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The Efficacy of Type F Fly Ash from Paiton Power Plant on the Compressive Strength of Concrete

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A B S T R A C T

Portland cement is the primary binder in concrete and plays a crucial role in defining its structural performance. However, its production contributes approximately 7% of global carbon dioxide emissions, necessitating sustainable alternative materials. One potential material is Type F fly ash derived from coal combustion waste in steam power plants. This study aims to evaluate the effectiveness of Type F fly ash from the Paiton Power Plant as a sustainable cement replacement material in concrete based on compressive strength performance. Fly ash was activated using an alkaline solution consisting of NaOH and Na_2SiO_3 with a ratio of 1:2.5, where the NaOH concentration was maintained at 10 M. Two water–cement ratios (W/C) of 0.45 and 0.55 were employed to investigate their influence on workability and compressive strength. Cylindrical specimens were tested at 28 days with fly ash replacement levels of 0%, 80%, 90%, and 100% by weight of cement. The results indicate that increasing fly ash content significantly enhances compressive strength. The optimal performance was achieved with 100% fly ash replacement, yielding a compressive strength of 48.48 MPa or an increase of 102.4% compared to conventional concrete. This performance is attributed to the high silica content of Type F fly ash, which promotes the formation of dense N-A-S-H gel through alkaline activation, resulting in a more compact and less porous microstructure. These findings demonstrate that Type F fly ash from the Paiton Power Plant can effectively function as a primary binder, offering a sustainable alternative for high-performance concrete production.

1. Introduction

The prevalent use of concrete as a fundamental construction material globally is attributable to its synergistic combination of favorable properties. These properties include high compressive strength, adaptability to various formwork configurations, cost-effectiveness, long-term durability, inherent fire resistance, and the practical advantage of cast-in-place construction. Compressive strength is a very important property because concrete is responsible

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for resisting the loads applied to the structure [1]. Cement plays a crucial role in concrete manufacturing, as it greatly influences both the properties of concrete and the overall production costs. Nevertheless, the production of cement poses environmental challenges, mainly due to its substantial CO_2 emissions. Data indicate that the cement sector accounts for roughly 7% of the world's total CO_2 emissions [2]. Therefore, it is necessary to reduce cement consumption in the concrete mix without sacrificing the quality of the final product. The use of by-products or waste from other industries as a partial replacement for cement is a recent advancement in concrete production, which has proven to be a more sustainable alternative to conventional Portland cement concrete [3], [4].

Fly ash is a residual material generated from coal combustion in thermal power plants. During the high-temperature burning of coal, fly ash forms as a fine particulate that is transported with flue gases and is usually captured using electrostatic precipitators or other filtration systems before being emitted into the atmosphere [5]. It appears as a fine powder primarily composed of unburned carbon (UC), various metal oxides such as silicon (Si), iron (Fe), calcium (Ca), and aluminum (Al), along with other inorganic constituents [6], [7]. Fly ash demonstrates pozzolanic behavior, which facilitates a chemical reaction with calcium hydroxide to form additional cementitious compounds. This reaction contributes to a denser microstructure, thereby enhancing the concrete's long-term performance and service life. A commonly employed variant is Class F fly ash which is rich in silica (SiO_2) and alumina (Al_2O_3), while containing relatively low levels of calcium, making it particularly well-suited as an additive in geopolymer concrete and as a partial replacement for cement [8].

Numerous studies have investigated the application of fly ash in concrete, particularly its pozzolanic behavior and potential to produce high-performance materials. Previous research has shown that a lower water–cement (w/c) ratio generally leads to higher compressive strength in conventional concrete. Meanwhile, class F fly ash has been reported to achieve compressive strengths ranging from 60 to 80 MPa when combined with alkaline activators, forming geopolymer-type binders [5], [9]. Furthermore, the concentration of NaOH and the Na_2SiO_3/NaOH ratio have been identified as critical parameters influencing strength development [10], [11]. However, limited studies have systematically evaluated the performance of locally sourced Type F fly ash from the Paiton Power Plant as a cement replacement material in conventional concrete mixtures. Furthermore, previous research has not examined the combined effect of a 10 M NaOH–Na_2SiO_3 activator system on Paiton fly ash at high substitution levels (80–100%) under different water–cement ratios (0.45 and 0.55).

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This study aims to evaluate the compressive strength of concrete with Type F fly ash substitution from Paiton PLTU. This study used variables water–cement (w/c) ratios, namely 0.45 and 0.55, and four levels of cement replacement by fly ash (0%, 80%, 90%, and 100% by weight). The selected w/c ratios represent relatively low and moderate water contents commonly used in structural concrete, allowing evaluation of their influence on workability and compressive strength development based on established concrete design principles. Testing was conducted through laboratory experimental methods with variations in fly ash content, the use of alkali activator $NaOH–Na_2SiO_3$, and variations in water–cement ratio, then compressive strength testing was conducted. It is hoped that this study can provide a more comprehensive understanding of the potential of local fly ash as the main binder in concrete and serve as a reference in the development of sustainable concrete materials.

2. Research Method

This experimental study was conducted to investigate the effect of Type F fly ash from the Paiton Power Plant as a cement replacement material on the compressive strength of concrete. The experimental variables consisted of two water–cement (w/c) ratios, namely 0.45 and 0.55, and four levels of cement replacement by fly ash (0%, 80%, 90%, and 100% by weight). The selected w/c ratios represent relatively low and moderate water contents commonly used in structural concrete, allowing evaluation of their influence on workability and compressive strength development based on established concrete design principles [13].

For each mix composition, three cylindrical specimens with dimensions of Ø15 cm × 30 cm were prepared, resulting in a total of 24 specimens. The mix design was calculated in accordance with SNI 03-3449-2002. After casting, all specimens were cured by full water immersion at room temperature (±27 °C) for 28 days prior to compressive strength testing. Compressive strength tests were conducted in accordance with SNI 03-1974-2011.

2.1 Material

The materials used in this study and their specific characteristics are as follows. The fly ash used was untreated Type F fly ash sourced directly from the Paiton Steam Power Plant, East Java. Alkaline Activator. The characteristics of the fly ash are shown in **Table 1**. Meanwhile, the fine aggregate analysis conforms to ASTM C136, with a fineness modulus of 2.52, which meets the specified gradation limits as shown in **Figure 1**. The fine aggregate utilized in this investigation conformed to Indonesian National Standard (SNI) T-15-1991-03. It consisted of naturally occurring sand or mechanically crushed stone particles, with a graded size distribution predominantly falling between 0.15 mm and 5 mm [19]. According to SNI 03

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2847 2002, coarse aggregates are defined as materials derived from natural gravel or crushed stone, containing coarse aggregate that is retained on a 4.75 mm sieve. The fineness modulus of the coarse aggregate was determined to be 6.44, with its sieve analysis in **Figure 2** confirming it falls within the permissible grading limits. The characteristics of fine and coarse aggregates are shown in **Table 2**. The fine aggregate used exhibited characteristics that tended to be moist, with a mud content of less than 10% of the specified limit. Therefore, it can be classified as clean fine aggregate and does not contain significant organic matter. The color test results also indicated values lower than the standard reference color. Meanwhile, the coarse aggregate had a mud content of less than 5% of the specified limit, indicating that the coarse aggregate was relatively free from mud and tended to be moist.

Table 1. Laboratory Test Results of Paiton Fly Ash

No	Test Description	Result (%)
1	SiO_2	90,2
2	Al_2O_3	0,5
3	Fe_2O	0,13
4	CaO	1,85
5	Na_2O	0,02
6	K_2O	0,008
7	MgO	0,62
8	SO_3	<0,008
9	LoI	0,21
10	Moisture Content	0,054
11	Fineness on 45 mikro-sieve	41,7

Source : Test Result of Paiton Fly Ash from Envilab Laboratory (2025).

Table 2. Analysis of Aggregate Characteristics

Description	Fine Aggregate	Coarse Aggregate
Specific Gravity	2,69 gr/cm³	2,58 gr/cm³
Infiltration	0,30 %	1,37 %
Humidity	3,22 %	1,55 %
Sludge Levels	0,85 %	1,69 %
Organic Matter Content	light brown	-
Fine Modulus	2,52	6,44
Loose Bulk Density Test	1,64 gr/cm³	1,35 gr/cm³
Compacted Bulk Density Test	1,74 gr/cm³	1,41 gr/cm³

Source: Author Research Results (2025).

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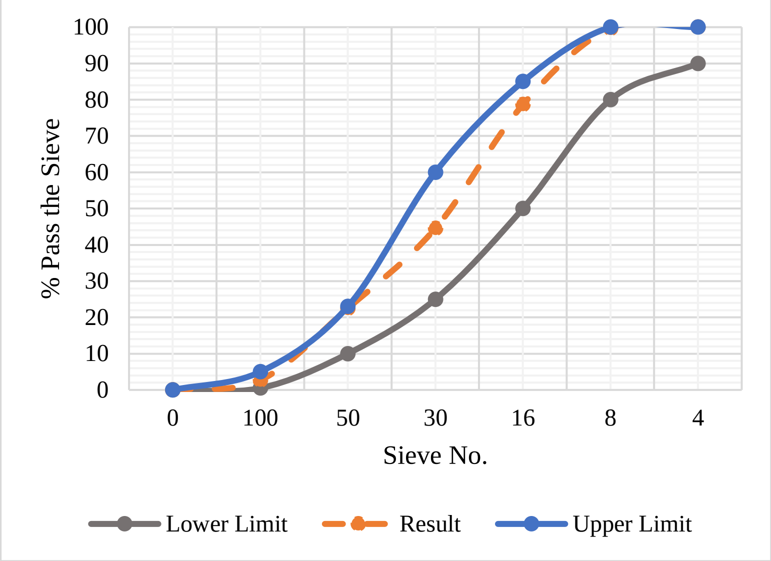
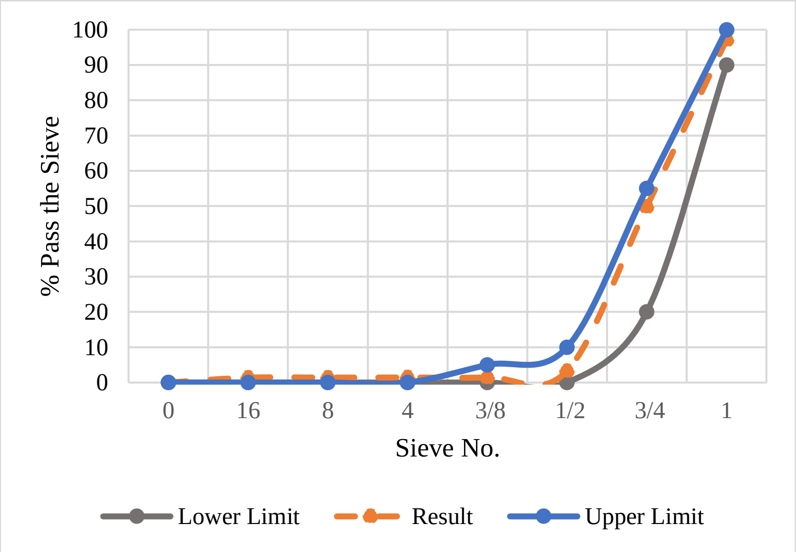


Source: Author Research Results (2025).

Figure 1. Sieve Analysis of Fine Aggregate



Source: Author Research Results (2025).

Figure 2. Sieve Analysis of Coarse Aggregate

A 10 M sodium hydroxide (NaOH) solution was used as the alkaline activator. The selection of 10 M NaOH was based on previous studies reporting that this concentration effectively promotes geopolymerization reactions in Class F fly ash systems, resulting in optimal strength development without excessive brittleness [10], [11]. The NaOH solution was prepared by dissolving 400 g of NaOH pellets (Mr = 40) in distilled water to produce one liter of solution. The solution preparation was conducted at room temperature, and the solution was allowed to cool to ambient temperature prior to use to ensure consistent reaction conditions. Sodium silicate (Na_2SiO_3) was combined with NaOH at a mass ratio of 2.5:1, following commonly adopted practice in alkali-activated fly ash systems.

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2.2 Sample

The mix designs for normal concrete were calculated based on SNI 03-3449-2002. For fly ash mixtures, cement was replaced by fly ash at 80%, 90%, and 100% by weight. The requirements for concrete materials were established following the guidelines of SNI 03 2834 2002, with W/C values of 0,45 and 0,55. The specifications for the quantities of materials used for each set of three test specimens per mix design, as listed in **Table 3** and **Table 4**.

Table 3. Job Mix Formula Calculation with W/C 0,45

Test Object	Coarse Aggregate	Fine Aggregate	Cement	Fly Ash	NaOH	$NaSiO_3$	Water
	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)
Normal	21,0	14,7	9,4	-	-	-	3,8
100% FA	21,0	14,7	-	9,4	1,1	2,7	-
90% FA	21,0	14,7	0,9	8,5	1,0	2,4	0,4
80% FA	21,0	14,7	1,9	7,5	0,9	2,2	0,8

Source: Author Research Results (2025).

Table 4. Job Mix Formula Calculation with W/C 0,55

Test Object	Coarse Aggregate	Fine Aggregate	Cement	Fly Ash	NaOH	$NaSiO_3$	Water
	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)
Normal	21,8	15,6	7,7	-	-	-	3,8
100% FA	21,8	15,6	-	7,7	1,0	2,6	-
90% FA	21,8	10,4	0,8	6,9	1,0	2,4	0,4
80% FA	21,8	15,6	1,5	6,2	0,9	2,1	3,8

Source: Author Research Results (2025).

For each mix composition, three cylindrical specimens with dimensions of Ø15 cm × 30 cm were prepared, resulting in a total of 24 specimens. After casting, all specimens were cured by full water immersion at room temperature (±27 °C) for 28 days prior to compressive strength testing.

2.3 Concrete Mixing Procedure

Concrete mixing was performed using a mechanical mixer following a standardized procedure. Coarse aggregate, fine aggregate, and binder materials (cement and/or fly ash) were dry-mixed for 2 minutes to achieve uniform distribution. Subsequently, the alkaline activator solution and remaining mixing water were added gradually, followed by wet mixing for 4 minutes, resulting in a total mixing time of 6 minutes, which is consistent with common laboratory practice for concrete mixing. Immediately after mixing, slump tests were conducted to assess workability. The fresh concrete was then cast into cylindrical molds in three layers, with each layer compacted using a vibrating table to minimize entrapped air. Specimens were

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demolded after 24 hours and cured in a water tank at room temperature (±27 °C) until the testing age of 28 days.

2.4 Testing

The workability of the fresh concrete was measured immediately after mixing in accordance with ASTM C143 to ensure consistency and compliance with the target slump. Meanwhile, compressive strength testing was conducted after 28 days of curing using a universal testing machine in accordance with SNI 03-1974-2011. The load was applied continuously until failure. The compressive strength (fc) was calculated by dividing the maximum load (Pmax) by the area (A).

3. Results and Discussions

3.1 Slump Test

The slump test results indicate a clear relationship between fly ash content, water–cement ratio, and workability. The slump test result for each mix formula can be seen in **Figure 3**. For both W/C ratios, increasing the fly ash substitution level resulted in higher slump values. At W/C = 0.45, the slump increased from approximately 100 mm for normal concrete to 180 mm for the 100% fly ash mixture, while at W/C = 0.55, the slump increased from 120 mm to approximately 200 mm.

This trend demonstrates a positive correlation between fly ash content and workability, which can be attributed to the spherical morphology of fly ash particles that reduces interparticle friction and improves flowability. Similar trends have been reported in previous studies, where fly ash was shown to enhance workability due to its ball-bearing effect [25]. However, despite the increased slump values, mixtures with high fly ash content exhibited a stickier consistency, indicating higher paste viscosity. This behavior suggests that increased workability does not necessarily correspond to improved handling stability. This finding implies that high-volume fly ash concrete may require admixtures or mix adjustments to maintain consistent workability during placement. Furthermore, mixtures with a w/c ratio of 0.55 consistently demonstrated higher slump values than their counterparts with a w/c ratio of 0.45, confirming the well-established principle that a higher water content enhances concrete fluidity.

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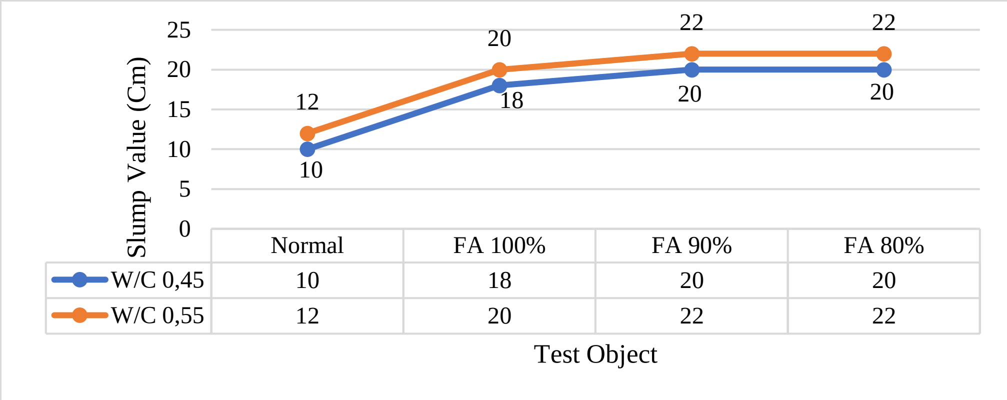


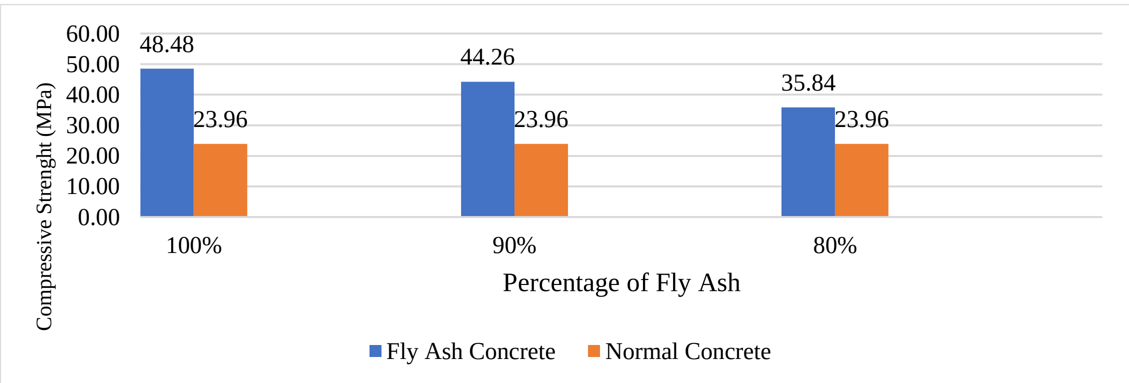
Source: Author Research Results (2025).

Figure 3. Fly Ash Percentage and W/C Ratio Effect on Workability

This increase in slump value is attributed to the reaction between fly ash and the alkaline activator, which produces N-A-S-H gel. Although the slump values obtained were higher, the resulting workability was less stable compared to that of normal concrete. Fly ash concrete tends to form a paste that is thick and sticky, making it less stable during the slump test. In contrast, normal concrete, C-S-H gel and calcium hydroxide ($Ca(OH)_2$), which are created during the process, give rise to innate lubricating properties. These properties enable the components to shift with greater ease and maintain stability, leading to enhanced handling and application characteristics.

C-S-H gel is predominantly found in concrete with 80% fly ash, as indicated by the increased slump test values, which occur due to the higher percentage of cement added. However, concrete with 80% fly ash exhibits a faster setting time compared to concrete with 100% and 90% fly ash, which tend to have longer setting times. This rapid setting time also affects workability if no admixture is added to delay the setting process of the 80% fly ash concrete. The addition of admixtures is therefore necessary to maintain good workability.

3.2 Compressive Strength



Source: Author Research Results (2025).

Figure 4. Compressive Strength W/C 0,45

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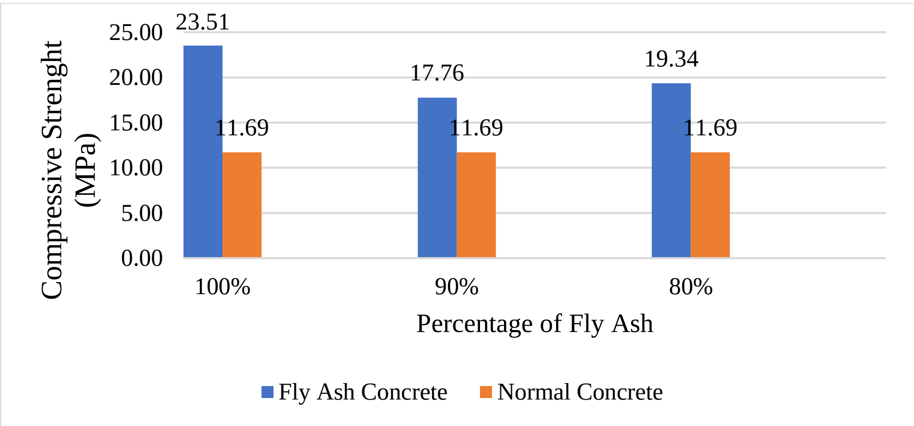
As presented in **Figure 4**, concrete incorporating 100% fly ash exhibited the highest compressive testing yielded an average result of 48.48 MPa, marking an increase of 102.4% over conventional concrete. The mix with 90% fly ash recorded the second-highest average compressive strength at 44.26 MPa, corresponding to an 84.7% improvement compared to normal concrete. In contrast, the 80% fly ash mixture achieved an average compressive strength of 35.84 MPa, reflecting a 49.6% enhancement relative to conventional concrete. The increase in compressive strength in concrete with fly ash mixtures shows that the higher the percentage of fly ash, the higher the compressive strength value.

This is due to the reaction between fly ash, which is a pozzolanic material, and the alkaline activator. The high silica content in Paiton fly ash reacts with the alkali, also rich in silica, producing N-A-S-H gel that optimally fills the pores of the concrete, making it denser compared to concrete without fly ash. In contrast, normal concrete, with the hydration reaction between cement and water, produces C-S-H gel and calcium hydroxide, which make the concrete more porous.



Source: Author Research Results (2025).

Figure 5. Compressive StrengthW/C 0,55

In **Figure 5**, the results indicate a positive correlation between fly ash content and compressive strength within the investigated range. This trend suggests that higher fly ash substitution levels enhance the formation of binding phases when sufficient alkaline activation is provided. Previous studies have reported comparable compressive strength ranges (40–60 MPa) for Class F fly ash-based systems activated with NaOH and Na_2SiO_3 [5], [9], confirming that the results obtained in this study are consistent with existing literature.

From a microstructural perspective, the superior performance of high fly ash mixtures can be explained by the formation of N-A-S-H gel resulting from the reaction between silica-rich fly ash and alkaline activators. This gel forms a dense and continuous matrix that

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effectively fills capillary pores, leading to reduced porosity compared to conventional Portland cement concrete, which primarily forms C-S-H gel and calcium hydroxide. Although the 100% fly ash mixture achieved the highest compressive strength, its higher workability and longer setting time may require careful control during field application. Conversely, mixtures with 80–90% fly ash offer a balance between strength gain and workability stability, making them more suitable for practical construction scenarios.

4. Conclusion

Type F fly ash from Paiton Steam Power Plant (PLTU Paiton) has significant potential as a cement substitute in concrete mixtures when activated alkaline using the $NaOH$–Na_2SiO_3 system. High levels of fly ash substitution (80–100%) have been shown to increase the compressive strength of concrete, with optimum performance achieved in a 100% fly ash mixture that produces a compressive strength of up to 48.48 MPa at 28 days, particularly at a water–cement ratio of 0.45. This increase in compressive strength is closely related to the high silica content in fly ash, which promotes the formation of a denser and less porous N-A-S-H gel matrix compared to conventional Portland cement-based concrete. Variations in the water–cement ratio also show consistent effects, with lower ratios producing better microstructure density and compressive strength. Although mixtures with very high fly ash content exhibit different workability characteristics, the research findings confirm that local fly ash from Paiton Steam Power Plant (PLTU Paiton) is suitable for use as a substitute material that functions as the main binder in the production of high-performance concrete that is more efficient and sustainable.

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