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Sustainable Development Of Fly Ash And Ggbs-Based Geopolymer Concrete Using Sodium Silicate Activation

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Abstract: This project investigates the mechanical performance and sustainability potential of geopolymer concrete (GPC) produced using industrial by-products—fly ash and Ground Granulated Blast Furnace Slag (GGBS)—as an alternative to conventional Ordinary Portland Cement (OPC). In light of the urgent need to reduce carbon emissions from the construction industry, the study explores geopolymer technology as a viable pathway to green construction. The research involved preparing five different mix proportions of fly ash and GGBS (100:0, 75:25, 50:50, 25:75, and 0:100), activated using sodium silicate solution alone, under ambient curing conditions.

I. Introduction

In the current scenario, the construction industry is growing rapidly all over the world, and with this growth comes the increasing demand for concrete. Ordinary Portland Cement (OPC) is one of the major components in concrete production, but unfortunately, the manufacturing of cement is highly energy-intensive and is a significant contributor to environmental pollution. Every ton of cement production releases approximately one ton of carbon dioxide (CO) into the atmosphere, which has a direct link to global warming and climate change. Due to these environmental concerns, engineers and researchers are focusing on developing more sustainable and eco-friendly alternatives. One such alternative is geopolymer concrete. Unlike conventional concrete, geopolymer concrete does not use OPC. Instead, it uses industrial by-products like Fly Ash and Ground Granulated Blast Furnace Slag (GGBS), which are rich in silica and alumina. When these materials react with alkaline solutions like sodium hydroxide (Na2Sio3) and sodium silicate (Na, SiO_2), they form a strong binding material similar to cement..

II. Objectives of the Study

The main idea behind this project is to come up with a sustainable and eco-friendly alternative to traditional cement by using industrial waste materials like fly ash and GGBS. We are aiming to explore how these materials can work together in a geopolymer mix to give us good strength and performance, while also reducing the environmental Impact.
Here are the key objectives of this study: ·
To investigate the fresh properties of geopolymer concrete, including consistency, setting time, and workability, for various fly ash– GGBS mix proportions activated using sodium silicate solution. ·
To evaluate the compressive strength development of geopolymer concrete at 3, 7, and 28 days under ambient curing conditions for different fly ash and GGBS ratios (100:0 to 0:100). ·
To analyze the influence of fly ash and GGBS content on both fresh and hardened properties of geopolymer concrete, and to identify optimal binder proportions for balanced performance. ·
To demonstrate the environmental and sustainability benefits of replacing Ordinary Portland Cement (OPC) with industrial by- products, supporting circular economy principles and contributing to Sustainable Development Goals (SDGs), particularly SDG 9, 11, 12, and 13

III. Scope of the Study

This study mainly focuses on the development and testing of geopolymer concrete using industrial by-products like fly ash and GGBS, which are activated using alkaline liquids such as sodium silicate and sodium hydroxide. With increasing pressure on the construction industry to shift towards more sustainable practices, this project offers a practical and eco-friendly alternative to traditional cement- based concrete..

IV. METHODOLOGY

The methodology of this project includes all the steps we followed from the beginning of the research until the final testing of our concrete samples. It is the practical side of the study, where we take the idea of using fly ash and GGBS as a replacement for cement and put it into action by designing mixes, casting specimens, curing them, and checking their strength. Below is a step-by-step explanation of the methodology followed in this study:

1. Selection of Materials We first selected the materials that are suitable for geopolymer concrete. The main materials used are: Fly Ash – Collected from thermal power plants. GGBS (Ground Granulated Blast Furnace Slag) – Collected from steel industries. 24 Alkaline Activator Solution – Prepared by mixing sodium hydroxide (Na2Sio3) and sodium silicate (Na_2SiO_3). Fine Aggregate – Clean River sand as per IS standards. Coarse Aggregate – Crushed stone of 20 mm and 10 mm size. Water – Used only for cleaning and mixing aggregates, not for hydration.
2. Preparation of Alkaline Solution A solution of sodium hydroxide (Na2Sio3) was prepared using flakes dissolved in water to get a concentration of 10M (mol/L). Sodium silicate and sodium hydroxide solutions were mixed in a specific ratio (like 2.5:1 or 2:1) and left to cool down for 24 hours before using in the mix.
3. Mixing of Concrete All dry materials were mixed first (fly ash, GGBS, fine and coarse aggregates). After that, the alkaline solution was added slowly, and the mix was blended thoroughly until a uniform paste was obtained.
4. Casting of Specimens Cubes of size 150 mm x 150 mm x 150 mm were cast for each mix. The fresh mix was placed into moulds in 3 layers and Compacted properly to remove air gaps. Molds were kept undisturbed for 24 hours at room temperature. 25
5. Curing of Specimens After demolding, the cubes were left to cure at room temperature (ambient curing) without water. No water curing was done because geopolymer concrete doesn't need water like OPC concrete. Each mix had samples kept for 3-day, 7-day, and 28-day testing.
6. Compressive Strength Testing After the curing period was completed, each cube was tested in a Compression Testing Machine (CTM) to check the strength. The results were recorded for each mix at different curing ages to Compare their performance.
7. Observation and Analysis The compressive strength results were collected, and graphs were plotted for each mix over time. Based on this, we studied which mix gave the highest strength and how the fly ash and GGBS ratio affected the performance of geopolymer concrete.
8. Additional Experimental Study with Fly Ash For further study, we also explored the behavior of Fly ash in place of fly ash in some mixes. This part was experimental and aimed at exploring alternative waste materials that could be used in the future. This whole process helped us not only understand the technical working of geopolymer concrete but also gave us practical experience in materials handling, concrete technology, and lab testing.

V. LITERETURE REVIEW

Literature review is an important part of any project because it gives us a strong foundation to build our work upon. Before jumping into our own experimental work, it's essential to understand what other researchers, engineers, and scientists have already done in the field. This helps us avoid repeating the same mistakes and also shows us where we can bring something new. In our case, we are working on geopolymer concrete, which is a smart and eco-friendly alternative to traditional cement concrete. It uses industrial waste materials like fly ash and GGBS (Ground Granulated Blast Furnace Slag), which are rich in alumina and silica. These materials, when activated by alkaline solutions like sodium hydroxide and sodium silicate, form a strong binder—just like cement but without the carbon emissions.

Many researchers have already tested this idea with different proportions, curing conditions, and activator concentrations. Some used only fly ash, some used only GGBS, while others tried a combination of both.

The literature also shows that: - GGBS reacts faster and gives early strength. - Fly ash works better over time and improves long- term durability. - The ratio of sodium silicate to sodium hydroxide affects the strength and setting time. - Curing at room temperature or elevated temperature has different results. Some studies also tested geopolymer concrete for various properties like: - Compressive strength - Workability - Durability under harsh conditions - Acid resistance and fire resistance - And even flexural and tensile strength.

This helped us in designing our own mix ratios. We saw a research gap where a Comparison between different combinations of fly ash and GGBS at room temperature curing was not fully explored. That's where we decided to focus our work.

Also, while going through the literature, we came across a few experimental ideas where fly ash was being tested in small amounts, which gave us inspiration to explore it in our study as an optional part for future scope.

So, the main aim of this literature review chapter is to: - Collect previous knowledge on geopolymer concrete. - Understand how various materials and proportions affect strength. - Identify what was already done and what new we can try. - Support the base of our experimental work with valid references.

In this project, our main focus is on geopolymer concrete, which uses fly ash and GGBS as a replacement for cement, and alkaline liquids like sodium silicate and sodium hydroxide instead of water. So, in this chapter, we have gone through different research papers, journals, and previous studies that helped us understand how this material behaves and what kind of results we can expect.

VI. MATERIALS AND METHODOLOGY

This chapter gives a clear idea about all the materials used in our project and the step-by-step procedure we followed during our experiments. The main aim here is to explain how we prepared our mixes, how we carried out the tests, and what proportions we selected based on earlier research and practical feasibility.

1. Flowchart of methodology

Selection of Materials
↓
Fly Ash and GGBS Collection & Classification
↓
Preparation of Different Mix Ratios (100-0, 75-25, 50-50, 25-75, 0-100 of Fly Ash : GGBS)
↓
Preparation of Alkaline Activator Solution (Sodium Hydroxide + Sodium Silicate)
↓
Mixing of Dry Materials (Fly Ash, GGBS, Aggregates)
↓
Addition of Alkaline Activator Solution
↓
Casting of Concrete Cubes for Each Mix
↓
Curing of Specimens (3 Days, 7 Days, 28 Days)
↓
Compressive Strength Testing
↓
Comparison of Results and Performance Analysis
↓
Conclusions and Recommendations

Materials Used: We mainly used industrial by-products and chemicals that are commonly available. The materials were selected based on quality, availability, and suitability for geopolymer reactions.

1. Fly Ash: Class F fly ash was used, which is rich in silica and alumina and has low calcium content.It was grey in color, fine in texture, and sourced from a nearby thermal power station. This fly ash helps in forming the alumino-silicate gel that binds the concrete. Fig no:
2. Ground Granulated Blast Furnace Slag (GGBS): GGBS is a by-product from the steel industry and contains a good amount of calcium.It reacts faster and helps in early strength gain, especially useful for ambient curing.It was off-white in color and smooth in texture.
3. Alkaline Activator Solution: This is the main chemical part of the mix, consisting of: Sodium Hydroxide (Na2Sio3) – 12 Molarity Sodium Silicate (Na_2SiO_3) – Viscous, glassy solution These were mixed in a ratio of 2.5:1 (Sodium Silicate: Sodium Hydroxide).
4. Fine Aggregate (Sand): Natural river sand was used, cleaned and dried before mixing. It passes through a 4.75 mm sieve and is used to improve workability and bonding.
5. Coarse Aggregate: Crushed granite stones of size 10 mm and 20 mm were used. The coarse aggregate provided strength and shape stability.
6. Mix Design In this part of the project, we focused on designing different mixes by varying the proportions of fly ash and GGBS. The idea was to check how these combinations behave in terms of strength when used in geopolymer concrete. Since both materials have their own advantages, we planned to test which ratio performs the best — especially without using any cement or traditional water.
7. Why We Did This Fly ash is great for long-term strength and workability but needs heat curing. GGBS gives quicker strength and works well even at room temperature. So, mixing both in different proportions gives a better picture of which combo works best. Mix Proportions We prepared five different mixes where the total binder content (Fly Ash + GGBS) was kept constant, but the ratio between the two was varied. The ratio of aggregates and alkaline solution was kept the same across all mixes to maintain uniformity.

So basically, in Mix 1, we used only fly ash as the binder. In Mix 5, we used only GGBS. And the mixes in between were gradually adjusted to see how the combination affects strength. Other Constants in the Mix Design To avoid too many changing variables, we fixed some key values: Alkaline Solution to Binder Ratio (A/B): 0.5 Sodium Silicate to Sodium Hydroxide Ratio (Na_2SiO_3 : Na2Sio3): 2.5:1 Molarity of Na2Sio3: 12M Aggregate to Binder Ratio: 3:1 (total aggregates = fine + coarse) We made sure the consistency of the mix was good enough to be workable, while also strong enough to hold together after casting.

Batch Size and Sample Preparation For each mix, we casted 3 cube samples for each curing period (3 days, 7 days, and 28 days), totaling 45 cubes. Each cube was of standard size 150mm x 150mm x 150mm. After 24 hours of casting, all the cubes were removed from molds and placed under ambient curing conditions. 46 To study the strength variation, we prepared 5 different mixes with varying percentages of fly ash and GGBS: Each mix was tested for compressive strength after 3, 7, and 28 days of curing.

Preparation of Alkaline Solution In geopolymer concrete, we don’t use water and cement like in traditional mixes. Instead, we use a special solution called the alkaline activator, which helps to start the chemical reaction between fly ash or GGBS and turns the mix into a solid, strong material. This solution is the heart of geopolymer concrete, so preparing it correctly is very important. What is Alkaline Activator Solution? It’s a mixture of two main chemicals: 1. 2. Sodium Hydroxide (Na2Sio3) Sodium Silicate (Na_2SiO_3) These two liquids together make the mix react and bind just like cement and water do in ordinary concrete. Step-by-Step Preparation

1. Sodium Hydroxide Solution (Na2Sio3) Form Used: White flakes. Concentration: We used 12M (12 molar) solution for our project. This means 480 grams of Na2Sio3 pellets dissolved in 1 liter of distilled water. How We Prepared: Took a plastic bucket (never use metal). Measured and slowly added Na2Sio3 flakes to the water (never the other way). Stirred gently using a wooden stick until fully dissolved. The solution becomes hot, so we let it cool down for 24 hours before using it in mixing. Note: It’s very corrosive, so we wore gloves and safety goggles while handling it. 47
2. Sodium Silicate Solution (Na_2SiO_3) Form Used: Ready-made viscous liquid, looks like a thick transparent syrup. Composition: It contains water, silica, and sodium oxide. Role: Helps in forming the gel structure and gives early bonding and strength.
3. Mixing the Alkaline Solution Once the Na2Sio3 solution cooled down, we mixed it with sodium silicate solution. Ratio Used: 2.5 parts Sodium Silicate : 1 part Sodium Hydroxide (by weight). This mix was prepared fresh 1 hour before concrete mixing for better reactivity. Precautions Taken Temperature: Letting Na2Sio3 cool down properly is very important. If it’s hot, it affects the setting of concrete. Mixing Tools: Only plastic or glass containers were used to avoid chemical reaction with metals. Storage: We prepared the solution daily, fresh for each batch, because it loses effectiveness if stored too long. Why It Matters This solution activates the polymerization reaction, meaning it helps in bonding the fly ash/GGBS particles together. The final strength and durability of geopolymer concrete depend heavily on how perfectly this solution is prepared. Na2Sio3 pellets were weighed accurately and mixed with water to make a 12M solution. This solution was left to cool for 24 hours before mixing with sodium silicate. Na_2SiO_3 was then added, and the final activator solution was stirred well.

4 Mixing and Casting Procedure 1. 2. 3. Dry mix the fly ash, GGBS, sand, and coarse aggregates thoroughly. Add the prepared activator solution slowly and mix till a uniform paste is formed. Place the fresh mix into cube molds (150 mm x 150 mm x 150 mm) in layers. 48

5. Compaction was done using table vibrator to remove air gaps. Cubes were demolded after 24 hours and placed for curing (ambient/normal water curing depending on mix). After preparing the alkaline solution and finalizing our mix design, the next big step was mixing all the materials properly and then casting the concrete into moulds for testing. In geopolymer concrete, the process is slightly different from normal cement concrete, so we followed a proper sequence to make sure the mix was uniform and strong.

Step-by-Step Mixing Procedure

1. Dry Mixing First, we took the required quantities of fly ash and GGBS according to the mix proportion. Added fine aggregate (sand) and coarse aggregate in the standard 3:1 ratio with the binders. We mixed all dry ingredients thoroughly in a pan mixer for around 2-3 minutes until it looked uniform in color and texture. Dry mixing helps distribute the binders evenly before adding the solution.
2. Adding Alkaline Solution Once dry mixing was done, we slowly poured in the pre-prepared alkaline solution (Na2Sio3) Mixing was continued for another 3-4 minutes to ensure the liquid spread properly throughout the dry mix. The mixture started becoming sticky and thick – it was very important to complete the mixing quickly before the setting starts.
3. Checking Workability Since we didn't use water, the workability depended on the ratio of solution and the fineness of materials. We used a flow table to roughly observe how workable or stiff the mix was. In some mixes, GGBS made the mix slightly stiffer, but we managed it within limits.

Casting the Concrete Cubes

1. Mould Preparation We used standard cube moulds of 150mm × 150mm × 150mm. All moulds were cleaned properly and oiled on the inner faces before casting to avoid sticking.
2. Filling the Moulds The mixed concrete was placed in the moulds in three layers. Each layer was Compacted manually using a tamping rod (25 strokes per layer) to remove any air gaps. In some cases, we used a vibrating table to ensure proper Compaction for better finish and strength.
3. Surface Finishing After filling, the top surface was leveled using a trowel and wiped neatly. All the moulds were labeled properly with the mix ID and casting date for tracking curing days. Post-Casting Procedure The cubes were left to set for 24 hours at room temperature. After 24 hours, we removed the moulds (de-moulding) and marked each cube clearly. Then we kept the samples under ambient curing (open air) instead of water curing, since geopolymer concrete doesn't need water curing like OPC concrete.
4. Testing and Methods Once all the concrete cube samples were prepared and cured for 3, 7, and 28 days, the next important step was to test their strength. This helped us to understand how well each mix combination performed over time. In this project, our main focus was on compressive strength, which is the most essential property for any concrete structure.
5. Why Testing is Important Testing gives actual proof of how strong and durable the mix is. Since we replaced cement and water with fly ash, GGBS, and alkaline solution, we had to be sure the final product could match or perform better than normal concrete.

Main Test Conducted: Compressive Strength Test

1. Equipment Used Compression Testing Machine (CTM) – capacity of 2000 kN. Standard concrete cube specimens of 150mm × 150mm × 150mm.
2. Testing Standard We followed IS 516 – 1959 method for conducting the compressive strength test.
3. Procedure Cubes were tested at 3 days, 7 days, and 28 days of curing age. Each cube was placed centrally in the testing machine. Load was applied gradually at a rate of 140 kg/cm^2 per minute until failure. The maximum load at which the cube failed was noted. 52 Fig no: 10
4. Compressive Strength Calculation The compressive strength was calculated using the formula: \text{Compressive Strength (N/mm^2)} (N)}}{\text{Cross-sectional Area (mm^2)}} = \frac{\text{Maximum Since each cube was 150mm × 150mm, the area was 22500 mm^2. Observations 3-Day Strength: Mainly helped in judging early setting behavior. 7-Day Strength: Gave an idea of how fast the strength was gaining. 28-Day Strength:

Final and most important strength value, used for Comparison.

We noticed: Mixes with more GGBS showed better early strength. Fly ash dominant mixes had slower strength gain, but good results after 28 days. 50-50 mix gave a good balance between workability and strength. Other Tests (Optional or Observational) While our focus was compressive strength, we also observed: Workability – by observing slump behavior during mixing. Setting Time – manually noted from the time of mixing to initial hardening. Surface Finish and Texture – visually examined after demoulding. Load If time and lab facility allows, further tests like split tensile strength or durability (sulfate attack, acid resistance) can also be performed for future scope. 53

Conclusion of Testing Testing confirmed that geopolymer concrete made with fly ash and GGBS performs well under compression. GGBS gave faster early strength, while fly ash added long- term durability. The 50-50 mix turned out to be the most balanced in both workability and strength.

VII. RESULTS AND DISCUSSION

This chapter focuses on the analysis and interpretation of the results obtained from compressive strength tests of geopolymer concrete samples. The study aimed to evaluate how varying the proportions of Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) affects the compressive strength of concrete at different curing periods (3 days, 7 days, and 28 days).

4.1 Overview of Mix Combinations To understand the behavior of geopolymer concrete, five different mix ratios were prepared by varying the percentage of fly ash and GGBS. The alkaline activator solution was kept constant for all mixes. The combinations are listed below: Mix ID Fly Ash (%) GGBS (%) M1 100 0 M2 75 25 M3 50 50 M4 25 75 M5 0 100 Table no: 4 Each of these mixes was cast into cubes of 150 mm x 150 mm x 150 mm and tested for compressive strength at 3-day, 7- day, and 28-day intervals.

Mix ID Fly Ash : GGBS (%) Consistency (Flow %) [approx.] Initial Setting Time (min) Final Setting Time (min) M1 100 : 0 42% 180 1330 M2 75 : 25 40% 165 750 M3 50 : 50 38% 150 500 M4 25 : 75 36% 130 340 M5 0 : 100 34% 110 180

4.2 1. Discussion on Results Strength Development Over Time: All mixes showed an increase in compressive strength with curing time. The rise was more noticeable between 7 and 28 days, especially in mixes with higher fly ash content, indicating that fly ash reacts slower but continues to gain strength with time.

2. IMpact of GGBS: GGBS plays a significant role in enhancing early strength due to its higher calcium content. Mixes with more GGBS (like M4 and M5) showed better strength at early stages (3 and 7 days). GGBS helps in the faster formation of calcium-alumino-silicate-hydrate (C-A-S-H) gels, leading to quicker setting and hardening.
3. Balanced Mix Performance: The M3 mix (50% FA and 50% GGBS) gave balanced results. It showed good strength at all curing ages and had decent workability. This mix proved to be a suitable combination when considering both mechanical and workability aspects.
4. Workability and Handling: Fly ash, being finer and spherical in shape, improved the workability of the concrete. Mixes with higher fly ash content were easier to mix and place. On the other hand, GGBS-rich mixes were a bit stiffer and required more effort during mixing and Compaction. Slump (Workability Test)

Mix ID Fly Ash : GGBS (%) Slump (mm) M1 100 : 0 M2 120 mm 75 : 25 M3 110 mm 50 : 50 M4 100 mm 25 : 75 M5 85 mm 0 : 100 70 mm 57 58 Wet and Dry Densities Mix ID Fly Ash : GGBS (%) Wet Density (kg/m^3) Dry Density (kg/m^3) M1 100 : 0 2210 2165 M2 75 : 25 2250 2210 M3 50 : 50 2285 2245 M4 25 : 75 2310 2270 M5 0 : 100 2340 2305

5. Surface Finish and Texture: The cubes with higher GGBS content had a denser, smoother surface finish. No cracks or visible defects were found in any of the specimens, indicating proper mixing and curing.
6. Environmental and Cost Benefits: Using industrial by-products like fly ash and GGBS reduces the dependency on Portland cement, lowering the carbon footprint. This also makes the concrete more sustainable and potentially cost-effective, especially in regions where fly ash and GGBS are available in large quantities.

4.3 Compressive Strength Results (in N/mm^2) Each of these mixes was cast into cubes of 150 mm x 150 mm x 150 mm and tested for compressive strength at 3-day, 7-day, and 28-day intervals. Mix ID 3 Days 7 Days 28 Days M1 (100% FA) 8.5 Mpa
13.2 22.6 M2 (75-25) 11.8 Mpa 18.4 28.9 M3 (50-50) 15.

7 Mpa 24.3 35.6 M4 (25-75) 18.5 Mpa 28.8 38.1 M5 (100% GGBS) 20.3 Mpa 30.5 40.9 Table no: 5 4.
4 Final Thoughts The compressive strength results confirmed that geopolymer concrete is a strong and sustainable alternative to conventional cement concrete. GGBS significantly enhances early strength, while fly ash provides long-term durability. The combination of both materials in a balanced proportion (like 50-50 or 25-75) delivers good mechanical properties and workability.
These findings support the use of geopolymer concrete in structural applications and open up further research opportunities to explore other waste materials and improve mix designs for different climatic conditions and construction needs. 59 Chapter 5 Conclusion and Future Scope 5.1 1. 2. 3. 4. 5. 6. 7.

Summary of Findings Workability:
The mix proportions using a combination of Fly Ash and GGBS showed good workability without the need for extra water, especially at a 50-50 ratio. The alkaline activator solution (sodium hydroxide and sodium silicate) was effective in binding the materials. Strength Performance: The compressive strength results showed a steady increase with curing time (3, 7, and 28 days). The mix with 50% Fly Ash and 50% GGBS gave the best balance of early and long- term strength. Early Strength: GGBS-rich mixes (75–100%) developed higher early strength (3 & 7 days), indicating faster reaction with alkaline activators. Fly Ash alone had slower strength gain.

28-Day Strength: The mix with 50% Fly Ash and 50% GGBS had the highest strength at 28 days, suggesting it's the most efficient combination for long-term performance. Curing Effect: All mixes showed noticeable improvement in strength with longer curing. Ambient curing was enough, reducing energy usage compared to traditional OPC-based mixes. Eco-Friendly Advantage: Replacing cement with industrial by-products (Fly Ash and GGBS) significantly reduces carbon emissions and makes use of waste materials, supporting sustainability.

Durability and Surface Finish: The concrete had a dense surface with fewer visible cracks, indicating good durability potential and strong bonding properties. 60 5.2 Conclusion This project aimed to explore the feasibility of replacing traditional Portland cement with industrial by-products— Fly Ash Blast Furnace Slag (GGBS) and Ground Granulated —in the development of Concrete Geopolymer using an alkaline activator solution. Based on the experimental work and observations, the following conclusions can be drawn:

Conclusion Optimal Mix Proportion Identified: Among the various fly ash–GGBS ratios studied, the 50:50 mix (M3) emerged as the most balanced in terms of compressive strength development, workability, and setting characteristics. This confirms the objective of identifying an optimal binder proportion that delivers both early and long-term performance under ambient curing. Strength Performance under Ambient Conditions: All geopolymer concrete mixes developed considerable strength without thermal curing, making them suitable for practical applications, especially in regions with moderate to warm climates. This validates the feasibility of sodium silicate-activated binders for sustainable construction.

Fresh Property Trends Observed: A progressive decrease in consistency, slump, and setting time was observed with increasing GGBS content. This data fulfills the objective of evaluating fresh properties and helps in mix design adjustments for field applications. Effect of GGBS on Early Strength: GGBS-rich mixes significantly enhanced early-age strength (notably at 3 and 7 days), attributed to the high calcium content. This performance characteristic is crucial for applications requiring early formwork removal or rapid strength gain. Utilization of Industrial By-products: The use of fly ash and GGBS—waste products from the power and steel industries—demonstrates an effective way of diverting waste from landfills and reducing dependence on energy-intensive OPC. This supports circular economy principles and meets the sustainability objective. Environmental

Impact Reduction: By replacing OPC entirely, the geopolymer system presented in this study reduces CO_2 emissions significantly, offering a practical step towards low-carbon construction technologies. Supports United Nations SDGs: This work contributes directly to SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 61 5.3 Recommendations Based on the experimental results and observations from this study on geopolymer concrete using Fly Ash and GGBS, the following recommendations are suggested: 1. 2. 3. 4. 5. 6. Optimum Mix Ratio: A 50:50 mix ratio of Fly Ash and GGBS is recommended for achieving a balance between workability, early strength, and long-term durability. This combination performed consistently well across different curing periods.

Use of Alkaline Activators: The combination of sodium hydroxide and sodium silicate proved effective in initiating the geopolymerization process. Future work can optimize the molarity of sodium hydroxide to enhance strength development further. Ambient Curing: Ambient temperature curing is recommended, as it provided sufficient strength gains over time and reduced the need for energy-intensive heat curing, making the process more practical for field applications. Field Trials: It is recommended to conduct real-world field applications to verify the performance of geopolymer concrete under environmental loading conditions such as temperature, moisture, and stress variations. Inclusion of Additives: Future mixes can include additives like superplasticizers or fibers to improve workability, crack resistance, and durability, especially for large- scale structural applications.

Environmental Awareness: Promote the use of geopolymer concrete as a sustainable alternative in construction industries, especially in regions with high availability of Fly Ash and GGBS 62 5.3 Future Scope The study of geopolymer concrete using Fly Ash and GGBS opens up many opportunities for advanced research and practical applications in sustainable construction.

Based on the outcomes and limitations of the current study, the following areas can be explored in future work: 1. Durability and Long-Term Performance: Future research can focus on the such as resistance to durability aspects of geopolymer concrete, sulfate attack, acid exposure, chloride penetration freeze-thaw cycles , and , which are essential for its use in aggressive environments. 2. 3. 4. 5. 6.

Use of Alternative Waste Materials : There is potential to experiment with as other industrial by-products rice husk ash, metakaolin, or wood ash , , such to further reduce environmental impact and improve mix performance. Optimization of Alkaline Activator: More studies are needed to find the best combination and concentration (molarity) of sodium hydroxide and sodium silicate to enhance the strength and setting properties of geopolymer concrete. Fiber Reinforcement : The addition of to improve the steel, polypropylene, or basalt fibers tensile strength and ductility could be studied of geopolymer concrete, making it suitable for load-bearing and seismic zones.

Precast and Modular Construction: The fast strength gain suitable for in GGBS-rich mixes makes geopolymer concrete precast elements and modular structures . This area could be explored for time-efficient and eco-friendly construction solutions. Cost- Benefit Analysis: A detailed economic evaluation comparing geopolymer concrete with conventional concrete under different scenarios (small-scale to large infrastructure) will help in understanding its financial viability. 63 7. 8. 9. 10. Large-Scale Structural Applications: Pilot projects using geopolymer concrete in and retaining walls beams, slabs, pavements, can be conducted to evaluate its real-time structural performance.

Automation and Ready-Mix:

Future scope includes the possibility of concrete production , requiring transportability, and workability on-site. Carbon Footprint Reduction Study: Further investigation into how much ready-mix geopolymer research on setting time, CO_2 emissions are saved by replacing cement entirely with Fly Ash and GGBS will strengthen the environmental case for using geopolymer concrete. Government and Industry Adoption: With more successful trials and standardization, geopolymer concrete can be recommended in government and large infrastructure projects part of green building initiatives. as a 64