INTERNATIONAL JOURNAL OF INNOVATION IN MECHANICAL CONSTRUCTION AND ENERGY
Vol. 2 No. 3 (2025), 110-117

IJIMCE
https://ijimce.ppj.unp.ac.id/index.php/ijimce
University of Negeri Padang

International Journal of Innovation in Mechanical Construction and Energy

ISSN: 3046-9112 e-ISSN: 3046-9104

The Effect of Using Palm Shell Fly Ash with Crushed Fine Aggregate on the Compressive Strength of Concrete

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Received 18 November 2025; Accepted 24 November 2025; Available online 28 November 2025

Abstract

Palm shell combustion waste produces fly ash containing chemical elements such as silica (SiO_2) and aluminum oxide (Al_2O_3), which can act as pozzolanic material. Pozzolans are materials containing silica (SiO_2) and aluminum oxide (Al_2O_3) that cannot harden or bind independently like cement when mixed with water, but can react with calcium hydroxide $Ca(OH)_2$ produced from the hydration process of cement, forming cementitious compounds. This study aims to determine the effect of palm shell fly ash as a substitution material and additive on the compressive strength of concrete with crushed fine aggregate variation. The tests were conducted with fly ash content of 0%, 15%, 17.5%, 20%, 22.5%, and 25% of cement weight. All specimens were cured under standard conditions and tested at 28 days. The results showed that, with crushed fine aggregate, the compressive strength of concrete with 20% fly ash substitution reached 30.848 MPa, which is 39.15% higher than concrete with fly ash as additive (22.169 MPa). From an engineering standpoint, the result indicating that the optimal substitution level of 20% fly ash yields the highest compressive strength with crushed fine aggregate provides valuable insight for practical mix design optimization. Although the compressive strength did not exceed that of plain concrete in all conditions, the performance improvement at certain substitution levels highlights the potential for fly ash to enhance durability, workability, and long-term strength development due to its pozzolanic reaction.However, compared with plain concrete without fly ash (24.166 MPa), the addition or substitution of fly ash did not result in a higher strength. The findings of this study have several important implications for sustainable construction materials and the broader field of concrete technology. The utilization of palm shell fly ash as a partial cement replacement demonstrates the potential for converting agricultural waste into value-added construction materials. This supports environmental sustainability by reducing cement consumption, which is a major source of CO_2 emissions, and by minimizing waste disposal problems from palm oil industries.

Keywords: *Palm shell fly ash, crushed fine aggregate, substitution, additive, compressive strength*

INTRODUCTION

Concrete is one of the most widely used construction materials in the world because of its high compressive strength, durability, and ease of molding into various structural forms. However, the growing demand for concrete has resulted in increased cement production, which significantly contributes to global carbon dioxide (CO_2) emissions. It is estimated that the production of one ton of Portland cement releases approximately one ton of CO_2 into the atmosphere, making the cement industry one of the largest contributors to global warming [1]. This environmental concern has encouraged researchers to develop alternative materials that can partially replace cement in concrete mixtures without compromising mechanical performance.

One promising approach is the utilization of industrial and agricultural by-products such as fly ash, silica fume, and slag as pozzolanic materials. Biomass combustion residues, particularly palm shell fly ash, contain high amounts of silica (SiO_2) and alumina (Al_2O_3), which are essential components of pozzolans [2]. These oxides can react with calcium hydroxide [$Ca(OH)_2$] produced during cement hydration to form calcium silicate hydrate (C–S–H), which improves the microstructure and mechanical strength of concrete [3]. Therefore, the use of palm shell fly ash as a partial cement replacement not only reduces cement consumption but also helps mitigate environmental issues related to palm oil industry waste accumulation [4].

In addition to binder modification, the selection of fine aggregate significantly affects the strength and durability of concrete. Natural river sand, commonly used as fine aggregate, has become increasingly scarce due to excessive extraction, leading to environmental degradation and ecological imbalance [5]. As an alternative, crushed fine aggregate produced from quarry or stone crushing operations provides angular particles that enhance inter-particle bonding and mechanical interlocking within the concrete matrix [6]. The combination of palm shell fly ash and crushed fine aggregate is therefore expected to produce concrete with improved compressive strength and greater sustainability value.

Based on this context, this study aims to investigate the effect of palm shell fly ash as a substitution and additive material on the compressive strength of concrete using crushed fine aggregate. The research also seeks to determine the optimum percentage of palm shell fly ash that achieves the best balance between strength and material efficiency. The results are expected to contribute to the development of sustainable concrete by promoting the use of local industrial by-products, reducing dependence on non-renewable resources, and supporting the achievement of the *Sustainable Development Goals* (SDGs), particularly those related to responsible consumption and production.

RESEARCH METHOD

This study used an experimental method conducted in the laboratory, involving cement, aggregate, and palm shell fly ash material testing.

2.1 Materials

The materials used were Type I Portland cement (PT Semen Padang), coarse aggregate (PT ATR), crushed fine aggregate (PTStatika Mitra Sarana), water, and palm shell fly ash (Type F) from PT Incasi Raya Group.

2.2 Laboratory Testing Procedure

Before the mixing process, all materials were tested to ensure their compliance with applicable technical standards. The testing procedures were carried out in accordance with the *Indonesian National Standards (SNI)* for concrete materials. The cement was tested for specific gravity, normal consistency, setting time, and soundness to verify its conformity with the quality requirements for Portland cement as specified in SNI 2049:2015. The aggregates—both fine and coarse—were examined for mud content, organic impurities, specific gravity, water absorption, sieve analysis, material passing the No. 200 sieve, hardness, unit weight, and abrasion resistance using the Los Angeles test, following SNI 1970:2016**,** SNI 1969:2016**,** and SNI 2417:2008. The palm shell fly ash was tested for specific gravity to determine its compatibility and reactivity potential as a supplementary cementitious material. The results of these material characterizations were then used as the basis for the concrete mix design, ensuring consistency, quality, and performance of the specimens.

2.3 Research Plan

In this experiment, three specimens were prepared for each test age and condition to ensure the reliability and reproducibility of the results. A total of 36 cylindrical specimens with dimensions of 150 mm in diameter and 300 mm in height were cast and tested at the age of 28 days. The specimens were divided into groups according to the percentage of palm shell fly ash used as both a cement substitution and an additive. This approach follows standard concrete testing procedures in accordance with SNI 03-1974-1990. for compressive strength testing of cylindrical concrete specimens [7]. The selected curing period of 28 days represents the standard age for evaluating the compressive strength of concrete, as it reflects the primary hydration and pozzolanic reaction development within the mixture [1][3].

Table 1. Number of test specimens

Fine Aggregate	Fly Ash *Percentage*						Total Slinder Test Pieces
	0%	**15%**	**17.5%**	**20%**	**22.5%**	**25%**	
Fly Ash Subtitusi	3	3	3	3	3	3	18
Fly ash Additive	3	3	3	3	3	3	18

2.4 Mix Design

The concrete mix design with crushed fine aggregate following to SNI 03-6468-2000.

2.5 Compressive Strength

Compressive strength testing at 28 days following to SNI 03-1974-1990

$$Fc = \frac{P}{A} \quad (1)$$

where : Fc = Compressive strength (MPa)
P = Load (kN)
A = specimen area (cm^2)

RESULTS AND DISCUSSION

3.1 Material Properties

The results of cement, aggregate, and fly ash testing are presented in Tables 2–7. All materials met SNI specifications, hence suitable for use in concrete mixes.

Table 2 Cement test results

Types of Testing	Test Method	Test Results	Standard Grades	Information
Specific gravity	SNI -15-2531-1991	2,983	2,8 – 3,1	Meet
Initial setting time	SNI 03-6827-2002	79,091	≥45	Meet
Cement's Permanence	SNI 04 - 1989 - F	1,364 mm	3 mm	Meet

(*Source: Testing Data)*

Table 3 Testing of crushed fine aggregates

Types of Testing	Test Method	Test Results	Standard Grades	Information
Specific gravity of Surface Saturated Dry	SNI 1969:2016	2.695	≥2,1	Meet
Absorption (%)	SNI 1969:2016	1.160	<3	Meet
Loose Bulk Density (gr/cm^3)	SNI 03-4804-1998	1.474	≥1,2	Meet
Compacted Bulk Density (gr/cm^3)	SNI 03-4804-1998	1.797	≥1,2	Meet
Fines Conten (%)	SNI 03-4142-1996	4.615	≤5%	Meet

Table 4 Medium aggregate testing

Types of Testing	Test Method	Test Results	Standard Grades	Information

Specific gravity of Surface Saturated Dry	SNI 1970:2016	2.518	≥2.1	Meet
Absorption (%)	SNI 1970:2016	2.757	<3	Meet
Loose Bulk Density (gr/cm^3)	SNI 03-4804-1998	1.421	≥1.2	Meet
Compacted Bulk Density (gr/cm^3)	SNI 03-4804-1998	1.642	≥1.2	Meet
Fines Conten (%)	SNI 03-4142-1996	0908	≤1	Meet

Table 5 Coarase aggregate testing

Types of Testing	Test Method	Test Results	Standard Grades	Information
Specific gravity of Surface Saturated Dry	SNI 1970:2016	2,597	≥2.1	Meet
Absorption (%)	SNI 1970:2016	2,115	<3	Meet
Loose Bulk Density (gr/cm^3)	SNI 03-4804-1998	1,458	≥1.2	Meet
Compacted Bulk Density (gr/cm^3)	SNI 03-4804-1998	1,607	≥1.2	Meet
Fines Conten (%)	SNI 03-4142-1996	0,820	≤1	Meet
Abrasion (%)	SNI 2417:2008	38,019	≤40	Meet
Crushingg (%)	SNI 03-4426-1997	30,018	≤40	Meet

Table 6 Results of fine aggregate sieve analysis

Nu	Sieve Size (mm)	Mixed Aggregate Pass Percentage (%)				Gradation Limits
		Fine Aggregate 42%	Medium aggregate 33%	Coarse aggregate 25%	Combined Aggregates	
1	25	100	100	67,41	100,00	100
2	19.5	100	88,75	31,19	79,08	74 – 93
3	9.5	99,44	46,14	10,74	59,68	47 – 82
4	4.75	97,11	12,47	4,63	46,06	28 – 70
5	2.36	62,01	4,62	1,68	27,99	18 – 57
6	1.18	34,53	2,51	0,91	15,56	10 – 46
7	0.6	21,99	1,95	0,85	10,09	6 – 32
8	0.3	11,62	1,33	0,83	5,52	4 – 19
9	0.15	6,22	0,84	0,62	3,05	0 – 4

Table 7 Fly ash test results

Types of Testing	Test Method	Test Results	Standard Grades	Information
Specific gravity	SNI-2531-1991	2,466	2,15 - 2,6	Meet

(*Source: Testing Data)*

The results of material testing are essential for ensuring the performance and durability of concrete. The specific gravity of cement and aggregates affects the density and compaction of the concrete mixture, influencing its compressive strength and workability. Water absorption and moisture content determine the amount of effective water in the mix, which directly impacts the water–cement ratio—a key factor controlling concrete strength and porosity [3]. Meanwhile, the abrasion resistance and hardness of coarse aggregates are indicators of their mechanical stability under load; aggregates with low abrasion loss contribute to higher long-term durability and resistance to surface wear [1].

Compliance with the Indonesian National Standards (SNI) in material testing ensures that all components meet the minimum quality requirements for structural concrete. Adhering to these standards helps maintain uniformity in material performance and prevents failures due to poor aggregate quality or inconsistent cement properties. Previous studies have shown that deviations from standard aggregate or cement characteristics can significantly reduce concrete strength and increase permeability, leading to premature deterioration [2]. Therefore, fulfilling SNI requirements is fundamental to achieving reliable and sustainable concrete performance.

3.2 Concrete Mixing

The concrete mixture requirements and slump results are shown in **Tables 8** and **Tables 9.**

Table 8 Material requirements per 1 m^3 *fly ash* as an additive

Material Type	Unit	Fly ash 0%	Fly ash 15%	Fly ash 17,5%	Fly ash 20%	Fly ash 22,5%	Fly ash 25%
Water	kg/m^3	5,44	5,44	5,44	5,44	5,44	5,44
Cemen	kg/m^3	20,82	20,82	20,82	20,82	20,82	20,82
Coarse aggregate	kg/m^3	17,84	17,84	17,84	17,84	17,84	17,84
Medium aggregate	kg/m^3	24,48	24,48	24,48	24,48	24,48	24,48
Fine aggregates	kg/m^3	21,89	21,89	21,89	21,89	21,89	21,89
Fly ash	kg/m^3	0	3,12	3,64	4,16	4,68	5,20
Sikacim Concrete	ml	143,12	143,12	143,12	143,12	143,12	143,12

Table 9 Material requirements per 1 m3 *of fly ash* as a substitute

Jenis Bahan	Unit	Fly ash 0%	Fly ash 15%	Fly ash 17,5%	Fly ash 20%	Fly ash 22,5%	Fly ash 25%
Water	kg/m^3	4,25	4,26	4,26	4,26	4,26	4,26
Cemen	kg/m^3	20,82	17,69	17,17	16,65	16,13	15,61
Coarse aggregate	kg/m^3	17,88	17,88	17,88	17,88	17,88	17,88
Medium aggregate	kg/m^3	24,52	24,52	24,52	24,52	24,52	24,52
Fine aggregates	kg/m^3	24,60	24,05	23,96	23,87	23,77	23,68
Fly ash	kg/m^3	0	2,60	3,04	3,47	3,90	4,34
Sikacim Concrete	ml	143,12	121,65	118,07	114,49	110,92	107,34

3.3 Analysis of Concrete Compressive Strength Results

Figure 1 illustrates the relationship between the use of fly ash—both as a cement substitution and as an additive—in concrete mixtures containing crushed fine aggregate and their resulting compressive strength. The red horizontal line represents the compressive strength value of concrete without fly ash. The compressive strength of the control mix (0% fly ash) was higher than that of mixes incorporating fly ash, either as a substitution or as an additive. In the mixture without fly ash (0%), the cement content remained fully active, allowing complete hydration and the formation of a dense and cohesive paste. This explains why the compressive strength of the 0% fly ash mix was greater than that of the mixes containing fly ash.

When a portion of cement was replaced or supplemented with fly ash—which has relatively low early reactivity—the resulting paste became less cohesive and less capable of effectively binding the crushed aggregate. Although fly ash possesses pozzolanic properties, it requires sufficient curing time to react with the calcium hydroxide ($Ca(OH)_2$) produced during cement hydration. At the 28-day testing age, the pozzolanic reaction of fly ash was not yet fully developed, and thus did not significantly contribute to the concrete's compressive strength.

This explains why the compressive strength of the concrete with fly ash substitution did not exceed that of the mix without fly ash (0%).

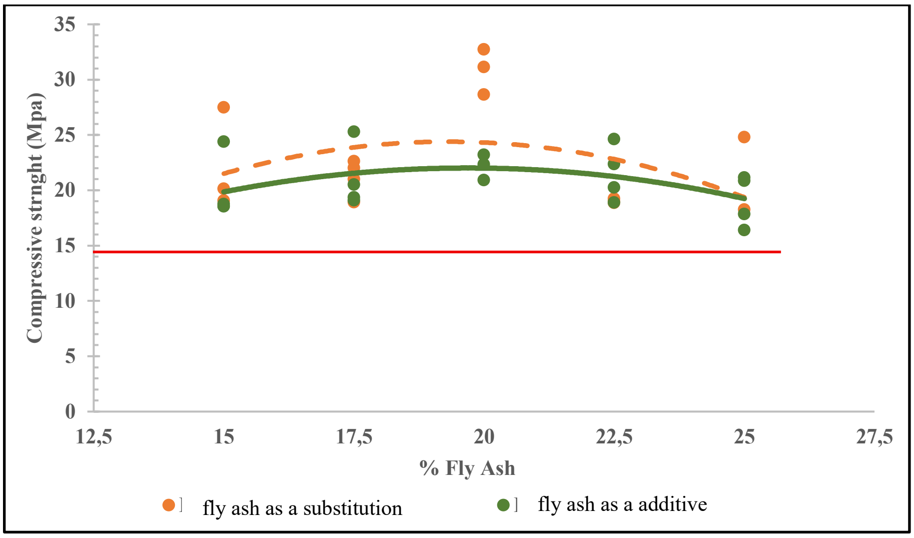

Fig. 1. Graph of the compressive strength test results of fine aggregate burst

From a microstructural perspective, this phenomenon can be explained by the chemical and physical mechanisms of the pozzolanic reaction. During hydration, the calcium silicate phases (C_3S and C_2S) in Portland cement react with water to form calcium silicate hydrate (C–S–H) gel, which is the primary source of concrete strength, and calcium hydroxide [$Ca(OH)_2$]. The amorphous silica (SiO_2) and alumina (Al_2O_3) contained in fly ash gradually react with $Ca(OH)_2$ to form secondary C–S–H and calcium aluminate hydrate (C–A–H) gels, which refine the pore structure and densify the cement matrix. However, this reaction proceeds slowly, particularly at early ages (before 28 days), due to the low reactivity of fly ash and the limited availability of $Ca(OH)_2$ at the early stage. Consequently, the immediate contribution of fly ash to strength development is minimal. Over time, as the pozzolanic reaction continues, more secondary C–S–H forms, enhancing the long-term strength and durability of the concrete.

Physically, the fine spherical particles of fly ash act as micro-fillers that can improve particle packing and reduce voids in the cement paste, thereby potentially enhancing the density and cohesiveness of the matrix. Nevertheless, when the fly ash content becomes excessive, the available calcium hydroxide becomes insufficient to react with all of the fly ash, leaving unreacted particles and increasing porosity. This results in a weaker interfacial transition zone (ITZ) between the paste and the crushed aggregate, reducing overall compressive strength.

Overall, the compressive strength of mixes with fly ash as a substitution was higher than that of mixes where fly ash was used as an additive. This can be attributed to the controlled replacement of cement in substitution, which maintains the overall volume of cementitious material and a balanced paste composition. In contrast, using fly ash as an additive increases the total powder content without proportionally contributing to the binding reaction, thereby slightly diluting the cementitious matrix. However, although fly ash substitution produced higher compressive strength than fly ash addition, neither method resulted in an improvement compared to concrete without fly ash (0%).

These findings align with previous studies such as those by Mehta and Monteiro (2014) and Thomas (2007), who reported that while fly ash contributes to long-term strength through the pozzolanic reaction, it tends to reduce early-age strength due to its slow reactivity. Additionally, studies such as Chindaprasirt et al. (2005) and Bhanja & Sengupta (2005) demonstrated that an optimum fly ash replacement level of 15–25% enhances strength and durability, while excessive replacement leads to strength reduction. The current results also agree with study [13], which showed that the use of crushed aggregates improves particle interlocking, thereby increasing compressive strength compared to natural aggregates. Similarly, reference [3] emphasized that the rough texture of crushed aggregates enhances the bond between the aggregate and cement paste, improving the concrete's load-bearing capacity. Reference [14] also reported that concrete made with crushed aggregates exhibited a 12–18% increase in compressive strength compared to that made with natural sand.

From a practical standpoint, the results indicate that palm shell fly ash (PSFA) can be utilized as a supplementary cementitious material to partially replace Portland cement in concrete production. Although its contribution to early strength is limited, its long-term pozzolanic reactivity can enhance durability, reduce permeability, and improve resistance to chemical attack. Moreover, the use of PSFA helps reduce cement consumption and the associated CO_2 emissions, supporting the development of more sustainable and environmentally friendly construction materials**.** The valorization of this agricultural waste not only addresses disposal issues but also adds economic value to palm oil industry by-products, promoting a circular economy in the construction sector.

CONCLUSION

The compressive strength of concrete with crushed fine aggregate and fly ash as substitution at 20% reached 30.848 MPa, 39.15% higher than fly ash as additive (22.169 MPa). However, both substitution and addition of fly ash did not enhance compressive strength beyond plain concrete without fly ash (24.166 MPa). Based on the analysis of the relationship between fly ash content and the compressive strength of concrete with crushed fine aggregate, it can be concluded that the incorporation of fly ash, either as a cement substitution or as an additive, affects the compressive strength of concrete but does not result in an improvement compared to the control mix without fly ash at 28 days. The optimum compressive strength was obtained at a fly ash content of approximately 20%, where the pozzolanic reaction begins to contribute to the formation of secondary binding compounds (C–S–H and C–A–H), leading to a denser and more refined microstructure. However, at early ages, this reaction is not yet fully developed due to the low initial reactivity of fly ash, resulting in lower strength compared to the control mixture.

The difference in performance between fly ash used as a substitution and as an additive is attributed to their distinct binding mechanisms. When fly ash is used as a cement substitution, the total volume of cementitious material remains balanced, resulting in a more stable paste compared to its use as an additive, which tends to increase the solid content without enhancing the chemical bonding reaction. Microstructurally, this difference influences the density of the paste and the strength of the interfacial transition zone (ITZ) between the paste and aggregate.

From a practical perspective, these findings indicate that palm shell fly ash (PSFA) has promising potential as a partial replacement for cement in sustainable concrete production. Although its contribution to early strength development is limited, PSFA can enhance long-term strength and durability through continued pozzolanic activity. Furthermore, the utilization of palm oil industry by-products helps reduce Portland cement consumption and CO_2 emissions, supporting the implementation of a circular economy and promoting environmental sustainability in the construction industry.

ACKNOWLEDGEMENT

This research was funded by the 2025 DIPA budget of Politeknik Negeri Padang. We extend our gratitude to Politeknik Negeri Padang for facilitating this research and to all other parties who have contributed to this study.

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