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Optimization of Fly Ash and GGBS Proportions in Paving Blocks for Compressive and Flexural Strength Pavements

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Abstract

The increasing demand for environmentally friendly infrastructure has encouraged innovation in construction materials that can reduce carbon emissions. One of the efforts undertaken is the utilization of industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as partial substitutes for cement in the production of paving blocks. This study aims to investigate the effect of varying fly ash and GGBS mixtures on the compressive and flexural strength of paving blocks, as well as to determine the optimal mixture proportion that meets structural strength standards for pavement applications, particularly in heavy vehicle parking areas. The experimental method employed four mixture variations of fly ash and GGBS in a 1:1 ratio, namely 0%, 7.5%, 15%, and 25% of the cement weight. Compressive strength tests were conducted at curing ages of 7, 14, and 28 days, while flexural strength tests were performed at 28 days. The results showed that the mixture containing 85% cement, 7.5% fly ash, and 7.5% GGBS achieved the highest compressive and flexural strength values, 21.5 MPa and 4.3 MPa, respectively. These values meet the quality requirements of Grade B as specified in SNI 03-0691-1996, indicating that the paving blocks are suitable for use in heavy vehicle parking areas. The findings demonstrate that the appropriate incorporation of fly ash and GGBS not only enhances the mechanical performance of paving blocks but also contributes to reducing cement consumption and carbon emissions. Thus, this research provides a significant contribution to the development of more sustainable.

Keywords: Paving Block, Fly Ash, GGBS, Compressive Strength, Flexural Strength, Sustainable Construction.

1. Introduction

Along with the progress of time, the demand for high-quality infrastructure continues to increase, particularly in road construction and other pavement applications. Cement-based paving blocks offer advantages in terms of aesthetics, ease of installation, and efficiency in maintenance [1]. Nevertheless, the cement content in paving block production has negative environmental impacts, contributing to climate change and carbon degradation due to carbon emissions generated during cement manufacturing. Therefore, efforts to mitigate these negative effects by partially replacing cement with alternative, eco-friendly materials have become essential, particularly in reducing the carbon footprint of cement production.

Ground Granulated Blast Furnace Slag (GGBS) and fly ash are industrial by-products that can serve as substitutes for cement in paving block mixtures. Fly ash, a by-product of coal combustion in power plants, possesses pozzolanic properties due to its silica and alumina content, which react with calcium hydroxide to form C-S-H, thereby enhancing the strength and durability of concrete [2]. Meanwhile, GGBS is a by-product of iron smelting in blast furnaces, consisting of oxides of silica, calcium, and alumina [3]. It has latent hydraulic reactivity that can improve mechanical properties such as compressive and flexural strength while reducing permeability [4]. Numerous academic studies [5] have demonstrated that the use of supplementary cementitious materials (SCMs) can significantly reduce carbon emissions and enhance the sustainability of concrete construction. Industry reports [6] further highlight SCMs as one of the key strategies in the ongoing efforts to decarbonize the cement sector, alongside innovations such as carbon capture technologies and low-carbon cement solutions. Despite various studies on the use of fly ash and GGBS, the optimal proportion of these two materials has not been fully explored.

Previous studies have investigated the use of fly ash and GGBS as partial replacements for cement in concrete mixtures. It has been shown that fly ash and GGBS can enhance compressive strength and chloride ion resistance in concrete [7] In another study, "Effect of GGBS and Burnt Paper Based Solid Wastes Ash in Making Sustainable Paver Blocks: An Experimental and Model Study" (2022), the incorporation of paper ash and GGBS in paving blocks achieved satisfactory compressive strength. Although research on the application of fly ash and GGBS in paving block production exists, a clear research gap remains in optimizing these materials specifically for heavy-duty pavement such as vehicle parking areas.

This study aims to fill this research gap by determining the most effective mixture proportions of fly ash and GGBS in paving blocks designed for heavy vehicle parking. The research not only seeks to improve compressive and flexural strength to withstand heavy loads, but also investigates the microstructural interactions of the blended materials. This approach is expected to advance knowledge on paving block formulations that are stronger, more durable, environmentally friendly, and cost-efficient.

The experimental design involves four mixture variations of fly ash and GGBS in a 1:1 ratio at replacement levels of 0%, 7.5%, 15%, and 25% of cement weight. The study evaluates the compressive and flexural strength of the produced paving blocks and seeks to determine the optimal mixture proportion for pavement applications. The proposed title of this study is "Optimization of Fly Ash and GGBS Proportions in Paving Blocks for Compressive and Flexural Strength in Pavement Applications." Accordingly, the results of this research are expected to contribute to the development of more sustainable and environmentally friendly construction materials while supporting the construction of efficient and durable infrastructure.

2. Research Methods

2.1 Approach, Location, and Time of Research

This research employed an experimental method with reference to SNI 03-0691-1996 for paving block specifications and ASTM C109/C109M-21 for compressive strength testing. The experiments were conducted at the Laboratory of Universitas Mercu Buana, Jakarta, and Universitas Islam Syekh Yusuf, Tangerang, during May–July 2025.

2.2 Research Variables

Compressive and flexural strength tests were carried out at 7, 14, and 28 days to evaluate the optimal mixture proportions of paving blocks. Cube specimens 5cmx5cmx5cm were prepared for compressive strength testing, while beam specimens 21cmx10.5cmx6cm were used for flexural strength testing. The mixtures incorporated a 1:1 ratio of fly ash to GGBS with replacement levels of 0%, 7.5%, 15%, and 25% f the total cement weight, referring to previous studies indicating that these ranges can enhance strength performance.

2.3 Research Samples

The number of research samples for compressive strength and flexural strength tests is shown in Table 1.

Table 1. Number of Samples for Compressive Strength and Flexural Strength Tests

No.	Sample	Compressive Strength Test			Flexural Strength Test	Total Samples
		7 Days	14 Days	28 Days	28 Days	
1.	100% Cement (Control)	3	3	3	1	10
2.	85% Cement + 7,5% FA + 7,5% GGBS (Variant 1)	3	3	3	1	10
3.	70% Cement + 15% FA + 15% GGBS (Variant 2)	3	3	3	1	10
4.	50% Cement + 25% FA + 25% GGBS (Variant 3)	3	3	3	1	10
	Total Samples					40

Note:
FA : Fly Ash
GGBS : Ground Granulated Blast Furnace Slag

Table 1 presents the number of samples used for compressive and flexural strength tests across four mixture variations. Each variation consisted of 10 specimens, resulting in a total of 40 samples. The mixture proportions include a control specimen with 100% cement and three experimental variants with partial replacement of cement by fly ash (FA) and ground granulated blast furnace slag (GGBS).

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2.4 Mix Design Calculation

The mix design for this study was developed in accordance with ASTM C109, with detailed proportions presented in Table 2. The calculated mixture volumes are sufficient to produce either six samples measuring 5cm×5cm×5cm or a single sample measuring 21.5cm×10cm×6cm.

Table 2. Material Requirements

Sample	Mold Volume (cm^3)	Cement (gram)	Fly Ash (gram)	GGBS (gram)	Sand (gram)	Water (gram)
1.	125	100% Cement: 500	-	-	100% Sand: 1375	242
2.	125	425	7,5% FA: 37,5	7,5% GGBS: 37,5	100% Sand: 1375	242
3.	125	350	15% FA: 75	15% GGBS: 75	100% Sand: 1375	242
4.	125	250	25% FA: 125	25% GGBS: 125	100% Sand: 1375	242

2.5 Paving Block Quality Requirements

The compressive strength requirements for paving blocks are specified in SNI 03-0691-1996, which stipulates that the blocks must meet the physical characteristics presented in Table 3.

Table 3. Requirements of paving blocks

Grade	Compressive Strength (MPa)		Flexural Strength (MPa)		Maximum Average Water Absorption. (%)
	Average	Min.	Average	Min.	
A	40	35	5	4.5	3
B	20	17.0	4.5	4	6
C	15	12.5	4	3.5	8
D	10	8.5	3.5	3	10

Note:
A : Paving for Highways
B : Paving for Parking Areas
C : Paving for Sidewalks
D : Paving for Garden Areas

3. Results and Discussions

3.1 Testing and Preparation of Materials

The material testing aims to evaluate the suitability of the materials used in paving block production in accordance with SNI 03-0691-1996. This stage serves as an initial step to assess the physical properties and quality of each component, including fine aggregate, cement, fly ash, GGBS, and water. The results of these tests provide the basis for determining material feasibility, ensuring that the produced paving blocks meet the established quality standards. Material testing for paving block production includes:

1. Fine Aggregate Testing
   The fine aggregate used in this study was Bangka sand, selected for its uniform particle size distribution and suitability for producing paving blocks with adequate strength and workability. Prior to the mix design process, a series of tests were conducted to evaluate the material's characteristics. The results of the fine aggregate characterization are presented in Table 4, while the testing procedures are documented in Figure 1.

Table 4. Summary of Fine Aggregate Testing

No.	Test	Standard	Result	Requirement	Unit	Remarks
1.	Sieve Analysis (Fineness Modulus)	SNI 03-1968-1990	3.30	2.30-3.10	-	Not Qualified
2.	Specific Gravity	SNI 1969-2008	3.0	1.6-3.3	gr/cm^3	Qualified
3.	Silt Content	SNI 03-4142-1996	32,63	5	%	Not Qualified
4.	Bulk Density	SNI 03-4804-1998	0,93	1,4 – 1,8	kg/m^3	Not Qualified
5.	Moisture Content	SNI 03-1971-2011	11.4	3-5	%	Not Qualified

Figure 1. Documentation of Fine Aggregate Testing

2. Cement Testing

The cement used in this study was Portland Composite Cement from PT. Semen Gresik. Prior to developing the mix design, a series of tests were conducted to evaluate the cement's characteristics. The test results are presented in Table 5, while the testing procedures are documented in Figure 2.

Table 5. Summary of Cement Testing

No.	Test	Standard	Result	Requirement	Unit	Remarks
1.	Specific Gravity	SNI 1969-2008	3.0	1.6-3.3	gr/cm^3	Qualified
2.	XRF (MgO)	ASTM C150	1,992	< 6	%	Qualified

Figure 2. Documentation of Cement Testing

3. Fly Ash Testing

The fly ash used in this study was sourced from PLTU Paiton, East Java. The fly ash was supplied as a ready to use powder. The test results are presented in Table 6, while the testing procedures are documented in Figure 3.

Table 6. Summary of Fly Ash Testing

No.	Test	Standard	Result	Requirement	Unit	Remarks
1.	Specific Gravity	SNI 03-2531-1991	2.5	2.2-2.6	gr/cm3	Qualified
2.	XRF (SiO2+AI2O3+Fe2O3)	ASTM C618	71,64	>70	%	Type F

Table 7. ASTM C618 Chemical Composition Requirements for Fly Ash

Parameter	Class		
	N	F	C
Silicon dioxide (SiO_2) + Aluminum oxide (Al_2O_3) + Iron oxide (Fe_2O_3), min, %	70.0	50.0	50.0
Calcium oxide (CaO), %	Report only	18.0 max	>18.0
Sulfur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max, %	3.0	3.0	3.0
Loss on ignition, max, %	10.0	6.0	6.0

Figure 3. Documentation of Fly Ash Testing

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4. GGBS
   The GGBS material used in this study was sourced from PT. Nexco Indonesia. The GGBS is a ready-to-use powder, and a series of tests were conducted prior to its us. The test results are presented in Table 8.

Table 8. Summary of GGBS Testing

No.	Test	Standard	Result	Requirement	Unit	Remarks
1.	Specific Gravity	SNI 1969-2008	3.0	1.6-3.3	gr/cm^3	Qualified
2.	XRF (SiO2+AI2O3+CaO)	ASTM C989	92,37	67	%	Not Qualified

5. Water
   Prior to its use in the paving block mixture, the water must be clean and free from impurities such as oil or fine particles.

3.2 Compressive Strength Test Results

Paving block testing was conducted to evaluate the quality of the produced paving blocks. This testing included a compressive strength test using Equation (2). The test results were analyzed to assess the blocks' load-bearing capacity and to determine whether they comply with the applicable reference standards. Additionally, the analysis was performed to compare the test outcomes across the different material mix variations used in the paving block production process The compressive strength tests were carried out at the Laboratory of Universitas Mercu Buana, Jakarta.

$$P = \frac{F}{A} \quad (2)$$

where P is the compressive strength of the material (N/m^2 or MPa), F is the maximum compressive load (N), and A is the cross-sectional area of the material (m^2).

Table 9. Compressive Strength Test Results

Variation	Average Compressive Strength (MPa)		
	7 Days	14 Days	28 Days
100% Cement (Control)	9,7	11,1	15,3
85% Cement + 7,5% FA + 7,5% GGBS (Variant 1)	11,7	16,3	21,5
70% Cement + 15% FA + 15% GGBS (Variant 2)	11,5	12,4	17,7
50% Cement + 25% FA + 25% GGBS (Variant 3)	10,1	11,6	15,2

Figure 4. Documentation of Compressive Strength Testing

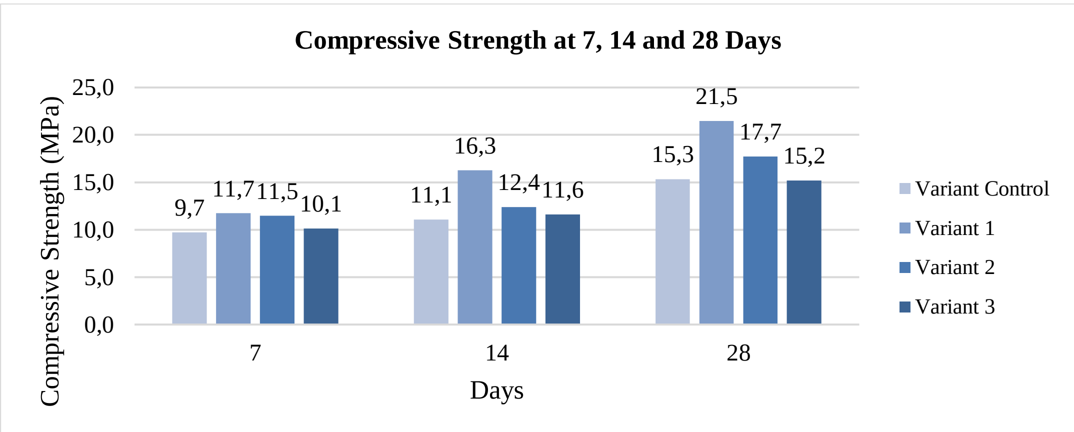

Figure 5. Compressive Strength Test at 7, 14 and 28 Days

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Table 10 presents the results of the compressive strength test at 7, 14, and 28 days, showing that all mixture variants experienced an increase in strength as the concrete aged. At 7 days, the highest value was obtained by Variant 1 at 11.7 MPa, while the control variant only reached 9.7 MPa. At 14 days, Variant 1 again demonstrated the best performance with 16.3 MPa, higher than the control at 11.1 MPa and the other variants. The most significant improvement was observed at 28 days, where Variant 1 reached 21.5 MPa, outperforming the control (15.3 MPa), Variant 2 (17.7 MPa), and Variant 3 (15.2 MPa). Based on these results, it can be concluded that the mixture composition in Variant 1 provides the most optimum proportion for improving the compressive strength of paving blocks.

3.3 Flexural Strength Test Results

The Flexural strength testing was conducted to evaluate the performance of paving blocks in resisting bending loads. The testing method applied the three-point loading system, where the specimen was placed on two supports and the load was applied at the midpoint of the upper surface. The flexural strength was calculated using Equation (3), with reference to the SNI 4154-2014 standard. The test results were analyzed to determine the ability of the paving blocks to withstand flexural stress and to assess their compliance with the applicable reference standards. In addition, the analysis was performed to compare the flexural strength values across the different material mix variations used in the production process. All flexural strength tests were carried out at the Laboratory of Universitas Islam Syekh Yusuf, Tangerang.

$$f_r = \frac{3PL}{2bd^2} \quad (3)$$

f_r is the flexural strength (MPa), P is the maximum test load (N), L is the span length between supports (mm), b is the width of the specimen (mm), and d is the height of the specimen (mm).

Table 10. Flexural Strength Test Results

Variation	Average Flexural Strength at 28 Days (MPa)
100% Cement (Variant Control)	3,2
85% Cement + 7,5% FA + 7,5% GGBS (Variant 1)	4,3
70% Cement + 15% FA + 15% GGBS (Variant 2)	3,0
50% Cement + 25% FA + 25% GGBS (Variant 3)	3,1

Figure 6. Documentation of Flexural Strength Testing

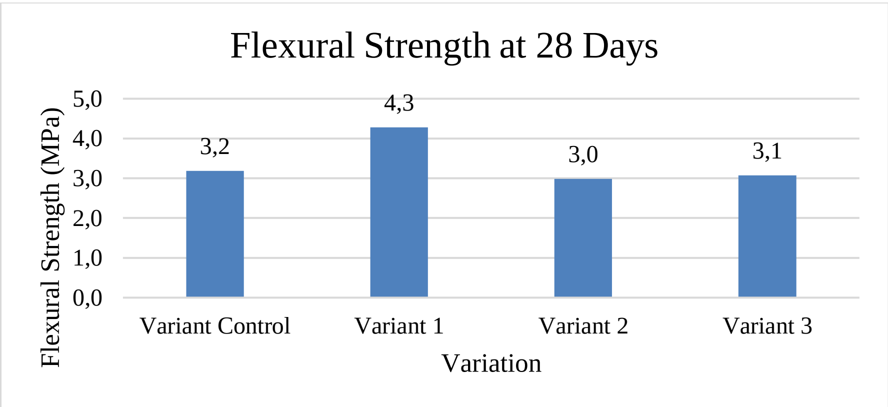

Figure 7. Flexural Strength Results Diagram at 28 Days

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Table 1 presents the results of the flexural strength test at 28 days, where *Variant 1* achieved the highest value of 4.3 MPa. In comparison, the control variant reached only 3.2 MPa, while *Variant 2* and *Variant 3* obtained 3.0 MPa and 3.1 MPa, respectively. These findings reinforce that the mixture composition in *Variant 1* not only improves compressive strength but is also more effective in enhancing the flexural strength of paving blocks.

4. Conclusion

Based on the research on the production of paving blocks using fly ash and GGBS at proportions of 0%, 7.5%, 15%, and 25% as partial cement replacement, and through compressive and flexural strength testing, it was found that the optimal compressive strength value of 21.5 MPa was achieved in Variant 1 at 28 days with a composition of 85% cement, 7.5% fly ash, and 7.5% GGBS, which falls into Quality Class B according to SNI 03-0691-1996. Meanwhile, the optimal flexural strength value of 4.3 MPa was also obtained in Variant 1 at 28 days with the same composition, classified as Quality Class B under SNI 4154-2014. This combination is considered effective because the cement content in the paving block remains sufficiently high, while the chemical reactions of fly ash and GGBS work optimally, resulting in a denser and stronger paving block structure. For future research, it is recommended to conduct a characterization of fly ash and GGBS materials based on their sources and production processes prior to the mix design. Testing with different mix ratios other than 1:1, such as 3:2 or 4:1, should be carried out to evaluate the dominance of each material on the characteristics of the paving blocks. In addition, the use of modified materials to enhance compressive and flexural strength should be further investigated. Further studies are also important to analyze the cement compound content from various brands, considering that variations in chemical composition may influence the properties of the mix, even though GGBS has the potential to partially replace cement.

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