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# Mechanical properties of High-Strenght concrete with bauxite sand as partial fine aggregate replacement

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**Abstract**
*Concrete is a key material in Indonesia's infrastructure development, with growing interest in sustainable alternatives to natural aggregates. This study evaluates the mechanical performance of high-strength concrete incorporating bauxite sand as a partial replacement for fine aggregate. The control mix (BMT-0) was designed with a water–cement ratio of 0.3 and a cement content of 550 kg/m³, using natural sand and crushed coarse aggregate, without any chemical admixtures. Four additional mixes (BMT-1 to BMT-4) included bauxite sand at replacement levels of 2.5%, 5%, 7.5%, and 10% by weight of fine aggregate. A total of 30 specimens were tested to assess compressive strength, splitting tensile strength, and modulus of elasticity. All mixes exceeded the minimum compressive strength requirement for high-strength concrete (41.4 MPa). The mix with 5% bauxite sand replacement (BMT-2) demonstrated the highest compressive strength (49.33 MPa) and tensile strength (3.46 MPa), while the 7.5% mix (BMT-3) achieved the highest modulus of elasticity (38,877.32 MPa). The results suggest that partial replacement of fine aggregate with 5% bauxite sand enhances concrete quality without compromising mechanical performance.*



## Introduction

Concrete is a fundamental material in global infrastructure development, prized for its durability, versatility, and cost-effectiveness (Mehta & Monteiro, 2014). In Indonesia, rapid urbanization and economic growth have increased the demand for concrete, particularly in regions such as the Riau Islands, where infrastructure expansion is a top priority (BPS-Statistics Indonesia, 2022). However, the increasing consumption of natural river sand as fine aggregate poses environmental concerns, including riverbed degradation and biodiversity loss (Kondolf, 1997). Consequently, there is a pressing need to identify sustainable and locally available alternatives to natural sand in the production of concrete (Mahima et al., 2021).

Bauxite sand, a by-product of bauxite ore processing, emerges as a promising substitute for fine aggregate. Indonesia is among the world's top bauxite producers, with significant reserves located in the Riau Islands, particularly in Lingga Regency, which holds approximately 168.96 million tons of bauxite resources (Ministry of Energy and Mineral Resources [ESDM], 2020). The extraction and processing of bauxite generate substantial quantities of bauxite sand, often considered waste, leading to environmental challenges related to its disposal (Rao et al., 2007). Utilizing bauxite sand in concrete not only addresses waste management issues but also reduces the reliance on natural sand, aligning with sustainable construction practices (Zhang et al., 2020).

Previous studies have explored the incorporation of bauxite residues in concrete. For instance, Danso and Boadi (2019) investigated the replacement of natural sand with bauxite mining waste in concrete production, reporting enhancements in compressive, tensile, and flexural strengths with increased bauxite content. Similarly, Valdi et al. (2021) investigated the use of bauxite tailings as a suitable aggregate substitute, observing improvements in mechanical properties at specific replacement levels. However, these studies primarily focused on normal-strength concrete and did not extensively address high-strength concrete applications (Kumar & Arvind, 2022).

High-strength concrete (HSC) presents unique challenges when incorporating alternative fine aggregates. Issues such as workability, durability, and compatibility with other mixed components become more pronounced in High-Strength Concrete (HSC) (Neville, 2011). Alternative aggregates, such as recycled brick fine aggregate, have been shown to reduce workability and potentially impact mechanical properties due to their higher water absorption and angular shapes (Ismail & Ramli, 2014). Therefore, it is crucial to evaluate the performance of bauxite sand in HSC to determine its viability as a sustainable alternative.

This study aims to investigate the mechanical properties of high-strength concrete incorporating bauxite sand as a partial replacement for fine aggregate. By evaluating replacement levels of 0%, 2.5%, 5%, 7.5%, and 10%, the research aims to determine the optimal proportion that strikes a balance between performance and sustainability. The findings will contribute to the body of knowledge on sustainable construction materials and provide practical solutions for regions with abundant bauxite resources, such as the Riau Islands.

## Constituent Materials

### *Fine aggregate*

This study utilized sand from Progo that had passed through a 4.75 mm sieve and gravel from Clereng, with a maximum size of 10 mm. Aggregates significantly influence the properties of mortar and concrete; therefore, selecting the appropriate aggregate is a crucial part of the concrete manufacturing process. Aggregates must comply with the requirements of SNI 03-1750-1990 on the Quality and Test Method of Concrete Aggregates.

### *Portland cement*

The cement used in this study for the manufacture of concrete is Portland Composite Cement (PCC) brand Tiga Roda Cement. Cement quality must be maintained by storing it in a shady and dry place. In addition, cement also plays a role in filling the voids between aggregates, thereby forming a dense or compact mass, although its volume accounts for only about 10% of the total volume of concrete (Tjokrodimuljo, 2007). Cement also functions as a paste when mixed with water, allowing concrete mixing to be divided into two groups: active and passive.

Cement contains active chemical compounds, including lime, silica, iron oxide, and alumina. These compounds react with water to form a paste that hardens over time. Table 1 presents the Oxide content of Portland cement**.**

Table 1. Oxide content of Portland cement (PC)

| **Oxide** | **Content (%)** |
|---|---|
| Lime (CaO) | 60-65 |
| Silica (SiO2) | 20-25 |
| Iron Oxide (Fe2O3) | 7-12 |
| Alumina | 7-12 |

Source: Mulyono (2004)

### *Bauxite sand*

Bauxite is residual soil from clay deposits in tropical and subtropical regions, such as Indonesia. Figure 1 depicts a picture of bauxite sand. Bauxite sands vary in color depending on the constituent minerals, but are often red or brown. These sands can range from fine to coarse-grained depending on the weathering and deposition processes in a particular location. Bauxite and its waste are converted into pozzolanic materials through the calcination process, which is commonly used as additives to enhance the technical properties of cement concrete (Zulkhairi & Hardiyatmo, 2012).

Figure 1. Bauxite sand

Bauxite sand results from the weathering process of granitic rocks, which are the bedrock of Bintan Island and the surrounding islands. Bauxite is a mixture of minerals, mainly aluminum hydroxide ($Al(OH)_3$), gibbsite, and boehmite, along with other minerals such as hematite, goethite, and quartz. When bauxite sands are formed, bauxite ore can be the main component, and the mineral content varies depending on local geological conditions. According to Zulkhairi and Hardiyatmo (2012), bauxite sand comprises fragmental grains with diameters greater than 2 mm, forming angular fragments.

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Bauxite sand found on Bintan Island and surrounding islands is derived from hornfels rock, which looks orange brown with a yellow tinge. Bauxite is easily broken and insoluble in water. Bauxite sands are chemically stable due to their dominant mineral composition, which is primarily aluminum oxide. Table 2 presents the composition of bauxite mining.

Table 2. Chemical composition of bauxite sand

| Composition | Unit | Mass (%) |
|---|---|---|
| Total silica (SiO2) | % | 18.77 |
| Aluminum (Al2O3) | mg/kg | 275502 |
| Iron (Fe2O3) | mg/kg | 69619 |
| Calcium (CaO) | mg/kg | 42043 |
| Magnesium (MgO) | mg/kg | 2893 |
| Potassium (K2O) | mg/kg | 229 |
| Sodium (Na2O) | mg/kg | 262 |
| Content | % | 2.68 |
| Loam Content | % | 0.76 |

Source: BBTKLPP Laboratory (2018)

### *Superplasticizer*

The superplasticizer product used in this research is Sika Viscocrete 1003, manufactured by PT Sika Indonesia. This type of superplasticizer is ideal for concrete mixes that require a longer transportation time, as it maintains the smoothness and flowability of the concrete. It also functions as a high-range water reducer. The percentage of superplasticizers used is the maximum recommended by PT Sika Indonesia, which is 0.6% of the total cement weight.

### *Silica fume*

Rahady (2019) states that using silica fume in amounts less than 3% by weight of cement is insufficient to increase the initial compressive strength of concrete, as this amount is insufficient to cover the surface of all coarse aggregate particles. However, the effective use of silica fume should not exceed 10% by weight of cement. Therefore, in this study, the percentage of silica fume was planned at 10%

by weight of cement.

## Research Methods

This experimental study was conducted at the Construction Material Technology Laboratory of Universitas Islam Indonesia to evaluate the mechanical properties of high-strength concrete using bauxite sand as a partial replacement for fine aggregate.

### *Materials*

The materials used include Portland Cement (Type I), natural river sand, crushed stone (max size 20 mm), clean tap water, and bauxite sand sourced from the Riau Islands. The bauxite sand had a specific gravity of 2.71 and water absorption of 3.2%. All materials met relevant Indonesian national standards (SNI).

### *Mix design for high-strength concrete*

Five concrete mixtures were prepared: one control (BMT-0) and four experimental mixes (BMT-1 to BMT-4) with 2.5%, 5%, 7.5%, and 10% bauxite sand replacing fine aggregate by weight. The mix was designed to achieve a 45 MPa target compressive strength with a water–to–cement ratio of 0.3 and a constant cement content of 550 kg/m³.

High-quality concrete mix design generally refers to the SNI 03-6468-2000 standard, which describes the procedures for planning high-quality concrete mixes using Portland cement combined with fly ash. This standard serves as the primary guideline for designing high-quality concrete, ensuring the careful selection and proportioning of materials to achieve optimal results. In practice, fly ash can be replaced with other similar materials to produce a material composition that achieves high-quality concrete.

The primary objective of this study's concrete mix design is to achieve high-quality compressive strength by calculating the mix design with a minimum planned concrete compressive strength of f'c> 42 MPa, utilizing a concrete mix composition combined with silica fume and superplasticizer additives. If the mix composition has reached the planned quality, bauxite sand replaces some of the sand. Details of the material composition are shown in Table 3.

Table 3. High-strength concrete mix design composition per 1 m$^3$

| Code | Cement (kg) | Sand (kg) | Coarse Aggregate (kg) | Water (kg) | *Silica fume* (kg) | *Superplasticizer* (kg) | Bauxite Sand | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Weight (kg) | % |
| BMT-0 | 436 | 597 | 1013 | 205.26 | 43.6 | 4.316 | 0 | 0 |
| BMT-1 | 436 | 582.075 | 1013 | 205.26 | 43.6 | 4.316 | 14.552 | 2.5 |
| BMT-2 | 436 | 567.15 | 1013 | 205.26 | 43.6 | 4.316 | 28.357 | 5 |
| BMT-3 | 436 | 552.225 | 1013 | 205.26 | 43.6 | 4.316 | 41.417 | 7.5 |
| BMT-4 | 436 | 537.3 | 1013 | 205.26 | 43.6 | 4.316 | 53.73 | 10 |

### *Mixing, casting, and curing*

Concrete was mixed using a mechanical mixer, poured into 15×30 cm cylindrical molds in three layers, and compacted. After 24 hours, specimens were demolded and cured in water at 23 ± 2°C for 28 days.

### *Testing*

At 28 days, specimens were tested for:

a. Compressive strength (ASTM C39).
b. Splitting tensile strength (ASTM C496).
c. Modulus of elasticity (ASTM C469).

### *Data analysis*

Mean values and standard deviations were calculated for each property. Results were compared across mixtures to determine the optimal level of bauxite sand replacement.

The concrete quality was specified as 42 MPa, using five variations, each with 6 test specimens, for 28 days, based on SNI 2847 (2019). The number of test specimens was 30 cylinders as described in Table 4.

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Table 4. Details of specimen distribution

| Code | Composition of bauxite sand (%) | Number of specimens | |
|---|---|---|---|
| | | Compressive strength and modulus of elasticity | Tensile strength |
| BMT-0 | 0 | 3 | 3 |
| BMT-1 | 2.5 | 3 | 3 |
| BMT-2 | 5.0 | 3 | 3 |
| BMT-3 | 7.5 | 3 | 3 |
| BMT-4 | 10.0 | 3 | 3 |

## Experimental Results

### *Analysis of fine aggregate*

Figure 2 illustrates the results of the sand grading curve, which shows the upper and lower boundaries.

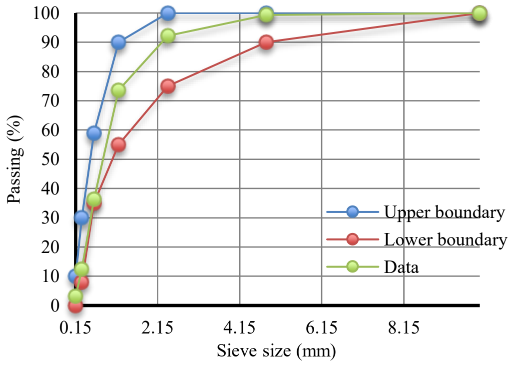


Figure 2. Grading curve of sand

### *Analysis of coarse aggregate*

A similar analysis shows the coarse aggregate sieve analysis results for the gradation curve in Figure 3, presenting the upper and lower boundaries.

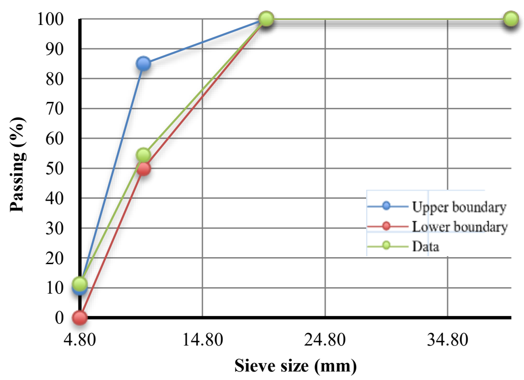


Figure 3. Grading curve of sand

### *Slump test*

The fine aggregate testing at Progo River is similar to that of Merapi sand, involving tests for lightness analysis, specific gravity, water absorption, solid and loose volume weight, and mud content. The test results are listed in Table 5.

Table 5. Slump test result

| No. | Code | Composition of bauxite sand (%) | Slump test (mm) |
|---|---|---|---|
| 1 | BMT-0 | 0 | 120 |
| 2 | BMT-1 | 2.5 | 113 |
| 3 | BMT-2 | 5.0 | 107 |
| 4 | BMT-3 | 7.5 | 89 |
| 5 | BMT-4 | 10.0 | 74 |

Based on the results presented in Table 5, it is concluded that the field results qualify the initial target slump planned in the previous mix design. In this study, the slump values obtained decreased because the concrete mix with bauxite aggregate reduced the workability of the concrete mix, as indicated by the slump value. After all, the absorption capacity of bauxite aggregate is more significant than that of fine aggregate (Lianasari, 2013). The concrete mixers in this study used a mixer and produced six cylinders per batch.

### *Compressive strength*

Concrete compressive strength testing evaluates the test specimen's ability to withstand the applied load. It is carried out for 28 days with a compressive strength plan of 42 MPa. Table 6 summarizes the compressive strength results.

Table 6. Compressive strengths summary

| Code | Number of samples | Compressive strength (MPa) | |
|---|---|---|---|
| | | Unit | Average |
| BMT-0 | 1 | 46.3 | 45.00 |
| | 2 | 44.5 | |
| | 3 | 44.2 | |
| BMT-1 | 1 | 45.6 | 46.37 |
| | 2 | 46.3 | |
| | 3 | 47.2 | |
| BMT-2 | 1 | 47.2 | 47.80 |
| | 2 | 53.6 | |
| | 3 | 42.6 | |
| BMT-3 | 1 | 46.7 | 47.20 |
| | 2 | 45.9 | |
| | 3 | 49.0 | |
| BMT-4 | 1 | 46.1 | 44.80 |
| | 2 | 45.5 | |
| | 3 | 42.8 | |

Referring to Table 6, it can be summarized that all test specimens in this study have exceeded the design quality compressive strength. Specifically, test specimens BMT-2 and BMT-3 recorded the highest compressive strength, at 47.80 MPa and 47.20 MPa, respectively, followed by BMT-1 at 46.30 MPa and BMT-4 at 44.80 MPa. Substitution of sand with bauxite sand at a 2.5% level showed an increase in compressive strength, with the optimum condition achieved at a 5% substitution level. However, further substitution to 7.5% caused a slight decrease in compressive strength. At the most considerable substitution of 10%, the compressive strength was significantly decreased, even lower than that of the control concrete (BMT-0).

The effect of volumetric weight differences on the mechanical properties of high-strength concrete produces high density and compressive strength. It is observed that the difference in volumetric weight of ordinary sand and bauxite sand is quite significant because the physical and mineralogical properties of the two types of sand are different. Ordinary sand (silica) generally has a volumetric weight of around 1,400–1,600 kg/m³, while bauxite sand, which comes from rocks rich in aluminum oxide, tends to have a higher volumetric weight, which is around 2,400–2,600 kg/m³.

Using bauxite sand increases the specific gravity of concrete because bauxite sand has a higher volumetric weight. Denser concrete generally has better compressive strength. Furthermore, bauxite sand, with its specific mineral content, can contribute to improved bonding between aggregate and cement paste, thereby increasing the compressive strength of concrete. However, this depends on the percentage of substitution and distribution of bauxite sand grains in the mixture, as discussed above.

***Tensile strength***

The splitting test on cylinder concrete is carried out using a Compressive Testing Machine (CTM) at 28 days to determine the tensile strength of concrete with different material compositions. Note that each material composition consists of three samples. The specimen test is set up by lying down and providing bearings on the right and left sides of the concrete, ensuring the concrete remains straight and does not change position.

The results of the concrete tensile strength test using the splitting method are listed in Table 3, followed by the tensile strength-to-compressive strength ratio of concrete with each composition. The tensile strength ratio to compressive strength in the control concrete is 7.13%, while the lowest and highest ratios are achieved in samples BMT-1 and BMT-2, respectively, at 5.30% and 7.24%. The achievement of the tensile strength to compressive strength ratio in this study was 8% lower, or 0.62. $\sqrt{f'c}$ (ACI).

Table 7 presents the tensile strength of high-strength concrete without admixture variation, which reaches 3.21 MPa. Meanwhile, high-quality concrete with bauxite sand substitution at the optimum tensile strength with a 5% bauxite sand mixture in BMT 2 gets an average value of 3.46 MPa, and the minimum tensile strength using bauxite sand substitution is in BMT-1 with bauxite sand substitution of 2.5% with an average tensile strength value of 2.46 MPa. At 28 days of concrete testing, the tensile strength of control concrete is 3.21 MPa and the optimum average tensile strength value with a mixture of 5.0% bauxite waste with a tensile strength of 3.46 MPa, and the lowest average tensile strength value is in a mixture of 2.5% with a substantial value of 2.46 MPa. (Rabihati et al. 2020).

Table 7. Tensile strength summary and its comparison to compressive strength

| Code | Number of samples | Maximum load (kN) | Tensile strength (MPa) | | Tensile to compressive strength ratio |
|---|---|---|---|---|---|
| | | | Unit | Average | Average |
| BMT-0 | 1 | 235 | 3.24 | 3.21 | 7.13 |
| | 2 | 245 | 3.83 | | |
| | 3 | 185 | 2.56 | | |
| BMT-1 | 1 | 222 | 3.11 | 2.46 | 5.30 |
| | 2 | 145 | 2.03 | | |
| | 3 | 160 | 2.24 | | |
| BMT-2 | 1 | 215 | 3.01 | 3.46 | 7.24 |
| | 2 | 269 | 3.87 | | |
| | 3 | 252 | 3.47 | | |
| BMT-3 | 1 | 215 | 2.99 | 3.39 | 7.18 |
| | 2 | 269 | 3.74 | | |
| | 3 | 252 | 3.43 | | |
| BMT-4 | 1 | 235 | 3.29 | 2.81 | 6.27 |
| | 2 | 185 | 2.59 | | |
| | 3 | 185 | 2.55 | | |

### *Modulus of elasticity*

The modulus of elasticity of concrete was meticulously analyzed to evaluate the material's flexibility and the deformation of test specimens under applied loads. The testing procedure, conducted with utmost precision, followed the guidelines of SNI 03-4169-1996. Ductility, defined as the ability of a structure to deform without losing its load-bearing capacity, was assessed by observing the increase in axial load at 10 kN intervals during stress-strain testing.

Recognizing the interdependence of properties, modulus of elasticity testing was conducted in conjunction with compressive strength testing. The calculations, demonstrating our commitment to a comprehensive approach, were based on experimental results and theoretical models. The tests employed a Compression Testing Machine (CTM) equipped with a dial gauge to measure deformation increments at every 10 kN load increase until the maximum load was reached.

The modulus of elasticity was determined with confidence using empirical formulas from ASTM C-469-94, SNI-2847-2019, FHWA (2000), and NBR-6118, as summarized in Tables 8–10.

Table 8. Modulus of elasticity based on ASTM C-469-94

| Code | Number of samples | Modulus of elasticity ($E_c$), MPa | |
|---|---|---|---|
| | | Unit | Average |
| BMT-0 | 1 | 26700.497 | 29962.70 |
| | 2 | 27539.414 | |
| | 3 | 35648.205 | |
| BMT-1 | 1 | 31471.140 | 31157.51 |
| | 2 | 28399.083 | |
| | 3 | 33602.332 | |
| BMT-2 | 1 | 30615.309 | 33721.78 |
| | 2 | 39036.848 | |
| | 3 | 31513.196 | |
| BMT-3 | 1 | 29699.051 | 34204.48 |
| | 2 | 34037.057 | |
| | 3 | 38877.323 | |
| BMT-4 | 1 | 32700.398 | 31144.17 |
| | 2 | 29342.542 | |
| | 3 | 31389.568 | |

The elastic modulus value calculated based on compressive strength reached its highest average using the NBR-6118 method for BMT-2, with a value of 38,674.15 MPa. Conversely, the lowest elastic modulus was calculated using the FHWA (2000) method, which yielded a value of 25,665.40 MPa.

Figure 4 presents a comparison of the modulus of elasticity using four different approaches, including ASTM C-469-94, SNI 2847-2019, FHWA, and NBR-6118. However, the SNI 2847-2019 yields results that are close to those of ASTM C-469-94, producing more realistic outcomes.

Table 9. Modulus of elasticity based on SNI 2847-2019 (MPa)

| Code | $E_c = 4700 \times \sqrt{f'c}$ | | $E_c = w_c^{1,5}\, 0{,}043 \times \sqrt{f'c}$ | |
|---|---|---|---|---|
| | Unit | Average | Unit | Average |
| BMT-0 | 31980 | 31526.90 | 34915 | 34657 |
| | 31352 | | 34041 | |
| | 31247 | | 35015 | |
| BMT-1 | 31738 | 32002.95 | 31785 | 31500 |
| | 31980 | | 31068 | |
| | 32290 | | 31648 | |
| BMT-2 | 32290 | 32458.66 | 32542 | 32384 |
| | 34409 | | 33769 | |
| | 30676 | | 30840 | |
| BMT-3 | 32118 | 32286.95 | 29282 | 32551 |
| | 31842 | | 34265 | |
| | 32900 | | 34107 | |
| BMT-4 | 31911 | 31454.34 | 32428 | 32551 |
| | 31703 | | 31933 | |
| | 30748 | | 28886 | |

Table 10. Modulus of elasticity based on FHWA (2000) and NBR-6118 (MPa)

| Code | $E_c = 3837 \times \sqrt{f'c}$ | | $E_c = 5600 \times \sqrt{f'c}$ | |
|---|---|---|---|---|
| | Ec (MPa) | Average (MPa) | Ec (MPa) | Average (MPa) |
| BMT 0 (0%) | 26094 | 25724 | 38104 | 37563 |
| | 25582 | | 37356 | |
| | 25496 | | 37230 | |
| BMT 1 (2,5%) | 25896 | 26113 | 37815 | 38131 |
| | 26094 | | 38104 | |
| | 26347 | | 38473 | |
| BMT 2 (5%) | 26347 | 26484 | 38473 | 38674 |
| | 28076 | | 40998 | |
| | 25030 | | 36550 | |
| BMT 3 (7,5%) | 26207 | 26344 | 38268 | 38469 |
| | 25981 | | 37939 | |
| | 26845 | | 39200 | |
| BMT 4 (10%) | 26038 | 25665 | 38022 | 37477 |
| | 25868 | | 37774 | |
| | 25089 | | 36636 | |

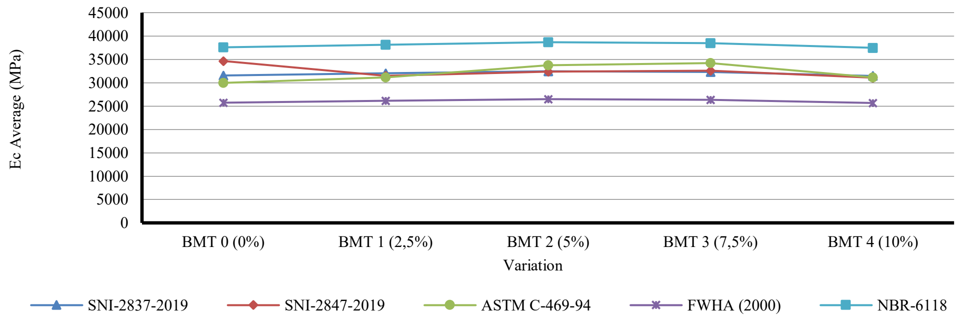


Figure 4. Comparison of modulus elasticity results

**Discussion**

The use of bauxite sand as a partially acceptable aggregate replacement had a positive influence on the mechanical properties of high-strength concrete, with optimal results observed at a 5% replacement level.

***Compressive and tensile strength***

Both compressive and tensile strengths peaked at 5% bauxite sand replacement (49.33 MPa and 3.46 MPa, respectively), then declined at higher levels of replacement. This improvement is attributed to the angularity and rough texture of bauxite particles, which enhance particle interlock and bonding. These findings are consistent with previous studies (e.g., Danso & Boadi, 2019; Bui et al., 2022), which also observed strength gains up to an optimal replacement threshold.

***Modulus of elasticity***

The highest modulus of elasticity was observed at a 7.5% replacement level (38,877.32 MPa), indicating that a slightly higher bauxite content may improve stiffness due to the inherent rigidity of the material. However, this did not correspond with the highest strength values.

***Practical implications***

The results suggest that using up to 5% bauxite sand can improve concrete quality while reducing dependence on natural sand. This suggestion is especially relevant for regions like the Riau Islands, where bauxite waste is abundant, and local fine aggregate is scarce.

***Limitations and future work***

The study focused only on mechanical properties at 28 days. Future research should investigate the long-term durability, workability, and environmental impacts to assess the potential of bauxite sand in concrete applications fully.

**Conclusion**

This study demonstrated that bauxite sand can be effectively utilized as a partial replacement for fine aggregate in high-strength concrete. All tested mixtures exceeded the minimum compressive strength requirement of 41.4 MPa, confirming the material's viability for structural applications. The mix containing 5% bauxite sand replacement (BMT-2) exhibited the highest compressive strength of 49.33 MPa and tensile strength of 3.46 MPa, indicating an optimal substitution level.

Additionally, the highest modulus of elasticity was observed in the 7.5% replacement mix (BMT-3), highlighting the influence of bauxite sand content on concrete stiffness. The dominant conical failure pattern observed across all samples indicated a uniform distribution and consistency in the mix proportions.

These findings contribute to the growing body of research on sustainable construction materials by introducing bauxite sand, a locally available, underutilized by-product, as a promising alternative to natural fine aggregates. The study provides a practical basis for further exploration and potential application in regions where conventional aggregates are limited, promoting both environmental and economic benefits in infrastructure development.

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