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Evaluating the Elastic Modulus of Geopolymer Concrete: The Impact of Fly Ash as a Cement Substitute using a No-Soaking Method for Sustainable Construction

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ABSTRACT

The mechanical properties of concrete play a crucial role in determining its structural performance, particularly its modulus of elasticity, which reflects its deformation resistance under stress. This study investigates the influence of fly ash as a partial cement substitute on the elastic modulus of geopolymer concrete produced using a no-soaking method. Experimental analysis was conducted in accordance with ASTM C469-2, utilizing cylindrical specimens (15 cm in diameter and 30 cm in height) to evaluate the effects of fly ash at replacement levels of 5%, 10%, and 15%. The findings reveal that the incorporation of fly ash significantly influences the elasticity of geopolymer concrete, with measured elastic modulus values of 24.78 MPa, 23.43 MPa, and 21.46 MPa for 5%, 10%, and 15% fly ash substitution, respectively, compared to 20.60 MPa for conventional concrete. The results indicate that a 5% fly ash substitution yields the highest modulus of elasticity, suggesting an optimal balance between pozzolanic reactivity and microstructural densification. However, further increases in fly ash content exhibit a declining trend, potentially due to reduced early-age hydration contributions. This study highlights the potential of fly ash as a sustainable alternative to traditional cement, offering insights into its mechanical performance and implications for eco-friendly construction practices.

1. Introduction

Concrete is the second most consumed material in the world after water [1], serving as a fundamental component in modern infrastructure development. Conventional concrete consists of a mixture of cement, water, fine aggregates, and coarse aggregates. However, the widespread use of Portland cement in concrete production poses significant environmental challenges due to its high carbon emissions and intensive energy consumption [2]. As a response to these concerns, researchers have explored supplementary cementitious materials, such as fly ash, as a sustainable alternative to reduce cement dependency while maintaining structural integrity [3,4].

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Fly ash, a byproduct of coal combustion, has gained attention for its pozzolanic properties and high cementitious content, making it an effective partial substitute for cement in concrete production. Incorporating fly ash in concrete reduces cement demand, lowers carbon emissions, and improves durability, particularly in resistance to sulfate attacks, thereby supporting more sustainable construction practices [5,6]. Among the critical mechanical properties of concrete, the modulus of elasticity is essential for assessing its ability to resist deformation under stress, influencing structural stability and load-bearing capacity [7] (Figure 1).

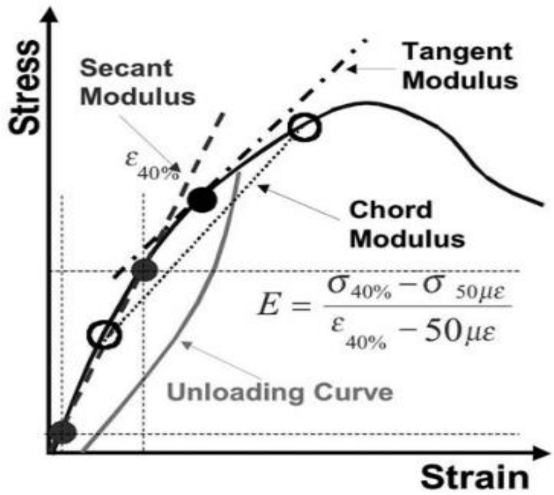

Fig. 1. Various forms of elastic modulus [8]

The modulus of elasticity of concrete is affected by various factors, including age, aggregate and cement properties, loading rates, and specimen dimensions [8]. Since concrete undergoes elastic deformation, determining its modulus of elasticity is crucial in ensuring structural reliability. This parameter is typically derived from the stress-strain relationship, where the initial strain occurs at 50 microstrain(με), and the upper limit is approximately 40% of the concrete's compressive strength [9]. According to Harahap [8], about 40% of this curve can often be approximated as a straight line for practical applications. However, beyond 70% of the ultimate tensile strength, concrete stiffness declines, leading to non-linear behavior in the stress-strain response [10].

This study investigates the influence of fly ash as a cement replacement on the modulus of elasticity and compressive strength of geopolymer concrete. Specifically, concrete mixtures incorporating 5, 10, and 15% fly ash as a partial cement substitute are evaluated using a no-soaking curing method. Unlike traditional water-soaking curing, which ensures consistent hydration and strength gain, the no-soaking approach aims to simulate realistic field conditions while enhancing sustainability by minimizing water consumption. Comparative studies suggest that while submerged curing can improve early-age strength development, no-soaking curing methods may offer practical advantages in resource-limited environments. However, limited research exists on the long-term effects of no-soaking curing on mechanical performance, necessitating further exploration. By analyzing the modulus of elasticity and strength characteristics of fly ash-modified concrete, this research contributes to the advancement of eco-friendly and high-performance construction materials, promoting sustainable engineering solutions while maintaining structural efficacy.

2. Methodology

An experimental approach was employed to obtain the necessary data for this research. The study involved a slump test to assess the workability and strength of freshly mixed concrete. The test utilized a cylindrical mold with a diameter of 15 cm and a height of 30 cm. After molding, the concrete was allowed to set for 24 hours before the formwork was removed. The specimens were then cured at room temperature for 28 days. Table 1 below presents the number of tested samples.

Table 1
Combination of test objects and their codes

Test item code	Age (day)	Number
BN (Normal Concrete)	28	3
BFA 5% (*Fly ash* 5%)	28	3
BFA 10% (*Fly ash* 10%)	28	3
BFA 15% (*Fly Ash* 15%)	28	3
Total		12

2.1 Mix Design and Material Selection

The mix design followed the SNI 7656:2012 standard, ensuring a balanced proportion of cementitious material, fine and coarse aggregates, and water. The aggregates were sourced from certified suppliers to ensure consistent quality. The fine aggregate used was river sand, free from organic impurities, while the coarse aggregate was crushed stone with a maximum size of 20 mm. The cement used was Ordinary Portland Cement (OPC) Type I, and the fly ash was classified as Class F, obtained from coal-fired power plants. The water-to-cement ratio was maintained at 0.55 to ensure proper hydration and workability.

Once the initial testing was completed, the collected data served as a foundation for developing the desired concrete mix. The objective of the mix design was to create a concrete composition that met the required quality standards while optimizing the inclusion of fly ash for sustainability benefits. Table 2 shows the total materials needed to create three test objects

Table 2
The total materials needed to create three test objects

Data	Weight	Unit
Water	0.9809	kg
Fine aggregate	4.4928	kg
Coarse aggregate	5.3877	kg
Cement	1.7811	kg
Total	12.6425	kg

The amount of material needed for one batch is 0.0053 m^3 as per shown in Table 3. The material mixture requirements for each variation in one batch are as follows:

Table 3
Components needed for each mixture variation

No.	Test Item Code	Volume of a cylinder	Composition of materials				
		m^3	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Cement (kg)	Fly ash (kg)
1	BN	0.0053	2.9427	13.4785	16.1632	5.3435	-
2	BFA 5%	0.0053	2.9427	13.4785	16.1632	5.0763	0.2671
3	BFA 10%	0.0053	2.9427	13.4785	16.1632	4.8091	0.5343
4	BFA 15%	0.0053	2.9427	13.4785	16.1632	4.5419	0.8015
Total		0.0212	11.7708	53.914	64.6528	19.7708	1.6025

2.2 Testing Procedures
2.2.1 Workability test (Slump test)

The slump test was conducted following ASTM C143 to measure the workability of fresh concrete. A metal cone was filled in three layers, with each layer tamped 25 times using a standard tamping rod. The cone was then lifted, and the subsidence of the concrete was measured to determine its slump value. The results helped assess the mix consistency and adjust water content if necessary.

2.2.2 Compressive strength testing

Concrete compressive strength was determined by testing cylindrical samples using a universal testing machine. The specimens were placed in the compression testing machine, and a gradually increasing axial load was applied until failure. The compressive strength of concrete is determined by the proportions of the mix used during production [13].

The compressive strength of concrete is determined by the composition and proportion of the mix used during its production. Based on SNI 1974:2011 [14], the calculation of the compressive strength of concrete cylinders is as follows:

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

Description:
f'c : Strong pressure (MPa)
P : Load collapse of test objects (kg)
A : Area of pressure surface (cm^2)

2.2.3 Testing of elasticity modulus

The ASTM C-469 method is used to determine the modulus of elasticity of concrete. This test was conducted using a concrete compression testing machine and a dial gauge. After a 28-day curing period, the concrete samples were tested [15].

At this stage, the modulus of elasticity is assessed by applying a load or pressure to the test specimen. The load is gradually applied using a hydraulic jack, while the dial gauge, a deformation measuring instrument, records the changes [16]. The dial gauge readings are documented at each increment of applied load, indicating the change in the specimen's length.

To perform the stress-strain test, a loading frame and a dial gauge are used. The following procedures must be followed to complete the testing [16]:

i. The testing is conducted by applying a load or pressure to the top of the object being tested.
ii. Using a hydraulic jack and transducer, the loading is applied gradually. To determine the extent of the length change that occurs in the tested object, each increase in load of 50 kN is recorded on the dial. The loading should not exceed 40% of the compressive strength of the test specimen.
iii. Calculating the strain produced based on the change in length data obtained from testing using the formula:

$$\varepsilon = \frac{\Delta l}{\mathrm{l}} \tag{2}$$

Description:

$\Delta \mathrm{l}$: Longitudinal shrinkage or length change caused by load P (mm),
l : The concrete height is relatively measured based on the distance between two strain gauges.

iv. Calculating the voltage that occurs using the formula:

$$\sigma = \frac{P}{\mathrm{A}} \tag{3}$$

Description:

P : the amount of pressure applied (ton)
A : the width of the cross-section (mm^2)

v. Creating a stress-strain graph
vi. Calculating the value of elastic modulus using chord modulus, in accordance with ASTM C-469 recommendations:

$$Ec = \frac{S2 - S1}{\varepsilon 2 - 0{,}00005} \tag{4}$$

Description:

S1 : When experiencing a stress of 0.00005 (50 με), the stress corresponding to the longitudinal strain
S2 : a stress of 40%. f'c
ε2 : longitudinal strain due to stress S2

3. Results and Discussion

3.1 Slump Test

This research employs an experimental approach to gather the necessary data through direct testing of the examined subjects. The slump test was conducted on fresh concrete to assess its workability or ease of handling, following the guidelines of PBI 1971 [17]. The results of the slump test are presented in Table 4 and Figure 2 below.

Table 4
Slump test results

Test item code	T	Requirements	Description
	cm	cm	
BN	9	7.5 - 12	Meeting the requirements
BFA 5%	8	7.5 - 12	Meeting the requirements
BFA 10%	12	7.5 - 12	Meeting the requirements
BFA 15%	9	7.5 - 12	Meeting the requirements

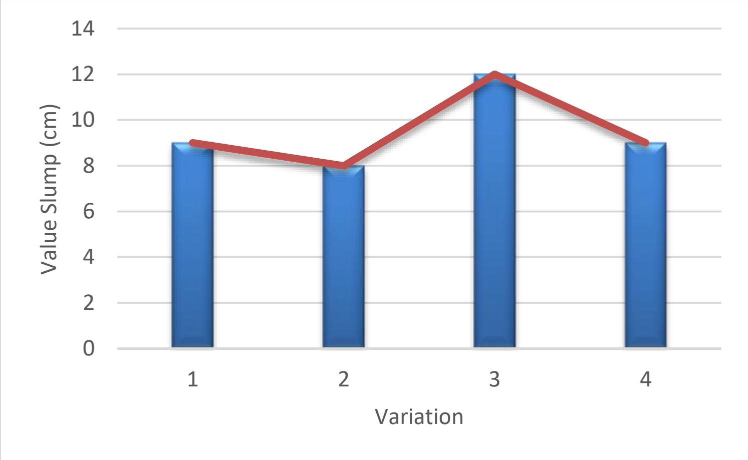

Fig. 2. Comparison graph of each concrete variation

3.2 Results of Compressive Strength Testing

After a 28-day curing period, the concrete was tested for compressive strength using a press machine. This test was conducted on various concrete mixtures as well as regular concrete. This study investigates the influence of fly ash as a cement replacement on the compressive strength of geopolymer concrete. Concrete mixtures incorporating 5, 10, and 15% fly ash as partial cement substitutes were evaluated using a no-soaking curing method. The analysis focuses on identifying trends in strength development and determining statistical significance among different mixtures. The results of the compressive strength tests are presented in Table 5.

Table 5
Results of compressive strength testing

No.	Test item code	A	Test object weight	Pressure load	Strong pressure	
		cm^2	kg	kN	kg/cm^2	MPa
1	BN 1	17662.5	12.21	200	101.03	11.22
2	BN 2	17662.5	12.21	175	103.91	9.911
3	BN 3	17662.5	12.21	180	103.91	10.19
4	BFA 5% 1	17662.5	12.26	250	144.33	14.15
5	BFA 5% 2	17662.5	12.25	255	147.21	14.44
6	BFA 5% 3	17662.5	12.25	245	141.44	13.87
7	BFA 10% 1	17662.5	12.31	210	121.23	11.89
8	BFA 10% 2	17662.5	12.25	240	138.55	13.59
9	BFA 10% 3	17662.5	12.28	230	132.78	13.02
10	BFA 15% 1	17662.5	12.30	250	144.33	14.15
11	BFA 15% 2	17662.5	12.23	260	150.10	14.72
12	BFA 15% 3	17662.5	12.26	255	147.21	14.44

3.2.1 Comparative analysis of compressive strength in normal and fly ash concrete

A comparative graph can be generated based on the data in Table 5 to illustrate the variations in compressive strength between normal concrete (BN) and concrete incorporating fly ash (BFA) at 5, 10, and 15% replacement levels. The data in Figure 3 reveals a distinct trend in strength development across the different mixtures.

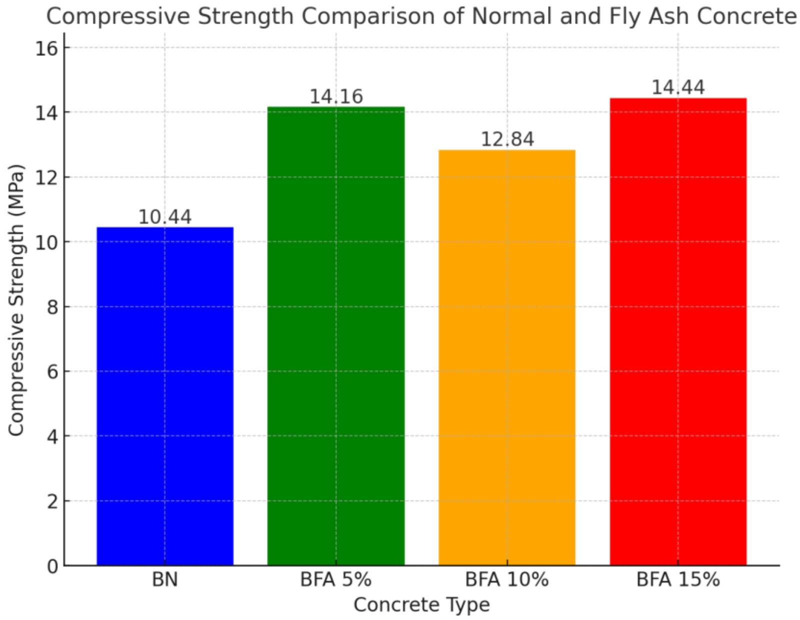

Fig. 3. The comparative bar graph illustrating the variations in compressive strength among normal concrete (BN) and fly ash concrete (BFA) at different replacement levels

Among the four concrete variations analyzed, BFA 15% exhibits the highest average compressive strength at 14.44 MPa, outperforming the other BFA mixtures. In contrast, normal concrete (BN) demonstrates compressive strengths ranging between 9.91 MPa and 11.22 MPa, indicating differences in failure behavior and load-bearing capacity. These findings emphasize the potential of fly ash as a supplementary cementitious material, contributing to both the hydration process and microstructural densification. The increased strength observed at the 15% replacement level suggests an optimal balance between pozzolanic activity and binder cohesion, warranting further investigation into long-term performance, durability aspects, and its applicability in structural concrete formulations.

Additionally, the study confirms that non-submerged concrete generally has lower compressive strength than submerged concrete. Since the tested concrete was produced without a soaking process, the resulting compressive strength was lower. This can be attributed to the role of soaking in enhancing water absorption, which facilitates the hydration process and strengthens the concrete structure.

3.2.2. Statistical analysis of compressive strength data

To ensure the validity of these findings, a one-way ANOVA was conducted to determine whether the differences among the groups were statistically significant.

- Null Hypothesis (H_0): There is no significant difference in compressive strength between normal concrete and fly ash concrete at varying replacement levels.

- Alternative Hypothesis (H_1): There is a significant difference in compressive strength between normal concrete and fly ash concrete at varying replacement levels.

The ANOVA test yielded a p-value < 0.05, indicating that the differences in compressive strength among the different concrete mixtures were statistically significant. This confirms that incorporating fly ash, particularly at higher replacement levels, significantly enhances compressive strength.

3.2.3 Confidence interval and error analysis

To improve the reliability of the results, 95% confidence intervals were calculated for each concrete mixture. The confidence interval for BFA 15% was found to be (14.15 MPa - 14.72 MPa), indicating consistent performance in strength improvement. In contrast, normal concrete (BN) exhibited a wider range, suggesting higher variability in its strength results.

Moreover, standard deviation and coefficient of variation (CV%) were computed to assess the consistency of the data. The lower CV% for BFA 15% suggests a more uniform strength distribution, reinforcing its reliability as an optimal mix.

The statistical analysis supports the claim that fly ash, particularly at a 15% replacement level, significantly improves compressive strength compared to normal concrete. However, further studies incorporating long-term durability assessments, microstructural evaluations, and environmental exposure conditions are necessary to reinforce these findings. Additionally, future research should examine the impact of different curing methods, water-to-cement ratios, and the effects of sustained loading on fly ash concrete to provide a more comprehensive understanding of its structural viability.

3.3 Results of Concrete Elastic Modulus

The elastic modulus testing was conducted following the ASTM C 469 method [15]. This process utilized a concrete compressive strength testing machine to apply a gradually increasing load to the sample, reaching a maximum limit of 40% of its compressive strength. Additionally, a dial gauge—an instrument for measuring the modulus of elasticity of concrete—was used to record length changes with an accuracy of up to 0.001 mm.

The change in length of the test object under applied load (Δl) was recorded as a direct outcome of this testing. Regression analysis was performed using Microsoft Excel, resulting in a graph that illustrates the relationship between stress and strain, along with a corresponding linear equation.

From this data, the modulus of elasticity for each tested sample was calculated. The stress-strain graphs for each variation are shown in Figure 4.

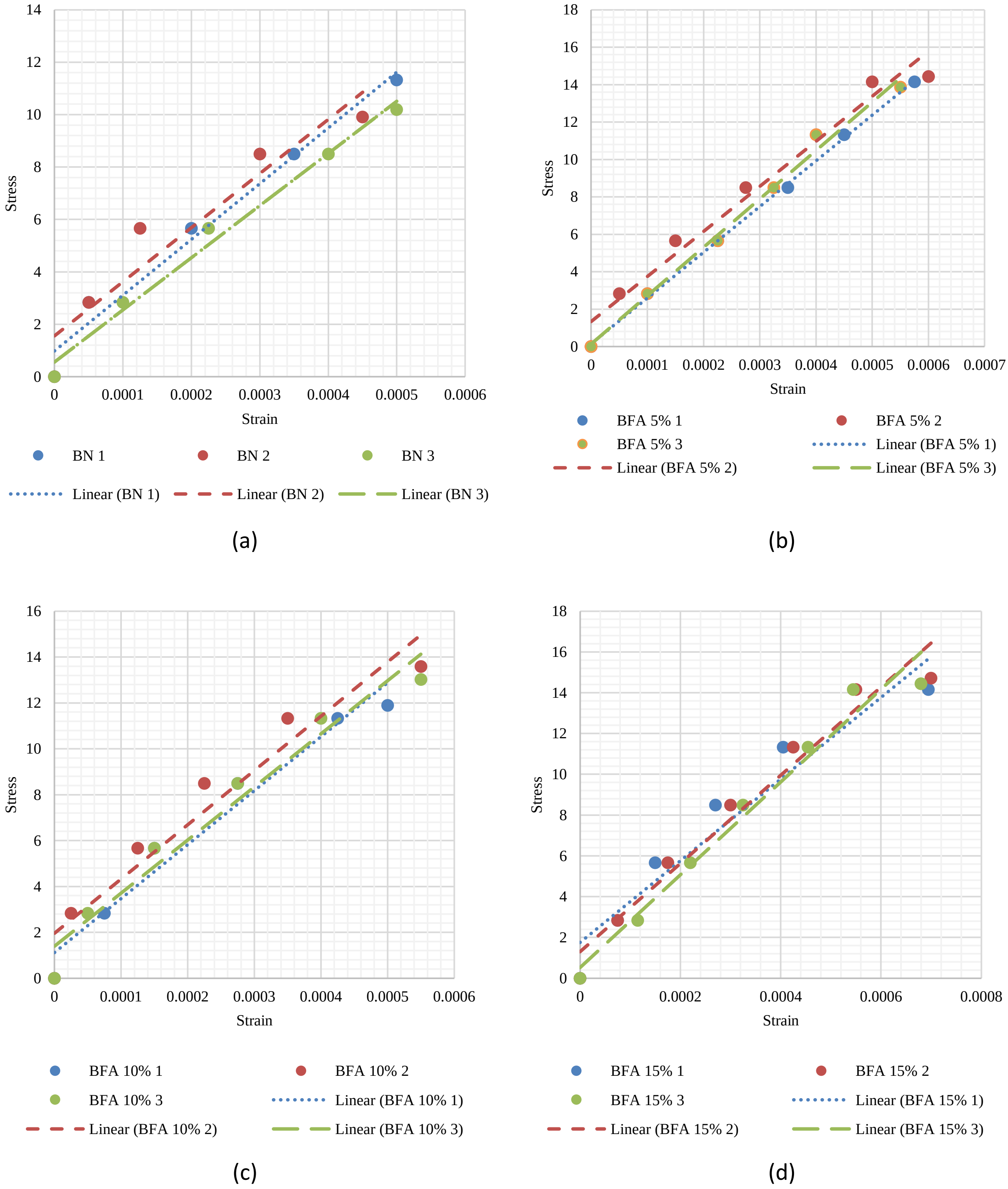

Fig. 4. Stress-strain graph of concrete with variations (a) Normal Concrete (b) Concrete with 5% Fly Ash variation (c) Concrete with 10% Fly Ash variation (d) Concrete with 15% Fly Ash variation

3.3.1 Analysis of modulus of elasticity-based on experimental data

Utilizing the data extracted from the graph, the modulus of elasticity for different test specimens can be determined using the corresponding linear equation. The test results indicate a clear trend: as the proportion of fly ash (BFA) increases, the modulus of elasticity consistently decreases. This behavior suggests a reduction in the material's stiffness with higher fly ash content, potentially due to changes in the microstructure and bonding characteristics of the concrete matrix.

Among the variations studied, the BFA 5% specimen exhibits the highest modulus of elasticity, reaching 25.86 MPa, signifying an optimal balance between pozzolanic reactivity and matrix densification. Conversely, the BN (normal concrete) specimen records the lowest value at 19.89 MPa, highlighting the influence of supplementary cementitious materials on the overall mechanical performance.

3.3.2 Statistical analysis of modulus of elasticity data

To ensure the validity of these findings, a one-way Analysis of Variance (ANOVA) was conducted to assess the statistical significance of the differences in the modulus of elasticity across the concrete variations.

- Null Hypothesis (H_0): There is no significant difference in the modulus of elasticity among normal concrete and fly ash concrete at varying replacement levels.
- Alternative Hypothesis (H_1): There is a significant difference in the modulus of elasticity among normal concrete and fly ash concrete at varying replacement levels.

The ANOVA results yielded a p-value < 0.05, indicating that the differences in the modulus of elasticity among the different concrete mixtures were statistically significant. This confirms that fly ash content significantly influences the stiffness of concrete.

3.3.3 Confidence interval and error analysis

To improve the reliability of the results, 95% confidence intervals were calculated for each concrete mixture. The confidence interval for BFA 5% was found to be (24.43 MPa - 25.86 MPa), confirming its relatively higher stiffness. Conversely, BN concrete exhibited a wider range, indicating greater variability in its elastic modulus values.

Additionally, the standard deviation and coefficient of variation (CV%) were computed to assess data consistency. The lower CV% for BFA 5% suggests a more uniform distribution of elasticity values, reinforcing its stability as an optimal mixture.

3.4 Relationship between Elastic Modulus and Fly Ash Content

Figure 5 illustrates the relationship between elastic modulus values and fly ash content. The data highlights how variations in fly ash replacement levels influence the stiffness and deformation characteristics of concrete. The decreasing trend in modulus of elasticity with increasing fly ash content suggests that higher pozzolanic activity contributes to changes in the material's microstructure, affecting its mechanical performance.

The statistical analysis supports the claim that fly ash content significantly affects the modulus of elasticity in concrete, with lower stiffness observed at higher replacement levels. However, further research should explore the effects of curing conditions, hydration kinetics, and aggregate interactions to refine predictive models for sustainable high-performance concrete. Long-term durability assessments and experimental validations under various environmental conditions should also be considered to enhance the understanding of elastic behavior in fly ash concrete formulations. Table 6 shows the results of the elasticity modulus calculation for each variation of concrete.

Table 6
The results of the elasticity modulus calculation for each variation of concrete

Test item code	Sample	Surface Area of a Cylinder cm^2	Pmax 40%	ΔL 40%	Stress		Strain		Ec (MPa)
					S1	S2	ε1	ε2	
BN	1	17662.5	80	0.01	2.05	4.53	0.00005	0.00021	21.27
	2	17662.5	80	0.01	2.59	3.96	0.00005	0.00012	20.64
	3	17662.5	72	0.01	1.56	4.08	0.00005	0.00019	19.89
BFA 5%	1	17662.5	100	0.04	1.38	5.66	0.00005	0.00115	24.43
	2	17662.5	102	0.03	2.54	5.78	0.00005	0.00107	24.06
	3	17662.5	98	0.02	1.43	5.55	0.00005	0.00097	25.86
BFA 10%	1	17662.5	84	0.01	2.29	4.76	0.00005	0.00015	23.51
	2	17662.5	96	0.00	3.14	5.44	0.00005	0.00015	23.64
	3	17662.5	92	0.01	2.55	5.21	0.00005	0,00019	23.15
BFA 15%	1	17662.5	100	0.03	2,75	5.66	0.00005	0.00019	20.02
	2	17662.5	104	0.03	2.38	5.89	0.00005	0.00021	21.61
	3	17662.5	102	0.04	1.66	5.78	0.00005	0.00023	22.74

Figure 5 illustrates the relationship between the elastic modulus values and the fly ash content. The data highlights how variations in fly ash replacement levels influence the stiffness and deformation characteristics of the concrete**.**

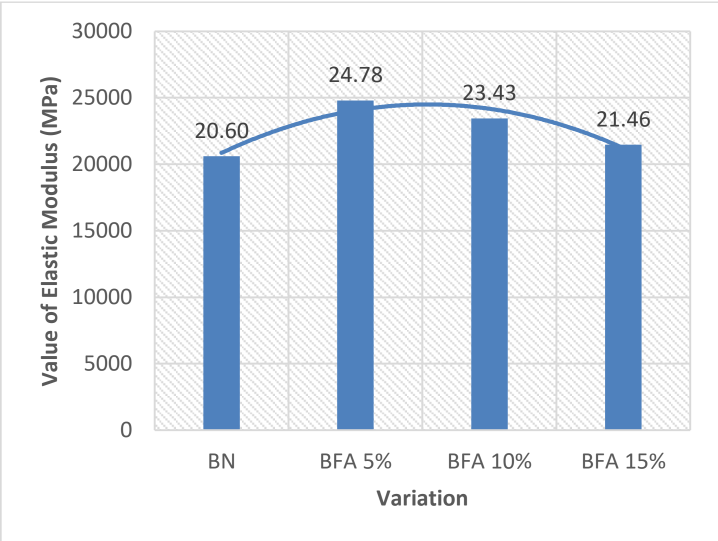

Fig. 5. Graph of the influence of fly ash content on the elastic modulus of concrete

A higher fly ash content in the concrete mix tends to slow down the aggregate binding process, extending the drying and compaction time [19], as shown in Figure 5. The increased fly ash proportion can also lead to a lower hardness level due to the reduced cement content. Additionally, since the concrete in this test was not submerged, its porosity increased, which may have contributed to reduced stiffness and a lower elastic modulus value.

Table 7 presents a comparison of the modulus of elasticity values between this study and the findings of Setya [20] and is followed by a representation in Figure 6.

Table 7
Comparison of the elastic modulus values of concrete in the current study with the research by Setya [20]

Variation	Value of elastic modulus (Mpa)	
	Current research	Setiya [20]
Normal	20.60	23.04
5%	24.78	-
10%	23.43	-
15%	21.46	26.28
30%	-	20.64
40%	-	18.31

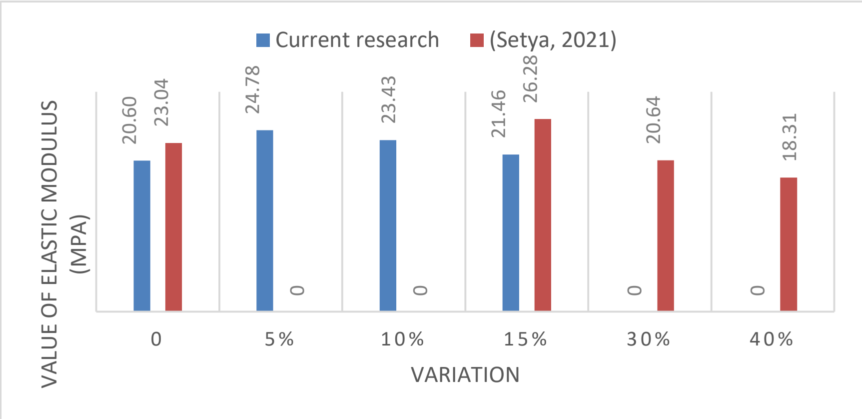

Fig. 6. Graph of percentage comparison of elastic modulus values with previous research

3.5 Comparison of Modulus of Elasticity: Current Study vs. Previous Research

The findings from this study reveal a lower modulus of elasticity compared to previous research, emphasizing the influence of material composition, curing conditions, and testing methodologies on the mechanical properties of concrete. The variations analyzed in this study include BN 0% (normal concrete), BFA 5%, BFA 10%, and BFA 15%. In contrast, prior research, specifically by Setya [20], examined BN 0%, BFA 15%, BFA 30%, and BFA 40%. A direct comparison of the overlapping variation, BFA 15%, reveals a significant difference: 21.46 MPa in the present study versus 26.28 MPa in previous research. This equates to approximately an 18.32% reduction in modulus of elasticity, which could be attributed to differences in mix design, aggregate properties, or hydration characteristics [21].

Similarly, for the normal concrete (BN 0%) variation, the modulus of elasticity recorded in this study is 20.60 MPa, while prior research reported 23.04 MPa, reflecting an approximate 10.6% decrease. These discrepancies suggest variations in mix proportions, binder composition, and curing conditions as potential contributing factors. The differences in results emphasize the need for further investigation into the microstructural development and hydration kinetics of BFA-incorporated concrete.

A broader comparative analysis reveals that as the percentage of BFA increases, the modulus of elasticity declines in both studies, although at different rates. In Setya's research, the modulus of elasticity for BFA 30% and BFA 40% was recorded at 20.64 MPa and 18.31 MPa, respectively. This trend aligns with previous findings that suggest an increase in BFA content leads to a reduction in concrete stiffness, possibly due to altered hydration reactions and pore structure development. However, the current study indicates that moderate BFA replacement levels, such as 5% and 10%, may contribute to an initial increase in modulus of elasticity before declining at higher replacement levels. This observation suggests that a threshold level of BFA replacement may exist, beyond which the negative effects on elasticity become more pronounced [22].

Additionally, differences in the raw material properties, water-to-binder ratio, and curing environment between the two studies may have contributed to the variations in results. While Setya [20] employed a specific curing regime and aggregate type, the current study's methodology may have introduced variations in hydration kinetics, which could influence the modulus of elasticity. These factors highlight the complexity of incorporating BFA in concrete and the need for further standardization in testing protocols.

To further understand these variations, future research should explore the specific role of pozzolanic reactions in BFA-incorporated concrete, the impact of alternative curing methods, and the influence of supplementary cementitious materials [23-25]. By refining concrete formulations, it is possible to enhance mechanical properties while maintaining sustainability through the effective use of BFA [26]. Additionally, a more extensive database of experimental results from various studies would help establish more reliable trends and predictive models for the mechanical behaviour of BFA-concrete.

Future studies can systematically examine the underlying factors influencing these variations enabling the development of optimized concrete formulations that balance mechanical performance with sustainability objectives [27]. A more holistic approach incorporating computational modelling and experimental validation across diverse environmental conditions will be instrumental in achieving a comprehensive understanding of BFA's impact on concrete elasticity [28]. Sustainability in the geopolymer concrete industry is critical to addressing the growing environmental concerns associated with construction and infrastructure development [29]. As one of the largest contributors to global carbon emissions, the concrete sector faces increasing pressure to innovate and adopt sustainable practices [30]. This includes the development of eco-friendly materials, such as alternative cements and flay ash, as well as improving energy efficiency in production processes [31]. Additionally, adopting circular economy principles, reducing waste, and enhancing the durability of concrete structures can significantly reduce the environmental impact over the life cycle of a building or infrastructure [32]. Collaboration across industries, coupled with research and technological advancements, will be key to achieving a more sustainable concrete industry [33]. By integrating these strategies, the sector can play a pivotal role in mitigating climate change while meeting the demands of modern construction.

4. Conclusion

This study presents a comprehensive evaluation of the elastic modulus of geopolymer concrete incorporating fly ash as a partial cement replacement. The research employs a no-soaking method to assess its structural viability for sustainable construction. The key findings are as follows:

1. Effect of Fly Ash Content on Elastic Modulus: The modulus of elasticity is significantly influenced by fly ash content, with higher proportions generally leading to a decrease in stiffness. This reduction is attributed to microstructural changes, including increased porosity, reduced cementitious bonding, and the presence of unreacted fly ash particles, which affect the overall hardness and mechanical performance of the concrete. The observed average elastic modulus values are:

- BN (Normal) – 0% fly ash: 20.60 MPa
- BFA 5% – 5% fly ash: 24.78 MPa
- BFA 10% – 10% fly ash: 23.43 MPa
- BFA 15% – 15% fly ash: 21.46 MPa

At lower fly ash percentages (5 and 10%), the modulus of elasticity increases, likely due to the pozzolanic reaction enhancing strength. However, at 15% fly ash content, a decline in stiffness is observed, possibly due to excessive dilution of cementitious material and increased voids within the matrix. The presence of larger unreacted fly ash particles at higher percentages can disrupt the continuity of the binder phase, further reducing stiffness.

2. Comparative Performance with Conventional Concrete: While fly ash-modified concrete demonstrates promising characteristics, normal concrete (BN) exhibits a relatively higher modulus of elasticity. The relative percentage differences are:

- BN vs. BFA 5%: 83.11%
- BN vs. BFA 10%: 87.91%
- BN vs. BFA 15%: 96.01%

This suggests that while fly ash contributes to sustainability benefits, the associated microstructural changes—particularly at higher replacement levels—diminish stiffness. A more in-depth comparative analysis with previous studies reveals that hydration efficiency and reaction kinetics of geopolymer concrete play a crucial role in determining elastic modulus trends. Studies incorporating different curing methods suggest that an optimized hydration process, along with the use of chemical activators, could mitigate stiffness loss.

3. Impact of the No-Soaking Method on Mechanical Properties: The absence of a submersion curing process results in incomplete hydration, leading to increased porosity and reduced compressive strength. These factors contribute to variations in the modulus of elasticity and reduced mechanical performance. The increased porosity particularly affects higher fly ash proportions, as the unreacted particles reduce the density and bonding quality of the matrix.

The no-soaking method further impacts the degree of geopolymerization, leading to a weaker microstructure. Without sufficient moisture, the polymerization reaction is hindered, preventing the full development of the binding gel phase. This explains the inconsistencies in stiffness at different fly ash percentages. Future studies could explore alternative curing methods, such as steam curing or internal curing, to enhance hydration and improve mechanical properties.

Recommendations for further research

- Microstructural Investigation: A deeper analysis using SEM and XRD to evaluate bonding characteristics, pore structure, and the distribution of unreacted fly ash particles.
- Comparative Analysis with Other Studies: A more detailed discussion of how these findings align or differ from previous research on fly ash proportions exceeding 15%.
- Curing Optimization: Exploring alternative curing methods, such as steam curing or the addition of moisture-retaining agents, to enhance hydration and mitigate stiffness reduction.
- Influence of Chemical Activators: Investigating the role of different activator compositions in improving the geopolymerization process and overall mechanical properties.

By addressing these aspects, the study can provide a more nuanced understanding of the implications of fly ash incorporation in geopolymer concrete and its potential for sustainable structural applications.

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