Enhancing High Early Compressive Strength of Fly Ash Substituted Concrete through Alkali Activators and Admixtures

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ABSTRACT

The construction industry increasingly demands concrete that can achieve high compressive strength within a short period to accelerate project timelines and improve efficiency. This study aims to develop high early-strength concrete (≥20 MPa within 24 hours) that is both environmentally friendly and workable. The approach involves substituting 30% of ordinary Portland cement (OPC) with fly ash and incorporating alkali activators (a combination of NaOH and Na_2SiO_3) along with a type E admixture (superplasticizer), Sika® ViscoCrete®-1050 HE TH, at 0.3% of the binder weight. Concrete mix designs were calculated using the absolute volume method, with a water-to-cementitious ratio of 0.25. The alkali activator was added at varying dosages: 0%, 2.5%, 5%, and 7.5% of the fly ash weight, with adjustments made to the total water content accordingly. Compressive strength tests were conducted at 24 hours, alongside slump tests to assess workability. Results showed that concrete without alkali activator had the lowest compressive strength at 20.4 MPa. The addition of alkali activators significantly enhanced the compressive strength of the concrete, with the optimum result achieved at 5% alkali activator content, reaching 36.8 MPa–an 84.2% increase compared to the control mix without alkali activator. All mixtures exhibited excellent workability with slump values exceeding 180 mm. This study demonstrates that combining fly ash, alkali activators, and superplasticizers in OPC-based concrete can produce high early-strength concrete with reduced cement usage. The findings offer a promising approach for efficient and sustainable construction practices.

Keywords: fly ash; alkali activator; superplasticizer; OPC; high early strength.

1 INTRODUCTION

Along with the demands of optimization in the construction sector, concrete technology is evolving towards improved performance, time efficiency, cost savings, safety, and sustainability (Yudhistira et al., 2024). In line with that, one of the innovations that is the primary focus in the construction industry is the development of high early compressive strength concrete. This type of concrete is designed with high performance to achieve the required compressive strength in a shorter time than conventional concrete, typically within a few hours to several days. High early-strength concrete can achieve structural concrete quality by completing the requirement of a compressive strength of at least 20 MPa within 24 hours. (Ananyachandran & Vasugi, 2022); (Yasin et al., 2017). High early-strength concrete is indispensable in projects that demand accelerated construction, such as precast elements, precast concrete, emergency repairs, and slipform paving, as it allows for faster removal of formwork without sacrificing compressive strength. This reduction in the time for the removal of formwork contributes significantly to increased productivity and construction cost efficiency (Nilimaa et al., 2023).

However, high early-strength concrete generally contains large amounts of OPC as its primary raw material (Park et al., 2021). The cement production process generates large amounts of carbon dioxide (CO_2) emissions, accounting for approximately 8-9% of global CO_2 emissions (Rissman et al., 2020). Consequently, concrete is less environmentally sustainable and falls short of fully aligning with the sustainability principles essential for optimizing the construction sector.

Various innovations have been developed to address this issue, one of which is substituting part of OPC cement with more environmentally friendly materials, known as supplementary cementitious materials (SCMs). The use of SCMs has been proven effective in reducing carbon emissions in concrete by replacing part or all of the clinker content without reducing the strength or durability of the concrete (Althoey et al., 2023). As part of these efforts, limiting cement use to a maximum of 460 kg/m^3 has also been proposed to reduce clinker consumption, control hydration temperature, and improve material efficiency, thereby supporting decarbonization targets in the construction sector (Mehta & Monteiro, 2006).

One material that is often used as a substitute for OPC cement is fly ash. Fly ash is a finely ground waste product from coal combustion in power plants, emitted from the combustion chamber by exhaust gases (American Coal Ash Association, 2003). Fly ash is a potential alternative in OPC cement substitution due to its high chemical attack resistance and abundant availability as a raw material (Adam, 2019). In addition to reducing OPC cement usage, fly ash can serve as an effort to utilize industrial waste, thereby fulfilling the sustainable aspects of construction materials. The use of fly ash in concrete mixtures is based on its fine particle size, which resembles cement, and its chemical composition, rich in silica and alumina, which supports pozzolanic reactions (Sideris et al., 2018). Through pozzolanic and/or hydraulic reaction mechanisms, fly ash as a cementitious material (SCM) contributes to developing the mechanical properties of hardened concrete (Bhatt et al., 2019). However, concrete with fly ash substitution tends to show a decrease in compressive strength at early ages due to the low pozzolanic reactivity during the initial hydration phase (Golewski, 2022).

To overcome the low initial compressive strength of concrete with fly ash substitution, several studies have explored the use of alkali activators such as NaOH and Na_2SiO_3 as well as the addition of admixtures in the form of superplasticizers. Research by Cornelis et al. (2018) showed that a geopolymer paste based on Class C fly ash with an alkali-to-fly ash (A) ratio of 0.4 and 14M NaOH could achieve a compressive strength of 35 MPa at 3 days. Unlike geopolymer systems that entirely replace water, the alkali activator in this study was used in limited quantities to enhance the pozzolanic reactivity of fly ash in the OPC cement hydration system. This combination is expected to effectively accelerate the formation of hydration compounds, thereby improving the compressive strength of concrete at an early age. Research by Amin et al. (2022) noted that OPC and fly ash hybrid concrete with a 70:30 ratio, supplemented with a combination of NaOH and Na_2SiO_3 alkali activators (ratio 2.75; 14 M), achieved a compressive strength of 46.2 MPa at 3 days. Another study supports this, where the use of a combination of alkali activators TEA, $Ca(OH)_2$, and Na_2SiO_3 can increase the compressive strength of the paste with 50% fly ash substitution to reach 24 MPa at 3 days (Sun et al., 2020). Meanwhile, another study showed that mortar with 50% fly ash substitution and 0.5 M NaOH alkali activator achieved a compressive strength of 13.8 MPa at 3 days and increased by 45.8% at 28 days compared to the control mortar (Chalee et al., 2021).

In addition to using alkali activators, superplasticizers can also affect the early performance of concrete, particularly the workability of fresh concrete mixtures. Research by Nikoloutsopoulos et al. (2021) shows that concrete with a combination of 30% fly ash, alkali activator, and superplasticizer can achieve a maximum compressive strength of up to 43.8 MPa in just 3 days. Another study also reported similar results, which noted that polycarboxylate-type superplasticizers exhibit good stability in OPC-based concrete systems with fly ash and alkali activator (NaOH and Na_2SiO_3) substitution. This combination can increase slump by up to 45% and produce compressive strength of up to 81.3 MPa in 3 days (Nematollahi & Sanjayan, 2014).

Based on the aforementioned background, this study aims to investigate the effect of incorporating fly ash, alkali activator, and type E admixture (superplasticizer) into concrete mixtures to achieve a minimum compressive strength of 20 MPa within 24 hours (high early strength) while maintaining a slump value of 18–20 cm to ensure workability, and limits cement content to a maximum of 460 kg/m^3 to reduce carbon emissions and enhance material efficiency. The study seeks to develop environmentally friendly concrete with a high early compressive strength that meets the technical standards for rapid construction practices.

2 METHOD

2.1 Material

2.1.1 Cementitious Material

The primary material used in this study was Portland cement type 1 (OPC) with the brand name Dynamix Sprint Pro, produced by PT. Semen Indonesia and meeting the criteria of SNI 15-2049-2004. Low-calcium fly ash from the Suralaya Power Plant was used as a partial cement substitute. The chemical composition of the fly ash was analyzed using X-ray fluorescence (XRF), as shown in Table 1. Based on the analysis results, the fly ash used was classified as Class F fly ash according to ASTM C618-22 standards, with a total oxide content of $SiO_2 + Al_2O_3 + Fe_2O_3$ exceeding 50% (79.01%) and a CaO content of 11.60%. Based on previous trials, the fly ash-to-OPC cement ratio used in the mixture was 30:70 based on the weight of cementitious materials.

Tabel 1. Result of XRF testing of fly ash.

Parameter	Result (%)
SiO_2	47,20
Al_2O_3	21,00
Fe_2O_3	10,81
CaO	11,60
MgO	4,60
SO_3	0,77
K_2O	0,88
Na_2O	1,55
MnO	0,19
TiO_2	0,13
P_2O_5	0,20
CI	0,076
LOI	1,10

Source: PT. Solusi Bangun Indonesia

2.1.2 Alkali Aktivator

The alkali activator used in this study is a combination of sodium silicate (Na_2SiO_3) solution and sodium hydroxide (NaOH) solution. The sodium hydroxide solution was prepared by dissolving 98.5% pure NaOH flakes in aquades. The concentration of the NaOH solution was set at 10M. Based on previous research, the ratio of sodium silicate to sodium hydroxide (R) was set at 2.0, while the ratio of alkali to cement (A) was 0.35 (Cornelis et al., 2018). The percentage of the alkali activator solution was varied at 0%, 2.5%, 5%, and 7.5% relative to the weight of fly ash, and the amount of alkali activator was reduced from the amount of water used.

2.1.3 Admixture

The admixture used in this study is a superplasticizer with the product Sika® ViscoCrete®-1050 HE TH yang diproduksi oleh PT. Sika Indonesia. produced by PT. Sika Indonesia. This superplasticizer is classified as an E-type admixture according to ASTM C494-04 standards, designed to enhance the workability of concrete mixtures and support the achievement of high early compressive strength. Based on trial-and-error testing during the initial testing phase, the percentage of superplasticizers used in this study was set at 0.3% of the total cementitious materials.

2.1.4 Aggregate

In this study, the aggregates used consisted of fine and coarse aggregates. The fine aggregate used was a combination of silica sand from Tayan, with a percentage of 70%, and optimum sand from Rumpin, Bogor, with a percentage of 30%. The coarse aggregate used came from Rumpin, Bogor, with a size of 10-20 mm, according to the requirements of SNI 03-2834-2000. The specifications of the aggregates used can be seen in Table 2.

Tabel 2. Results of aggregate characteristic tests.

Parameter	Silica Sand	Optima Sand	Split 10/20
Finess modulus (FM)	2,498	3,28	6,774
Spesific gravity (SG)	2,66	2,53	2,58
Absorption (%)	0,4	2,04	2,08
Material finer than < 200 micron (%)	1	2,3	1,7
Unit weight (ton/m^3)	1,39	1,43	1,48
Organic impurities	No. 5	No. 1	-
Los Angeles (%)	-	-	17,88

Source: PT. Solusi Bangun Indonesia

2.2 Material Preparation, Mixing, and Workability Testing

Sodium hydroxide (NaOH) solution with a concentration of 10M is prepared by dissolving NaOH flakes in aquadest until the final volume reaches 1 liter. The amount of NaOH flakes required can be calculated using Equation (1). After the dissolution process, the solution is left to rest for 24 hours at room temperature to ensure temperature stability and solution homogeneity before being used in the concrete mixing process.

$$M = \frac{mass\ of\ NaOH\ flakes}{Mr} \times \frac{1000}{V} \quad (1)$$

where M is the desired molarity of NaOH (mol/L), Mr is the molar mass of NaOH (40 g/mol), 1000 is the volume conversion factor from mL to L, and V is the volume of solution to be made (mL).

The concrete mixing process was conducted using a mixer. The procedure began with a dry mixing of OPC and fly ash until a homogeneous mix was achieved. Subsequently, the superplasticizer previously dissolved in water was added and mixed for ± 2 minutes to ensure even distribution. The alkali activator solution was added to the mixture. At this stage, the mixture typically exhibited a temporary increase in viscosity; however, continuing mixing for approximately 3 minutes restored a fluid and homogeneous consistency. The fine aggregate was added, followed by the coarse aggregate, in the established mixing sequence.

The fresh concrete was immediately subjected to a slump test specified in SNI 1972:2008 to determine its workability properties. This test was performed on each variable of the concrete mixture. The fresh concrete was then cast into cylindrical molds measuring 100 mm in diameter and 200 mm in height, with three specimens prepared for each mix variation. All specimens were cured at room temperature under ambient laboratory conditions until testing.

2.3 Compressive Strength Test

Testing was conducted 24 hours after casting to determine the early-age compressive strength. Three concrete specimens represented each mix variation, and the average compressive strength of these specimens was reported as the final test result. The tests were carried out according to SNI 1974-2011 standard using a Compressive Testing Machine with a maximum capacity of 2000 kN. The compressive strength of concrete was calculated using Equation (2).

$$f'_c = \frac{P}{A} \quad (2)$$

where f'_c is compressive strength (MPa), P is the maximum load applied at failure (N), and A is the area of the cross-section of the test specimen (mm^2).

2.4 Mix Design

Mix design of paste, mortar, and concrete using the absolute volume method based on research by Satyarnoa et al. (2014). Mix design using the absolute volume method was carried out to determine the proportions of paste, mortar, and concrete mix ingredients and their total solid volume in $1m^3$.

2.4.1 Mix Design of Paste

The mixed design of the paste mixture based on absolute volume can be calculated using Equation (3).

$$V_c + V_{fa} + V_{sv} + V_{ac} + V_w = 1m^3 \quad (3)$$

where V_c is the absolute volume of cement, V_{fa} is the absolute volume of fly ash, V_{sv} is the absolute volume of superplasticizer, V_{ac} is the absolute volume of alkali activator, and V_w is the absolute volume of water.

A fly ash-to-OPC ratio of 30:70 by weight was used based on the trial mix. The water-to-cementitious material ratio (FAS_m) was fixed at 0.25. The superplasticizer dosage was determined by weight as a percentage of the total cementitious content (OPC + fly ash). Based on the findings of Cornelis et al. (2018), the sodium hydroxide (NaOH) concentration was set at 10 M, with a Na_2SiO_3-to-NaOH weight ratio (R) of 2.0, and an alkali activator-to-binder ratio (A) of 0.35. The percentage of alkali activators used was calculated based on the weight of fly ash, and the amount of alkali activators was subtracted from the amount of water used. The calculation can be performed using Equation (4).

$$\frac{(1-X)W_{cm}}{G_{sc}\,\gamma_w}+\frac{XW_{cm}}{G_{sfa}\,\gamma_w}+\frac{YW_{cm}}{G_{ssv}\,\gamma_w}+\frac{(FAS_m-ZAX)W_{cm}}{G_{sw}\,\gamma_w}+\frac{ZAXW_{cm}}{G_{sac}\,\gamma_w}=1m^3 \quad (4)$$

where W_{cm} is the weight of cementitious, G_{sc} is the specific gravity of cement, G_{sfa} is the specific gravity of fly ash, G_{ssv} is the specific gravity of superplasticizer, G_{sw} is the specific gravity of water, G_{sac} is the specific gravity of alkali activator, γ_w is the unit weight of water, X is the mass of *fly ash*, Y is the mass of superplasticizer, dan Z is the percentage of alkali activator.

2.4.2 Mix Design of Mortar

The analysis of mortar mix composition is based on the composition of the paste mix. The mortar mix calculation is related to the mortar ratio (R_m), which is the ratio between the absolute volume of paste (V_p) and the absolute volume of fine aggregate voids (V_{ragh}). The absolute volume of fine aggregate voids (V_{ragh}) in 1m^3 can be figured using Equation (5). A mortar ratio (R_m) of 1.4 was selected based on trial-and-error adjustments, as it provided the most optimal consistency. This value is consistent with the findings of Cornelis, Priyosulistyo, & Satyarno (2018).

$$V_{ragh}=1-\frac{B_{sagh}}{G_{sagh}\gamma_w} \quad (5)$$

where V_{ragh} is the absolute volume of fine aggregate voids, B_{sagh} is the unit weight of fine aggregate, and Gsagh is the specific gravity of fine aggregate.

Once V_{ragh} is determined, the total mortar mixture in 1m^3 can be calculated using Equation (6). Subsequently, the weight of fine aggregate (W_{agh}) can be obtained based on that volume using Equation (7).

$$\frac{(1-X)W_{cm}}{G_{sc}\,\gamma_w}+\frac{XW_{cm}}{G_{sfa}\,\gamma_w}+\frac{YW_{cm}}{G_{ssv}\,\gamma_w}+\frac{(FAS_m-ZAX)W_{cm}}{G_{sw}\,\gamma_w}+\frac{ZAXW_{cm}}{G_{sac}\,\gamma_w}=V_{ragh}R_m \quad (6)$$

$$V_{ragh}R_m=1-\frac{W_{agh}}{G_{sagh}\gamma_w}=1m^3 \quad (7)$$

2.4.3 Mix Design of Concrete

The mix design of concrete is calculated based on the mix design of paste and mortar. The concrete mix calculation is related to the concrete ratio (R_b), which is the ratio between the absolute volume of mortar (V_m) and the absolute volume of coarse aggregate voids (V_{ragk}). Based on findings of Cornelis et al. (2022), a concrete ratio (R_b) 1.4 was used, as it provided the most optimal consistency. The absolute volume of coarse aggregate voids in 1m^3 can be determined using Equation (8).

$$V_{ragk}=1-\frac{B_{sagk}}{G_{sagk}\gamma_w} \quad (8)$$

where V_{ragk} is the absolute volume of coarse aggregate voids, B_{sagk} is the weight of coarse aggregate voids, and G_{sagk} is the specific gravity of coarse aggregate voids.

Once Vr_{agk} is determined, the total concrete mixture in 1m^3 can be calculated using Equation (9).

$$\frac{(1-X)W_{sm}}{G_{sc}\,\gamma_w}+\frac{XW_{cm}}{G_{sfa}\,\gamma_w}+\frac{YW_{sm}}{G_{ssv}\,\gamma_w}+\frac{(FAS_m-Z0{,}35X)W_{sm}}{G_{sw}\,\gamma_w}+\frac{Z0{,}35\,XW_{cm}}{G_{sac}\,\gamma_w}=V_{ragh}R_mV_{ragk}\,R_b \quad (9)$$

The weight of fine aggregate (W_{agh}) can be determined using Equation (10), while the weight of coarse aggregate (W_{agk}) can be calculated using Equation (11).

$$V_{ragh}R_mV_{ragk}\,R_b+\frac{W_{agh}}{G_{sagh}\gamma_w}=V_{ragk}\,R_b \quad (10)$$

$$V_{ragk}R_b=1-\frac{W_{agk}}{G_{sagk}\gamma_w}=1m^3 \quad (11)$$

The concrete mix design for 1m^3 can be seen in the Table 3, and the concrete mix material requirements for three specimens can be seen in the Table 4.

Tabel 3. The concrete mix design for 1m^3.

Material	B-AF0	B-AF2.5	B-AF5	B-AF7.5
OPC (kg/m^3)	454.6	455.3	456.0	456.7
Fly Ash (kg/m^3)	194.9	195.1	195.4	195.7
Water (kg/m^3)	162.4	160.9	159.4	158.0
Superplasticizer (kg/m^3)	1.9	2.0	2.0	2.0
Alkali activator (kg/m^3)	0	1.7	3.4	5.1
Fine Aggregate (kg/m^3)	545.8	545.8	545.8	545.8
Coarse Aggregate (kg/m^3)	1040.0	1040.0	1040.0	1040.0
Total	2399.5	2400.8	2402.0	2403.3

Tabel 4. Concrete mix material requirements.

Material	B-AF0	B-AF2.5	B-AF5	B-AF7.5
OPC (g)	2676.4	2680.5	2684.7	2688.9
Fly Ash (g)	1147.0	1148.8	1150.6	1152.4
Water (g)	955.8	947.3	938.7	930.1
Superplasticizer (g)	11.5	11.5	11.5	11.5
Alkali activator (g)	0	10.1	20.1	30.2
Fine Aggregate (g)	3213.4	3213.4	3213.4	3213.4
Coarse Aggregate (g)	6123.0	6123.0	6123.0	6123.0
Total	14127.1	14134.5	14142.0	14149.5

3 RESULT AND DISCUSSION

3.1 Workability

The addition of alkali activators significantly influences the characteristics of fresh concrete, as illustrated in Figure 1. Fresh concrete exhibits low viscosity in the control mix without an alkali activator, resulting in segregation in the form of a separation between paste and aggregate, as shown in Figure 1a. As the concentration of the alkali activator increases, the homogeneity of the fresh concrete mixture improves, and segregation can be minimized. At a 2.5% addition of the alkali activator, the fresh concrete mixture shows better homogeneity with reduced segregation, as shown in Figure 1b. The fresh concrete mixture with 5% alkali activator addition shows the most optimal homogeneity and consistency across all mixture variations, while retaining its flowable nature due to a superplasticizer, as shown in Figure 1c. Subsequently, adding a 7.5% alkali activator caused an increase in mixture viscosity, slightly reducing workability. Nevertheless, the mix remains homogeneous and stable, with no visible signs of segregation, as shown in Figure 1d.

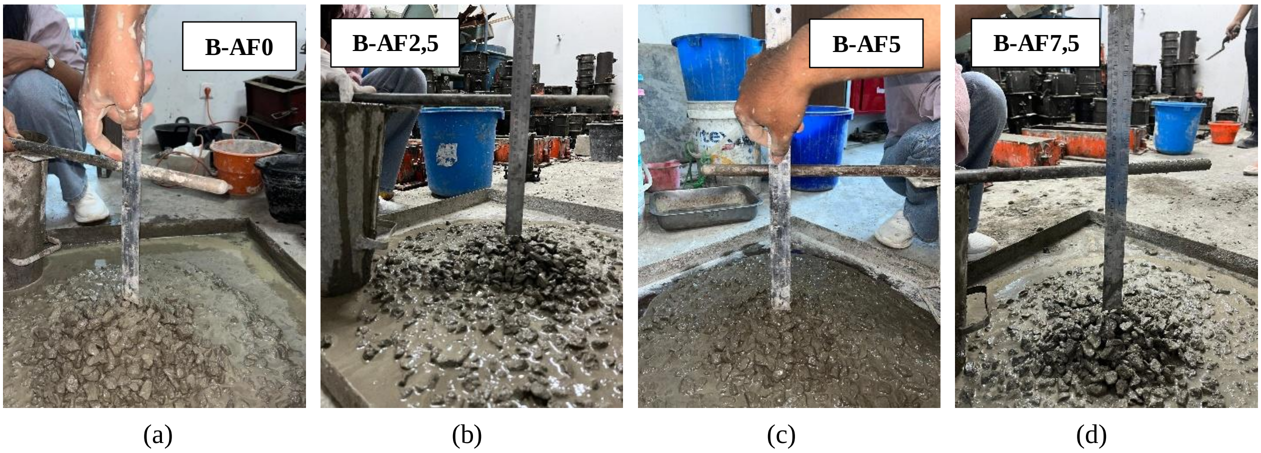

Figure 1. Concrete slump test result (a) concrete mixture without alkali activator; (b) concrete mixture with 2.5% alkali activator; (c) concrete mixture with 5% alkali activator; (d) concrete mixture with 7,5% alkali activator.

All concrete mix variations in this study showed slump values exceeding 180 mm, above the target workability range of 180-200 mm. Based on concrete workability classification, these slump values fall into the very high workability category, suitable for precast concrete or prestressed concrete, both in architectural and structural elements (Daczko, 2012; Neville, 2011). Figure 2 shows the effect of alkali activator percentage on slump values in concrete mixtures with alkali activator variations of 0%, 2.5%, 5%, and 7.5%. Adding an alkali activator to concrete mixtures increases the slump value. Adding a 2.5% alkali activator to the concrete mixture results in a 5.13% increase in slump value compared to concrete without an alkali activator. A more significant increase in slump value occurs with adding a 5% alkali activator, amounting to 15.38%. However, when the percentage of the alkali activator was increased to 7.5%, the slump value only increased by 10.26% compared to concrete without the alkali activator. The results of this study indicate that increasing the percentage of alkali activators does not necessarily lead to a proportional increase in slump value. This behavior is attributed to the increased viscosity of the mixture at higher alkali activator dosages, which leads to a thicker consistency and, consequently, a reduction in the slump value (Gaurav et al., 2023). These research results align with previous studies, which noted that concrete mixtures with high alkali activator concentrations exhibit a decrease in slump value due to increased mixture viscosity (M, 2025).

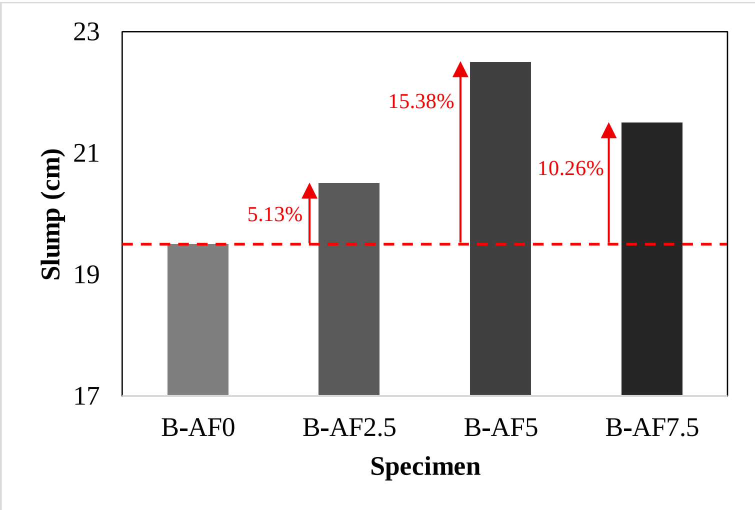

Figure 2. Comparison of the percentage of alkali activator to the slump value.

3.2 Compressive Strength

The condition of the concrete after 24 hours of curing at room temperature is presented in Figure 3. The control concrete, without the addition of an alkali activator, exhibited visible porosity due to segregation during mixing, where paste and aggregates separated, as shown in Figure 3a. In contrast, concrete with the addition of alkali activators appeared more homogeneous and stable, with no signs of porosity. At a 2.5% alkali activator dosage as shown in Figure 3b, the concrete showed a more uniform and intact surface, indicating improved cohesion and reduced segregation. A 5% addition of alkali activator, as shown in Figure 3c, resulted in the concrete achieving the most compact and smooth surface among all variations, indicating enhanced mixture stability and binder-aggregate interaction. Concrete with the addition of 7.5% alkali activator still shows good homogeneity, although its surface is slightly rougher due to increased mixture viscosity, as shown in Figure 3d. All specimens were prepared for compressive strength testing to evaluate early-age mechanical performance.

(a) (b)

(c) (d)

Figure 3. The condition of the concrete after 24 hours of curing (a) concrete without alkali activator; (b) concrete with 2.5% alkali activator; (c) concrete with 5% alkali activator; (d) concrete with 7.5% alkali activator.

All concrete mix variations in this study satisfied the criteria for high early compressive strength concrete, defined as achieving a compressive strength of ≥ 20 MPa at 24 hours (Ananyachandran & Vasugi, 2022). Concrete without an alkali activator resulted in the lowest compressive strength of 20.4 MPa at 24 hours, only 2.2% higher than the requirement. This result is due to the low cohesion in the fresh concrete mix, which results in segregation and the formation of voids during the hardening process, thus reducing the density and compressive strength of the concrete (Neville, 2011).

The addition of an alkali activator at 2.5% increases the compressive strength to 32.7 MPa, or an increase of 63.5% from the requirements of high early-strength concrete. Meanwhile, adding a 5% alkali activator produced the highest compressive strength of 36.8 MPa or an increase of 84.2% from the requirements of high early-strength concrete. This result is due to the combination of NaOH and Na2SiO3, which accelerates the dissolution of silica and alumina from fly ash and the initial hydration of cement, forming gels C–S–H and N–A–S–H that strengthen the microstructure at an early age (Jiao et al., 2025).

However, with the addition of a 7.5% alkali activator, the compressive strength decreased to 28.8 MPa, although this value is still 44.1% higher than the minimum limit of compressive strength of high-early strength concrete. This decrease is attributed to the excess of alkali ions that increase viscosity and form coarse gels and secondary crystalline phases that inhibit the formation of C–S–H (Behfarnia et al., 2017). The complete results of compressive strength testing of concrete with various activators at 24 hours of age are shown in the Table 5 dan Figure 4.

Tabel 5. Results of compressive strength testing of concrete with various activators at 24 hours of age.

Specimen ID	Age (hours)	Compressive strength (MPa)	Average of compressive strength (MPa)
B-AF0	24	20.09	20.4
	24	20.80	
	24	18.98	
B-AF2.5	24	31.31	32.7
	24	31.91	
	24	34.85	
B-AF5	24	34.97	36.8
	24	38.93	
	24	36.62	
B-AF7.5	24	26.85	28.8
	24	25.43	
	24	34.20	

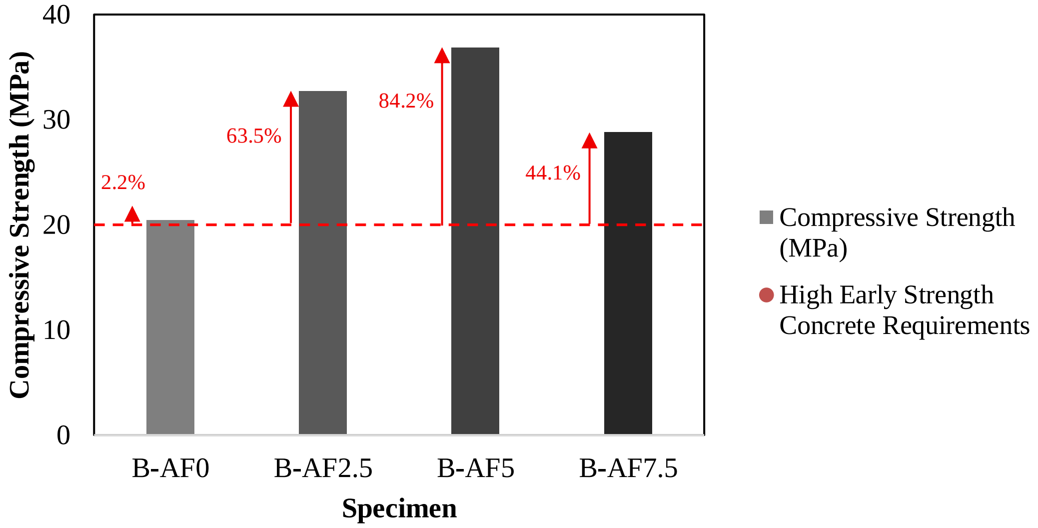

Figure 4. Results of compressive strength testing of concrete with various activators at 24 hours of age.

Thus, although all mix variations met the minimum requirement for high early-strength concrete, alkali activators significantly enhanced concrete performance, enabling compressive strength values to exceed the threshold. These findings highlight that combining fly ash substitution, alkali activators, and admixtures in OPC-based concrete presents a promising approach for producing high early-strength concrete with strong potential for advancing future concrete technology. However, it is important to note that the dosage of alkali activators must be carefully controlled, as excessive amounts may adversely affect the density and mechanical properties of the concrete. Therefore, maintaining an optimal balance is essential to maximize performance without compromising material quality.

4 CONCLUSION

All concrete mix variations tested showed slump values greater than 180 mm, which is classified as very high workability. The combination of 30% fly ash substitution to OPC cement, the addition of an alkali activator, and the use of Sika® ViscoCrete®-1050 HE TH admixture proved effective in meeting the criteria of high early strength concrete with compressive strength exceeding 20 MPa at 24 hours. The concrete mix achieved the most optimal formulation by adding a 5% alkali activator, which produced the highest compressive strength of 36.8 MPa, or an increase of up to 82.4% from the requirements of high-early strength concrete. In addition to providing superior mechanical performance, the combination of fly ash substitution, alkali activator, and admixtures also reduced the use of OPC cement to <460 kg/m^3 for each mix. It contributes to material efficiency in concrete production and produces more environmentally friendly concrete.

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REFERENCE

Adam, A. A. (2019). The Effects of Water to Solid Ratio, Activator to Binder Ratio, and Lime Proportion on the Compressive Strength of Ambient-Cured Geopolymer Concrete. *Journal of the Civil Engineering Forum*, *5*(2), 161. https://doi.org/10.22146/jcef.43878

Althoey, F., Ansari, W. S., Sufian, M., & Deifalla, A. F. (2023). Advancements in low-carbon concrete as a construction material for the sustainable built environment. *Developments in the Built Environment*, *16*. https://doi.org/10.1016/j.dibe.2023.100284

American Coal Ash Association. (2003). *Fly Ash Facts for Highway Engineers*. https://www.fhwa.dot.gov/pavement/recycling/fafacts.pdf

American Society for Testing and Materials. (2004). *ASTM C494-04 Standard Specification for Chemical Admixture for Concrete*.

American Society for Testing and Materials. (2022). *ASTM C618-22 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. ASTM International. https://doi.org/10.1520/C0618-22

Amin, M., Elsakhawy, Y., Abu el-hassan, K., & Abdelsalam, B. A. (2022). Behavior evaluation of sustainable high strength geopolymer concrete based on fly ash, metakaolin, and slag. *Case Studies in Construction Materials*, *16*. https://doi.org/10.1016/j.cscm.2022.e00976

Ananyachandran, P., & Vasugi, V. (2022). Development of a sustainable high early strength concrete incorporated with pozzolans, calcium nitrate and triethanolamine: An experimental study. *Sustainable Energy Technologies and Assessments*, *54*. https://doi.org/10.1016/j.seta.2022.102857

Badan Standar Nasional Indonesia. (2008). *SNI 1972-2008 Uji Slump*.

Badan Standardisasi Nasional. (2004). *SNI 15-2049-2004 Semen Portland*.

Badan Standardisasi Nasional. (2011). Cara Uji Kuat Tekan Beton dengan Benda Uji Silinder,SNI 1974-2011. *Badan Standardisasi Nasional Indonesia*.

Behfarnia, K., Taghvayi Yazeli, H., & Khalili Khasraghi, M. B. (2017). AUT Journal of Civil Engineering The Effect of Alkaline Activator on Workability and Compressive Strength of Alkali-Activated Slag Concrete. *Civil Eng*, *1*(1), 55–60. https://doi.org/10.22060/ceej.2017.12375.5190

Bhatt, A., Priyadarshini, S., Acharath Mohanakrishnan, A., Abri, A., Sattler, M., & Techapaphawit, S. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review. *Case Studies in Construction Materials*, *11*. https://doi.org/10.1016/j.cscm.2019.e00263

Chalee, W., Soeurt, R., Pachana, P., & Songpiriyakij, S. (2021). Improvement of High-Volume Fly Ash Cementitious Material Using Single Alkali Activation. *International Journal of Concrete Structures and Materials*, *15*(1). https://doi.org/10.1186/s40069-021-00482-9

Cornelis, R., Priyosulistyo, H., & Satyarno, I. (2018). *Workability and Strength Properties of Class C Fly Ash-Based Geopolymer Mortar*. https://doi.org/10.1051/matecconf/20192

Cornelis, R., Priyosulistyo, H., Satyarno, I., & Rochmadi. (2018). The Investigation on Setting Time and Strength of High Calcium Fly Ash Based Geopolymer. *Applied Mechanics and Materials*, *881*, 158–164. https://doi.org/10.4028/www.scientific.net/amm.881.158

Cornelis, R., Priyosulityo, H., Satyarno, I., Rochmadi, & Rustendi, I. (2022). Effect of the Mortar Volume Ratio on the Mechanical Behavior of Class CI Fly Ash-Based Geopolymer Concrete. *Civil Engineering Journal (Iran)*, *8*(9), 1920–1935. https://doi.org/10.28991/CEJ-2022-08-09-012

Daczko, J. A. (2012). *THE EFFECTIVE USE OF A NOVEL WORKABILITY-RETAINING ADMIXTURE IN PRECAST/PRESTRESSED CONCRETE PRODUCTION*.

Gaurav, G., Kandpal, S. C., Mishra, D., & Kotoky, N. (2023). A comprehensive review on fly ash-based geopolymer: a pathway for sustainable future. In *Journal of Sustainable Cement-Based Materials* (Vol. 13, Issue 1, pp. 100–144). Taylor and Francis Ltd. https://doi.org/10.1080/21650373.2023.2258122

Golewski, G. L. (2022). The Role of Pozzolanic Activity of Siliceous Fly Ash in the Formation of the Structure of Sustainable Cementitious Composites. *Sustainable Chemistry*, *3*(4), 520–534. https://doi.org/10.3390/suschem3040032

Jiao, Z., Zhang, S., Wang, Y., Dong, Z., & Lu, Z. (2025). Influence of fly ash content on pore structure regulation in alkali-activated slag under alkaline conditions. *Construction and Building Materials*, *485*. https://doi.org/10.1016/j.conbuildmat.2025.141863

M, M. M. (2025). Preliminary Investigation of the Material Properties of Metakaolin Based Geopolymer Concrete (MKGPC) Using NaOH and Na2SiO3 as an Activator. *UNIZIK Journal of Engineering and Applied Sciences*, *5*(1), 2086–2097.

Mehta, P. K., & Monteiro, P. J. M. (2006). *Concrete : Microstructurem Properties, and Materials*. https://doi.org/http://dx.doi.org/10.1036/0071462899

Nematollahi, B., & Sanjayan, J. (2014). Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer. *Materials and Design*, *57*, 667–672. https://doi.org/10.1016/j.matdes.2014.01.064

Neville, A. M. (2011). *Neville - properties of concrete*. Pearson Education Limited.

Nikoloutsopoulos, N., Sotiropoulou, A., Kakali, G., & Tsivilis, S. (2021). Physical and mechanical properties of fly ash based geopolymer concrete compared to conventional concrete. *Buildings*, *11*(5). https://doi.org/10.3390/buildings11050178

Nilimaa, J., Gamil, Y., & Zhaka, V. (2023). Formwork Engineering for Sustainable Concrete Construction. *CivilEng*, *4*(4), 1098–1120. https://doi.org/10.3390/civileng4040060

Park, S., Wu, S., Liu, Z., & Pyo, S. (2021). The role of supplementary cementitious materials (Scms) in ultra high performance concrete (uhpc): A review. In *Materials* (Vol. 14, Issue 6). MDPI AG. https://doi.org/10.3390/ma14061472

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., … Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. In *Applied Energy* (Vol. 266). Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2020.114848

Satyarnoa, I., Solehudina, A. P., Meyartoa, C., Hadiyatmokoa, D., Muhammada, P., & Afnana, R. (2014). Practical method for mix design of cement-based grout. *Procedia Engineering*, *95*, 356–365. https://doi.org/10.1016/j.proeng.2014.12.194

Sideris, K., Justnes, H., Soutsos, M., & Sui, T. (2018). Fly ash. In *RILEM State-of-the-Art Reports* (Vol. 25, pp. 55–98). Springer Netherlands. https://doi.org/10.1007/978-3-319-70606-1_2

Standardisasi, B., & Bsn, N. (2000). *SNI 03-2834-2000 : Tata cara pembuatan rencana campuran beton normal*.

Sun, G., Tang, Q., Zhang, J., & Liu, Z. (2020). Early activation of high volume fly ash by ternary activator and its activation mechanism. *Journal of Environmental Management*, *267*. https://doi.org/10.1016/j.jenvman.2020.110638

Yasin, A. K., Bayuaji, R., & Susanto, T. E. (2017). A review in high early strength concrete and local materials potential. *IOP Conference Series: Materials Science and Engineering*, *267*(1). https://doi.org/10.1088/1757-899X/267/1/012004

Yudhistira, A. T., Satyarno, I., Nugroho, A. S. B., & Handayani, T. N. (2024). Effect of Construction Delays and the Preventive Role of Concrete Works Optimization: Systematic Literature Review. *TEM Journal*, *13*(2), 1203–1217. https://doi.org/10.18421/TEM132-34