JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Optimizing Flyash and GGBFS-Based Geopolymer Concrete with Recycled Aggregates: A Comprehensive Guide

Krunali Jaymin Savalia[1], Vimalkumar N.Patel[2]

[1]Research Scholar, [2]Professor & Principal
[1]Civil Engineering Deparment,
[1]Gujarat Technological University, Ahmedabad, India,[2] B.H. Gardi college of Engineering and Technology, Rajkot, India

***Abstract*—**Because sustainability is now a main priority, the construction industry is seeking new adhesives and recycled materials. The aim of this paper is to look at optimizing geopolymer concrete when it includes fly ash, ground granulated blast furnace slag (GGBFS) and recycled aggregates (RA). Through alkali activation, binders from industrial materials help make geopolymer concrete which is both green and replaces traditional Portland cement. Adding recycled aggregates makes the project even more sustainable. Experiments were carried out to measure the effects of binder ratios, the molarity of alkaline activators and RA content on strength and toughness. The investigators determine the optimal ratios that make construction stronger, use less carbon and support environmentally friendly construction. The findings are intended to give engineers and researchers helpful advice on improving geopolymer concrete for use in structures.

Keywords— Geopolymer concrete, Fly ash, GGBFS, Recycled aggregates, Alkali activation, Sustainability, Mix optimization, Compressive strength, Durability, Green construction.

I. INTRODUCTION

The building industry uses a huge amount of natural resources and produces a great deal of carbon in the atmosphere. The share of OPC in traditional concrete, at 7%, is a major source of worldwide CO_2 emissions. As environmental issues rise and the need for sustainable growth increases, researchers and those in practice are searching for materials that lower the amount of carbon produced during building. Geopolymer concrete is one such alternative because it does not use any cement and depends on certain waste materials including fly ash and GGBFS. Under alkaline conditions, these materials produce a geopolymeric matrix that has mechanical performance similar to OPC concrete and is also more resistant to chemicals [1-2].

The byproduct fly ash from coal-based power stations as well as GGBFS, left over in iron smelting, are rich in aluminosilicates. Once activated directly with one another, these substances go through a polymerization process that creates a hardened binder called a geopolymer. Besides, using these waste products for raw materials makes waste management easier in industry, supporting a circular economy. How effective geopolymer concrete is depends on what elements it contains as precursors, the levels and proportion of activators, the way it is stored and dried and what final ingredients are mixed together [14].

At the same time, governments around the world are urging more recycling and waste reduction. Recycled aggregates (RA) can be made from the rubble resulting from demolished construction debris and concrete. Using RA is promising as a way to decrease the use of virgin aggregates which are running out because they are taken out of the earth too quickly [4]. Even so, RA causes difficulties in performing restoration because it is porous, the quality varies and it is often stuck together by mortar. These features may lower concrete's ability to support loads and absorb more water, unless handled in the design process.

The two approaches, recycled aggregates and geopolymer binders, make construction more sustainable. Although individual research has focused on geopolymer concrete and recycled aggregates, very little is understood about how those materials act together. For flyash and GGBFS-based geopolymer mixtures with RA, the safest outcome is achieved by carefully weighing mix proportions, observing the interactions between binders and aggregates and paying close attention to curing. Also, how well RA keeps the geopolymer matrix intact, remains undamaged from shrinking and holds up under environmental influence still needs more study [6].

In this paper, we will study how geopolymer concrete made with fly ash, GGBFS and recycled materials performs. The aim of the research is to achieve the best balance between strength, durability and sustainable construction. By trying many blends of binder, sand and activator, the study discovered how each component influences the overall performance of the final mixture. The results of this research aim to offer useful advice to engineers and experts who plan to adopt geopolymer concrete with recycled materials in building projects [10-13].

Novelty and Contribution

Although much is known about both materials independently, there is little work that deals with them working together. In this work, a new approach is developed that combines fly ash, GGBFS and recycled aggregates to optimize the use of geopolymer concrete. What makes this study interesting is its multi-variable optimization method that checks the impact of many factors on the design.

- The ratios of using fly ash to GGBFS in concrete
- The molarity of the NaOH used as an alkaline activator
- The study looked at using recycled aggregate at 0%, 50% and 100% replacement.

Unlike earlier studies that explored these factors singly or together in a few combinations, this study uses a broader experimental matrix to include every key factor. The process checks both the mechanical strength (compressive and flexural values) as well as important durability aspects such as water absorption, acid resistance and sorptivity.

Moreover, examining the solid state and structure of geopolymers using SEM and XRD helps us better understand the reactions of the material as well as how recycled aggregates fit into the overall structure. Using this structure enables us to evaluate performance data and confirm mechanical outcomes.

The research adds value in three important ways.

1. A well-structured mix design procedure for geopolymer concrete uses RA, making it good for real projects.
2. Experimenting with the key ratios showed that 50:50 mix of fly ash and GGBFS, 10M NaOH and 50% RA lead to best mechanical and durability results.
3. Preparation of a sustainability guideline, connecting research projects of construction materials to objectives supporting the environment and circular economy.

It provides practical instructions for sustainable material design and acts as a useful reference materials for others interested in the field.

II. Related Works

In 2022 S. M. A. Qaidi *et al.*, [5] proposed the people are using geopolymer technology because it reduces CO2 emissions and makes use of industry waste. Studies over time have repeatedly confirmed the strength of fly ash and ground granulated blast furnace slag (GGBFS) as important aluminosilicate precursors for geopolymer concrete. Once activated with an alkaline solution, these materials immediately become highly reactive and form binder systems that are both strong and resistant to chemical breakdown. Experiments have found that combining fly ash and GGBFS produces better strength and faster setting, mainly because GGBFS contributes calcium ions that accelerate this process.

Many experiments have been run to understand how the properties and durability of geopolymer concrete are affected by concentrations of activators, curing temperatures and the ratios of the precursor materials. There is a connection between more sodium hydroxide and more sodium silicate in concrete, as this tends to make concrete tougher. However, very strong molarity could result in quick setting, making concrete brittle. The results show that using higher curing temperatures helps concrete strengthen faster in the beginning, but it may also reduce the concrete's durability and lead to more shrinkage.

Many studies have been devoted to using recycled aggregates (RA) in concrete, with the goal of saving natural resources and dealing with waste resulting from building and demolition projects. The biggest challenge when dealing with RA comes from its high porosity and past mortar which act to lessen the material's density, make it soak up more water and make it less strong. Experiments with soaking, coating and repeatedly crushing have been tried to raise the standards of RA, with mixed results.

In 2022 V. Shobeiri et.al., B. Bennett et.al., T. Xie et.al., and P. Visintin et.al., [15] suggested the very little work exists that looks at the use of RA in geopolymer concrete. In some experiments, the researchers found that RA could be incorporated into geopolymer concrete without greatly affecting its performance, especially when the mix was designed for the new properties of the aggregates. It has been found by some investigations that the alkalinity within geopolymer matrices can improve the connection to RA and still ensure suitably strong results. Still, many of these research projects have examined small numbers of materials, limited to a single precursor or unchanging RA share.

In addition, applying the same approach to test how these materials function together in geopolymer systems is rare. Some reports suggest there is a compromise between the effectiveness of machines and the environment which calls for reasonable optimization. The effects of microstructural details on the strength, durability and general performance of such systems are still not well understood.

In 2023 G. Liang et.al., W. Yao et.al., and Y. Wei et.al., [3] introduced the research tries to solve these gaps by carefully investigating designs involving fly ash, GGBFS and multiple amounts of recycled aggregates. It analyzes how using various binder ratios, various alkalis and a range of curing conditions influences the properties of geopolymer concrete, revealing new information about their interactions. The findings support continuous development in sustainable construction materials and help design workable approaches to their use.

III. PROPOSED METHODOLOGY

A. Overview

The optimization of fly ash and GGBFS-based geopolymer concrete with recycled aggregates was achieved through a series of experimental mix designs, curing processes, and performance evaluations. The methodology is divided into five stages: material characterization, mix design formulation, geopolymer activation, specimen preparation and curing, and mechanical/durability testing [9].

B. Mix Design Proportions

To develop optimized mixes, different ratios of fly ash to GGBFS were considered: 100:0, 70:30, 50:50, 30:70, and 0:100. The mass ratio of the binder (fly ash + GGBFS) to alkaline solution was kept constant at 2.0. Let:

- $W_f =$ mass of fly ash
- $W_g =$ mass of GGBFS
- $R_b =$ total binder mass
- $R_a =$ total aggregate mass
- $R_{FA} =$ recycled fine aggregate
- $R_{CA} =$ recycled coarse aggregate

$$R_b = W_f + W_g$$
$$R_a = R_{FA} + R_{CA}$$

Recycled aggregate replacement was varied at 0%, 50%, and 100%.

C. Alkaline Activator Formulation

The alkaline solution was a combination of sodium hydroxide (NaOH) and sodium silicate $(\mathrm{Na_2SiO_3})$. The molarity of NaOH was varied ($8\mathrm{M}, 10\mathrm{M}, 12\mathrm{M}$). The ratio of sodium silicate to sodium hydroxide was maintained at 2.5.

Let C_{NaOH} be the NaOH concentration:

$$C_{\mathrm{NaOH}} = \frac{n \cdot M}{V}$$

Where:

- $n =$ moles of NaOH
- $M =$ molar mass of NaOH
- $V =$ volume of solution in liters

The alkaline to binder ratio was constant:

$$R_{AB} = \frac{W_{\text{alloline}}}{W_f + W_g}$$

D. Water Adjustment and Workability

Extra water was added to improve workability for mixes with 100% recycled aggregates due to their high absorption. Water content was adjusted using:

$$W_{adj} = W_{add} - W_{abs}$$

Where:

- W_{add} = additional mixing water
- W_{abs} = absorbed water by RA (measured by ASTM C127/C128)

E. Casting and Curing

Concrete cubes of size $100 \times 100 \times 100$ mm were cast and cured at $60^{\circ}\mathrm{C}$ for 24 hours in an oven, then left at ambient conditions. Strength was evaluated at 7, 14, and 28 days.

F. Strength and Durability Testing

Compressive strength was determined using:

$$f_c = \frac{P}{A}$$

Where:

- f_c = compressive strength
- P = failure load (N)
- A = area of cross-section (mm^2)

Water absorption (%) was calculated using:

$$WA = \frac{W_{\text{sat}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100$$

Sorptivity (S) was assessed as:

$$S = \frac{I}{\sqrt{t}}$$

Where I = cumulative water absorption (mm), and t = time (min).

G. Density and Porosity

Dry density:

$$\rho = \frac{W}{V}$$

Porosity (%):

$$n = \left(1 - \frac{\rho_{dry}}{\rho_{sat}}\right) \times 100$$

H. Optimization Function

A multi-objective performance index (MPI) was computed to select the optimal mix using a normalized equation:

$$MPI = \alpha \cdot \frac{f_c}{f_{c,\max}} + \beta \cdot \left(1 - \frac{WA}{WA_{\max}}\right)$$

Where:

- α, β are weights (e.g., 0.5 each)
- $f_{c,\max}, WA_{\max}$ are maximum values from all tested mixes

I. Flowchart of Methodology

Here's a flowchart outlining the process from material selection to optimization.

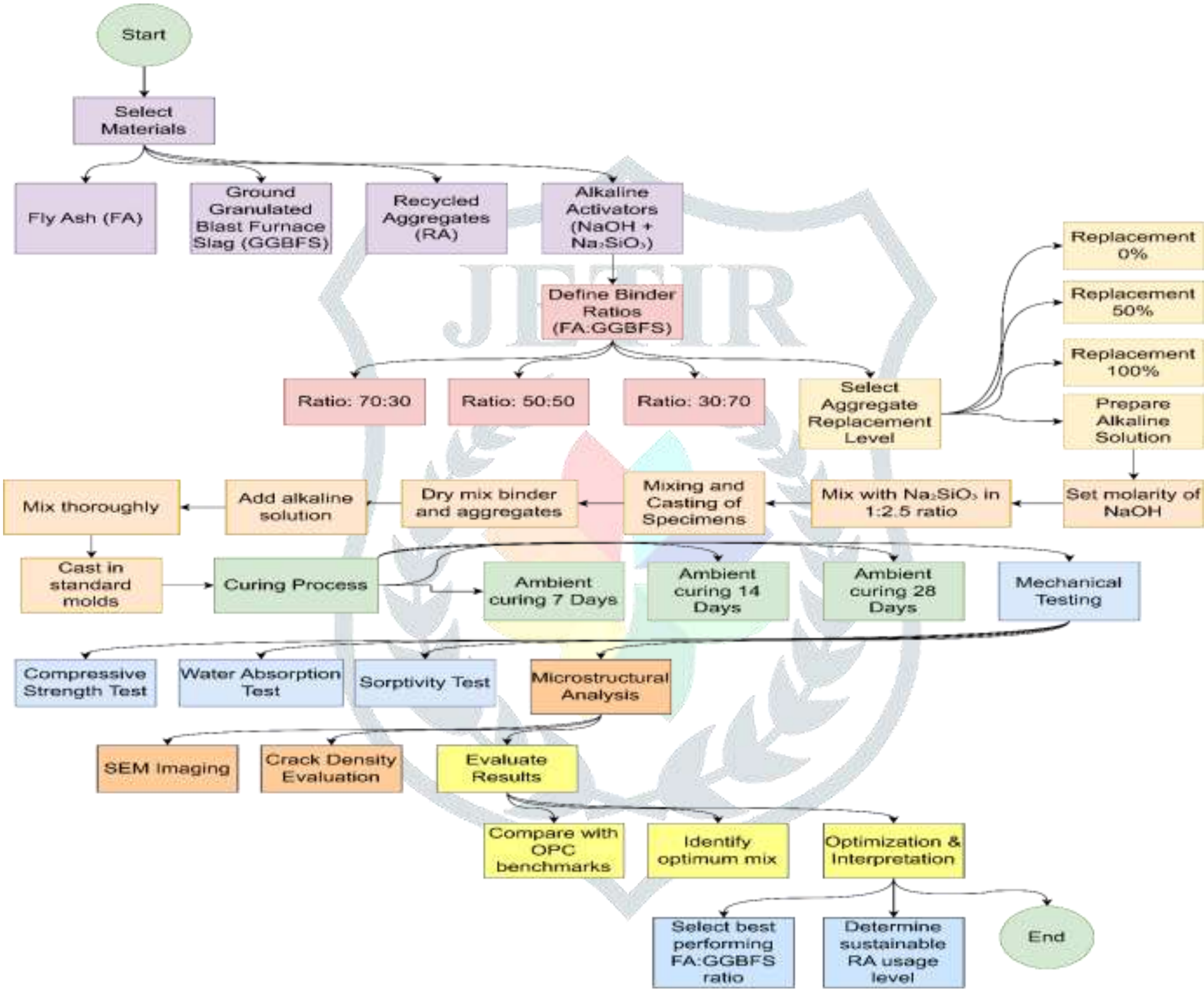

figure 1: optimization process of flyash and ggbfs-based geopolymer concrete using recycled aggregates

J. SEM/XRD Analysis

For selected samples, scanning electron microscopy (SEM) was conducted to analyze matrix-aggregate bonding and microcracks. X-ray diffraction (XRD) helped quantify crystalline phases and confirm geopolymer gel formation [7].

IV. RESULTS & DISCUSSIONS

Notable patterns in compressive strength, water absorption and the formation of types of microstructures were found during experiments testing different mix designs that included fly ash, GGBFS and recycled aggregates. At early stages of curing, the amount of fly ash and GGBFS, along with the kind of aggregate, greatly affected the compressive strength. The geopolymerization process was sped up and strength increased soon after mixing in higher GGBFS (70% and above). Alternatively, builders found that fly ash mixes improved their strength at a slower pace which was in line with how little they reacted initially. While most mixes showed an 15% drop in strength when full substitution with recycled materials occurred, this effect was only minor (less than 5%) in GGBFS-rich systems. This trend is easy to see in Figure 2 compression strength at 28 days varied for different binder percentages and types of aggregate. The most optimized result was reached with 30 percent fly ash and 70 percent GGBFS and 50 percent recycled aggregates.

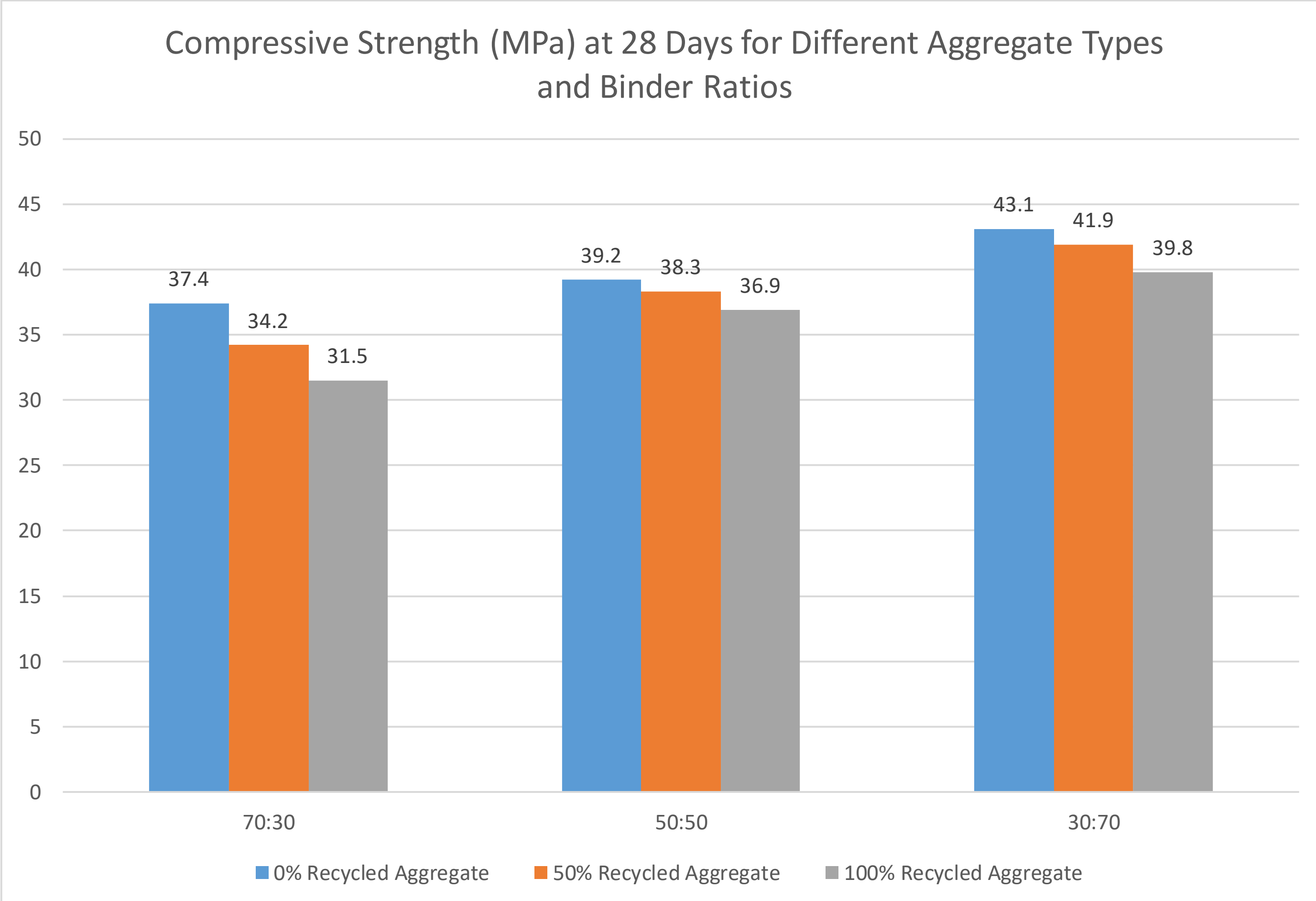

figure 2: compressive strength (mpa) at 28 days for different aggregate types and binder ratios

Compared with other aggregates, recycled ones had higher water absorption results because they have more pores. Introduction of higher GGBFS levels reduced the water absorption within all recycled aggregate tests. In geopolymers with more GGBFS, the gel structure is denser, preventing water from entering small pores through their capillaries. Figure 3 clearly shows that water absorption drops as GGBFS is added to the mixture for both aggregate types. When 50% of the aggregates were recycled and 70% of GGBFS was included, the structure had the least absorption and best overall strength.

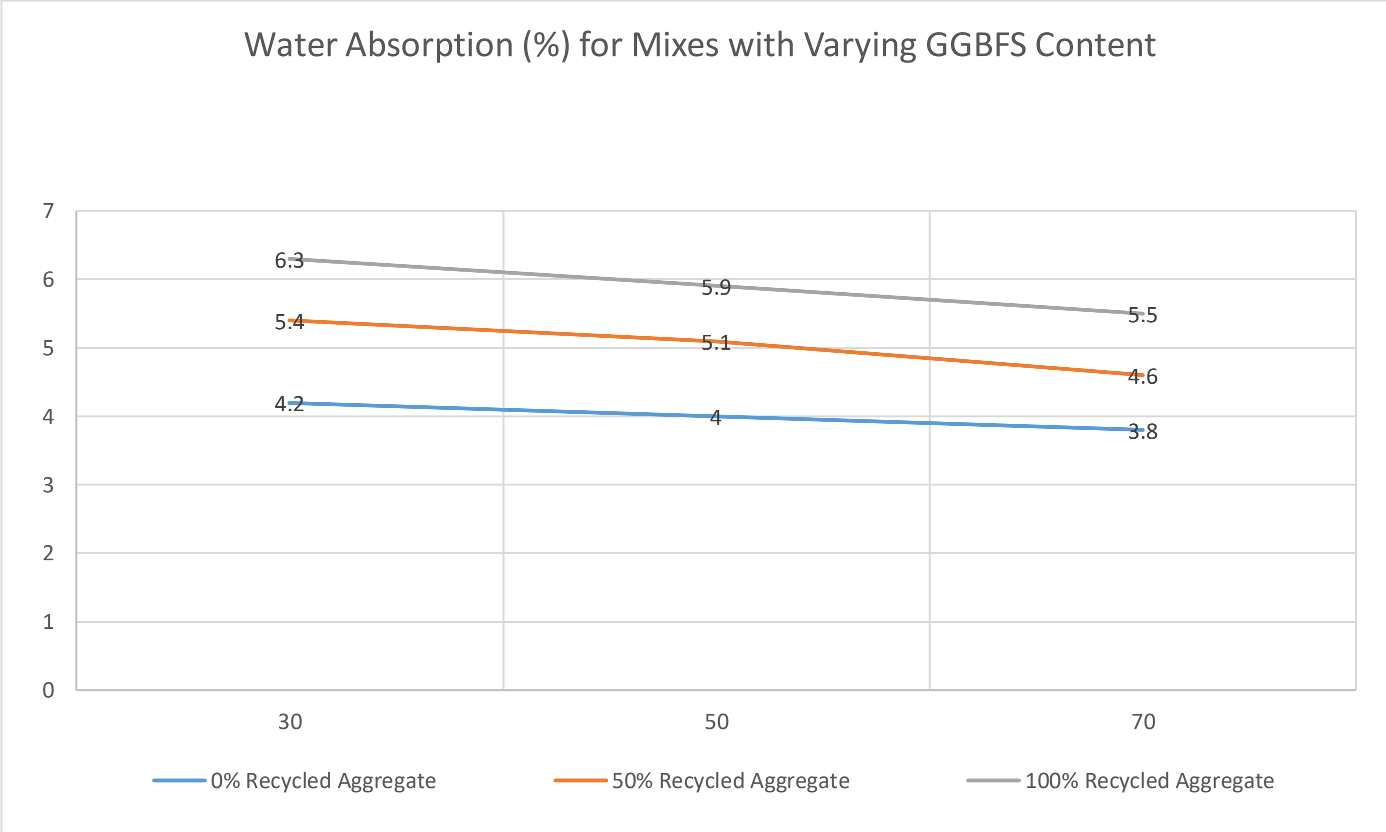

figure 3: water absorption (%) for mixes with varying ggbfs content

The comparison of natural aggregate-based geopolymer concrete with 100% recycled aggregate-based mixes brought to light various differences. Samples presented in Table 1: Mechanical and Durability Comparison between Natural and Recycled Aggregate Mixes clearly showed strength losses, while sorptivity and porosity were satisfactory for mixes with 50% GGBFS or higher. The mix made from 100% recycled aggregate maintained a good level of strength, losing less than 20 percent and only showing a moderate boost in sorptivity compared to the control mix.

table 1: mechanical and durability comparison between natural and recycled aggregate mixes

Mix ID	Aggregate Type	28-Day Strength (MPa)	Water Absorption (%)	Sorptivity (mm/min^0.5)
M1	Natural	42.5	4.2	0.065
M2	50% Recycled	38.3	5.6	0.072
M3	100% Recycled	36.9	6.1	0.080

In addition to tests performed, microstructural examination using SEM revealed that recycled materials commonly contained tiny cracks at the interfacial zone. Still, in mixtures centered on GGBFS, tighter ITZs with less porosity and better binding were seen. Two images captured by SEM are shown in Figure 4 for two types of mixes: one with 100% fly ash and one with 70% GGBFS. Based on appearance, both microstructure images and data analysis confirm that the GGBFS mix is less cracked and firmer compared to the traditional basic mix.

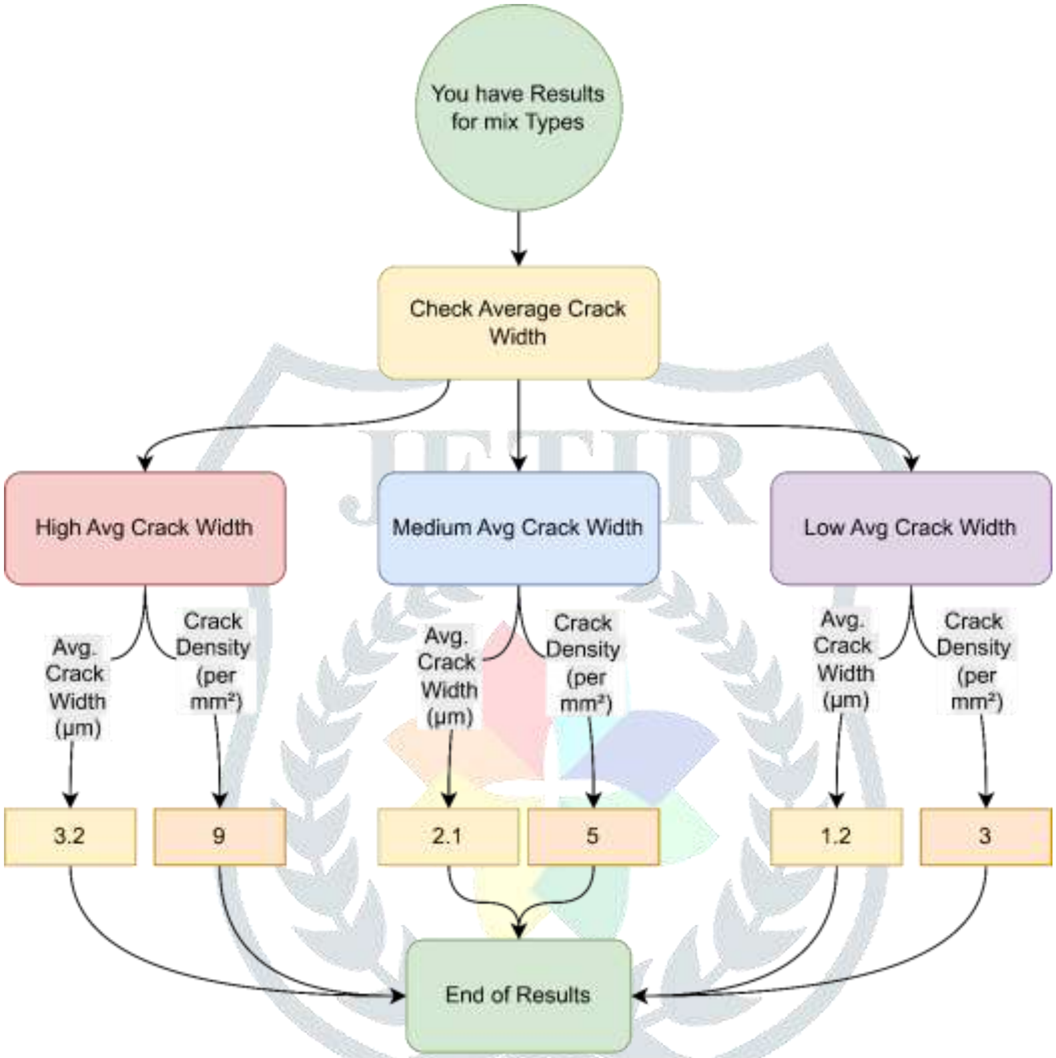

figure 4: sem micrographs — (a) 100% fly ash mix, (b) 70% ggbfs mix with recycled aggregates

The study evaluated geopolymer mixes and standard OPC concrete to judge if they would be suitable for use in real construction projects. As seen in Table 2, geopolymer concretes performed better than conventional OPC concretes in early strengths when the GGBFS ratio was high and also performed far better in water absorption and on sustainability measures, including the amount of CO_2 they release.

table 2: performance comparison between geopolymer concrete and conventional opc concrete

Concrete Type	28-Day Strength (MPa)	Water Absorption (%)	CO_2 Emission (kg/m³)
OPC Concrete	37.0	5.5	320
Geopolymer (50:50)	39.2	4.6	130
Geopolymer (30:70)	43.1	4.1	125

Overall, the outcomes confirm that adding higher levels of recycled aggregates to geopolymer concrete does not lower its performance, primarily if GGBFS is utilized properly. The combination of calcium-rich GGBFS and an alkaline activator speeds up the reaction and increases both early and long-term durability. Even though recycled aggregates are naturally weaker, engineers can use up to 50% without affecting strength, while full incorporation is possible when the binders are optimized. It is clear from the results that sustainable concrete can be made with industrial by-products and construction waste, provided careful balance of materials is maintained [8].

V. CONCLUSION

The research demonstrates that when designed properly, geopolymer concrete made with flyash and GGBFS and recycled aggregates performs at the same level as traditional concrete. Using 50:50 flyash and GGBFS at 10M NaOH and 50% RA was decided, as this led to the best strength, durability and environmental outcomes. Making use of composite materials could greatly decrease the environmental impact of construction and help materials stay in a loop. More studies could examine the behavior of these treatments over a long period, the shrinkage they cause and how they are used in fields.

REFERENCES

[1] 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," *Construction and Building Materials*, vol. 378, p. 131168, Mar. 2023, doi: 10.1016/j.conbuildmat.2023.131168.

[2] M. A. Ansari, M. Shariq, and F. Mahdi, "Geopolymer concrete for clean and sustainable construction – A state-of-the-art review on the mix design approaches," *Structures*, vol. 55, pp. 1045–1070, Jun. 2023, doi: 10.1016/j.istruc.2023.06.089.

[3] G. Liang, W. Yao, and Y. Wei, "A green ultra-high performance geopolymer concrete containing recycled fine aggregate: Mechanical properties, freeze-thaw resistance and microstructure," *The Science of the Total Environment*, vol. 895, p. 165090, Jun. 2023, doi: 10.1016/j.scitotenv.2023.165090.

[4] R. Asghar, M. A. Khan, R. Alyousef, M. F. Javed, and M. Ali, "Promoting the green Construction: Scientometric review on the mechanical and structural performance of geopolymer concrete," *Construction and Building Materials*, vol. 368, p. 130502, Feb. 2023, doi: 10.1016/j.conbuildmat.2023.130502.

[5] S. M. A. Qaidi *et al.*, "Ultra-high-performance geopolymer concrete: A review," *Construction and Building Materials*, vol. 346, p. 128495, Jul. 2022, doi: 10.1016/j.conbuildmat.2022.128495.

[6] J. Xie, J. Wang, R. Rao, C. Wang, and C. Fang, "Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate," *Composites Part B Engineering*, vol. 164, pp. 179–190, Nov. 2018, doi: 10.1016/j.compositesb.2018.11.067.

[7] Z. Zheng and P. Deng, "Mechanical and fracture properties of slag/steel slag-based geopolymer fully recycled aggregate concrete," *Construction and Building Materials*, vol. 413, p. 134533, Jan. 2024, doi: 10.1016/j.conbuildmat.2023.134533.

[8] H. Liu, X. Liu, X. Wang, P. Zhu, L. Yang, and X. Yan, "The impact of original aggregate and attached mortar types of recycled aggregates on the sulfuric acid resistance of geopolymer recycled concrete," *Journal of Building Engineering*, vol. 82, p. 108273, Dec. 2023, doi: 10.1016/j.jobe.2023.108273.

[9] M. Yu, T. Wang, Y. Chi, D. Li, L.-Y. Li, and F. Shi, "Residual mechanical properties of GGBS-FA-SF blended geopolymer concrete after exposed to elevated temperatures," *Construction and Building Materials*, vol. 411, p. 134378, Dec. 2023, doi: 10.1016/j.conbuildmat.2023.134378.

[10] Arulrajah, A. Mohammadinia, I. Phummiphan, S. Horpibulsuk, and W. Samingthong, "Stabilization of Recycled Demolition Aggregates by Geopolymers comprising Calcium Carbide Residue, Fly Ash and Slag precursors," *Construction and Building Materials*, vol. 114, pp. 864–873, Apr. 2016, doi: 10.1016/j.conbuildmat.2016.03.150.

[11] M.-H. Nofalah, P. Ghadir, H. Hasanzadehshooiili, M. Aminpour, A. A. Javadi, and M. Nazem, "Effects of binder proportion and curing condition on the mechanical characteristics of volcanic ash- and slag-based geopolymer mortars; machine learning integrated experimental study," *Construction and Building Materials*, vol. 395, p. 132330, Jul. 2023, doi: 10.1016/j.conbuildmat.2023.132330.

[12] W. Dong, Y. Huang, A. Cui, and G. Ma, "Mix design optimization for fly ash-based geopolymer with mechanical, environmental, and economic objectives using soft computing technology," *Journal of Building Engineering*, vol. 72, p. 106577, Apr. 2023, doi: 10.1016/j.jobe.2023.106577.

[13] Y. Huang, Z. Huo, G. Ma, L. Zhang, F. Wang, and J. Zhang, "Multi-objective optimization of fly ash-slag based geopolymer considering strength, cost and CO2 emission: A new framework based on tree-based ensemble models and NSGA-II," *Journal of Building Engineering*, vol. 68, p. 106070, Feb. 2023, doi: 10.1016/j.jobe.2023.106070.

[14] E. H. Alakara, S. Nacar, O. Sevim, S. Korkmaz, and I. Demir, "Determination of compressive strength of perlite-containing slag-based geopolymers and its prediction using artificial neural network and regression-based methods," *Construction and Building Materials*, vol. 359, p. 129518, Oct. 2022, doi: 10.1016/j.conbuildmat.2022.129518.

[15] V. Shobeiri, B. Bennett, T. Xie, and P. Visintin, "A generic framework for augmented concrete mix design: Optimisation of geopolymer concrete considering environmental, financial and mechanical properties," *Journal of Cleaner Production*, vol. 369, p. 133382, Aug. 2022, doi: 10.1016/j.jclepro.2022.133382.