolymer concrete (GPC) with and without recycled fine aggregates (RFA):

• **Fly Ash (Class F)** – Low-calcium fly ash sourced from a thermal power plant was used as the primary aluminosilicate binder.



**Fig 1:** Class F fly ash

• **Ground Granulated Blast Furnace Slag (GGBS)** – Added as a mineral admixture to enhance early strength.

• **Alkaline Activators** – An 8 M sodium hydroxide (NaOH) solution and sodium silicate ($Na_2SiO_3$) solution with $SiO_2:Na_2O$ ratio of ~2.0 were used in equal mass ratio.

• **Fine Aggregates** – Manufactured sand (M-sand) and RFA obtained from crushed concrete debris. RFA was used as partial and full replacement of M-sand.

• **Coarse Aggregates** – Crushed angular aggregates of 10 mm nominal size, conforming to IS 383:1970.

• **Superplasticizer** – A polycarboxylic ether-based high-range water reducer (Auramix 400, Fosroc) was used to improve workability.

• **Water** – Clean potable water was used for mixing and preparation of activator solutions.



**Figure 2:** Manufacture sand used for investigation

### 4.2 Material Characterization

**M-Sand:**

• Specific Gravity: 2.33

• Fineness Modulus: 3.47

- Moisture Content: 0.5%
- Conformed to Zone II grading as per IS 383.

**Recycled Fine Aggregate (RFA):**
- Specific Gravity: 2.30
- Fineness Modulus: 3.46
- Water Absorption: 5.6%
- Derived from processed CDW, exhibiting higher porosity.

**Coarse Aggregate (10 mm down):**
- Specific Gravity: 2.64
- Fineness Modulus: 8.05
- Water Absorption: 0.81%
- Aggregate Impact Value: 21.34%
- Aggregate Crushing Value: 25.67%
- All properties within IS 383 permissible limits.

### 4.3 Alkaline Activator Preparation

Sodium hydroxide pellets were dissolved in water to prepare an 8M solution, with a concentration of 320 g/L. Sodium silicate was blended in a mass ratio of 1:1 with NaOH. The activator solution was prepared 24 hours prior to mixing to ensure stability. The calculated water contribution from both activator components was factored into the mix water content.

### 4.4 Mix Design Methodology



**Figure 3. Design Mix Preparation**

The GPC mix was designed for a target compressive strength of M60, based on the guidelines proposed by Rangan et al. and modified as per IS 456:2000. The following design assumptions were made:

- **Wet Density of GPC:** 2400 kg/m³
- **Alkaline to Binder Ratio (A/B):** 0.35
- **Fly Ash + GGBS Content:** 408 kg/m³ (Fly Ash: 366 kg/m³, GGBS: 40 kg/m³)
- **Sodium Silicate / Sodium Hydroxide Ratio:** 2.5
- **Superplasticizer Dosage:** 3% by mass of binder
- **Fine Aggregate Proportion:** 30% of total aggregate
- **Coarse Aggregate Proportion:** 70% of total aggregate

### 4.5 Final Mix Proportions

Step 1: Wet density of GPC is calculated and found out to be 2400kg/m³

Step 2: Mass of combined aggregate =77% of mass of concrete
= (77 x 2400/100) = 1848 kg/m³.

Step 3: Mass of binders and the alkaline liquid = 2400 - 1848 =552 kg/m³.

Step 4: Alkaline liquid to binder ratio by mass = 0.35

Step 5: Mass of fly ash + GGBS = 552/(1+0.35) = 408 kg/m³.

Mass of GGBS = 10% of fly ash = (10 x 408/100) = 40 kg/m³.

Mass of fly ash = 368 kg/m³.
Step 6: Mass of alkaline liquid = 552-408 = 144 kg/m³.
Step 7: Ratio of sodium silicate to sodium hydroxide solution = 2.5
Step 8: Mass of sodium hydroxide solution = 144/(1+2.5) = 41 kg/m³
For 1 molar sodium hydroxide solution, 40g of sodium hydroxide pellets are dissolved in 1 liter of water. ie. for 1 molar: 40g pellets → 1000g or 1000ml of water.
For 8 molars: 8 x 40g of pellets → 1000g or 1000ml of water.
Total sodium hydroxide solution = (8 x 40 + 1000) = 1320g.
% of sodium hydroxide solids in NaOH solution = (320/(1000 + 320)) x 100 = 24.24%. In sodium hydroxide solution, solids = 0.2424 x 41 = 9.938kg.
and water = 41-9.938 = 31.062kg.
Step 9: Mass of sodium silicate solution = 144 - 41 = 103 kg/m³.
Step 10: Water content in sodium silicate solution = 55.9%.
In sodium silicate solution, water = 0.559 x 103 = 58 kg, and solids = 103 - 58 = 45 kg. Therefore, total mass of water = 58+31.062 = 89.062 kg.
Step 11: Coarse aggregate = 0.70 x 1848 = 1294 kg/m³.
Step 12: Fine aggregate = 0.30 x 1848 = 555 kg/m³.

### 4.6.2 MIX DESIGN PROPORTIONS

| Material | Quantity (kg/m³) |
|---|---|
| Fly Ash (Class F) | 366 |
| GGBS | 40 |
| Coarse Aggregate (10 mm) | 1295 |
| Fine Aggregate (M-sand/RFA) | 555 |
| Sodium Hydroxide Solution (8M) | 41 |
| Sodium Silicate Solution | 103 |
| Total Water (from activator & ext.) | 89.06 |
| Superplasticizer (Auramix 400) | 3% of binder |

## MIX PROPORTION FLOWCHART
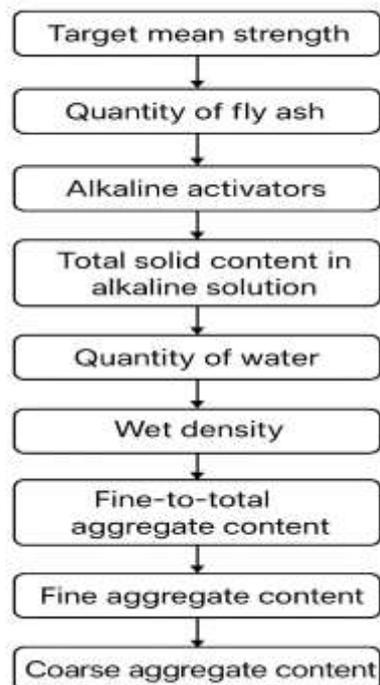
## 5. Experimental Program

### 5.1 Scope and Test Matrix

This study investigates the performance of M60-grade geopolymer concrete (GPC) with fly ash as a complete replacement for cement and recycled fine aggregate (RFA) as a partial replacement for manufactured sand (M-sand). Five different mix groups were developed by replacing M-sand with RFA at 0%, 25%, 50%, 75%, and 100% by weight.

For each replacement level, 25 cube specimens (150 mm), 25-cylinder specimens (100 mm × 200 mm), and 25 prism specimens were cast and tested to assess compressive, split tensile, and flexural strength respectively. The tests were conducted at 7 and 28 days in accordance with IS 516:1959 and IS 5816:1999.

### 5.2 Activator Preparation

An 8M sodium hydroxide (NaOH) solution was prepared by dissolving solid NaOH pellets in water (320 g/L concentration) and allowing it to cool for 24 hours. This solution was then mixed with sodium silicate solution at a 1:1 mass ratio to produce the alkali activator. The composition of sodium silicate used contained 16.37% $Na_2O$, 34.35% $SiO_2$, and 49.72% $H_2O$.

### 5.3 Batching and Mixing Procedure

All raw materials fly ash, GGBS, M-sand, RFA, coarse aggregates, water, alkaline activators, and superplasticizer were batched by weight using digital weighing scales to ensure precision.

Dry materials were initially mixed to achieve a uniform blend. Subsequently, alkaline solutions and superplasticizer were added to produce a homogeneous and workable geopolymer concrete mix.

### 5.4 Casting and Compaction

Fresh concrete was poured into greased steel moulds in layers and compacted using a table vibrator to minimize entrapped air. Specimens for compressive strength (150 mm cubes), split tensile strength (100 mm × 200 mm cylinders), and flexural strength (100 mm × 100 mm × 500 mm prisms) were cast for all RFA replacement ratios.

### 5.5 Curing Regime

After 24 hours of ambient setting, specimens were demoulded and subjected to a hybrid curing regime:

- Steam Curing for 3 days in a controlled chamber,
- Followed by ambient air curing up to 7 and 28 days depending on the testing schedule.

This curing approach was adopted to simulate field-like accelerated strength development often required for geopolymer systems.

### 5.6 Fresh Concrete Testing

### 5.6.1 Slump Test

Workability was assessed using the slump cone test (as per IS 1199). The cone was filled in three layers; each tamped 25 times. A true slump of approximately 80 mm was observed, indicating good flowability and consistency suitable for standard placement methods in construction.

## 6. RESULTS AND DISCUSSION

This section presents the results of the experimental investigation conducted on M60-grade geopolymer concrete (GPC) using varying proportions of recycled fine aggregate (RFA) as partial to full replacements for manufactured sand (M-sand). The assessment covers fresh and hardened concrete properties including workability, compressive strength, flexural strength, and split tensile strength.

### 6.1 Workability of Fresh Concrete

Workability of the fresh GPC mixes was evaluated using the slump cone and compaction factor methods. As shown in Table 6.1, the slump value and compaction factor progressively decreased with increasing RFA content.

**Table 6.1: Workability Test Results**

| RFA Replacement (%) | Slump (mm) | Compaction Factor |
|---|---|---|
| 0% | 65 | 0.902 |
| 25% | 62 | 0.893 |
| 50% | 59 | 0.879 |

| RFA Replacement (%) | Slump (mm) | Compaction Factor |
|---|---|---|
| 75% | 55 | 0.845 |
| 100% | 48 | 0.794 |

This decline in workability is attributed to the higher water absorption and rough texture of RFA, which leads to a stiffer mix. The observed slump variation confirmed the need for superplasticizer dosage adjustment to maintain workability.

**6.2 Determination of Optimum RFA Replacement**

To establish the optimum replacement level of RFA, compressive strength of mortar cubes was evaluated at 7, 14, and 28 days. The results are presented in Table 6.2.

**Table 6.2: Compressive Strength of Mortar (MPa)**

| RFA (%) | 7 Days | 14 Days | 28 Days |
|---|---|---|---|
| 0% | 32.58 | 46.85 | 54.60 |
| 25% | 33.92 | 47.88 | 56.41 |
| 50% | 33.16 | 46.62 | 55.85 |
| 75% | 31.45 | 45.20 | 52.55 |
| 100% | 30.87 | 44.54 | 51.60 |

An optimum performance was achieved at 50% RFA replacement, beyond which a reduction in strength was observed due to the weaker interfacial bonding and higher porosity of recycled fines.

**6.3 Compressive Strength of Geopolymer Concrete**

Cube specimens were tested to evaluate the compressive strength at 7 and 28 days using 8M and 10M sodium hydroxide solutions. The results are tabulated in **Table 6.4**.

**Table 6.4: Compressive Strength of GPC (MPa)**

| Curing Period | Molarity | RFA Replacement (%) → | 0% | 25% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|---|
| 7 Days | 8M | | 30.21 | 32.10 | 31.84 | 29.56 | 28.44 |
| | 10M | | 32.58 | 33.92 | 33.16 | 31.45 | 30.87 |
| 28 Days | 8M | | 52.80 | 54.21 | 54.02 | 51.14 | 49.88 |
| | 10M | | 54.60 | 56.41 | 55.85 | 52.55 | 51.60 |

At both curing ages, compressive strength increased with the use of 10M activator. A peak strength of 56.41 MPa was observed at 25% RFA with 10M NaOH at 28 days. Beyond 50% RFA, a decline in compressive strength occurred due to reduced matrix cohesion and increased voids.

**6.4 Flexural Strength of GPC**

Beam specimens (100×100×500 mm) were tested for flexural strength at 7 and 28 days. The results are given in Table 6.5.1.

**Table 6.5.1: Flexural Strength (N/mm²)**

| Curing Period | RFA Replacement (%) → | 0% | 25% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|
| 7 Days | | 13.65 | 13.94 | 13.19 | 12.61 | 12.25 |
| 28 Days | | 21.67 | 22.15 | 21.84 | 20.47 | 20.20 |

An increase in flexural strength was recorded up to 25–50% RFA. At higher substitution levels, decreased matrix integrity contributed to lower flexural resistance.

**6.5 Split Tensile Strength of GPC**

Cylindrical specimens (100 mm × 200 mm) were tested to determine the split tensile strength. Results are shown in Table 6.5.2.

**Table 6.5.2: Split Tensile Strength (N/mm²)**

| Curing Period | RFA Replacement (%) → | 0% | 25% | 50% | 75% | 100% |
|---|---|---|---|---|---|---|
| 7 Days | | 1.52 | 1.64 | 1.40 | 1.33 | 1.28 |
| 28 Days | | 2.70 | 3.10 | 2.50 | 2.02 | 1.86 |

The tensile strength followed a similar trend to compressive strength, with the maximum value at 25% RFA, confirming that moderate replacement levels improve load transfer across the matrix.

**Scanning Electron Microscopy (SEM) Analysis of Geopolymer Concrete**

Scanning Electron Microscopy (SEM) is a vital technique used to analyze the microstructural characteristics of geopolymer concrete (GPC), providing high-resolution imagery that reveals the morphology, texture, and phase distribution within the material. The SEM analysis of GPC highlights the effectiveness of the geopolymerization process and the structural integrity of the aluminosilicate matrix.

SEM images typically show a dense and cohesive microstructure, characterized by well-formed geopolymeric gel that binds the precursor particles, such as fly ash or GGBS. The matrix displays reduced porosity and enhanced particle packing, which contribute to improved mechanical strength and durability. The gel phase often appears as a continuous, amorphous structure that indicates successful polymerization.

Notably, undissolved or partially reacted particles of crystalline hydro-aluminosilicates are commonly visible in the matrix. These remnants suggest incomplete dissolution of raw materials or the presence of inert phases, which may act as micro-fillers and enhance the mechanical interlock within the matrix. Their presence also suggests areas where further activation could improve the material's performance.
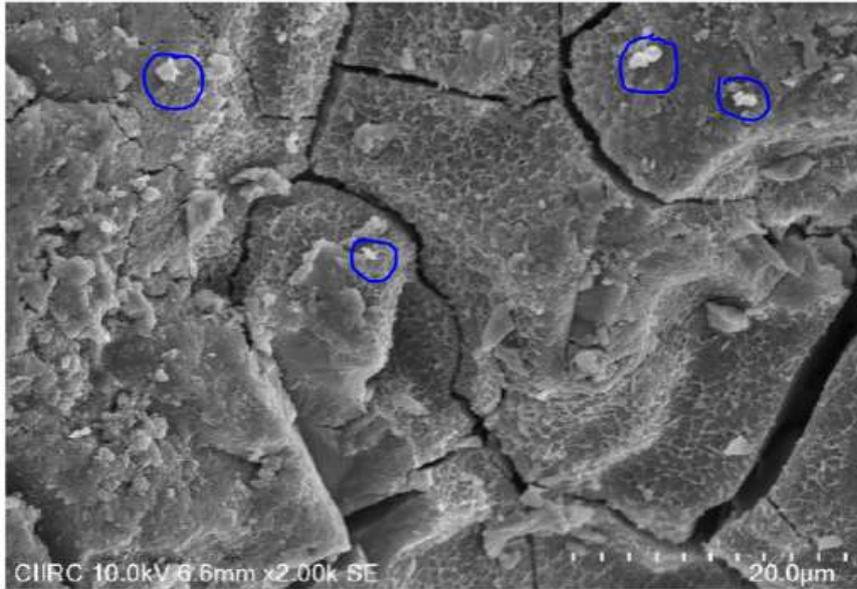
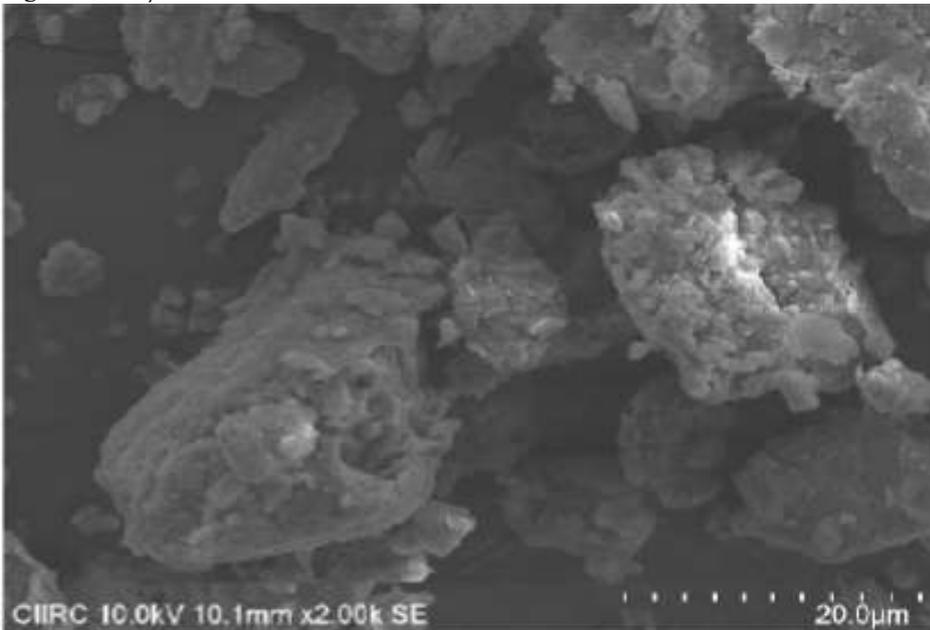**Figure 4.** Crystallized undissolved Aluminates and Silicates



**Figure 5.** SEM Analysis showing geopolymer concrete

**6.6 Summary of Observations**

- Workability decreased with increasing RFA due to higher absorption and angularity.
- Compressive strength peaked at 25–50% RFA and declined thereafter.
- 10M NaOH consistently outperformed 8M in all mechanical properties.
- Flexural and tensile strength followed the same trend, validating 25–50% RFA as optimal.

**7. CONCLUSION**

This study demonstrates the viability of geopolymer concrete (GPC) as a sustainable and high-performance alternative to conventional Portland cement concrete, particularly when incorporating recycled fine aggregates (RFA). Based on the experimental results and analysis, the following key conclusions are drawn:

- Geopolymer concrete utilizing Class F fly ash as the primary binder, activated with an alkaline solution of sodium hydroxide and sodium silicate, achieved satisfactory mechanical performance and workability for M60 grade concrete, while eliminating the use of Portland cement.

- Partial replacement of M-sand with RFA up to 50% enhanced compressive, tensile, and flexural strengths, with the optimum performance observed at 25–50% RFA substitution. Beyond this threshold, strength properties declined due to increased porosity and weaker aggregate-matrix bonding.
- The workability of GPC decreased with increasing RFA content owing to the high water absorption capacity and angularity of RFA. To counteract this effect, the incorporation of a polycarboxylate-based superplasticizer was essential in achieving desirable flow characteristics.
- Increasing the molarity of sodium hydroxide solution from 8M to 10M resulted in an approximate 5% increase in compressive strength, indicating improved polymerization and matrix densification at higher alkaline concentrations.
- Curing temperature and duration significantly influenced strength development. A combination of steam and ambient air curing accelerated the geopolymerization process, leading to early strength gain and improved long-term performance.
- The reuse of RFA in GPC not only supports circular economy principles by minimizing construction and demolition waste, but also contributes to the reduction of embodied carbon, making it a technically feasible and environmentally advantageous option for future infrastructure applications.

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