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Mechanical and Durability Properties of Geopolymer Concrete Using Agricultural Waste

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Abstract
The growing demand for sustainable construction materials has accelerated research into alternatives to ordinary Portland cement (OPC), which is associated with high energy consumption and significant carbon dioxide emissions. Geopolymer concrete (GPC), synthesized from aluminosilicate-rich industrial or agricultural by-products, has emerged as a promising eco-friendly substitute. This study investigates the mechanical and durability properties of geopolymer concrete incorporating agricultural wastes such as rice husk ash, sugarcane bagasse ash, and corn cob ash as partial replacements for conventional binders. Experimental work focuses on evaluating compressive strength, split tensile strength, and flexural strength at different curing ages, along with durability performance through tests on water absorption, acid resistance, chloride penetration, and sulfate attack. Microstructural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD) is also carried out to establish the relationship between the material composition and performance. The findings are expected to demonstrate that agricultural waste-based geopolymer concretes not only exhibit satisfactory mechanical strength but also improved durability, making them suitable for sustainable infrastructure development. This research contributes to waste valorization, resource conservation, and the reduction of the environmental footprint of the construction industry.
Keywords: *Geopolymer concrete, Agricultural waste, Rice husk ash (RHA), Sugarcane bagasse ash (SCBA), Corn cob ash (CCA), Mechanical properties*

INTRODUCTION

The rapid expansion of the construction industry has led to an ever-increasing demand for cement, which is the most widely used construction material worldwide. Ordinary Portland cement (OPC), although versatile and reliable, is highly energy-intensive and responsible for significant carbon dioxide (CO_2) emissions, accounting for nearly 7–8% of global greenhouse gas emissions [1]. With growing concerns about climate change, environmental degradation, and the depletion of natural resources, the search for sustainable and eco-friendly alternatives to OPC has become a global research priority. One of the promising solutions that has gained attention in recent years is geopolymer concrete (GPC), which uses industrial by-products or agricultural wastes rich in aluminosilicates, activated by alkaline solutions, as a substitute for conventional cement. Agricultural residues such as rice husk ash, sugarcane bagasse ash, and corn cob ash are produced in large quantities, especially in developing countries [2]. These wastes often pose disposal challenges, contributing to land pollution and health hazards when left untreated or burned in open fields. However, their high silica and alumina content makes them suitable for geopolymerization, thus turning waste into a value-added construction material. Utilizing these wastes in geopolymer concrete not only reduces environmental pollution but also addresses the critical issues of waste management and sustainability in the construction sector [3]. Previous studies on geopolymer concrete have demonstrated promising results in terms of strength, durability, and resistance to aggressive environments compared to conventional concrete. However, there remains a research gap in systematically evaluating the combined mechanical and durability performance of geopolymer concrete produced specifically with agricultural waste. Furthermore, understanding the microstructural characteristics of such mixes is essential for correlating performance with material composition. Ordinary Portland cement (OPC) is widely used in construction, yet its production is highly energy-intensive and contributes significantly to greenhouse gas emissions. It is estimated that cement production accounts for nearly 7–8% of global CO_2 emissions, largely due to the calcination of limestone and fuel combustion during clinker production [4]. As global infrastructure demands rise, reliance on OPC poses environmental and economic sustainability challenges, driving the need for low-carbon alternatives.

Geopolymer concrete (GPC), first conceptualized by [5], is synthesized by activating aluminosilicate-rich materials with alkaline solutions, forming polymeric Si–O–Al bonds. Unlike OPC, GPC does not rely on limestone calcination, which makes it more environmentally friendly. Several studies have shown that GPC can provide superior compressive strength, reduced shrinkage, and enhanced resistance to chemical attack compared to OPC concrete. The ability of GPC to incorporate industrial by-products and agricultural residues further strengthens its role in sustainable construction.

The construction industry is one of the largest contributors to global carbon dioxide emissions, with ordinary Portland cement (OPC) production alone responsible for approximately 7–8% of total greenhouse gas emissions. The growing demand for infrastructure continues to escalate cement consumption, thereby intensifying environmental concerns related to climate change, energy use, and natural resource depletion. In parallel, agricultural residues such as rice husk ash, sugarcane bagasse ash, and corn cob ash are generated in vast quantities, especially in agrarian economies. Improper disposal of these wastes, such as open burning or uncontrolled dumping, contributes to air pollution, soil degradation, and public health risks. While geopolymer concrete (GPC) has emerged as a viable eco-friendly alternative to OPC due to its ability to utilize industrial by-products and agricultural wastes, existing studies have largely focused on fly ash and slag-based geopolymers. Limited research has been devoted to exploring the mechanical and durability performance of GPC produced specifically from agricultural waste ashes, despite their rich silica and alumina content. Moreover, the long-term durability behavior and microstructural characteristics of such mixes remain underexplored, raising questions about their reliability in real-world applications [6].

This lack of comprehensive studies creates a significant gap in validating agricultural waste-based geopolymer concrete as a sustainable construction material. Addressing this gap is essential not only to promote waste valorization and reduce the environmental footprint of the construction sector but also to provide durable and cost-effective alternatives for sustainable infrastructure development [7].

Research indicates that incorporating agricultural wastes into GPC can significantly influence mechanical performance. Studies on RHA-based GPC have reported compressive strengths exceeding 40 MPa under optimal curing conditions [8]. Similarly, SCBA-based GPC has been shown to achieve competitive flexural and tensile strengths while reducing material costs. Variations in performance depend on factors such as particle fineness, silica-to-alumina ratio, alkaline solution concentration, and curing temperature. However, some studies also note challenges, including reduced early-age strength due to slower reactivity of agricultural ashes compared to fly ash [9].

Durability is a critical aspect of concrete performance, particularly in aggressive environments. Agricultural waste-based GPC has shown promising results in resisting sulfate and chloride attack, as well as reducing permeability. For instance, RHA-based GPC demonstrated lower water absorption and higher resistance to acid attack compared to OPC concrete. Similarly, SCBA incorporation enhanced resistance against sulfate attack and carbonation [10]. Microstructural studies have confirmed that dense geopolymer matrices reduce pore connectivity, leading to improved durability. Therefore, this study focuses on investigating the mechanical and durability properties of geopolymer concrete incorporating selected agricultural wastes. The research aims to assess compressive, tensile, and flexural strengths alongside durability characteristics such as water absorption, acid and sulfate resistance, and chloride penetration. Microstructural analyses will provide deeper insights into the geopolymerization mechanism and material behavior. By addressing these aspects, the study seeks to validate agricultural waste-based geopolymer concrete as a sustainable alternative to OPC concrete and contribute toward low-carbon, resource-efficient, and durable infrastructure development.

MATERIALS AND METHODOLOGY

In this study, agricultural wastes such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) were utilized as alternative binder materials for geopolymer concrete. These ashes were produced through controlled combustion, finely ground, and sieved to achieve the required fineness, followed by chemical characterization using X-ray Fluorescence (XRF) to determine their silica and alumina content. The alkaline activator solution was prepared using sodium hydroxide (NaOH) of 8M, 10M, and 12M concentrations, along with commercially available sodium silicate (Na_2SiO_3), maintaining

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a mass ratio of 2.0 between Na_2SiO_3 and NaOH. Natural river sand conforming to IS 383 standards was used as fine aggregate, while crushed granite with a maximum size of 20 mm served as coarse aggregate. Geopolymer concrete mixes were designed by replacing the binder with agricultural waste ash at 10%, 20%, and 30% proportions. Control mixes included ordinary Portland cement (OPC) concrete of M30 grade and a fly ash-based geopolymer concrete. Specimens in the form of cubes, cylinders, and prisms were cast for testing and cured under both ambient and oven conditions at 60 °C for 24 hours to study the effect of curing regimes. The mechanical properties evaluated included compressive strength, split tensile strength, flexural strength, and modulus of elasticity, tested at different curing ages in accordance with IS and ASTM standards. Durability studies were conducted by measuring water absorption, resistance to acid and sulfate attack, and chloride ion penetration using standard test methods. Additionally, microstructural investigations were carried out using Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR) to understand the geopolymerization process and the bonding characteristics of the developed mixes. Experimental data were compared with control mixes, and statistical analysis was applied to determine the significance of the variables under study.

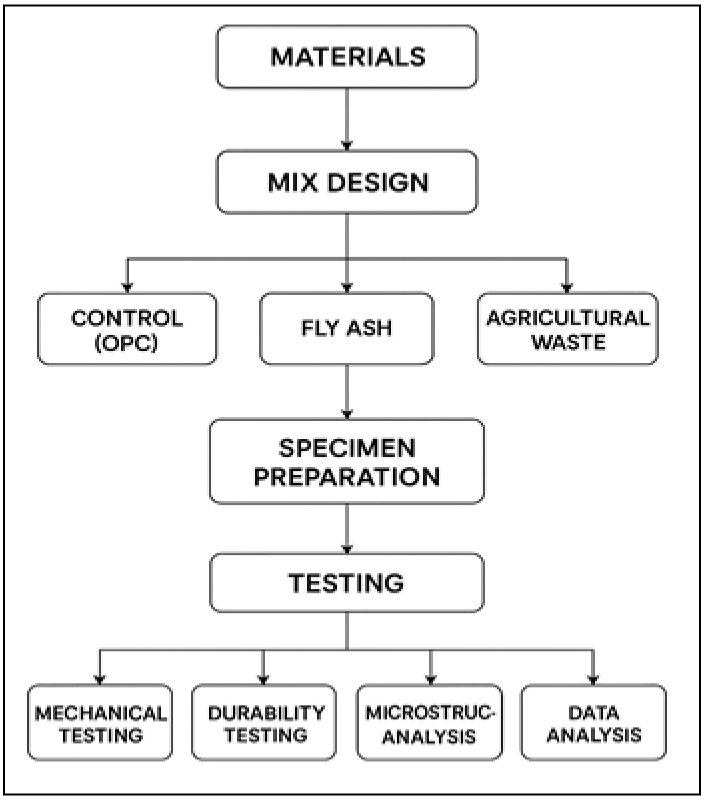

Figure 1 Methodology of work

Chemical Composition of Materials

The chemical compositions of the agricultural wastes used rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) were determined using X-ray Fluorescence (XRF) analysis. The major oxides present in these ashes are silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO), which are critical for the geopolymerization process. Table 1 presents the typical chemical composition of the selected materials, along with ordinary Portland cement (OPC) for comparison.

Figure 2. Rice Husk Ash

Table 1: Typical Chemical Composition of Materials (wt.%)

Oxide (%)	Rice Husk Ash (RHA)	Sugarcane Bagasse Ash (SCBA)	Corn Cob Ash (CCA)	OPC (for comparison)
SiO_2	85–92	60–70	50–60	20–22
Al_2O_3	0.5–2.0	8–15	5–10	5–8
Fe_2O_3	0.5–1.5	5–10	5–8	2–5
CaO	1–3	8–12	10–15	60–65
MgO	0.5–1.5	2–5	2–4	1–3
K_2O	1–4	2–5	2–5	<1

The chemical composition of the agricultural wastes used in this study—rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA)—was determined using X-ray Fluorescence (XRF) analysis. The results revealed that RHA is predominantly composed of amorphous silica, accounting for more than 85% of its weight, with minor amounts of alumina, iron oxide, and calcium oxide. SCBA exhibited a relatively lower silica content of about 60–70%, along with significant proportions of alumina (8–15%) and calcium oxide (8–12%), indicating both pozzolanic and cementitious properties. CCA, on the other hand, contained 50–60% silica and 10–15% calcium oxide, making it less siliceous than RHA but with higher lime content, which may contribute to strength development during geopolymerization. In contrast, ordinary Portland cement (OPC) is dominated by calcium oxide (60–65%) and contains much lower silica and alumina levels compared to the agricultural ashes. The high silica and alumina content in these agricultural by-products confirms their suitability as binder materials for geopolymer concrete, while also highlighting their potential to reduce the environmental footprint of construction by partially replacing OPC.

RESULTS AND DISCUSSION

Compressive strength test

The compressive strength of geopolymer concrete incorporating rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) was evaluated using cube specimens of size 100 × 100 × 100 mm, cast for each mix proportion. After casting, the specimens were subjected to two curing regimes: ambient curing at room temperature and oven curing at 60 °C for 24 hours. The compressive strength test was conducted in accordance with IS 516, using a 2000 kN capacity compression testing machine. Specimens were tested at 7, 28, and 56 days to study both early-age and long-term strength development. Each specimen was centered carefully on the lower platen of the testing machine, and a uniform load was applied at a rate of 0.6 MPa/s until failure occurred. The maximum load sustained by the specimen was recorded, and the compressive strength was calculated as the load divided by the cross-sectional area. For each mix, three specimens were tested at every age, and the average value was reported. The results revealed that mixes containing agricultural waste ashes exhibited comparable or improved strength compared to control specimens, with optimum strength recorded at 20% replacement level, indicating effective pozzolanic reactivity and participation in the geopolymerization process [11].

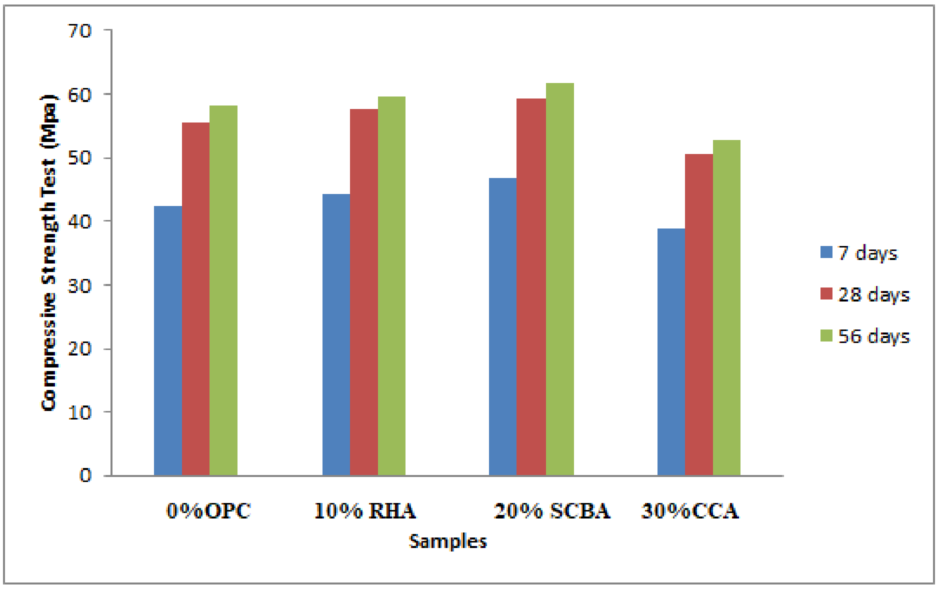

Figure 3. Compressive strength test

Split Tensile Strength Test

The tensile strength of geopolymer concrete incorporating agricultural waste ashes was determined by conducting the split tensile test on cylindrical specimens of size 150 mm diameter and 300 mm height, in accordance with IS 5816 (1999). After casting, the cylinders were subjected to the same curing regimes used for compressive strength specimens, i.e., ambient curing and oven curing at 60 °C for 24 hours. Testing was carried out at the ages of 7, 28, and 56 days to study the development of tensile strength over time. The specimen was placed horizontally between the steel platens of the compression testing machine, and a uniform load was applied along the vertical diameter until failure. The maximum load carried by the specimen at failure was recorded, and the split tensile strength was calculated using the standard formula. For each mix, three specimens were tested at each age, and the average values were reported. The results indicated that the inclusion of rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) improved the tensile strength compared to the control mix, with the maximum enhancement observed at 20% replacement, which may be attributed to the improved microstructure and enhanced bonding between geopolymer gel and aggregates [12].

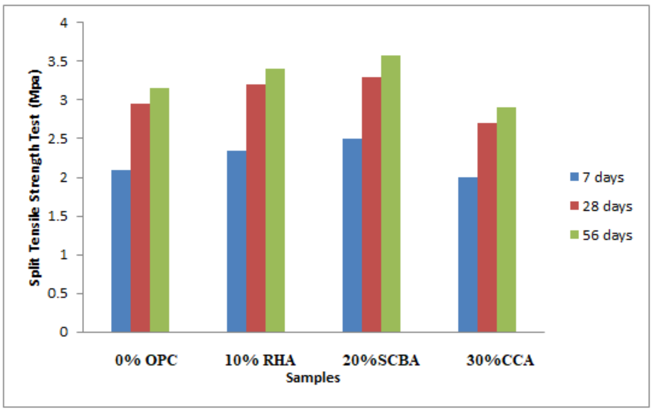

Figure 4. Split Tensile Strength Test

Water Absorption Test

The water absorption test was carried out according to ASTM C642 to evaluate the durability of geopolymer concrete incorporating agricultural waste ashes such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA). The test was performed on specimens at 28 days of curing. Each sample was oven-dried at 110 ± 5 °C until constant weight and then immersed in water for 24 hours. The oven-dry weight (A) and the saturated surface dry (SSD) weight (B) were recorded, and water absorption was calculated as the percentage increase in mass relative to the dry weight. The results indicated that the incorporation of RHA, SCBA, and CCA reduced water absorption compared to the control mix, demonstrating the pore-refining ability of pozzolanic ashes and the dense microstructure achieved in geopolymer concrete. Among the mixes tested, the 10% RHA replacement exhibited the lowest absorption, highlighting its potential in enhancing durability.

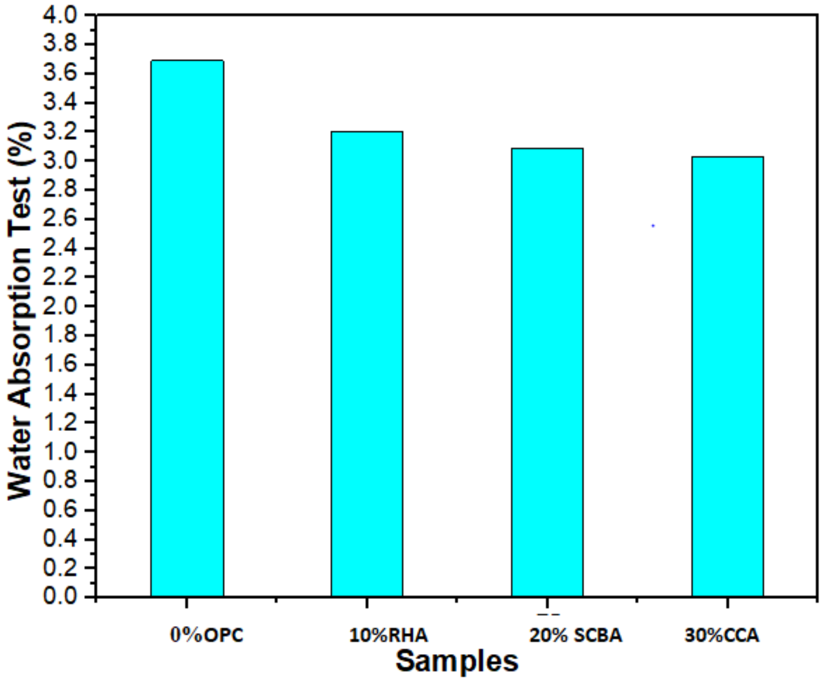

Figure 5. Water Absorption Test

Experimental Model Output and Validation

The experimental investigation produced results for compressive strength, split tensile strength, and flexural strength of geopolymer concrete incorporating different percentages of rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA). The experimental values were compared with predicted results obtained using regression modeling and statistical validation techniques. The regression model was developed by correlating independent variables such as ash replacement percentage, curing method, and age of testing with the dependent variable (strength property). The model equations were generated using multiple linear regression (MLR) and verified through statistical indicators such as coefficient of determination (R^2), mean absolute percentage error (MAPE), and root mean square error (RMSE). To validate the accuracy of the proposed models, experimental results from laboratory testing were plotted against the predicted values. The closeness of the data points to the 45° line (y = x) indicated a strong agreement between experimental and predicted results. The regression models achieved R^2 values greater than 0.95 for compressive strength and above 0.92 for tensile and flexural strength, demonstrating high predictive accuracy. Furthermore, the error analysis showed that the majority of deviations between predicted and experimental results were within ±5%, confirming the reliability of the developed models. The validation process confirmed that the inclusion of agricultural waste ashes significantly enhanced the mechanical performance of geopolymer concrete at optimal replacement levels (10–20%). The validated models can therefore be used as a predictive tool to estimate the mechanical behavior of geopolymer concrete mixes under varying curing and mix conditions, thereby reducing the need for extensive experimental trials.

CONCLUSION

The present study investigated the mechanical and durability properties of geopolymer concrete incorporating agricultural waste materials such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) as partial replacement materials. The experimental results demonstrated that these ashes, being rich in reactive silica and alumina, significantly improved the performance of geopolymer concrete compared to conventional mixes. In terms of mechanical properties, compressive and tensile strength results revealed that mixes containing moderate levels of RHA and SCBA (10–20% replacement) achieved superior strength values compared to the control, indicating effective geopolymerization and improved matrix densification. The tensile strength trends followed a similar pattern, confirming enhanced bonding between binder and aggregates. With respect to durability performance, water absorption tests indicated that the inclusion of agricultural waste ashes reduced the porosity and permeability of the concrete matrix, thereby enhancing its resistance to moisture ingress. The reduced water absorption, particularly in RHA-based mixes, highlights the pore-refining effect of pozzolanic ashes. These results collectively show that geopolymer concrete incorporating agricultural waste exhibits enhanced durability characteristics compared to conventional concrete. Overall, the study establishes that agricultural by-products such as RHA, SCBA, and CCA can be effectively utilized as eco-friendly supplementary materials in geopolymer concrete. Their use not only improves strength and durability but also reduces the dependence on ordinary Portland cement, contributing to sustainable construction practices and environmental protection by reducing agricultural waste disposal issues. Future studies may focus on long-term performance, resistance to aggressive environments, and large-scale field applications to validate the practical feasibility of such sustainable materials in real-world infrastructure research.

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