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Experimental Evaluation of the Mechanical Properties of Geopolymer Concrete Using Recycled Coarse Aggregates from Construction Waste

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Abstract
The rapid growth of construction and demolition activities has significantly increased the generation of construction waste, with concrete waste representing the largest proportion. This study aimed to investigate the effect of Recycled Concrete Aggregate (RCA) as a partial replacement for natural coarse aggregate on the compressive strength of fly ash-based geopolymer concrete and to determine the optimum RCA content that provides the best mechanical performance. This research employed a laboratory experimental design with RCA replacement levels of 0%, 25%, 50%, 75%, and 100% by weight of coarse aggregate. The geopolymer binder was produced using fly ash activated with an alkaline solution consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at a 2:1 ratio. Tests for compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity were conducted after 28 days of curing in accordance with applicable ASTM standards. The results showed that RCA incorporation improved the compressive strength of geopolymer concrete up to an optimum replacement level. The compressive strength values obtained for RCA replacement levels of 0%, 25%, 50%, 75%, and 100% were 25.98 MPa, 26.65 MPa, 30.21 MPa, 24.25 MPa, and 23.91 MPa, respectively. The highest compressive strength was achieved at 50% RCA replacement, representing an increase of approximately 16.3% compared with the control mixture. However, further increases in RCA content resulted in reduced strength due to increased porosity, higher water absorption, and the presence of residual mortar attached to recycled aggregates. These findings indicate that a 50% RCA replacement level represents the optimum proportion for producing sustainable fly ash-based geopolymer concrete with enhanced compressive strength and environmental benefits.

INTRODUCTION

The construction industry is one of the largest consumers of natural resources and generators of solid waste worldwide. Rapid urbanization and infrastructure development have significantly increased the volume of construction and demolition waste (CDW), particularly concrete waste generated from demolished structures. The accumulation of concrete waste in landfills has created environmental challenges and increased pressure on natural resource consumption. Consequently, recycling and reusing concrete waste have become important strategies for achieving sustainable construction and reducing environmental impacts (Li et al., 2024).

One of the most promising approaches to managing concrete waste is the utilization of Recycled Concrete Aggregate (RCA) as a substitute for natural coarse aggregate in concrete production (Ahmed et al., 2020; Makul et al., 2021; Shah et al., 2021). RCA is obtained from crushed concrete debris and can reduce the demand for virgin aggregates while minimizing landfill disposal. Previous studies have demonstrated that RCA can be effectively incorporated into concrete; however, its physical characteristics, including higher porosity, lower density, and greater water absorption, may influence the mechanical performance of the resulting concrete (Abousnina et al., 2025).

In addition to aggregate consumption, the environmental burden associated with ordinary Portland cement (OPC) production has become a major concern (Jalal et al., 2025; Kim et al., 2022). Cement manufacturing contributes substantially to global carbon dioxide (CO_2) emissions due to limestone calcination and the high energy requirements of clinker production. Recent studies have indicated that the cement industry remains one of the largest industrial contributors to greenhouse gas emissions, encouraging researchers to develop alternative low-carbon binder systems (Barbhuiya et al., 2025). Therefore, sustainable construction materials that reduce cement consumption are increasingly needed to support global carbon reduction targets.

Geopolymer concrete has emerged as a viable alternative to conventional OPC-based concrete. Unlike traditional concrete, geopolymer concrete utilizes aluminosilicate-rich materials, such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume, which are activated using alkaline solutions to form a hardened binder matrix. This technology offers several environmental and engineering advantages, including lower CO_2 emissions, improved chemical resistance, enhanced durability, and efficient utilization of industrial by-products (Nguyen & Huynh, 2025). Furthermore, geopolymer technology aligns with sustainable development principles by converting industrial waste materials into value-added construction products.

Fly ash-based geopolymer concrete has attracted considerable attention because fly ash is abundantly available as a by-product of coal-fired power plants and contains significant amounts of silica and alumina required for geopolymerization. Research has shown that fly ash-based geopolymer concrete can achieve mechanical properties comparable to or exceeding those of conventional concrete under appropriate curing conditions (Rajput et al., 2024). Consequently, the combination of fly ash utilization and recycled aggregate incorporation represents a promising strategy for producing environmentally sustainable concrete.

Recent studies have focused on the combined application of geopolymer binders and recycled aggregates to further improve sustainability in the construction sector. According to Ghazouani et al. (2025), geopolymer-recycled aggregate concrete has the potential to simultaneously reduce cement-related emissions and construction waste generation. This dual sustainability benefit makes geopolymer concrete incorporating RCA an attractive material for future infrastructure development. Moreover, the geopolymer matrix may improve the interfacial bonding between recycled aggregates and the surrounding binder paste, thereby mitigating some deficiencies commonly associated with RCA.

Despite these advantages, the influence of RCA on the mechanical properties of geopolymer concrete remains an active area of investigation. The residual mortar attached to RCA particles often increases porosity and weakens the interfacial transition zone, which may negatively affect compressive strength, tensile strength, flexural strength, and modulus of elasticity (Lu et al., 2024). Several researchers have reported reductions in mechanical performance at high RCA replacement levels due to the lower quality of recycled aggregates compared with natural aggregates.

Conversely, other studies have shown that partial replacement of natural aggregates with RCA can maintain or even improve concrete performance when appropriate mix proportions are applied. For example, geopolymer concrete containing moderate levels of recycled aggregates has demonstrated satisfactory compressive strength and durability characteristics. The incorporation of supplementary materials, such as GGBS and silica fume, has also been reported to enhance matrix densification and improve the bond between RCA and geopolymer paste, thereby improving mechanical properties (Singh et al., 2023).

Furthermore, environmental assessments have indicated that geopolymer concrete containing recycled aggregates can significantly reduce environmental impacts compared with conventional concrete. A life-cycle assessment conducted by researchers found that the combined use of recycled aggregates and geopolymer binders could reduce environmental burdens by approximately 50–60% while maintaining acceptable engineering performance (Singh et al., 2023; Manzoor et al., 2026). These findings highlight the considerable potential of geopolymer-recycled aggregate concrete to support sustainable construction practices and circular economy objectives.

Although numerous studies have investigated geopolymer-recycled aggregate concrete, inconsistencies remain regarding the optimal RCA replacement level. Variations in source materials, aggregate quality, alkaline activator concentration, curing conditions, and mix design parameters have resulted in different conclusions among researchers (Zhang et al., 2023). Therefore, further experimental studies are needed to evaluate the influence of RCA content on the mechanical performance of fly ash-based geopolymer concrete under controlled conditions (Rathore & Meesala, 2025).

Based on the background outlined above, this study aimed to investigate the effect of RCA replacement on the compressive strength of fly ash-based geopolymer concrete. RCA was used as a replacement for natural coarse aggregate at levels of 0%, 25%, 50%, 75%, and 100%. The findings of this research are expected to provide valuable insights into the development of sustainable geopolymer concrete utilizing recycled construction waste while contributing to resource conservation and environmental sustainability in the construction industry.

METHODS

This research employed a laboratory experimental method to investigate the effect of Recycled Concrete Aggregate (RCA) replacement for natural coarse aggregate on the mechanical properties of fly ash-based geopolymer concrete. RCA was incorporated at replacement levels of 0%, 25%, 50%, 75%, and 100% by weight of the coarse aggregate. Fly ash was used as the primary precursor material, while the alkaline activator consisted of a 10 M sodium hydroxide ($NaOH$) solution and sodium silicate (Na_2SiO_3) solution with a 2:1 mass ratio. The research procedures included material characterization, mix design, specimen preparation, curing, mechanical testing, and data analysis.

The materials used in this study consisted of fly ash, natural sand as fine aggregate, natural coarse aggregate, RCA, sodium hydroxide ($NaOH$), sodium silicate (Na_2SiO_3), water, and superplasticizer. The RCA was obtained from demolished concrete waste, which was crushed, cleaned, and sieved to meet coarse aggregate grading requirements. Prior to concrete production, material testing was conducted to determine physical properties, including specific gravity, water absorption, and particle size distribution, to ensure material suitability for geopolymer concrete production.

The geopolymer concrete mixtures were designed to achieve a target compressive strength of 25 MPa at 28 days. The proportions of fly ash, alkaline activator, fine aggregate, water, and admixture were maintained consistently across all mixtures, while only the RCA replacement percentage was varied. Concrete specimens were cast and cured under controlled laboratory conditions before mechanical testing. The mechanical properties were evaluated through compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity tests conducted at 28 days. The mix proportions for each concrete mixture are presented in Table X.

Table 1. Mix Proportions of Geopolymer Concrete

Material	Quantity (kg/m³)
Fly Ash	400
Fine Aggregate (Sand)	650
Total Coarse Aggregate	1,050
Sodium Hydroxide Solution (10 M)	45
Sodium Silicate Solution	90
Additional Water	20
Superplasticizer	5

Source: Author's mix design (2025) based on preliminary trial mixtures

The variations in RCA replacement levels are presented in

Table 2. Variations of RCA Replacement Levels

Mix ID	Natural Coarse Aggregate (kg/m³)	RCA (kg/m³)
RCA 0%	1,050	0
RCA 25%	787.5	262.5
RCA 50%	525	525
RCA 75%	262.5	787.5
RCA 100%	0	1,050

Source: Author's mix design (2025)

The production of geopolymer concrete began with the dry mixing of fly ash, sand, natural coarse aggregate, and RCA until a homogeneous mixture was achieved. Subsequently, the alkaline activator solution, consisting of NaOH and Na_2SiO_3, was added gradually while mixing continued in a concrete mixer. The fresh concrete was then cast into molds and compacted using a vibrating table to minimize entrapped air and improve compaction. After 24 hours, the specimens were demolded and cured under ambient laboratory conditions until the 28-day testing age.

Mechanical properties were evaluated at 28 days. The test types, standards, and specimen dimensions are summarized in

Table 3. Types of Tests, Standards, and Specimen Dimensions

Test	Standard	Specimen Dimension
Compressive Strength	ASTM C39/C39M	Cylinder Ø100 × 200 mm
Splitting Tensile Strength	ASTM C496/C496M	Cylinder Ø100 × 200 mm
Modulus of Elasticity	ASTM C469/C469M	Cylinder Ø100 × 200 mm
Flexural Strength	ASTM C78/C78M	Beam 150 × 150 × 600 mm

Source: ASTM International standards (2023)

The compressive strength test was conducted according to ASTM C39/C39M using a compression testing machine. The maximum load applied to the specimen was recorded and the compressive strength was calculated using Equation (1):

$$f'_c = \frac{P}{A}$$

where $f_c'$is the compressive strength (MPa), $P$is the maximum applied load (N), and $A$is the cross-sectional area of the specimen (mm²).

The splitting tensile strength test was performed in accordance with ASTM C496/C496M by applying a compressive load along the diameter of the cylindrical specimen until failure. The splitting tensile strength was calculated using Equation (2):

$$f_t = \frac{2P}{\pi LD}$$

where f_t is the splitting tensile strength (MPa), P is the maximum load (N), L is the length of the cylinder (mm), and D is the diameter of the cylinder (mm).

The modulus of elasticity test was carried out according to ASTM C469/C469M using a compressometer attached to the cylindrical specimen. The stress–strain relationship obtained during loading was used to determine the modulus of elasticity. The modulus of elasticity was calculated using Equation (3):

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005}$$

where E_c is the modulus of elasticity (MPa), S_1 is the stress corresponding to a longitudinal strain of 50 microstrain, S_2 is the stress corresponding to 40% of the ultimate load, and ε_2 is the longitudinal strain at stress S_2.

The flexural strength test was conducted in accordance with ASTM C78/C78M using a third-point loading method on beam specimens. The flexural strength was calculated using Equation (4):

$$f_r = \frac{PL}{bd^2}$$

where f_r is the flexural strength (MPa), P is the maximum applied load (N), L is the span length (mm), b is the width of the specimen (mm), and d is the depth of the specimen (mm).

RESULTS AND DISCUSSION

Effect of RCA on the Compressive Strength of Geopolymer Concrete

Compressive strength is the primary parameter used to evaluate the quality and structural performance of concrete under axial loading. The compressive strength test was conducted at 28 days using cylindrical specimens with dimensions of Ø100 × 200 mm in accordance with ASTM C39/C39M. The test results are presented in

Table 4. Compressive Strength of Geopolymer Concrete at 28 Days

RCA (%)	Compressive Strength (MPa)
0	25.98
25	26.65
50	30.21
75	24.25
100	23.91

Source: Laboratory test results (2025)

The compressive strength results indicate that the incorporation of Recycled Concrete Aggregate (RCA) significantly affected the mechanical performance of fly ash-based geopolymer concrete. The compressive strength values measured at 28 days for RCA replacement levels of 0%, 25%, 50%, 75%, and 100% were 25.98 MPa, 26.65 MPa, 30.21

MPa, 24.25 MPa, and 23.91 MPa, respectively. The variation in compressive strength for all concrete mixtures is presented in **Figure 1**.

The control mixture containing 100% natural coarse aggregate achieved a compressive strength of 25.98 MPa. When 25% RCA was introduced, the compressive strength increased slightly to 26.65 MPa, representing an improvement of approximately 2.58% compared with the control mixture. A more substantial increase was observed at 50% RCA replacement, with compressive strength reaching 30.21 MPa. This value corresponds to an increase of 16.28% over the control specimen and represents the highest strength achieved among all mixtures tested. These results suggest that incorporating RCA at moderate replacement levels can improve the mechanical behavior of geopolymer concrete.

The improvement in compressive strength may be attributed to several factors. Recycled concrete aggregates generally have a rough, angular surface texture, which enhances mechanical interlocking between the aggregate particles and the geopolymer binder. Moreover, the residual mortar attached to the RCA surface may improve the bond within the interfacial transition zone (ITZ), facilitating more efficient stress transfer throughout the concrete matrix. The combination of these effects can produce a denser and more homogeneous microstructure, resulting in improved compressive strength.

However, when the RCA replacement level was increased to 75% and 100%, the compressive strength decreased to 24.25 MPa and 23.91 MPa, respectively. The reduction in strength is mainly associated with the inherent characteristics of recycled aggregates, including higher porosity, greater water absorption capacity, and the presence of microcracks in the adhered mortar. These properties can increase internal voids and weaken the aggregate–matrix interface, thereby reducing the concrete's load-carrying capacity.

Overall, the results indicate that a 50% RCA replacement level is optimal for maximizing the compressive strength of fly ash-based geopolymer concrete while maintaining the sustainability benefits of recycled construction materials.

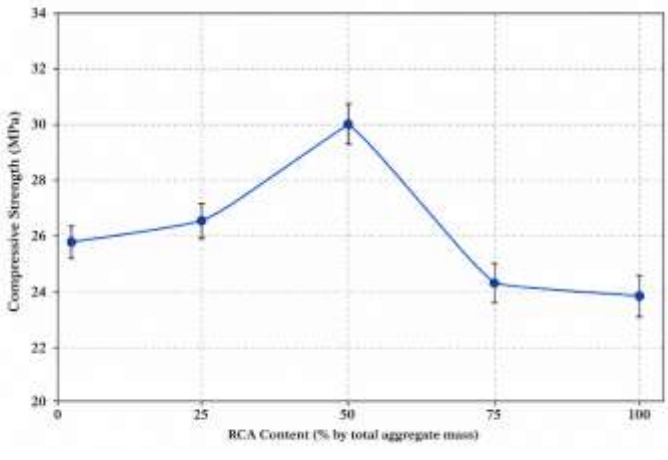

Figure 1. Compressive Strength of Geopolymer Concrete at 28 Days
Source: Author's data analysis (2025)

Effect of RCA on the Splitting Tensile Strength of Geopolymer Concrete

The splitting tensile strength test was performed to evaluate the tensile behavior of geopolymer concrete under indirect tension. Testing was conducted in accordance with ASTM C496/C496M using cylindrical specimens with dimensions of Ø100 × 200 mm. The results are presented in

Table 5. Splitting Tensile Strength of Geopolymer Concrete at 28 Days

RCA (%)	Splitting Tensile Strength (MPa)
0	2.93
25	2.98
50	3.21
75	3.05
100	2.71

Source: Laboratory test results (2025)

The splitting tensile strength results showed a trend similar to that observed for compressive strength, indicating that the incorporation of Recycled Concrete Aggregate (RCA) significantly influenced the tensile performance of fly ash-based geopolymer concrete. The variation in splitting tensile strength for all mixtures at 28 days is presented in **Figure 2**.

The control mixture exhibited a splitting tensile strength of 2.93 MPa. The incorporation of 25% RCA slightly increased the tensile strength to 2.98 MPa, and the highest splitting tensile strength was achieved at 50% RCA replacement, reaching 3.21 MPa, which represents an increase of approximately 9.56% compared to the control specimen. This result indicates that tensile strength improved up to a moderate RCA replacement level.

The improvement in tensile performance can be attributed to stronger bonding between RCA particles and the geopolymer matrix. The rough and angular surface texture of recycled aggregates increases mechanical interlocking and internal friction, resulting in more effective stress transfer within the concrete. Furthermore, the residual mortar attached to RCA may contribute to a stronger interfacial transition zone (ITZ), thereby improving the concrete's resistance to tensile cracking.

However, at RCA replacement levels of 75% and 100%, the splitting tensile strength decreased to 3.05 MPa and 2.71 MPa, respectively. This reduction suggests that excessive RCA incorporation results in a greater amount of residual mortar with pores and microcracks. These defects facilitate crack initiation and propagation under tensile loading, leading to lower tensile strength and reduced structural performance.

In addition, regression analysis between compressive strength and splitting tensile strength produced a coefficient of determination (R^2) of 0.93, indicating a very strong correlation between the two mechanical properties. Overall, this finding confirms that improvements in compressive strength are generally accompanied by corresponding increases in tensile strength, underscoring the strong link between the two properties.

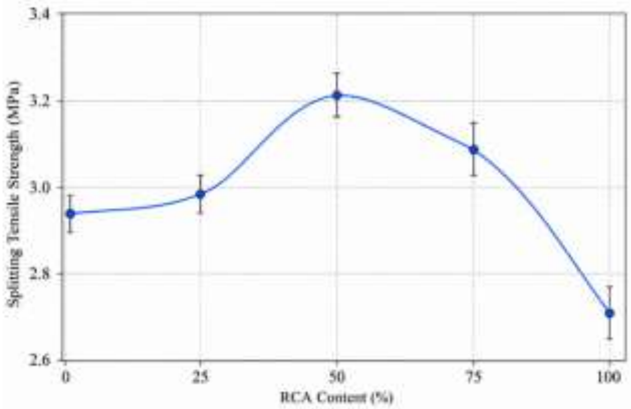

Figure 2. Splitting Tensile Strength of Geopolymer Concrete at 28 Days

Source: Author's data analysis (2025)

Effect of RCA on the Flexural Strength of Geopolymer Concrete

Flexural strength represents the ability of concrete to resist tensile stresses caused by bending loads and is an important indicator of structural performance. In this study, the flexural strength of fly ash-based geopolymer concrete with various RCA replacement levels was evaluated using 150 × 150 × 600 mm beam specimens in accordance with ASTM C78/C78M. The test results are presented in

Table 6. Flexural Strength of Geopolymer Concrete at 28 Days

RCA (%)	Flexural Strength (MPa)
0	4.34
25	4.28
50	4.68
75	4.29
100	4.11

Source: Laboratory test results (2025)

The flexural strength results showed that the incorporation of Recycled Concrete Aggregate (RCA) significantly influenced the bending performance of fly ash-based geopolymer concrete. The variation in flexural strength for all mixtures at 28 days is presented in **Figure 3**.

The highest flexural strength was recorded at 50% RCA replacement, reaching 4.68 MPa, which represents an increase of approximately 7.83% compared to the control concrete. This improvement indicates that moderate RCA incorporation can enhance geopolymer concrete's resistance to tensile stresses induced by bending loads.

However, at higher RCA replacement levels of 75% and 100%, the flexural strength decreased to 4.29 MPa and 4.11 MPa, respectively. This reduction is associated with increased porosity of residual mortar, higher water absorption, and microstructural defects in recycled aggregates. These characteristics weaken the aggregate–matrix bond and reduce the concrete's capacity to resist flexural stresses.

The trend in flexural strength closely follows that of compressive strength, suggesting that the quality of the geopolymer matrix and the effectiveness of the ITZ are crucial in determining the flexural behavior of geopolymer concrete. Overall, the results indicate that 50% RCA replacement provides the optimum balance between sustainability and mechanical performance.

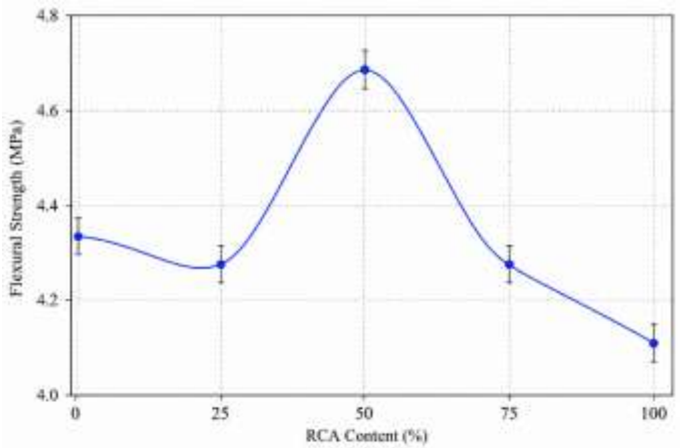

Figure 3. Flexural Strength of Geopolymer Concrete at 28 Days

Source: Author's data analysis (2025)

Effect of RCA on the Modulus of Elasticity of Geopolymer Concrete

The modulus of elasticity is an important mechanical property that reflects concrete's stiffness and its ability to resist elastic deformation under applied loads. A higher modulus of elasticity indicates greater resistance to deformation and improved structural rigidity. In geopolymer concrete, this property is influenced by factors such as aggregate characteristics, binder composition, porosity, and the quality of the interfacial transition zone between the aggregate and matrix. In this study, the modulus of elasticity was determined to evaluate the effect of Recycled Concrete Aggregate (RCA) incorporation on the stiffness performance of fly ash-based geopolymer concrete. The test was conducted in accordance with ASTM C469/C469M using cylindrical specimens with a diameter of 100 mm and a height of 200 mm (Ø100 × 200 mm). The measured values provide insight into the elastic behavior of the concrete mixtures and their ability to withstand service loads without excessive deformation. The experimental results obtained from the modulus of elasticity tests are summarized in

Table 7.

Table 7. Modulus of Elasticity of Geopolymer Concrete at 28 Days

RCA (%)	Modulus of Elasticity (GPa)
0	24.82
25	25.27
50	26.83
75	25.15
100	24.58

Source: Laboratory test results (2025)

The modulus of elasticity results demonstrated a trend similar to that observed for compressive strength, indicating that the incorporation of Recycled Concrete Aggregate (RCA) significantly influenced the stiffness and elastic behavior of fly ash-based geopolymer concrete. The modulus of elasticity is a critical mechanical property that reflects concrete's ability to resist deformation under applied loads. Generally, concrete with a higher modulus of elasticity exhibits greater stiffness and lower strain under the same loading conditions. The variation in modulus of elasticity for all mixtures at 28 days is presented in **Figure 4**.

The control mixture containing 100% natural coarse aggregate exhibited a modulus of elasticity of 24.82 GPa. The incorporation of RCA at a 25% replacement level resulted in a slight increase in stiffness. The highest modulus of elasticity was observed at 50% RCA replacement, reaching 26.83 GPa, an increase of approximately 8.10% compared with the control mixture. This result suggests that moderate RCA incorporation can enhance the stiffness and deformation resistance of geopolymer concrete. The increase in elastic modulus at this replacement level indicates that the concrete matrix was able to transfer stresses more effectively and resist elastic deformation under loading.

The improvement in modulus of elasticity can be attributed to the enhanced aggregate–matrix interaction and the development of a denser geopolymer microstructure. The rough, angular surface texture of RCA promotes better mechanical interlocking with the geopolymer binder, while the residual mortar attached to the recycled aggregates may improve bonding within the interfacial transition zone (ITZ). A stronger ITZ enhances stress transfer between the aggregate particles and the surrounding matrix, resulting in greater stiffness and reduced deformation. Furthermore, the geopolymerization process may contribute to the formation of a compact binder structure, thereby improving the overall integrity of the concrete.

However, when the RCA replacement level exceeded 50%, the modulus of elasticity gradually decreased. The values recorded at 75% and 100% RCA replacement were 25.15 GPa and 24.58 GPa, respectively. This reduction is primarily associated with the inherent characteristics of recycled aggregates, including higher porosity, increased water absorption, and the presence of microcracks in the adhered mortar. These defects create weak zones within the concrete and reduce stress transfer, resulting in lower stiffness and greater deformation under applied loads.

A strong positive correlation was observed between compressive strength and modulus of elasticity, indicating that increases in concrete strength were accompanied by corresponding increases in stiffness. Overall, the results demonstrate that a 50% RCA replacement level provides the optimal stiffness performance for fly ash-based geopolymer concrete while maintaining the sustainability benefits of recycled aggregate utilization.

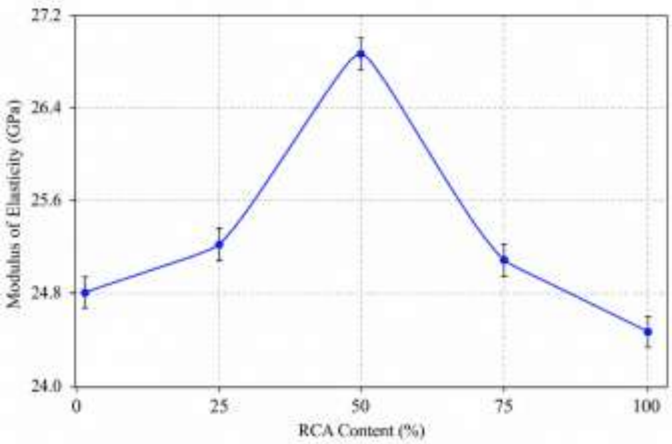

Figure 4. Modulus of Elasticity of Geopolymer Concrete at 28 Days
Source: Author's data analysis (2025)

Overall, the results demonstrate that RCA replacement significantly influences the mechanical performance of fly ash-based geopolymer concrete. All mechanical properties, including compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity, improved as the RCA content increased from 0% to 50%. Beyond this level, the properties gradually declined.

Optimum performance was achieved at 50% RCA replacement, where the concrete attained a compressive strength of 30.21 MPa, a splitting tensile strength of 3.21 MPa, a flexural strength of 4.68 MPa, and a modulus of elasticity of 26.83 GPa. These improvements can be attributed to enhanced aggregate-matrix bonding, improved mechanical interlocking, and a denser microstructure within the geopolymer concrete.

Conversely, higher RCA contents (75–100%) resulted in reduced mechanical performance due to increased residual mortar, higher porosity, and microcracking within the recycled aggregates. These factors weakened the concrete's internal structure and reduced its ability to resist loading.

Therefore, the study concludes that a 50% RCA replacement level is the optimum proportion for producing sustainable fly ash-based geopolymer concrete with superior mechanical properties while promoting the recycling of construction and demolition waste in accordance with circular economy and sustainable construction principles.

CONCLUSION

This study evaluated the influence of Recycled Concrete Aggregate (RCA) as a partial replacement for natural coarse aggregate on the mechanical properties of fly ash-based geopolymer concrete. The experimental results demonstrated that RCA content significantly affected the compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of geopolymer concrete. The mechanical properties generally improved with increasing RCA replacement up to 50%, indicating that an appropriate proportion of recycled aggregate could enhance geopolymer concrete performance. The optimum performance was achieved at a 50% RCA replacement level. At this level, the compressive strength reached 30.21 MPa, representing an increase of 16.28% compared with the control mixture. The highest splitting tensile strength, flexural strength, and modulus of elasticity were also obtained at 50% RCA replacement, with values of 3.21 MPa, 4.68 MPa, and 26.83 GPa, respectively. These findings suggest that moderate RCA incorporation improved the aggregate–matrix bond and enhanced the interfacial transition zone, resulting in a denser and stronger geopolymer matrix.

However, increasing the RCA replacement level to 75% and 100% resulted in reductions in all measured mechanical properties. This decline was attributed to the higher porosity, greater water absorption capacity, residual mortar, and microcracks associated with recycled aggregates, which adversely affected bond quality and the structural integrity of the concrete. Based on the findings, a 50% RCA replacement level is recommended as the optimum proportion for producing fly ash-based geopolymer concrete with improved mechanical performance. The incorporation of RCA into geopolymer concrete provides a sustainable approach for recycling construction and demolition waste, reducing the consumption of natural aggregates, conserving natural resources, and supporting environmentally responsible construction practices. Furthermore, this approach contributes to the implementation of circular economy principles within the construction industry.

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