Optimization of Compressive Strength of Geopolymer Concrete Based on Rice Husk Ash and Fly Ash with Banana Stem Fiber for Rigid Pavement

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Abstract

Geopolymer concrete is an environmentally friendly alternative to Portland cement concrete by utilizing industrial and agricultural waste. This study aimed to investigate the effect of banana sheath fiber on the compressive strength of geopolymer concrete containing 95% fly ash and 5% rice husk ash (RHA), activated with 12 M sodium hydroxide (NaOH) and a sodium silicate to sodium hydroxide (Na_2SiO_3/NaOH) ratio of 2.0. An experimental laboratory method was conducted using 15 × 15 × 15 cm cube specimens with banana sheath fiber contents of 0%, 0.1%, and 0.2%. Compressive strength tests were performed at curing ages of 7, 14, and 28 days using a Compression Testing Machine (CTM) in accordance with SNI 1974:2011. The control mixture without fiber achieved the highest compressive strength of 33.9 MPa at 28 days and was the only mixture that met the target strength of 30 MPa. Mixtures containing 0.1% and 0.2% fiber achieved maximum strengths of 25.5 MPa and 28.5 MPa, respectively. Although fiber addition did not improve compressive strength, it reduced surface cracking after testing, indicating its potential to enhance the performance of geopolymer concrete for rigid pavement applications.

Keywords: *Banana Sheath Fiber, Compressive Strength, Fly Ash, Geopolymer Concrete, Rice Husk Ash.*

A. INTRODUCTION

The construction industry is one of the sectors that contributes significantly to global carbon emissions, primarily due to the use of Portland cement as the main binder in concrete. Albadrani (2025) reported that cement production accounts for approximately 8–10% of global CO_2 emissions. This condition has encouraged the development of more environmentally friendly construction materials through the utilization of industrial and agricultural waste as constituents of sustainable concrete (Endale et al., 2023; Hidayat et al., 2025).

One of the emerging innovations is geopolymer concrete, which uses silica- and alumina-rich materials as a substitute for Portland cement with the aid of alkaline activator solutions. Compared with conventional concrete, geopolymer concrete is capable of significantly reducing carbon emissions, has good chemical resistance, and demonstrates high mechanical performance, making it increasingly developed as a sustainable construction material (Ahmed et al., 2021; Pourdolat et al., 2024; Sharma et al., 2024). Fly ash is the most widely used material in geopolymer concrete. In addition to its high silica and alumina content, fly ash promotes a more stable geopolymerization process and is able to produce high compressive strength when combined with an appropriate activator composition (Ahmed et al., 2021; Olii et al., 2025). Verma et al. (2024) reported that fly ash-based geopolymer concrete can achieve a compressive strength of approximately 35 MPa at 28 days, while Batuwita et al. (2025) stated that the use of fly ash also provides sustainability benefits through industrial waste utilization.

In addition to fly ash, rice husk ash (RHA) is an agricultural waste material with a high amorphous silica content. The high silica content in rice husk ash serves as a source of reactive silica that improves the geopolymer gel structure, thereby increasing matrix density when used at an optimum dosage. As a result, it has considerable potential to enhance the geopolymerization process and has become one of the alternative materials widely investigated in environmentally friendly concrete (Arifin & Sanwani, 2023; Mahdi et al., 2025). Research by Bohua Ma et al. (2025) showed that the use of nano rice husk ash in geopolymer concrete can improve compressive strength, thermal resistance, and durability when applied at an optimum dosage. These findings indicate that the characteristics and proportion of RHA strongly influence geopolymer matrix formation and the mechanical performance of concrete. Insyira et al. (2023) and Yawan et al. (2025) showed that the addition of RHA up to 10% can increase the compressive strength of geopolymer concrete, whereas Albadrani (2025) reported that the optimum RHA content is in the range of 5–7.5%. Excessive use of RHA may reduce compressive strength due to disruption of the aluminosilicate balance in the geopolymer system (Wardhono et al., 2024).

The success of geopolymer concrete formation is also influenced by the type of alkaline activator used. Handayani et al. (2022) stated that the use of NaOH solution at a concentration of 10–12 M provides optimum results, while Oti et al. (2024) explained that the ratio of Na_2SiO_3 to NaOH affects geopolymer matrix formation and the development of compressive strength. Therefore, this study uses 12 M NaOH solution with a Na_2SiO_3/NaOH ratio of 2.0. In addition to NaOH molarity, the alkaline solution-to-binder ratio and the curing process are also critical factors determining the compressive strength development of geopolymer concrete because they influence the rate of geopolymerization and the formation of aluminosilicate gel (Ahmed et al., 2021).

Although geopolymer concrete has good compressive strength, it remains brittle and therefore prone to cracking. The addition of natural fibers is intended to increase ductility, inhibit crack propagation, and improve post-cracking behavior without altering the fundamental concept of geopolymer concrete as an environmentally friendly material (Anwar & Kusumastuti, 2016; Rohman & Damara, 2024). One approach to address this weakness is the incorporation of natural fibers, including banana stem fiber. Li et al. (2025) explained that natural fibers can improve crack resistance and post-cracking behavior in geopolymer concrete. Lamichhane et al. (2024) reported that the use of banana fiber at an optimum dosage can improve the mechanical properties of geopolymer concrete, while Pilien et al. (2022) showed that banana fiber acts as crack bridging, thereby inhibiting crack propagation. Excessively high fiber content may increase porosity and reduce concrete compressive strength (Al-Massri et al., 2024).

In this study, the target compressive strength was set at 30 MPa, equivalent to concrete quality of approximately K-300 to K-325. Based on SNI 2847:2019, this compressive strength falls under the category of structural concrete and has the potential to be applied in constructions requiring adequate load-bearing capacity, including rigid pavement. Compressive strength testing was conducted using a Compression Testing Machine (CTM) in accordance with SNI 1974:2011.

Based on previous studies, the use of fly ash, RHA, and banana stem fiber has been extensively investigated separately. However, studies combining 95% fly ash, 5% RHA, and low-dose banana stem fiber at 0.1% and 0.2% with 12 M NaOH activator and a Na_2SiO_3/NaOH ratio of 2.0 remain very limited. In addition, most previous studies used fiber contents above 0.25%, so information on the influence of lower fiber dosages on the compressive strength of geopolymer concrete has not been widely reported.

The selection of banana stem fiber variations of 0.1% and 0.2% was based on the consideration that low fiber addition is expected to provide a bridging effect within the geopolymer matrix without reducing mixture homogeneity. Excessively high fiber content may lead to fiber balling, reduce workability, and increase voids (porosity), which may negatively affect concrete compressive strength. Therefore, this study selected lower fiber dosages to evaluate whether a minimum amount of fiber can contribute to improving geopolymer concrete behavior, particularly in terms of compressive strength and crack control.

Most previous studies have generally examined the effects of fly ash, rice husk ash, or banana stem fiber separately, or used relatively high fiber dosages, whereas research combining low RHA content with banana stem fiber addition in geopolymer concrete remains very limited (Arifin & Sanwani, 2023; Olii et al., 2025).

The novelty of this study lies in the use of a combination of 95% fly ash, 5% rice husk ash, and the addition of 0.1% and 0.2% banana stem fiber with 12 M NaOH activator and a Na_2SiO_3/NaOH ratio of 2.0 to evaluate the achievement of a 30 MPa compressive strength target as a basis for developing more environmentally friendly geopolymer concrete with potential application in rigid pavement construction.

Based on the foregoing, this study aims to analyze the effect of adding 0.1% and 0.2% banana stem fiber on the compressive strength of geopolymer concrete based on 95% fly ash and 5% rice husk ash. The results are expected to provide information on the optimum mixture composition and serve as a reference for the development of geopolymer concrete as a sustainable construction material.

B. METHOD

1. Research Location

This study was conducted at the Concrete Technology Laboratory, Department of Civil Engineering, Universitas Serang Raya. All experimental procedures, including material preparation, geopolymer concrete mixing, specimen casting, curing, and compressive strength testing, were carried out under controlled laboratory conditions to ensure the consistency and reliability of the experimental results.

2. **Materials**

The primary materials used in this study were fly ash (FA) and rice husk ash (RHA) as the geopolymer binder. The binder consisted of 95% fly ash and 5% rice husk ash by total binder weight. Fly ash was selected as the primary precursor because of its high silica and alumina contents, which effectively promote the geopolymerization process. Rice husk ash was incorporated as a supplementary precursor to increase the reactive silica content within the geopolymer system.

Fine aggregate and coarse aggregate were used as filler materials in the geopolymer concrete mixture. The alkaline activator consisted of a 12 M sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3), with a Na_2SiO_3/NaOH mass ratio of 2.0. In addition, banana stem fiber was incorporated as a reinforcing material at dosages of 0%, 0.1%, and 0.2% by binder weight.

3. **Mix Design**

The geopolymer concrete mix was designed using fly ash (95%) as the primary binder and rice husk ash (5%) as the supplementary binder, based on the total binder weight. The alkaline activation system consisted of 12 M sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3), with a Na_2SiO_3/NaOH mass ratio of 2.0.

The experimental program evaluated three levels of banana stem fiber addition: 0%, 0.1%, and 0.2% by binder weight. These fiber contents were selected to investigate their influence on the compressive strength development of geopolymer concrete at curing ages of 7, 14, and 28 days.

Table 1. Geopolymer Concrete Mix Variations

Variation	Fly Ash (%)	Rice Husk Ash (%)	Banana Stem Fiber (%)
BG 0%	95	5	0
BG 0.1%	95	5	0.1
BG 0.2%	95	5	0.2

The detailed composition of the materials making up geopolymer concrete for each mixture variation is presented in Table 2.

Table 2. Mix Design per m³ Geopolymer Concrete

Material	BG-0 (0% Fiber) (kg)	BG-0.1 (0.1% Fiber) (kg)	BG-0.2 (0.2% Fiber) (kg)	BG-0.3 (0.3% Fiber) (kg)
Fly Ash (FA)	1.3274	1.3274	1.3274	1.3274
Rice Husk Ash (RHA)	0.0699	0.0699	0.0699	0.0699
Alkaline Activator (Total)	0.6288	0.6288	0.6288	0.6288
Coarse Aggregate	4.2518	4.2518	4.2518	4.2518

Fine Aggregate	1.8222	1.8222	1.8222	1.8222
Banana Stem Fiber	0.0000	0.0014	0.0028	0.0042
Superplasticizer	0.0279	0.0279	0.0279	0.0279
Total	**8.1000**	**8.1014**	**8.1028**	**8.1042**

After the mixture composition was determined, all materials were mixed until homogeneous and molded using a cube mold measuring 15 cm × 15 cm × 15 cm. Each variation was made as many as three test specimens at the testing age of 7 days, 14 days, and 28 days so that the total number of test specimens used in this study was 27 samples.

4. Method Analysis

The research method used was a laboratory experiment. The research phase began with a literature review and collection of references related to geopolymer concrete, fly ash, rice husk ash, and the use of banana stem fiber as a reinforcing material.

Next, material characteristics were tested, including fine aggregate, coarse aggregate, fly ash, rice husk ash, and banana stem fiber. Once the material characteristics were determined, a geopolymer concrete mix was designed with a composition of 95% fly ash, 5% rice husk ash, and varying amounts of banana stem fiber at 0%, 0.1%, and 0.2%.

Test specimens were prepared using 15 cm × 15 cm × 15 cm cube molds. After the molding process, the specimens were allowed to cure for 24 hours before being removed from the molds. The specimens were then wrapped in aluminum foil and oven cured for 24 hours to accelerate the geopolymerization process. The specimens were then stored at room temperature until they reached their test ages of 7, 14, and 28 days.

Compressive strength testing was conducted on all test specimens using a Compression Testing Machine (CTM). Three specimens were prepared for each mix variation at each testing age, resulting in a total of 27 specimens. The test results were then analyzed to determine the effect of banana stem fiber addition on the compressive strength of fly ash and rice husk ash-based geopolymer concrete. The research flowchart is presented in Figure 1.

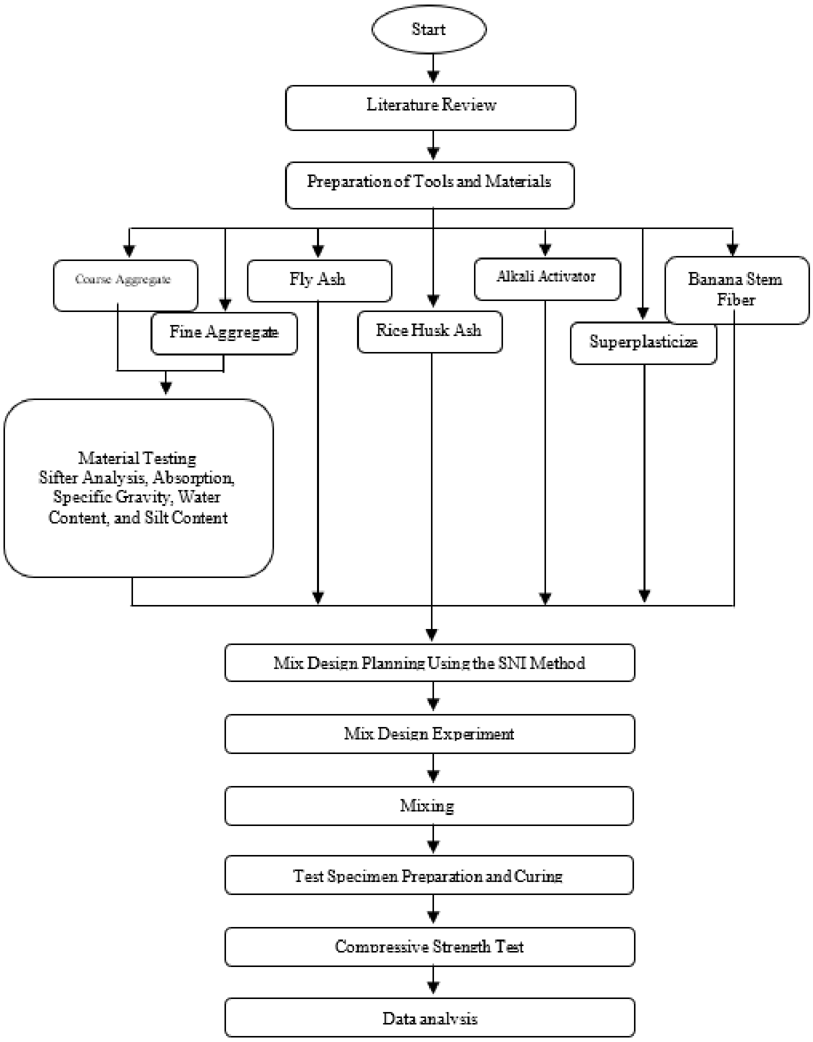

Figure 1. Research Method Flowchart

C. RESULT AND DISCUSSION

1. Material Characterization Results

Prior to the preparation of geopolymer concrete, all constituent materials were characterized to verify their suitability for use in the experimental program. The characterization included tests on fine aggregate, coarse aggregate, fly ash, rice husk ash (RHA), and banana stem fiber. The test results served as the basis for confirming that all materials satisfied the required technical specifications and were suitable for incorporation into the geopolymer concrete mixture.

2. Fine Aggregate Test Results

The physical properties of the fine aggregate were evaluated to determine its suitability for use in the geopolymer concrete mixture. The parameters examined included mud content, specific gravity, water absorption, and fineness modulus.

Table 3. Fine Aggregate Test Results

Test Parameter	Test Result	Reference Standard	Requirement	Remarks
Mud Content (%)	8.15%	SNI ASTM C117:2012	≤ 5%	Does Not Comply
Apparent Specific Gravity	2.47*	SNI 1970:2016	2.40–2.90	Complies*
Moisture Content (%)	5.48%	SNI 1970:2016	—	Used for Mix Design Correction

Based on the test results in Table 3, the fine aggregate had a silt content of 8.15%, an apparent specific gravity of 47.38%, and a water content of 5.48%. These results indicate that the silt content and apparent specific gravity did not meet the requirements of SNI ASTM C117:2012 and SNI 1970:2016, while the water content was used as a basis for corrections in the mix design process. A high silt content indicates the presence of fine particles adhering to the aggregate surface, potentially reducing the adhesion between the aggregate and the geopolymer paste. A low apparent specific gravity value indicates that the aggregate has poorer physical characteristics than normal aggregate.

Before being used in the preparation of test specimens, the fine aggregate used had a relatively high silt content, so it underwent a cleaning process. Cleaning was carried out by washing the aggregate with clean water until the water appeared clear. The aggregate was then dried at room temperature before being used in the mixing process. After cleaning, the silt content in the aggregate was reduced, making the aggregate cleaner and suitable for use as a component of geopolymer concrete. The fine aggregate mud content still does not fully meet the standard requirements so that this condition is one of the factors suspected of influencing the compressive strength results of geopolymer concrete.

3. **Coarse Aggregate Test Results**

Coarse aggregate testing is carried out to determine the physical characteristics of the aggregate used in the geopolymer concrete mixture.

Table 4. Coarse Aggregate Test Results

Test Parameter	Test Result	Reference Standard	Requirement	Remarks
Mud Content (%)	2.15%	SNI ASTM C117:2012	≤ 1%	Does Not Comply
Moisture Content (%)	7.06%	SNI 1969:2016	—	Used for Mixing Water Correction
Los Angeles Abrasion (%)	35.82%	SNI 2417:2008	≤ 40%	Complies

Based on the test results in Table 4, the coarse aggregate has a specific gravity of SSD of ..., a mud content of 2.15%, a water content of 7.06%, and a Los Angeles wear value of 35.82%. This wear value has met the maximum requirement of 40% based on SNI 2417:2008, so the aggregate has good abrasion resistance and is suitable for use as a constituent material of geopolymer concrete. Meanwhile, a mud content value that exceeds the required limit indicates that the aggregate needs to be cleaned before use, while the water content is used as a basis for correction in mix design.

4. Compressive Strength Test Results

Compressive strength testing was conducted using a Compression Testing Machine (CTM) on 15 cm × 15 cm × 15 cm cube specimens. Testing was carried out at 7 days, 14 days, and 28 days to determine the development of the geopolymer concrete compressive strength due to the addition of banana stem fiber.

The compressive strength value is calculated using Equation (1).

$$f'c = \frac{P}{A} \quad (1)$$

With:

f'c = Concrete Compressive Strength (MPa)

P = maximum load when the test object experiences failure (N)

A = area of compression of the test object (mm^2)

The compressive strength values obtained from each variation were calculated as the average of the three test specimens. The test results were then analyzed to determine the effect of the addition of banana stem fiber on the compressive strength of fly ash and rice husk ash-based geopolymer concrete.

Compressive strength tests were conducted at 7, 14, and 28 days to determine the strength development of the geopolymer concrete due to the addition of banana stem fiber. Testing was conducted on three mixture variations: BG-0 (no fiber), BG-0.1 (0.1% fiber), and BG-0.2 (0.2% fiber). Each variation consisted of three test specimens at each testing age.

Table 5. Geopolymer Concrete Compressive Strength Results at 7 Days

Mix Variation	Specimen I (MPa)	Specimen II (MPa)	Specimen III (MPa)	Maximum Compressive Strength (MPa)
BG-0 (0% Fiber)	17.9	24.8	29.2	**29.2**
BG-0.1 (0.1% Fiber)	10.3	10.4	17.2	**17.2**
BG-0.2 (0.2% Fiber)	12.6	13.9	19.4	**19.4**

Based on the results of the compressive strength test of geopolymer concrete at the age of 7 days presented in Table 5, the highest compressive strength values were obtained for the BG 0% variation of 29.2 MPa, the BG 0.1% variation of 17.2 MPa, and the BG 0.2% variation of 19.4 MPa. The test results showed that the variation without the addition of banana stem fiber (BG 0%) produced the highest compressive strength compared to the variation with the addition of fiber. Meanwhile, the addition of banana stem fiber of 0.2% produced a higher compressive strength than the 0.1% variation, but was still below the compressive strength of geopolymer concrete without fiber. Thus, at the age of 7 days the addition of banana stem fiber did not show an increase in compressive strength compared to the control variation.

Table 6. Geopolymer Concrete Compressive Strength Results at 14 Days

Mix Variation	Specimen I (MPa)	Specimen II (MPa)	Specimen III (MPa)	Maximum Compressive Strength (MPa)
BG-0 (0% Fiber)	13.4	19.0	27.4	**27.4**
BG-0.1 (0.1% Fiber)	18.5	20.6	24.0	**24.0**
BG-0.2 (0.2% Fiber)	9.3	11.6	23.6	**23.6**

Based on the results of the compressive strength test of geopolymer concrete at 14 days old presented in Table 6, the highest compressive strength values were obtained for the 0% BG variation of 27.4 MPa, the 0.1% BG variation of 24.0 MPa, and the 0.2% BG variation of 23.6 MPa. The test results show that the variation without the addition of banana stem fiber (0% BG) still produces the highest compressive strength. However, the difference in compressive strength between the 0.1% BG and 0.2% BG variations compared to the control variation is relatively smaller compared to the test results at 7 days old. This indicates that as the concrete ages, the compressive strength of each variation develops, although it has not yet exceeded the compressive strength of the variation without fiber.

Table 7. Geopolymer Concrete Compressive Strength Results at 28 Days

Mix Variation	Specimen I (MPa)	Specimen II (MPa)	Specimen III (MPa)	Maximum Compressive Strength (MPa)
BG-0 (0% Fiber)	26.8	32.0	33.9	**33.9**
BG-0.1 (0.1% Fiber)	25.5	11.0	24.8	**25.5**
BG-0.2 (0.2% Fiber)	26.2	28.5	18.2	**28.5**

Based on the compressive strength test results of geopolymer concrete at 28 days, presented in Table 7, the highest compressive strength values were obtained for the 0% BG variation, at 33.9 MPa, the 0.1% BG variation at 25.5 MPa, and the 0.2% BG variation at 28.5 MPa. The test results indicate that the variation without the addition of banana stem fiber (BG 0%) produced the highest compressive strength compared to all variations studied and exceeded the research compressive strength target of 30 MPa. Meanwhile, the variation with the addition of 0.2% banana stem fiber produced a higher compressive strength than the 0.1% variation, but both variations were still below the specified compressive strength target. In general, the test results at 28 days indicate that the addition of banana stem fiber at 0.1% and 0.2% concentrations was not able to increase the compressive strength of geopolymer concrete compared to the mixture without fiber.

To facilitate analysis of compressive strength development over the entire test period, the average compressive strength results are presented in Table 6.

Table 8. Recapitulation of the Development of the Highest Compressive Strength of Geopolymer Concrete

Mix Variation	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
BG-0 (0% Fiber)	29.2	27.4	33.9
BG-0.1 (0.1% Fiber)	17.2	24.0	25.5
BG-0.2 (0.2% Fiber)	19.4	23.6	28.5

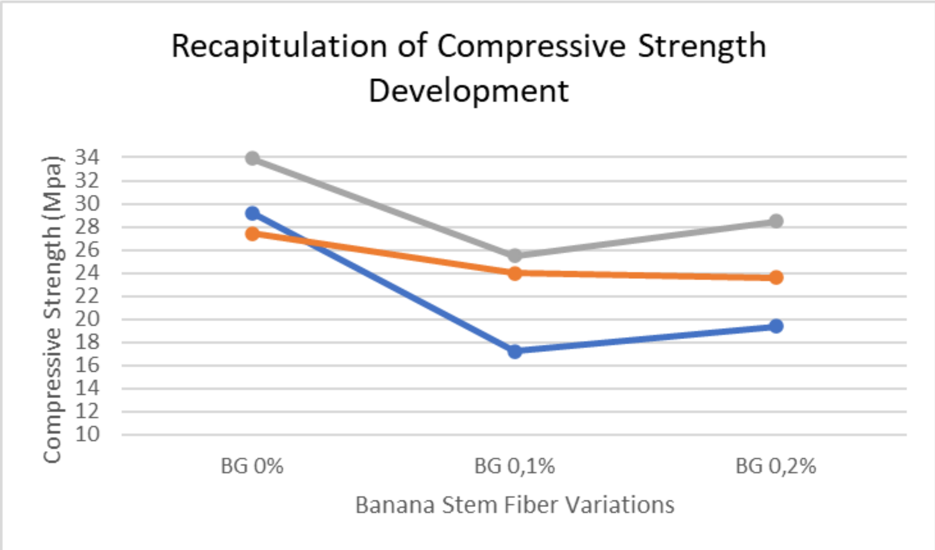

Figure 2. Summary Graph of Geopolymer Concrete Compressive Strength Development

Based on the recapitulation of compressive strength test results presented in Table 8 and Figure 5, the development of compressive strength of geopolymer concrete shows different trends in each mixture variation. The variation without the addition of banana stem fiber (BG 0%) produces the highest compressive strength at each test age, which is 29.2 MPa at 7 days, 27.4 MPa at 14 days, and increases to 33.9 MPa at 28 days. The BG 0.1% variation produces compressive strengths of 17.2 MPa, 24.0 MPa, and 25.5 MPa, while the BG 0.2% variation produces compressive strengths of 19.4 MPa, 23.6 MPa, and 28.5 MPa at 7, 14, and 28 days, respectively. In general, the compressive strength of all variations increases up to 28 days, although fluctuations occur at 14 days. Based on these results, the variation without fiber addition (BG 0%) showed the best compressive strength development and was the only variation that successfully exceeded the research compressive strength target of 30 MPa at 28 days. The addition of banana stem fiber at 0.1% and 0.2% was unable to produce a higher compressive strength than the control mixture, although the 0.2% BG variation showed better compressive strength development than the 0.1% BG variation at 28 days.

These results align with research by Ahmad Rohman and Damara (2024), who reported that increasing the banana stem fiber content does not always improve the mechanical properties of concrete because fiber can increase voids in the mixture if the fiber dispersion is uneven. Similar findings were also reported by Olii et al. (2025), who found that increasing the proportion of certain additives can cause a decrease in compressive strength due to disruption of the geopolymer matrix density.

5. **Effect of Adding Banana Leaf Fiber on the Compressive Strength of Geopolymer Concrete**

Based on the results of compressive strength tests at 7, 14, and 28 days, the addition of 0.1% and 0.2% banana stem fiber was not able to produce a higher compressive strength compared to geopolymer concrete without fiber (BG 0%). A comparison of the compressive strength values of each variation with the control variation (BG 0%) is presented in Table 9.

Table 9. Percentage Change in Compressive Strength of Geopolymer Concrete against Control Variation (BG 0%)

Comparison	7 Days (%)	14 Days (%)	28 Days (%)
BG-0.1 vs. BG-0	−41.10	−12.41	−24.78
BG-0.2 vs. BG-0	−33.56	−13.87	−15.93

Note: *Negative values indicate a reduction in maximum compressive strength relative to the control mixture (BG-0) at the corresponding curing age.*

Based on Table 9, the BG-0.1 mixture exhibited reductions in maximum compressive strength of 41.10%, 12.41%, and 24.78% at curing ages of 7, 14, and 28 days, respectively, relative to the control mixture. Similarly, the BG-0.2 mixture showed reductions of 33.56%, 13.87%, and 15.93% at 7, 14, and 28 days, respectively. These results indicate that the incorporation of banana stem fiber, at the dosages investigated, was unable to enhance the compressive strength of geopolymer concrete to the level achieved by the fiber-free control mixture.

The reduction in compressive strength observed in the fiber-reinforced mixtures is likely attributable to several factors associated with the production process of geopolymer concrete. As a natural fiber, banana stem fiber possesses a relatively high water absorption capacity and may absorb part of the alkaline activator solution, thereby reducing the availability of the activator required for effective geopolymerization, particularly when the fibers are not uniformly dispersed within the matrix. In addition, the presence of fibers may increase the formation of internal voids and overall porosity, resulting in weaker bonding between the geopolymer matrix and aggregates. These conditions are considered the primary factors contributing to the lower compressive strength of the fiber-reinforced mixtures compared with the control.

Another factor that may have affected the experimental results was the condition of the fine aggregate. The measured mud content reached **8.15%**, exceeding the maximum allowable limit specified by the applicable standard. Furthermore, the aggregates were not in a Saturated Surface Dry (SSD) condition prior to mixing. Both factors may have impaired the interfacial bonding between the geopolymer paste and the aggregates. During mixing, the geopolymer concrete also exhibited very low workability, making conventional slump testing impractical. The reduced workability likely hindered adequate compaction, leading to increased internal voids and consequently lower compressive strength.

The curing method adopted in this study may also have influenced the strength development of the geopolymer concrete. After remaining in the molds for 24 h, the specimens were demolded, wrapped with aluminum foil to minimize moisture loss, and subjected to oven curing for an additional 24 h before being stored at room temperature until the designated testing ages. Oven curing was intended to accelerate the geopolymerization reaction by promoting faster formation of aluminosilicate gels. This curing regime contributed to the development of early-age compressive strength, particularly at 7 days, compared with specimens cured solely under ambient conditions.

The condition of the fine aggregate may have further contributed to the observed strength reduction. Because the aggregates were not in an SSD condition, they likely absorbed part of the NaOH and Na_2SiO_3 activator solutions during mixing. This absorption reduced the amount of activator available to react with the aluminosilicate precursors and accelerated the setting process, thereby limiting the available time for proper mixing and compaction. Consequently, the geopolymerization reaction may not have proceeded optimally, resulting in lower compressive strength.

Slump testing was not performed because the fresh geopolymer concrete exhibited behavior that differed substantially from conventional Portland cement concrete. When the mixture had a relatively stiff consistency, no measurable slump occurred, making the standard slump test inapplicable. Conversely, when additional liquid was introduced to improve flowability, the deformation pattern no longer satisfied the acceptance criteria of the conventional slump test. Therefore, the slump test was not considered an appropriate method for evaluating the workability of the geopolymer concrete mixtures investigated in this study.

Although the addition of banana stem fiber did not improve compressive strength, the experimental observations suggest that its primary contribution was to enhance crack resistance rather than load-bearing capacity. This finding is consistent with the study of Muhammad Latif et al. (2024), who reported that banana stem fiber improved the flexural behavior of concrete, although its effectiveness depended strongly on the fiber dosage. The control specimens without fiber exhibited wider cracks and more brittle failure after compressive loading, whereas the fiber-reinforced specimens showed fewer visible surface cracks and a more gradual failure process. These observations indicate that banana stem fiber acted as a crack-bridging reinforcement, restricting crack propagation under compressive loading. Similar conclusions were reported by Pilien et al. (2022), Lamichhane et al. (2024), and Li et al. (2025), who demonstrated that natural fibers contribute more significantly to improving crack resistance and ductility than to increasing the compressive strength of geopolymer concrete.

The results demonstrate that the incorporation of **0.1%** and **0.2%** banana stem fiber did not increase the compressive strength of fly ash–rice husk ash-based geopolymer concrete. Nevertheless, the fibers improved the post-failure behavior by reducing surface cracking after compressive loading, indicating their potential to enhance the mechanical performance of geopolymer concrete from the perspective of crack resistance and structural integrity rather than compressive strength alone.

6. Evaluation of the Feasibility of Geopolymer Concrete against the Target Compressive Strength of 30 MPa (K-300) and Potential Application in Rigid Pavements

One of the objectives of this research is to evaluate the ability of fly ash (FA) and rice husk ash (RHA)-based geopolymer concrete to achieve the target compressive strength of 30 MPa. This compressive strength value is equivalent to concrete quality around K-300 to K-325 and is included in the structural concrete category which is commonly used in various construction works, including rigid pavement construction. Evaluation was carried out based on the results of the highest compressive strength at 28 days of each mixture variation.

Table 10. Evaluation of the achievement of the 30 MPa compressive strength target

Mix Variation	28-Day Compressive Strength (MPa)	Target Strength (MPa)	Achievement (%)	Remarks
BG-0 (0% Fiber)	33.9	30	113.00	Achieved
BG-0.1 (0.1% Fiber)	25.5	30	85.00	Not Achieved
BG-0.2 (0.2% Fiber)	28.5	30	95.00	Not Achieved

Based on Table 10, the BG-0 mixture achieved the highest 28-day compressive strength of 33.9 MPa, corresponding to 113.00% of the target compressive strength established for this study. This result demonstrates that geopolymer concrete incorporating 95% fly ash and 5% rice husk ash (RHA) without banana stem fiber successfully satisfied the target compressive strength of 30 MPa. In contrast, the BG-0.1 and BG-0.2 mixtures achieved compressive strengths of 25.5 MPa and 28.5 MPa, corresponding to 85.00% and 95.00% of the target strength, respectively. Consequently, neither fiber-reinforced mixture met the specified compressive strength requirement.

The experimental results indicate that the incorporation of banana stem fiber at dosages of **0.1%** and **0.2%** did not improve the compressive strength of geopolymer concrete beyond that of the control mixture. Nevertheless, the BG-0.2 mixture exhibited higher compressive strength than BG-0.1 and produced results closer to the target value. These findings suggest that banana stem fiber still has potential for application in geopolymer concrete, provided that further optimization is undertaken through alternative fiber dosages, fiber surface treatments, or improved dispersion techniques to enhance the interaction between the fibers and the geopolymer matrix.

From the perspective of pavement engineering, the BG-0 mixture, which achieved a compressive strength of 33.9 MPa, demonstrates potential for application as an alternative material for rigid pavement construction, as it exceeded the target compressive strength established in this study. In addition to its satisfactory mechanical performance, the developed geopolymer concrete incorporates industrial waste in the form of fly ash and agricultural waste in the form of rice husk ash and banana stem fiber, thereby providing additional environmental benefits through waste valorization and reduced reliance on Portland cement.

The findings demonstrate that fly ash–rice husk ash-based geopolymer concrete has considerable potential as a sustainable construction material. Among the mixtures investigated, the fiber-free mixture (BG-0) exhibited the optimum performance by successfully achieving the target compressive strength of 30 MPa. In contrast, the incorporation of banana stem fiber contributed more significantly to crack control and post-failure behavior than to improvements in compressive strength, indicating that its principal benefit lies in enhancing the toughness and crack resistance of geopolymer concrete rather than increasing its load-bearing capacity.

The results of this study demonstrate that geopolymer concrete incorporating 95% fly ash and 5% rice husk ash (RHA) without banana stem fiber achieved the highest 28-day compressive strength of 33.9 MPa, making it the only mixture that exceeded the target compressive strength of 30 MPa established in this study. In contrast, the incorporation of banana stem fiber at dosages of 0.1% and 0.2% did not improve the compressive strength compared with the control mixture. Nevertheless, the mixture containing 0.2% fiber exhibited higher compressive strength than the 0.1% mixture, indicating that increasing the fiber dosage within an appropriate range may still provide benefits to the mechanical performance of geopolymer concrete.

The reduction in compressive strength observed in the fiber-reinforced mixtures is likely attributable to several factors, including non-uniform fiber dispersion within the geopolymer matrix, the use of fine aggregates that had not reached the Saturated Surface Dry (SSD) condition, and the absorption of part of the alkaline activator solution by the aggregates during mixing. These factors reduced the effectiveness of the geopolymerization reaction and hindered the formation of a dense and well-developed geopolymer matrix. In addition, the relatively stiff consistency of the fresh geopolymer concrete prevented conventional slump testing from being performed effectively, limiting the evaluation of mixture workability.

Conversely, the application of oven curing for 24 h after demolding had a positive effect on the early-age strength development of the geopolymer concrete. This curing regime accelerated the geopolymerization process by promoting faster formation of aluminosilicate gels compared with ambient curing. These findings confirm that curing conditions are among the key factors governing the mechanical performance of geopolymer concrete.

Although banana stem fiber did not increase compressive strength, visual observations during testing indicated that the fiber effectively reduced the extent of surface cracking after compressive loading. This finding suggests that the primary function of banana stem fiber in the present study was to act as a crack-bridging reinforcement rather than as a compressive strength enhancer. Similar observations have been reported by Pilien et al. (2022), Lamichhane et al. (2024), and Li et al. (2025), who concluded that natural fibers contribute more significantly to improving ductility and crack resistance than to increasing the compressive strength of geopolymer concrete. Likewise, Anwar and Kusumastuti (2016) reported that natural fibers improve the tensile behavior and crack resistance of geopolymer composites, while Wong (2022) emphasized that fiber reinforcement primarily enhances durability and crack resistance rather than compressive strength.

This study confirms that fly ash–rice husk ash-based geopolymer concrete has considerable potential as a sustainable and environmentally friendly construction material. Among the mixtures investigated, the fiber-free mixture (BG-0) exhibited the optimum performance, achieving a 28-day compressive strength of 33.9 MPa, thereby exceeding the target strength of 30 MPa. This performance indicates its suitability for structural applications requiring moderate-strength concrete, including rigid pavements, local access roads, parking areas, concrete sidewalks, and lightweight structural concrete elements with strength comparable to K-300 concrete.

The fiber-reinforced mixtures containing 0.1% and 0.2% banana stem fiber achieved compressive strengths of 25.5 MPa and 28.5 MPa, respectively, and therefore did not satisfy the target strength established for rigid pavement applications. However, their improved crack resistance suggests potential applicability in concrete elements where resistance to crack propagation and post-cracking performance are of greater importance than maximum compressive strength. Future studies should therefore investigate fiber surface treatment, alternative fiber dosages, improved fiber dispersion techniques, and further optimization of the geopolymer mix design to maximize the contribution of banana stem fiber to the mechanical performance and durability of geopolymer concrete. In addition, future developments should explore the use of fly ash–rice husk ash-based geopolymer concrete in structural repair applications and aggressive service environments, where its sustainability, mechanical performance, and durability offer promising advantages (Astuti et al., 2024).

D. CONCLUSION

The addition of 0.1% and 0.2% banana stem fiber to geopolymer concrete based on 95% fly ash and 5% rice husk ash was not able to increase the compressive strength compared to mixtures without fiber. The use of fiber did reduce cracks on the surface of the test specimen after loading, potentially improving the post-cracking behavior of geopolymer concrete. Based on the research results, the geopolymer concrete mixture without fiber addition was the most optimal composition to achieve the research target compressive strength of 30 MPa. These results indicate that fly ash and rice husk ash-based geopolymer concrete have the potential to be developed as a more environmentally friendly construction material. The use of banana stem fiber still requires optimization of content and treatment to improve compressive strength.

REFERENCES

1. Ahmed, H. U., Mohammed, A. A., Rafiq, S., Mohammed, A. S., Mosavi, A., Sor, N. H., & Qaidi, S. M. A. (2021). Compressive strength of sustainable geopolymer concrete composites: A state-of-the-art review. *Sustainability (Switzerland)*, *13*(24). https://doi.org/10.3390/su132413502
2. Al-Massri, G., Ghanem, H., Khatib, J., El-Zahab, S., & Elkordi, A. (2024). The Effect of Adding Banana Fibers on the Physical and Mechanical Properties of Mortar for Paving Block Applications. *Ceramics*, *7*(4), 1533–1553. https://doi.org/10.3390/ceramics7040099
3. Albadrani, M. A. (2025). Strength Development of PPC Concrete with Rice Husk Ash: Optimal Replacement Levels for Sustainable Construction. *Sustainability (Switzerland)*, *17*(18). https://doi.org/10.3390/su17188258
4. Anwar, S., & Kusumastuti, E. (2016). Jurusan Kimia FMIPA Universitas Negeri Semarang Gedung D6 Kampus Sekaran Gunungpati Telp. (024)8508112 Semarang 50229 Sejarah Artikel: Diterima Pebruari. *J. Chem. Sci*, *5*(1). http://journal.unnes.ac.id/sju/index.php/ijcs
5. Arifin, D. N., & Sanwani, E. (2023). Potential utilization of natural zeolite, fly ash and rice husk ash for geopolymer concrete production. *Mining of Mineral Deposits*, *17*(3), 86–92. https://doi.org/10.33271/mining17.03.086
6. Astuti, P., Isnaini, M. S., Ammar, S. D., & Purnama, A. Y. (2024). Strength characteristic and life cycle cost of sustainable bio-patch repair geopolymer mortar using rice husk ash as an alternative silica and alumina source. *BIO Web of Conferences*, *144*. https://doi.org/10.1051/bioconf/202414406003
7. Batuwita, I., Sampath, K. H. S. M., & Ranathunga, A. S. (2025). Exploring the Suitability of Fly Ash and Rice Husk Ash in One-Part Geopolymer: A Case Study for Sustainable, Low-Carbon Construction. *Moratuwa Engineering Research Conference, MERCon*, 521–526. https://doi.org/10.1109/MERCon67903.2025.11217075
8. *Bohua Ma_Next generation ultra high performance geopolymer concrete Optimizing calcium aluminate cement clinker and nano rice husk ash for mechanical strength, durability and thermal resistance.pdf*. (n.d.).
9. Endale, S. A., Taffese, W. Z., Vo, D. H., & Yehualaw, M. D. (2023). Rice Husk Ash in Concrete. In *Sustainability (Switzerland)* (Vol. 15, Number 1). MDPI. https://doi.org/10.3390/su15010137
10. Handayani, L., Aprilia, S., Abdullah, Rahmawati, C., Aulia, T. B., Ludvig, P., & Ahmad, J. (2022). Sodium Silicate from Rice Husk Ash and Their Effects as Geopolymer Cement. *Polymers*, *14*(14). https://doi.org/10.3390/polym14142920
11. Hidayat, R. T., Prabowo, Y. S., & Mahendra, M. O. (2025). *Optimasi Campuran Beton dengan Subtitusi Limbah Abu Sekam Padi dan Pecahan Genteng terhadap Kuat Tekan Beton*. 162–170. https://doi.org/10.33364/konstruksi/v.23-2.2685
12. Insyira, A. H., Wijayanti, Y., Setyandito, O., Putra, D. P., Adi Soekotjo, N., Sasongko, E., & Anda, M. (2023). Study of using Coal Fly Ash (CFA) and Rice Husk Ash (RHA) on the Compressive Strength of Geopolymer Concrete. *E3S Web of*

Conferences, *426*. https://doi.org/10.1051/e3sconf/202342601011
13. Lamichhane, N., Lamichhane, A., & Gyawali, T. R. (2024). Enhancing mechanical properties of mortar with short and thin banana fibers: A sustainable alternative to synthetic fibers. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e30652
14. Li, Z., Li, J., Lu, W., & Zhang, Y. (2025). Research Progress and Application Prospects of Plant Fibers in Geopolymer Concrete: A Review. In *Materials* (Vol. 18, Number 10). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/ma18102342
15. Mahdi, S. N., Babu R, D. V., Ohno, M., Thomas, B. S., Nagaratnam, B., & Nawaukkaratharnant, N. (2025). Investigating the Durability Characteristics of Brick Fired Rice Husk Ash as Sustainable Material for Fly Ash Based Geopolymer Concrete. *Engineered Science*, *36*, 1–13. https://doi.org/10.30919/es1633
16. Olii, M. R., Mangewa, N., Abdul Djau, R., Nento, S., & Zailani Olii, A. K. (2025). Optimalisasi Kuat Tekan Beton Geopolimer Menggunakan Fly Ash Dan Abu Sekam Padi. *Jurnal Teknik Sipil Cendekia (Jtsc)*, *6*(2), 1454–1468. https://doi.org/10.51988/jtsc.v6i2.286
17. Oti, J., Adeleke, B. O., Mudiyanselage, P. R., & Kinuthia, J. (2024). A Comprehensive Performance Evaluation of GGBS-Based Geopolymer Concrete Activated by a Rice Husk Ash-Synthesised Sodium Silicate Solution and Sodium Hydroxide. *Recycling*, *9*(2). https://doi.org/10.3390/recycling9020023
18. Pilien, V. P., Garciano, L. E. O., Promentilla, M. A. B., Guades, E. J., Leaño, J. L., Oreta, A. W. C., & Ongpeng, J. M. C. (2022). Optimization of Banana Fiber Reinforced Fly Ash Based Geopolymer Mortar. *Chemical Engineering Transactions* , *94*, 427–432. https://doi.org/10.3303/CET2294071
19. Pourdolat, N., Gupta, R., & Mandor, A. (2024). *Development of fly-ash-based geopolymer concrete for sustainable infrastructure Development of Fly Ash-based Geopolymer Concrete for Sustainable Infrastructure*. (December), 1–14. https://www.researchgate.net/publication/387180752
20. Rohman, A., & Damara, B. (2024). Pengaruh Penambahan Variasi Limbah Serat Pelepah Pisang terhadap Kuat Lentur Beton. *Jurnal Talenta Sipil*, *7*(1), 102. https://doi.org/10.33087/talentasipil.v7i1.377
21. Sharma, U., Gupta, N., Bahrami, A., Özkılıç, Y. O., Verma, M., Berwal, P., Althaqafi, E., Khan, M. A., & Islam, S. (2024). Behavior of Fibers in Geopolymer Concrete: A Comprehensive Review. In *Buildings* (Vol. 14, Number 1). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/buildings14010136
22. Verma, P., Goldar, D., Daniyal, M., & Singh, S. K. (2024). Effect of Rice Husk Ash on the Properties and Performance of Geopolymer Concrete. *SSRG International Journal of Civil Engineering*, *11*(11), 11–22. https://doi.org/10.14445/23488352/IJCE-V11I11P102
23. Wardhono, A., Risdianto, Y., Sabariman, B., & Hidajati, N. W. (2024). *Investigation of Rice Husk Ash Substitution as An Alternative Material on Fly Ash-based Geopolymer Mortar* (pp. 263–269). https://doi.org/10.2991/978-94-6463-626-0_26

24. Wong, L. S. (2022). Durability Performance of Geopolymer Concrete: A Review. *Polymers*, *14*(5). https://doi.org/10.3390/polym14050868
25. Yawan, G., Prabowo, Y. S., & Mahendra, M. O. (2025). Analisis Kuat Tekan Beton Dengan Variasi Pecahan Genteng Sebagai Agregat Kasar dan Abu Sekam Padi Sebagai Agregat Halus. *Jurnal Konstruksi*, *23*(2), 183-189. https://doi.org/10.33364/konstruksi/v.23-2.2918