



Compressive Strength Performance of High-Volume Fly Ash Concrete with CaCO_3 Addition

Yosi Noviari Wibowo^a, Tatas Tatas^{a*}, Yuyun Tajunnisa^a, Amalia Firdaus Mawardi^a, Miftaql Zanah^a



^aDepartement of Civil Infrastructure Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60116, Indonesia

Corresponding author: tatas@its.ac.id

Abstract

This study investigates the compressive strength performance of High-Volume Fly Ash (HVFA) concrete with added CaCO_3 as a sustainable alternative to Ordinary Portland Cement (OPC) for infrastructure applications. The experimental research replaces a significant portion of cement with fly ash—a byproduct of coal combustion—aiming to reduce greenhouse gas emissions associated with concrete production. Two HVFA concrete mixtures were developed, substituting 37% and 47% of cement content with fly ash and adding 3% CaCO_3 to enhance mechanical properties. Material characterization, including XRF and XRD analysis, confirmed the suitability of fly ash for concrete production based on ASTM C618-19 standards. Aggregate gradation, moisture content, and specific gravity tests were conducted to optimize the mix design. Compressive strength tests were performed at 7, 14, and 28 days, showing that HVFA concrete with 37% fly ash substitution achieved higher strength values, reaching 25.92 MPa at 28 days, compared to the 47% mix, which reached 24.68 MPa. Slump tests indicated sufficient workability, with a measured slump of 10 cm for FA37C3 and 12 for FA47C3. These findings suggest that HVFA concrete with moderate fly ash substitution, complemented by CaCO_3 addition, can achieve compressive strength and workability comparable to OPC, supporting the development of environmentally friendly concrete solutions.

Keywords: CaCO_3 ; Compressive strength; High-volume fly ash; Workability

1. Introduction

Concrete production is one of the most significant contributors to global greenhouse gas emissions due to its heavy reliance on Ordinary Portland Cement (OPC), which releases substantial amounts of CO_2 during manufacturing [1, 2]. As the demand for sustainable infrastructure grows, there is an urgent need to explore environmentally friendly alternatives to OPC-based concrete. High-Volume Fly Ash (HVFA) concrete presents a promising solution by replacing a considerable portion of OPC with fly ash—a byproduct of coal combustion that, when used as a binder, can enhance concrete's durability and sustainability [3].

Research on HVFA concrete has shown that substituting cement with fly ash can reduce the carbon footprint of concrete production, a critical step in mitigating the environmental impact of the construction industry. This reduction is particularly significant compared to other environmental concerns, as cement production alone accounts for approximately 7-8% of global CO_2 emissions. By replacing a portion of cement with fly ash, a byproduct of coal combustion, HVFA concrete not only reduces the reliance on energy-intensive OPC but also repurposes industrial waste, thereby addressing two pressing environmental challenges simultaneously while maintaining acceptable mechanical properties [3, 4]. However, increasing the fly ash content often results in a decrease in compressive strength, particularly at early ages [5, 6], which limits its practical application in structural projects. This reduction in early-age strength can hinder the use of HVFA concrete in time-sensitive construction scenarios, where adequate strength development within a short timeframe is critical. Addressing this issue is essential to broaden the usability of HVFA concrete in infrastructure projects that require both sustainability and reliable mechanical performance. Previous research has experimented with various supplementary materials, including silica fume and metakaolin, to enhance the mechanical properties of HVFA concrete. However, these additives often fall short of providing sufficient strength gains, particularly for structural applications where compressive strength is critical [7, 8, 9]. To address this limitation, recent studies have turned to calcium carbonate (CaCO_3) as a promising additive due to its potential to accelerate the pozzolanic reaction in HVFA mixtures, thereby improving early and late-age compressive strength [10, 11, 12, 13].

However, most of these studies have not optimized specific replacement levels of fly ash and CaCO_3 to balance early-age strength development with long-term mechanical performance. This research aims to fill this gap by investigating the combined effects of varying fly ash and CaCO_3 proportions, thereby providing more targeted insights into the practical application of HVFA concrete.

The utilization of calcium carbonate (CaCO_3) in High-Volume Fly Ash (HVFA) concrete has garnered significant attention due to its promising benefits in enhancing both mechanical performance and environmental sustainability. CaCO_3 not only serves as a filler material but also actively accelerates the cement hydration process by providing nucleation sites for the formation of Calcium Silicate Hydrate (CSH), which is essential for the strength development of concrete. Additionally, CaCO_3 interacts chemically with the aluminate phases present in fly ash, resulting in the formation of calcium carboaluminate hydrates that improve the microstructural density and resistance of HVFA concrete to chemical attacks. This chemical interaction also mitigates the typical reduction in early-age strength often observed in HVFA concrete. Beyond its chemical contributions, the fine particles of CaCO_3 enhance the packing density of the concrete matrix, reducing porosity and increasing its durability against environmental degradation. Furthermore, as an inexpensive and widely available material, CaCO_3 contributes to reducing the production costs of eco-friendly concrete, making it a highly sustainable choice for modern construction. This study seeks to leverage these advantages to optimize HVFA concrete, creating a material that combines environmental benefits with mechanical properties comparable to conventional concrete.

2. Materials and Method

2.1. Materials

A. Precursors

Table 1. The chemical composition of precursor materials.

Oxide	Fly Ash (wt%)	Cement (wt%)	CaCO_3 (wt%)
SiO_2	41.04	19.45	0.01
Al_2O_3	19.36	5.38	0.10
Fe_2O_3	13.39	2.95	0.09
CaO	16.72	6.13	56
MgO	5.68	2.35	0.36
SO_3	0.64	2.06	0.01
Na_2O	1.63	0.11	-
K_2O	0.79	0.45	0.01
Cl	0.02	-	-
P_2O_5	0.24	0.13	-
TiO_3	0.85	0.28	-

Table 2. The results of XRD test of fly ash.

Solid Particle	Percentage (%)
Quartz (crystalline phase)	8.84
Brownmillerite (crystalline phase)	5.44
Perclase (crystalline phase)	2.71
C_3A (crystalline phase)	4.49
Andesine (crystalline phase)	1.31
Magnetite (crystalline phase)	0.76
Lime (crystalline phase)	0.53
Maghemite (crystalline phase)	0.76
Calcite magnesian (Crystalline Phase)	1.59
Mullite 3:2 (crystalline phase)	5.37
Mullite 2:1 (crystalline phase)	1.57

Solid Particle	Percentage (%)
Iron alpha (crystalline phase)	0.18
Hematite (crystalline phase)	0.38
Hkl_phase (amorphous phase)	64.04

The chemical composition and mineralogical characterization of the precursor materials utilized in the study are presented in Tables 1 and 2. The fly ash, sourced from the Nusantara Power Plant, Probolinggo, Indonesia, is predominantly composed of silica (SiO_2) at 41.04%, alumina (Al_2O_3) at 19.36%, and iron oxide (Fe_2O_3) at 13.39%, with a significant calcium oxide (CaO) content of 16.72%. Based on ASTM C618 [14], these characteristics align with the typical profile of Class F fly ash, suitable for high-volume applications due to its pozzolanic properties.

For the Portland Pozzolan Cement (PPC) used, the SiO_2 content is markedly lower at 19.45%, with CaO at 6.13%, indicating a supplementary cementitious material blended with ordinary Portland cement to enhance durability and strength. Additionally, the incorporation of calcium carbonate (CaCO_3) at 3% in the cement and as an additive at 56 wt% is strategically utilized to modify the matrix for enhanced compressive strength. Fig. 1 shows the documentation of binder material.

X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses were conducted at the Semen Indonesia Laboratory. X-ray diffraction analysis of the fly ash, detailed in Table 2, identifies the presence of both amorphous and crystalline phases. The amorphous content significantly predominates at 64.04%, which is crucial for the pozzolanic reaction in high-volume fly ash concrete [15]. Crystalline phases include quartz at 8.84%, mullite, and several calcium-aluminate phases, which contribute to the material's mechanical properties and reactivity.



(a)



(b)



(c)

Figure 1. (a) portland pozzolan cement; (b) CaCO_3 ; (c) fly ash.

B. Aggregates

The characteristics of the aggregates used in the concrete formulation are outlined in Table 3, detailing both fine and coarse aggregates. The fine aggregate, derived from Lumajang, exhibits a fineness modulus of 2.66, placing it within Gradation Zone 4, indicative of finer textures suitable for dense and cohesive concrete mixes. This sand reports a moisture content of 0.94% and a saturated surface dry (SSD) specific gravity of 2.70, signifying high-quality sand with minimal impurities and optimal density for concrete applications. Additionally, the absorption rate of 0.96% suggests a relatively low porosity, advantageous for maintaining the water-cement ratio and enhancing the durability of the concrete.

Table 3. Properties of fine and coarse aggregates.

No	Parameter	Fine aggregate properties value	Coarse aggregate properties value	Unit
1	Fine modulus	2.66	3.95	
2	Moisture	0.94	0.42	%
3	Specific gravity (SSD)	2.70	2.581	g/cm ³
4	Absorption	0.96	1.80	%
5	Max size	-	20	mm
6	Gradation Zone	Zone 4	-	

Coarse aggregate (gravel) sourced from a stone-crushing facility in Pasuruan, features a fineness modulus of 3.95, reflecting a coarser grain conducive to creating robust concrete structures. It presents a moisture content of 0.42%, significantly reducing potential alterations in the mix's moisture equilibrium. The specific gravity measured at 2.581 under SSD conditions implies a slightly less dense material, which can influence the mix's weight and structural calculations. The absorption rate stands at 1.80%, highlighting a higher porosity that requires adjustments in water content for optimal mix performance. The maximum aggregate size is noted as 20 mm.

2.2. Mix Design

This study aims to achieve a compressive strength of 25 MPa for high-volume fly ash concrete (HVFA) at 28 days. It employs a basic mix design for PPC concrete as a reference, in accordance with SNI 3-2834-2000 on the methodology for preparing normal concrete mix designs. The proportion of fly ash substituting cement is based on previous research by Dikdayana [16], which found that substituting more than 50% fly ash significantly reduces compressive strength. According to that study, HVFA achieved compressive strengths below 20 MPa with a 50% fly ash proportion at 28 days, demonstrating the critical need to optimize fly ash replacement levels to balance sustainability goals with structural performance requirements. To address this, replacement levels of 37% and 47% fly ash were selected in this research, aiming to explore their potential in maintaining compressive strength above the 25 MPa threshold while significantly reducing cement usage.

To enhance the compressive strength, previous study [17] suggested that adding 3% CaCO₃ could improve the performance of HVFA by accelerating the pozzolanic reaction and improving early-age strength. In this research, fly ash replaces a portion of the cement, adjusted according to the percentage of CaCO₃ added. The selected variations—37% fly ash with 3% CaCO₃ (FA37C3) and 47% fly ash with 3% CaCO₃ (FA47C3)—reflect a systematic approach to filling the gap in optimizing HVFA concrete mix designs for both early and long-term performance. These compositions aim to address the limitations of HVFA concrete identified in prior studies, such as reduced early-age strength and variability in long-term mechanical properties. The mix design of HVFA and PCC Concrete are outlined in Table 4.

Table 4. Mix design of HVFA and PCC concrete.

Materials	PPC (kg/m ³)	FA37C3 (kg/m ³)	FA47C3 (kg/m ³)
Cement	410.0	246.0	305.0
Fly Ash	-	151.7	192.7
Sand	636.9	636.9	636.9

Materials	PPC (kg/m^3)	FA37C3 (kg/m^3)	FA47C3 (kg/m^3)
CaCO ₃	-	12.3	12.3
Gravel	1137.5	1137.5	1137.5
Water	172.2	172.2	172.2
w/b ratio	0.42	0.42	0.42

*w/b ratio = water to binder ratio

2.3. Mixing and Curing

The concrete mixing process begins with cleaning the mixer's interior walls and removing any residual water to ensure no contamination of materials that could affect the quality of the concrete mix. Aggregates are added to the mixer in sequence, starting with gravel followed by sand. The mixer is then activated and rotated for approximately three minutes to achieve a homogeneous mixture of the aggregates. Once the aggregates are evenly mixed, cement, fly ash, and CaCO₃ are introduced into the blend. This mixture is continuously stirred for about seven minutes to ensure even distribution of all components within the mix. The next step involves adding water to the mixture, which is mixed until the concrete achieves the desired homogeneity, typically taking around five minutes.

After the mixing process is complete, the fresh concrete mix, which has been thoroughly combined, undergoes a slump test to determine the consistency of the mix. The fresh concrete is then poured into cylindrical molds measuring 100x200 mm. The test specimens are allowed to set for one day before being removed from the molds.

Curing the concrete, a critical next stage in the concrete production process, involves submerging the specimens in controlled conditions (Fig. 2) according to the planned test ages of 7, 14, and 28 days. This immersion process is crucial to ensure that the concrete develops the maximum strength and durability as specified.



Figure 2. Water storage tank curing.

2.4. Testing

This paper includes two primary tests: compressive strength test and workability test using the slump method. The following details the procedures and standards adhered to during these tests.

A. Compressive Strength Test

The compressive strength of concrete is assessed at 7, 14, and 28 days to determine the material's quality, targeting a strength of 25 MPa at the 28-day. These tests are conducted in accordance with SNI 1974:2011 [18], which outlines the standard procedures for testing the compressive strength of concrete using cylindrical test specimens. The test specimens used are cylinders with dimensions of 100x200 mm. Compressive strength testing is performed after the specimens are removed from the curing pond and allowed to stabilize at room temperature (26°C) for 24 hours prior to testing. This ensures the accuracy and consistency of the results.

B. Workability Test

This research also conducts a slump test to evaluate the workability of fresh concrete. This test is carried out following the guidelines of SNI 1972:2008 [19]. The slump test procedure begins by moistening the slump cone mold and placing it on a flat, moist, non-absorbent, and rigid surface. As the mold is filled with fresh concrete, the base of the cone is stepped on to secure it in place. Each layer of concrete within the mold is compacted with 25 strokes using a tamping rod, focusing on three layers, each approximately one-third of the mold's volume. After the fresh concrete is compacted and the surface is leveled with the tamping rod, the mold is carefully lifted vertically within 5 ± 2 seconds to avoid disturbing the concrete's initial settling. The reduction in height of the concrete from the mold is then measured immediately after the mold is removed, quantifying the slump. Concrete with a slump value of less than 15 mm may not be sufficiently plastic, and concrete with a slump greater than 230 mm may lack the necessary cohesiveness for this test. Therefore, careful attention must be paid when interpreting the results of these tests to ensure accurate assessments of the concrete's workability and structural integrity.

3. Results and Discussion

3.1. Compressive Strength

After the casting process, the test specimens will be removed from the cylindrical molds at 1 day old (± 24 hours) and then subjected to immersion curing for 7, 14, and 28 days. Three specimens are used for each testing age, and each is weighed prior to the compressive strength test. This is done to ascertain the weight of the test specimens.

Table 5 records individual test specimen weights, compressive strengths, and the average specific gravity of the concrete along with the standard deviation of the compressive strength values. For the FA37C3 mix, the average compressive strengths observed were 20.08 MPa at 7 days, 24.29 MPa at 14 days, and 25.92 MPa at 28 days (Fig. 2). The progression in strength demonstrates an effective gain, with a steady increase in strength over time, confirming the mix's suitability for structural applications requiring gradual strength development. The standard deviation values remained relatively low, indicating consistent performance across the test specimens. Conversely, the FA47C3 mix showed average compressive strengths of 21.40 MPa at 7 days, 24.37 MPa at 14 days, and 24.68 MPa at 28 days (Fig. 2). Notably, the FA47C3 mix exhibited a higher initial strength at 7 days compared to the FA37C3 mix. However, the 28-day strength was marginally lower than that of the FA37C3 mix, suggesting that a higher fly ash content could potentially inhibit long-term strength gain. This result underscores the importance of balancing fly ash substitution levels to achieve both early and long-term strength, addressing a critical gap in optimizing HVFA concrete mix designs for structural applications.

The standard deviation at 28 days was significantly higher at 6.76, reflecting a larger variability in the strength outcomes, which could be attributed to factors affecting the consistency of the mix or the curing conditions. The variability observed in the FA47C3 mix suggests the need for stricter control of material proportions and curing methods when incorporating higher fly ash content to ensure uniform performance. These findings reinforce the idea that optimizing fly ash content is critical not only for achieving desirable strength levels but also for minimizing inconsistencies that could affect practical applications.

This aligns with the research by Dikdayana [16], which found that higher proportions of fly ash can reduce compressive strength. These results underline the influence of fly ash and CaCO_3 proportions on the compressive strength development of concrete. While both mixes exhibit suitable properties for structural use, the variance in long-term strength between them provides critical insights into optimizing concrete mix designs for specific performance

criteria. By demonstrating that FA37C3 achieves a more consistent balance between early-age and long-term strength, this study highlights its potential as a reliable option for structural applications, filling gaps in previous research focused solely on maximizing fly ash substitution.

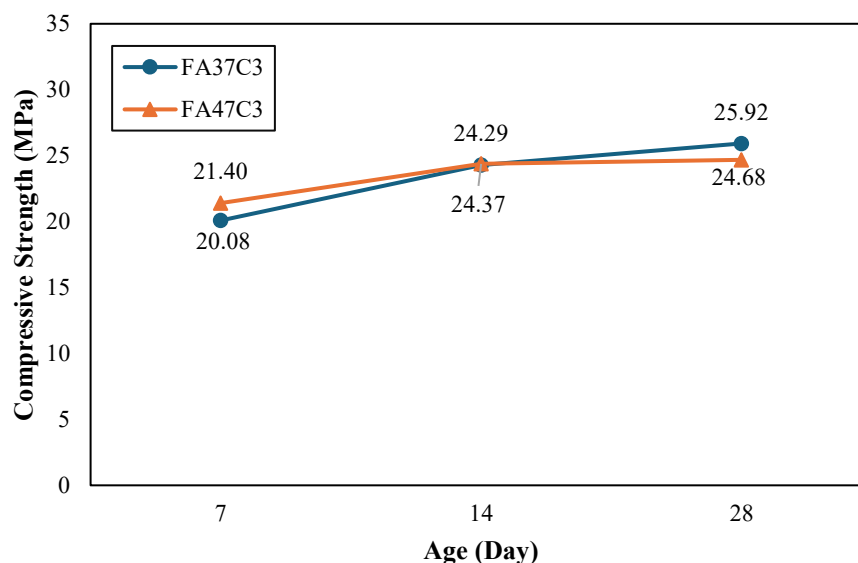


Figure 3. Compressive strength test results.

Table 5. The compressive strength results.

Age	Code	Compressive Strength (MPa)		Specific Gravity	
		FA37C3	FA47C3	FA37C3	FA47C3
7	Sample 1	18.98	21.78	2.560	2.585
	Sample 2	20.76	20.00	2.547	2.585
	Sample 3	20.51	22.42	2.560	2.560
	Average	20.08	21.40	2.556	2.577
	S.Deviation	0.79	1.02	-	-
14	Sample 1	22.80	21.02	2.484	2.649
	Sample 2	24.08	23.82	2.560	2.522
	Sample 3	25.99	28.28	2.535	2.585
	Average	24.29	24.37	2.526	2.585
	S.Deviation	1.31	2.99	-	-
28	Sample 1	27.01	27.01	2.535	2.560
	Sample 2	27.64	33.89	2.547	2.522
	Sample 3	23.82	15.29	2.560	2.566
	Sample 4	25.22	22.55	2.554	2.560
	Average	25.92	24.68	2.549	2.552
	S.Deviation	1.50	6.76	-	-

The substantial substitution of cement with fly ash in high-volume fly ash (HVFA) concrete does not compromise structural strength levels, primarily due to the beneficial role of added CaCO_3 . Previous research [20] stated that the inclusion of nano- CaCO_3 is particularly effective, as it significantly enhances the hydration process. This accelerated hydration leads to the formation of additional calcium silicate hydrate (CSH) phases, which are crucial for achieving higher compressive strength. The nano- CaCO_3 particles act as nucleation sites, promoting the formation of CSH throughout the cement paste and thus enhancing the microstructural integrity of the concrete. This study builds

on these findings by demonstrating that CaCO_3 , when paired with optimized fly ash substitution levels, provides a practical and scalable alternative for enhancing HVFA concrete performance.

3.2. Workability

The workability of concrete, a critical factor influencing its handling and placement characteristics, was evaluated through slump tests for two mix variations, FA37C3 and FA47C3. The results of these tests (Fig. 4) provided valuable insights into the effects of differing fly ash and CaCO_3 content on the concrete's plasticity. For the FA37C3 mix, the slump test yielded a result of 10 cm, indicative of a relatively stiff mixture. This degree of slump suggests that while the mix is workable, it exhibits a lower plasticity, which might influence its compactability and consolidation processes during placement. A slump of 10 cm is generally suitable for structural applications where less workable, more cohesive concrete is desired to reduce segregation and bleeding.

On the other hand, the FA47C3 mix demonstrated a slightly higher slump value of 12 cm. This increased slump indicates greater plasticity and workability, potentially facilitating easier handling and placement of the concrete. Previous study [20] findings corroborate the notion that increasing fly ash content generally improves slump values. This aligns with the observed trend in the current study where the FA47C3 mix, with its higher fly ash ratio, outperformed the FA37C3 in terms of slump, thus facilitating better workability. However, it is essential to consider that while higher slump values aid in better workability, they might also raise concerns regarding the stability and cohesiveness of the mix, especially under the influence of external forces during placement.



Figure 4. slump test results.

4. Conclusions

In the study, the compressive strength and workability of high-volume fly ash (HVFA) concrete with the addition of CaCO_3 were investigated, focusing on two mix variations, FA37C3 and FA47C3. The research conclusively demonstrates that HVFA concrete can achieve satisfactory structural performance while contributing to environmental sustainability.

For the FA37C3 mix, the compressive strength tests showed a consistent increase in strength over the testing period, achieving a notable strength of 25.92 MPa at 28 days. This is indicative of the potential of this mix to be used in structural applications where durability and strength are required. The slump test for this mix gave a result of 10 cm, suggesting a good balance between workability and stiffness, making it suitable for structural applications that demand

a denser, more cohesive concrete. By maintaining a moderate fly ash substitution level at 37% and incorporating 3% CaCO_3 , FA37C3 addresses the challenges of early-age strength reduction often observed in HVFA concrete, filling a critical gap in optimizing both strength and workability for structural use.

On the other hand, the FA47C3 mix, with a higher percentage of fly ash, demonstrated a slightly lower compressive strength of 24.68 MPa at 28 days. Although this is slightly less than the FA37C3 mix, it still falls within a range that is acceptable for many structural applications. The slump test for FA47C3 indicated a higher workability with a value of 12 cm. This increased slump suggests that the FA47C3 mix is more fluid and easier to work with during construction, offering advantages in applications requiring better flowability and ease of placement. However, the observed variability in compressive strength for FA47C3 underscores the need for stricter control over material proportions and curing conditions to ensure consistent performance. These findings emphasize the importance of balancing fly ash content to optimize both plasticity and strength.

Overall, the study affirms that by adjusting the content of fly ash and CaCO_3 , HVFA concrete can meet or exceed the compressive strength requirements of traditional concrete while also providing improved sustainability profiles. Both FA37C3 and FA47C3 demonstrate viable performance characteristics, confirming that HVFA concrete is a practical and environmentally friendly alternative for modern construction needs. By demonstrating the benefits of combining optimized fly ash levels with CaCO_3 , this research addresses gaps in previous studies, offering a scalable solution for sustainable and structurally reliable concrete.

Acknowledgment

The authors extend their gratitude to PT Solusi Bangun Indonesia (SBI) Tbk for supplying cement and to PT PLN Nusantara Power UP Tanjung Awar-Awar for providing fly ash. The authors would also like to acknowledge **Institut Teknologi Sepuluh Nopember (ITS)** for funding this research through the departmental funding scheme. This support has significantly contributed to the successful execution of this study.

References

- [1] Y. Wang, Z. Wen, M. Xu, J. Chen, and P. He, "Plant-level green transformation strategy in China's cement industry: Considering energy conservation and emission reduction co-benefits," *J. Clean. Prod.*, vol. 467, no. October 2023, p. 142945, 2024.
- [2] M. E. Bildirici, "Cement production, environmental pollution, and economic growth: evidence from China and USA," *Clean Technol. Environ. Policy*, vol. 21, no. 4, pp. 783–793, 2019.
- [3] G. Deng *et al.*, "Pozzolanic reactivity of carbonated high-calcium fly ash: A mechanism study," *Constr. Build. Mater.*, vol. 446, no. 8, p. 138015, 2024.
- [4] H. S. Jang and S. Xing, "A model to predict ammonia emission using a modified genetic artificial neural network: Analyzing cement mixed with fly ash from a coal-fired power plant," *Constr. Build. Mater.*, vol. 230, p. 117025, 2020.
- [5] O. J. Udeze, B. S. Mohammed, A. U. Adebajo, and I. Abdulkadir, "Optimizing an eco-friendly high-density concrete for offshore applications: A study on fly ash partial replacement and graphene oxide nano reinforcement," *Case Stud. Chem. Environ. Eng.*, vol. 9, no. 10, p. 100592, 2024.
- [6] Q. Jin, W. Liao, X. Ni, and H. Ma, "Low-grade fly ash in portland cement blends : A decoupling approach to evaluate reactivity and hydration effects," *Cement*, vol. 18, no. 9, p. 100119, 2024.
- [7] L. Lam, Y. L. Wong, and C. S. Poon, "Degree of hydration and gel/space ratio of high-volume fly ash/cement systems," *Cem. Concr. Res.*, vol. 30, no. 5, pp. 747–756, 2000.
- [8] C. Herath, C. Gunasekara, D. W. Law, and S. Setunge, "Performance of high volume fly ash concrete

- incorporating additives: A systematic literature review,” *Constr. Build. Mater.*, vol. 258, p. 120606, 2020.
- [9] R. Roychand, S. De Silva, D. Law, and S. Setunge, “High volume fly ash cement composite modified with nano silica, hydrated lime and set accelerator,” *Mater. Struct. Constr.*, vol. 49, no. 5, pp. 1997–2008, 2016.
- [10] C. H. Huang, S. K. Lin, C. S. Chang, and H. J. Chen, “Mix proportions and mechanical properties of concrete containing very high-volume of Class F fly ash,” *Constr. Build. Mater.*, vol. 46, pp. 71–78, 2013.
- [11] T. Matschei, B. Lothenbach, and F. P. Glasser, “The role of calcium carbonate in cement hydration,” *Cem. Concr. Res.*, vol. 37, no. 4, pp. 551–558, 2007.
- [12] R. D. Hooton, M. Nokken, and M. D. . Thomas, *Portland-Limestone Cement : State-of-the-Art Report and Gap Analysis For CSA A 300 0*. University of Toronto, 2007.
- [13] J. Péra, S. Husson, and B. Guilhot, “Influence of finely ground limestone on cement hydration,” *Cem. Concr. Compos.*, vol. 21, no. 2, pp. 99–105, 1999.
- [14] American Society for Testing and Materials, “ASTM C618-19, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,” *Annu. B. ASTM Stand.*, no. C, p. 5, 2019.
- [15] S. S. Alterary and N. H. Marei, “Fly ash properties, characterization, and applications: A review,” *J. King Saud Univ. - Sci.*, vol. 33, no. 6, p. 101536, 2021.
- [16] D. Idam Rifka, *Pembuatan Beton Berbahan Dasar High Volume Fly Ash (HVFA) (dan High Volume Bottom Ash (HVBA) untuk Bahan Rumah*. Institut Teknologi Sepuluh Nopember, 2023.
- [17] F. Havy, *Studi Potensi Pemanfaatan Pasir Silika Limbah Sandblasting sebagai Pengganti Agregat Halus oada Beton High Volume Fly Ash*. Politeknik Perkapalan Negeri Surabaya, 2023.
- [18] SNI-1974, “Cara Uji Kuat Tekan Beton dengan Benda Uji Silinder,SNI 1974-2011,” *Badan Stand. Nas. Indones.*, p. 20, 2011.
- [19] SNI 1972-2008, “Cara Uji Slump Beton,” *Badan Standar Nas. Indones.*, p. 5, 2008.
- [20] F. U. A. Shaikh and S. W. M. Supit, “Mechanical and durability properties of high volume fly ash (HVFA) concrete containing calcium carbonate (CaCO₃) nanoparticles,” *Constr. Build. Mater.*, vol. 70, pp. 309–321, 2014.