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Experimental Study on Mechanical Properties of Glass Powder Blended Geopolymer Concrete

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Abstract- In the present study, an experimental investigation has been carried out to evaluate the mechanical and durability properties of geopolymer concrete incorporating glass powder as a partial replacement of Ground Granulated Blast Furnace Slag (GGBS). The primary objective is to utilize waste glass as a sustainable construction material and reduce dependency on conventional cementitious materials. Five different mixes were prepared with glass powder replacement levels of 0%, 10%, 15%, 20%, and 25%. The mix proportions were designed by keeping coarse aggregate, fine aggregate, and sodium silicate constant, while GGBS was partially replaced with glass powder. The properties studied include compressive strength, flexural strength, and water absorption. The results indicated that up to 15% replacement of GGBS with glass powder improves strength due to pozzolanic reaction, while higher replacement reduces strength. The study concludes that glass powder can be effectively used in geopolymer concrete for sustainable construction.

Keywords- Geopolymer Concrete, Glass Powder, Compressive Strength, Flexural Strength, Water Absorption.

I. INTRODUCTION

Concrete is one of the most widely used construction materials across the world due to its versatility, strength, durability, and cost-effectiveness; however, the production of Ordinary Portland Cement (OPC), which is the primary binding material in conventional concrete, is responsible for significant environmental concerns, particularly the emission of large quantities of carbon dioxide (CO_2), depletion of natural resources, and high energy consumption, making it one of the major contributors to global warming and climate change. In order to overcome these environmental challenges and move towards sustainable construction practices, researchers have developed geopolymer concrete as an innovative and eco-friendly alternative, which eliminates the use of OPC and instead utilizes industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binder materials that are activated using alkaline solutions like sodium silicate and sodium hydroxide, thereby significantly reducing carbon emissions while maintaining comparable or even superior mechanical properties. At the same time, the disposal of waste glass has emerged as a serious environmental issue due to its non-biodegradable nature and the increasing volume of glass waste generated from domestic, industrial, and commercial sources, most of which is dumped in landfills, leading to land pollution, resource wastage, and long-term environmental hazards; hence, the reuse and recycling of waste glass in construction materials has gained considerable attention as a sustainable solution. When waste glass is finely ground into powder form, it exhibits excellent pozzolanic properties because of its high silica content, which enables it to react with alkaline activators in geopolymer systems and participate in the formation of additional binding gels such as calcium-alumino-silicate-hydrate (C-A-S-H) and sodium-alumino-silicate-hydrate (N-A-S-H), thereby enhancing the strength and durability of concrete.

Furthermore, the incorporation of glass powder improves particle packing, reduces porosity, and contributes to better microstructural development, making it a promising supplementary material in geopolymer concrete. In this context, the present study focuses on evaluating the performance of geopolymer concrete by partially replacing GGBS with varying percentages of glass powder, namely 0%, 10%, 15%, 20%, and 25%, while keeping other parameters constant, in order to determine the optimum replacement level that provides maximum strength and durability along with improved sustainability, thereby contributing to effective waste management and the development of green construction materials for future infrastructure.

II. LITERATURE REVIEW

Al-saeed Abdelsalam Maaty, Mariam Farouk Ghazy and Mohamed Gamal Eldmarny (2025) in their review study titled *"Geopolymer Concrete Performance Utilising Waste Glass: A Review"* comprehensively analyzed the potential of waste glass (WG) as a sustainable material in geopolymer concrete (GPC). The study focused on addressing environmental challenges associated with conventional cement production, which contributes significantly to global carbon dioxide emissions and resource depletion. The authors reviewed the incorporation of waste glass in geopolymer concrete prepared using industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), aiming to enhance sustainability and performance. The review covered various aspects of GPC including fresh properties, mechanical properties, durability characteristics such as permeability resistance, sulfate resistance, and fire resistance, along with microstructural behavior. The findings indicated that finely ground waste glass exhibits strong pozzolanic reactivity, which contributes to improved bonding and matrix densification.

Ashwin Raut et al. (2025) in their study titled *"Optimizing Glass Powder and Slag-Based Geopolymers: Enhancing Thermo-Mechanical Strength Resistance for Sustainable Construction Applications"* investigated the combined use of glass powder (GP) and ground granulated blast furnace slag (GGBS) to improve the performance of geopolymer materials, particularly under elevated temperature conditions. The study aimed to address the research gap related to the behavior of slag-based geopolymers at high temperatures while enhancing mechanical strength, fire resistance, and workability for sustainable construction applications. The experimental program utilized Response Surface Methodology (RSM) to develop predictive models and optimize the mix design parameters. Key variables considered in the study included sodium hydroxide (NaOH) molarity, sodium silicate to sodium hydroxide ratio (SS/SH), and glass powder content. Fresh properties such as flow value and setting time were evaluated, along with hardened properties including compressive strength at normal temperature (28°C) and elevated temperatures (200°C and 800°C), as well as cyclic compressive strength. The results indicated that the developed RSM models were highly accurate and reliable, with prediction errors less than 6%.

Meysam Pourabbas Bilondi et al. (2025) in their study titled "*Experimental Studies on Mix Design and Properties of Ceramic-Glass Geopolymer Mortars Using Response Surface Methodology"* investigated the mechanical and microstructural performance of geopolymer mortars incorporating ceramic waste powder (CWP) and recycled glass powder (RGP) as sustainable binder materials. The study aimed to develop an optimized mix design using response surface methodology (RSM) to enhance strength characteristics while promoting the utilization of industrial waste materials in construction. The experimental program involved the use of Box–Behnken design to evaluate the influence of key parameters such as CWP content, alkaline activator ratio ($NaOH/Na_2SiO_3$), solution-to-binder (S:B) ratio, and oven curing duration on compressive strength. Mechanical properties were assessed through compressive strength at 3 and 28 days, flexural strength, and ultrasonic pulse velocity (UPV). Additionally, microstructural and chemical analyses were carried out using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) to study the internal morphology and geopolymerization process.

Tonggui Cheng et al. (2024) in their study titled "Effect of Waste Glass Powder and Bamboo Fiber on the Physico-Mechanical Properties and High-Temperature Behavior of a Fly Ash-Based Geopolymer" investigated the combined influence of waste glass powder (WGP) and bamboo fiber (BF) on the performance of fly ash-based geopolymer composites under ambient and elevated temperature conditions. The study aimed to enhance the reactivity, strength, and thermal resistance of geopolymer materials by incorporating industrial waste and natural fibers, thereby promoting sustainable construction practices. The experimental program involved partial replacement of fly ash with WGP at proportions of 2.5%, 5%, 7.5%, and 10%, along with the addition of bamboo fiber at 1% to 2.5%. The fresh and physical properties such as fluidity, setting time, density, and water absorption were evaluated, while mechanical properties were assessed through compressive and flexural strength tests. Furthermore, the behavior of geopolymer composites at high temperatures (200°C to 800°C) was studied using thermogravimetric analysis, mass loss measurement, thermal shrinkage, scanning electron microscopy (SEM), X-ray diffraction (XRD), and optical microscopy.

Zhaoliang Sheng et al. (2024) in their study titled *“Influence of Waste Glass Powder on Printability and Mechanical Properties of 3D Printing Geopolymer Concrete”* investigated the effect of waste glass powder (WGP) as a sustainable precursor material in 3D printing geopolymer concrete (3DPC) based on slag and fly ash. The study aimed to reduce cement consumption and enhance sustainability while improving printability and mechanical performance of geopolymer concrete. The experimental program focused on varying the WGP content from 0% to 20% to evaluate its influence on fresh and hardened properties of 3D printed concrete. The fresh properties were assessed in terms of printability, buildability, and extrudability using a specially designed extrusion system, while hardened properties were evaluated through compressive strength and flexural strength tests at different curing ages. Microstructural analysis was carried out using scanning electron microscopy (SEM), X-ray diffraction (XRD), and particle size distribution techniques to understand the internal morphology and chemical characteristics of the material. The results indicated that the incorporation of WGP significantly influenced the geopolymer reaction and rheological behavior of the mix. It was observed that WGP content below 10% accelerated hydration and improved buildability, whereas higher content (above 10%) enhanced extrudability but slightly reduced the reaction rate.

Prashant G. Sawarkar et al. (2024) in their study titled *“Properties of Blast Furnace Slag Geopolymer Concrete”* investigated the development of sustainable geopolymer concrete using ground granulated blast furnace slag (GGBS) as the primary binder material and sodium silicate as the alkali activator. The study aimed to address major limitations associated with conventional geopolymer systems, such as the use of highly concentrated alkaline solutions like sodium hydroxide and the requirement of elevated temperature curing, which are not practical for field applications. The experimental program focused on producing geopolymer concrete using only sodium silicate as the activating solution, thereby improving safety and ease of handling. The concrete specimens were cured under ambient temperature conditions for 7, 14, and 28 days to evaluate real-world applicability. The mechanical properties of the developed concrete were assessed through compressive strength and flexural strength tests. The results indicated that satisfactory strength can be achieved without the use of highly corrosive alkali solutions or heat curing, demonstrating the feasibility of ambient-cured geopolymer concrete for structural applications. The study concluded that sodium silicate-based geopolymer systems using GGBS can provide a sustainable, safe, and practical alternative to conventional cement concrete, especially for in-situ construction works.

K Chandramouli et al. (2023) in their study titled *“Mechanical Properties of Concrete by Partial Replacement of Fine Aggregate with Glass Powder for M40”* investigated the potential use of waste glass powder as a partial replacement for fine aggregate in conventional concrete to enhance sustainability and reduce the consumption of natural resources. The study aimed to address environmental concerns associated with excessive use of river sand and disposal of glass waste by utilizing crushed glass powder as an alternative material. The experimental program involved replacing fine aggregate with waste glass powder at different proportions of 0%, 10%, 15%, 20%, and 25% in concrete mixes. The performance of the concrete was evaluated through compressive strength and split tensile strength tests at curing periods of 28, 56, and 90 days. The results obtained from glass powder concrete were compared with those of conventional concrete to assess its effectiveness. The findings revealed that the incorporation of glass powder significantly influenced the strength characteristics of concrete. It was observed that replacement of fine aggregate with glass powder up to 15% resulted in improved compressive strength and tensile strength compared to conventional concrete.

Ayesha Siddika et al. (2021) in their review study titled *“Waste Glass in Cement and Geopolymer Concretes: A Review on Durability and Challenges”* critically analyzed the utilization of waste glass (WG) in both conventional cement concrete and geopolymer concrete to address environmental concerns associated with glass waste disposal and cement production. The study emphasized that a large quantity of waste glass is generated globally, most of which is disposed of in landfills, creating environmental challenges. The authors reviewed the potential of incorporating waste glass either as a binder or as aggregate in concrete to enhance sustainability and performance. The review focused on evaluating the influence of waste glass on microstructural properties, durability characteristics, and overall performance of concrete. Various durability aspects such as shrinkage behavior, resistance to chemical attack, chloride penetration, freeze–thaw resistance, and thermal and electrical properties were examined.

W Kushartomo and Sofianto (2020) in their study titled *“Mechanical Properties of Powder Concrete with a Geopolymer Bond”* investigated the feasibility of using geopolymer binder as a sustainable alternative to conventional Portland cement in reactive powder concrete (RPC). The study focused on reducing carbon dioxide emissions by replacing traditional cement with geopolymer derived from industrial waste materials such as fly ash. Additionally, glass powder was used as a partial replacement for quartz powder to further enhance sustainability and material efficiency. The experimental program involved the preparation of geopolymer powder concrete with different mix

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proportions based on varying volume ratios of geopolymer binder and glass powder. The geopolymer binder was produced using fly ash activated with an alkaline solution consisting of sodium hydroxide and sodium silicate.

Jedulius G (2018) in the study titled *"Experimental Study on Glass Fibre Concrete"* investigated the influence of glass fibers on the mechanical properties of conventional concrete with the aim of improving its tensile strength, ductility, and crack resistance. The study addressed the inherent limitations of plain concrete such as low tensile strength, brittleness, and susceptibility to microcrack propagation, which affect its structural performance. The experimental program involved the addition of alkali-resistant glass fibers (CEM-FILL anti-crack type) with a diameter of 14 microns and an aspect ratio of 857 in varying proportions ranging from 0.33% to 1% by weight of concrete. The study evaluated key mechanical properties including compressive strength, flexural strength, toughness, and modulus of elasticity to assess the performance of glass fiber reinforced concrete (GFRC). The results indicated that the incorporation of glass fibers significantly improved the overall behavior of concrete. It was observed that glass fibers effectively controlled crack initiation and propagation, thereby enhancing ductility and toughness. The flexural strength showed noticeable improvement due to fiber bridging action, while compressive strength exhibited moderate enhancement. The presence of fibers also improved strain capacity and energy absorption characteristics of concrete.
Sathish Kumar V, Blessen Skariah Thomas and Alex Christopher (2012) in their study titled *"An Experimental Study on the Properties of Glass Fibre Reinforced Geopolymer Concrete"* investigated the mechanical performance of geopolymer concrete composites (GPCC) incorporating fly ash and glass fibres as reinforcement. The study aimed to develop a sustainable alternative to conventional Portland cement concrete by utilizing industrial by-products such as fly ash and enhancing its properties through fibre reinforcement. The experimental program involved the preparation of geopolymer concrete using 100% replacement of Ordinary Portland Cement (OPC) with fly ash, activated by alkaline liquids. The alkaline liquid to fly ash ratio was maintained at 0.4. Glass fibres were added in small proportions of 0.01%, 0.02%, and 0.03% by volume of concrete to evaluate their influence on strength and performance. The study focused on assessing mechanical properties, particularly compressive strength and early-age strength development. The results indicated that the inclusion of glass fibres significantly improved the performance of geopolymer concrete composites.

III. RESEARCH GAP

Despite extensive research on geopolymer concrete and the use of waste glass, there is limited experimental work focusing on the partial replacement of GGBS with glass powder under ambient curing conditions. Most studies have considered low replacement levels, while the behavior at higher percentages (20–25%) is not well established. Additionally, there is a lack of clear identification of the optimum glass powder content for achieving maximum strength and durability. Therefore, this study aims to investigate the performance of geopolymer concrete with varying glass powder content to determine the optimum replacement level and address these research gaps.

IV. PROPOSED METHODOLOGY

The materials used in the present experimental study include coarse aggregate, fine aggregate, Ground Granulated Blast Furnace Slag (GGBS), glass powder, and sodium silicate solution, each playing a significant role in the performance of geopolymer concrete. Coarse aggregate of size 20 mm was used, which provides the main structural strength and load-bearing capacity to the concrete, while fine aggregate (river sand) was used to fill the voids between coarse aggregates and improve the workability and density of the mix. GGBS was used as the primary binder material due to its high calcium content and good reactivity under alkaline conditions, which contributes to the development of strength in geopolymer concrete. Glass powder, obtained by finely grinding waste glass, was used as a partial replacement of GGBS in varying percentages (0%, 10%, 15%, 20%, and 25%), and due to its high silica content, it exhibits pozzolanic properties that enhance the geopolymerization process and improve the microstructure of concrete. Sodium silicate solution was used as the alkaline activator, which plays a crucial role in initiating the chemical reaction between GGBS and glass powder, leading to the formation of strong binding gels such as C-A-S-H and N-A-S-H. All materials were carefully selected and proportioned to ensure uniformity, workability, and consistency of the geopolymer concrete mix, while maintaining constant aggregate and activator content across all mixes to accurately evaluate the effect of glass powder replacement.

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Table 4.1: Mix Proportion

Mix ID	Glass Powder (%)	Coarse Aggregate (kg/m²)	Fine Aggregate (kg/m²)	Glass Powder (kg/m²)	GGBS (kg/m²)	Sodium Silicate (kg/m²)
GP0	0	1176	504	0	520	200
GP10	10	1176	504	52	468	200
GP15	15	1176	504	78	442	200
GP20	20	1176	504	104	416	200
GP25	25	1176	504	130	390	200

Figure 4.1: Manual Mixing of Geopolymer Concrete Incorporating Glass Powder in Laboratory Setup

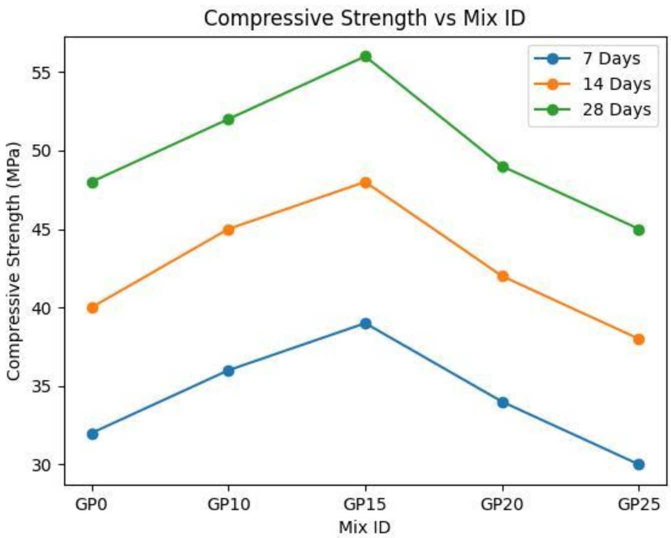
Figure 4.2: Casting of Specimens

Figure 4.3: Flexural Strength Testing of Geopolymer Concrete Specimen Using Universal Testing Machine in Laboratory

V. RESULTS AND DISCUSSION

Table 5.1: Compressive Strength Results (MPa)

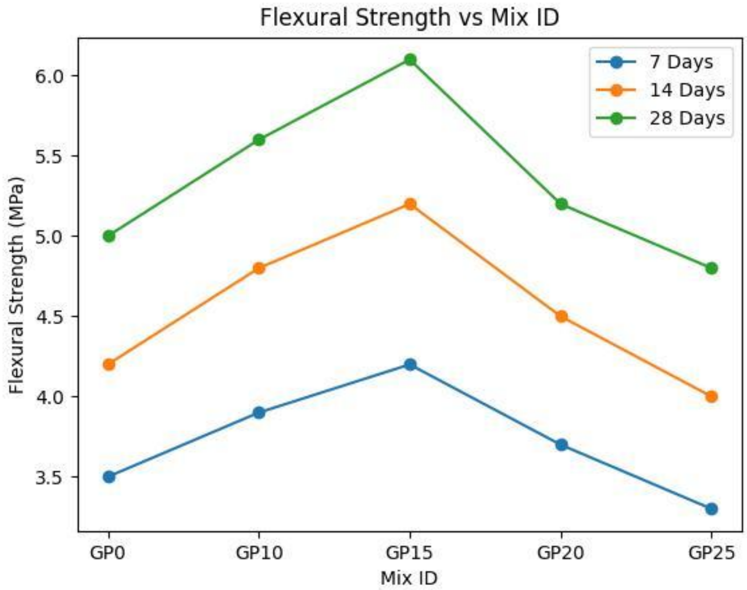
Mix ID	Glass Powder (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
GP0	0	32	40	48
GP10	10	36	45	52
GP15	15	39	48	56
GP20	20	34	42	49
GP25	25	30	38	45



Graph 5.1: Compressive Strength Results (MPa)

Table 5.2: Flexural Strength Results (MPa)

Mix ID	Glass Powder (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
GP0	0	3.5	4.2	5.0
GP10	10	3.9	4.8	5.6
GP15	15	4.2	5.2	6.1
GP20	20	3.7	4.5	5.2
GP25	25	3.3	4.0	4.8



Graph 5.2: Flexural Strength Results (MPa)

CONCLUSION

Based on the experimental results presented in Table 5.1 and Table 5.2, the following conclusions are drawn from the study on glass powder blended geopolymer concrete:

1. The compressive strength of geopolymer concrete increases with the increase in glass powder content up to 15% replacement of GGBS, after which it starts decreasing. The maximum compressive strength of 56 MPa at 28 days was observed for the mix GP15, indicating it as the optimum replacement level.
2. The flexural strength also follows a similar trend as compressive strength, where the strength increases up to 15% replacement and then decreases. The highest flexural strength of 6.1 MPa at 28 days was achieved for GP15, confirming improved bonding and matrix strength.
3. Early age strength (7 days and 14 days) shows consistent improvement with the addition of glass powder up to 15%, which indicates faster geopolymerization due to the presence of reactive silica in glass powder.
4. Beyond 15% replacement (i.e., GP20 and GP25), both compressive and flexural strengths decrease due to reduction in effective binder content and weaker matrix formation caused by excess glass powder.
5. The improvement in strength up to optimum level is attributed to better particle packing, pore refinement, and formation of additional geopolymeric gels (C-A-S-H and N-A-S-H), which enhance the overall microstructure of concrete.
6. The study confirms that waste glass powder can be effectively utilized as a sustainable construction material in geopolymer concrete, reducing environmental pollution and dependency on conventional cementitious materials.
7. From overall performance analysis, 15% glass powder replacement is recommended as the optimum percentage for achieving maximum strength and durability.

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