# The impact of calcium hydroxide addition on HVFA mortar and concrete properties

*Adrian Joener Pratom*o Ringu[1], *Evan* Andreas[1], *Antoni* Antoni[2*], and *Djwantoro* Hardjito[2]

[1]Graduate Program of Civil Engineering, Petra Christian University, Jl. Siwalankerto No 121-131, Surabaya, Indonesia
[2]Department of Civil Engineering, Petra Christian University, Jl. Siwalankerto No 121-131, Surabaya, Indonesia

**Abstract.** Fly ash, a by-product of coal combustion, can be used as a cement substitute. High-volume fly ash (HVFA) concrete refers to fly ash substituting more than 50% of the cement. Previous research has indicated a decrease in compressive strength with an increase in fly ash content. Moreover, HVFA concrete exhibits low early strength due to the limited availability of calcium hydroxide resulting from cement hydration, which is insufficient to drive the pozzolanic reaction. This study, therefore, introduces additional calcium hydroxide to the mixture to react with class C and F fly ash in HVFA concrete. The fly ash replaces 50% and 60% of the Portland cement by mass, and the study investigates the impact of adding calcium hydroxide at 10%, 20%, and 30% of the fly ash content by mass. The addition of calcium hydroxide to the HVFA concrete mixture resulted in decreased workability and accelerated initial setting time. However, this addition did not influence the early strength of the mortar and concrete. Interestingly, it was found that the compressive strength at 28 and 56 days increased with the increase in calcium hydroxide content. The increase in later-age strength was more pronounced in HVFA concrete with class F fly ash, which can be attributed to the enhanced availability of calcium hydroxide, thereby facilitating the pozzolanic reaction.

## 1 Introduction

Cement industries currently contribute an estimated 7% to 8% of global greenhouse emissions [1]. In 2020 alone, Indonesian cement industries produced 33.8 million tons of carbon dioxide emissions. Therefore, there is a pressing need for alternatives, such as fly ash, to substitute for cement. According to Indonesia's Government Regulation No. 22-2021, fly ash, a waste product from coal combustion in power plants, has been removed from the dangerous and poisonous materials list. Concurrently, data from the Indonesian Entrepreneur Association indicate that coal combustion waste, which includes fly ash and bottom ash, reached 10-15 million tons [2]. These conditions suggest a significant potential for utilizing fly ash produced from power plants in Indonesia. However, fly ash currently replaces less than 50% of cement.

The quality of fly ash depends on the quality of the coal and the combustion process in power plants. As per ASTM C618-22, fly ash is categorized into classes N, C, and F [3]. Class C fly ash contains more than 18% CaO in its total composition, while class F contains less than 18% CaO. Class C fly ash exhibits both pozzolanic and cementitious properties, while class F fly ash is only pozzolanic.

Fly ash from pulverized coal combustion power plants possesses round and smooth particles, making the concrete mix more workable and requiring less water than normal concrete. High-volume fly ash concrete (HVFA), where fly ash substitutes more than 50% of cement, has low early strength due to the slow pozzolanic reaction [4]. However, its compressive strength gradually increases as fly ash reacts with the calcium hydroxide produced during cement hydration [5-9]. Optimal compressive strength is achieved when fly ash substitutes between 20% and 40% of the Portland cement [10-11]. But when the substitution exceeds 50%, the compressive strength does not continue to increase [12-18].

In HVFA concrete mixes, the calcium hydroxide derived from Portland cement hydration is insufficient for the pozzolanic reaction. Thus, the addition of external calcium hydroxide could be necessary [19]. Produced from the calcination of calcium carbonate and converted into calcium hydroxide by the slaking process, calcium hydroxide is a strong alkaline often used as an additive for fly ash mixes [20–23]. It can also be used in the form of lime water [24-26]. In this study, calcium hydroxide in powder form is added to the HVFA mortar and concrete. The fly ash used was sourced from Paiton and Pacitan, Sudimoro power plants, both located in East Java, Indonesia. Notably, the Sudimoro power plant, a new source of fly ash, has the potential for use as a binder for construction material but has yet to be widely utilized in the construction industry [27]. This research evaluates the impact of adding calcium hydroxide to the mixture on superplasticizer demands, the initial setting time of the mortar mixture,

*Corresponding author: antoni@petra.ac.id

and the compressive strength development of the HVFA mortar and concrete.

## 2 Experimental method

### 2.1 Materials

The fly ash used in this research originated from two power plants: one in Paiton, Probolinggo, East Java, and the other in Sudimoro, Pacitan, East Java, Indonesia. The fly ash from the Paiton power plant had a pH of 12, a normal consistency of 0.18, and a specific gravity of 2.62. Meanwhile, the fly ash from the Sudimoro power plant had a pH of 10.5, a normal consistency of 0.17, and a specific gravity of 2.61. The results of the X-Ray Fluorescence (XRF) analysis for both types of fly ash are displayed in Table 1. According to ASTM C618-22, the Paiton fly ash is categorized as class C due to its CaO content being higher than 18%, while the Sudimoro fly ash, with its lower CaO content, is categorized as class F [3].

**Table 1.** Fly ash composition from XRF analysis.

| Chemical Composition | FA P (Paiton) (%) | FA S (Sudimoro) (%) |
|---|---|---|
| $SiO_2$ | 25.45 | 40.8 |
| $Al_2O_3$ | 7.75 | 13.25 |
| $Fe_2O_3$ | 31.25 | 25.25 |
| CaO | **25.95** | **13.9** |
| MgO | 1.25 | 0.5 |
| $K_2O$ | 1.375 | 1.845 |
| $TiO_2$ | 1.2 | 1.555 |
| $MnO_2$ | 0.265 | 0.305 |
| $P_2O_5$ | 0.505 | 0.83 |
| $SO_3$ | 0.55 | 1.5 |
| BaO | 0.475 | 0.25 |

The Portland cement used in this study was Ordinary Portland Cement (OPC), sourced from PT Solusi Bangunan. Calcium hydroxide ($Ca(OH)_2$) was obtained by processing calcium oxide from a local quarry in Tuban, East Java, Indonesia. Silica sand, with a fineness modulus of 2.053, was used as fine aggregate for mortars. For the concrete, sand from Lumajang and crushed limestone with a 2.5 cm nominal diameter were used. The superplasticizer used was the polycarboxylate-based Sika Viscocrete 1003.

### 2.2 Mixture composition

The compositions of the mortars and concretes in this research included mixes with varying fly ash and $Ca(OH)_2$ content. The binder was composed of cement and fly ash, with the fly ash replacing 50% and 60% of the Portland cement by mass. Water-to-binder ratios were set at 0.3 for the mortar and 0.4 for the concrete mixtures.

The $Ca(OH)_2$ powder was added to the mortar mixture at 0%, 10%, 20%, and 30% of the fly ash by mass. For the concrete mixture, $Ca(OH)_2$ was added at 0%, 20%, and 30% by mass of the fly ash. The mix designs for the mortar and concrete mixtures, applicable for both class C and F fly ash, are shown in Table 2 and Table 3, respectively. The class C fly ash from the Paiton power plant is denoted as "P," while the class F fly ash from Sudimoro is represented by "S." The concrete mixture is marked as "B" to distinguish it from the mortar mix designs.

The superplasticizer demand was determined as the dosage required to achieve the target workability, defined as a diameter of 15±1 cm in the flow table test for mortar and a slump of 9±1 cm for concrete.

The initial setting time was assessed using a penetrometer, with the mortar cast in 15×15×15 $cm^3$ molds. The penetrometer was inserted one inch deep into the mixes, and the initial setting time was recorded when the penetration stress reached 500 psi (3.45 MPa).

For the compressive strength test, mortar samples were made in 5×5×5 $cm^3$ cubes, and concrete samples were fashioned into cylinders with a diameter of 10 cm and a height of 20 cm. Compressive strength tests were conducted at 7, 28, and 56 days, with three samples tested on each day.

**Table 2.** Mix designs of Paiton (P) and Sudimoro (S) HVFA mortar with a variation of FA content and the addition of $Ca(OH)_2$.

| Code | w/b | Water (g) | Cement (g) | Fly Ash (g) | $Ca(OH)_2$ (g) | Fine Aggregate (g) |
|---|---|---|---|---|---|---|
| P/S50-0 | 0.3 | 90 | 150 | 150 | 0 | 600 |
| P/S50-10 | | | | | 15 | |
| P/S50-20 | | | | | 30 | |
| P/S50-30 | | | | | 45 | |
| P/S60-0 | 0.3 | 90 | 120 | 180 | 0 | 600 |
| P/S60-10 | | | | | 18 | |
| P/S60-20 | | | | | 36 | |
| P/S60-30 | | | | | 54 | |

**Table 3.** Mix design of Paiton (P) and Sudimoro (S) HVFA concrete with a variation of FA content and the addition of $Ca(OH)_2$.

| Code | w/b | Water ($kg/m^3$) | Cement ($kg/m^3$) | Fly ash ($kg/m^3$) | $Ca(OH)_2$ ($kg/m^3$) | Fine Aggregates ($kg/m^3$) | Coarse Aggregates ($kg/m^3$) |
|---|---|---|---|---|---|---|---|
| BP/BS50-0 | 0.4 | 195.0 | 243.8 | 243.8 | 0.0 | 761.5 | 934.6 |
| BP/BS50-20 | | | | | 48.8 | | |
| BP/BS50-30 | | | | | 73.1 | | |
| BP/BS60-0 | 0.4 | 195.0 | 195.0 | 292.5 | 0.0 | 757.7 | 929.9 |
| BP/BS60-20 | | | | | 58.5 | | |
| BP/BS60-30 | | | | | 87.8 | | |

## 3 Results and discussions

### 3.1 Superplasticizer demand

This study maintained a minimal water-to-binder ratio (w/b) to curb excessive bleeding in the mixture resulting from high fly ash content. A w/b of 0.3 was used for mortars, while a ratio of 0.4 was employed for the concrete mixture. Fig. 1 demonstrates the superplasticizer demand needed to achieve the desired workability for Paiton (P) and Sudimoro (S) fly ash with varying additions of $Ca(OH)_2$. The results indicate that a higher dosage of superplasticizer was necessary for higher $Ca(OH)_2$ content to achieve the target workability. Similar outcomes were observed for both Paiton and Sudimoro fly ash concretes, as shown in Fig. 2. The diminished workability of the mortar and concrete mixture with the addition of calcium hydroxide was anticipated, as the $Ca(OH)_2$ powder absorbs free water in the mixture due to the irregular shape of the calcium hydroxide particles. The findings suggest that controlling the mixture's workability with a superplasticizer rather than additional water is more effective.

### 3.2 Initial setting time

The initial setting time test results are displayed in Fig. 3. Adding $Ca(OH)_2$ accelerates the initial setting time. In the Paiton fly ash mortar mixture without added $Ca(OH)_2$, the initial setting time reaches 300 and 320 minutes for 50% and 60% fly ash substitution, respectively. However, when calcium hydroxide is added at 30% of the total fly ash, the initial setting time decreases to 105 minutes for both mixes with fly ash substituting 50% and 60% of cement. The same trend was observed for the Sudimoro fly ash mortar mixtures. The higher the $Ca(OH)_2$ content, the faster the initial setting time becomes. The result indicates that a high-volume fly ash mixture reacts more quickly when more $Ca(OH)_2$ is available in the fresh mixture.

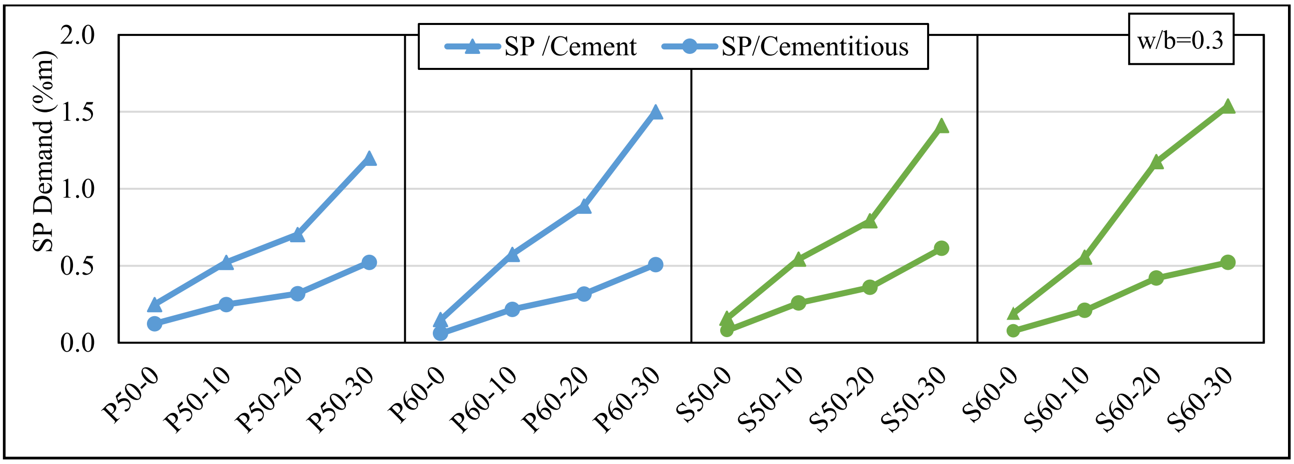


**Fig. 1.** HVFA mortars superplasticizer demand for flow table test with a target diameter of 15 ± 1 cm.

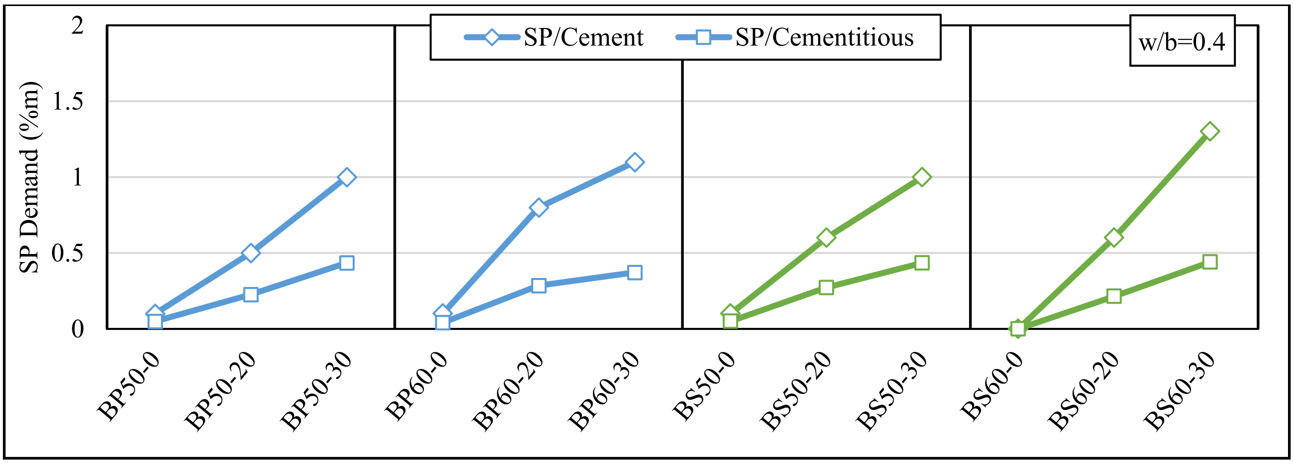


**Fig. 2.** HVFA concretes superplasticizer demand for a target slump of 9 ± 1 cm.

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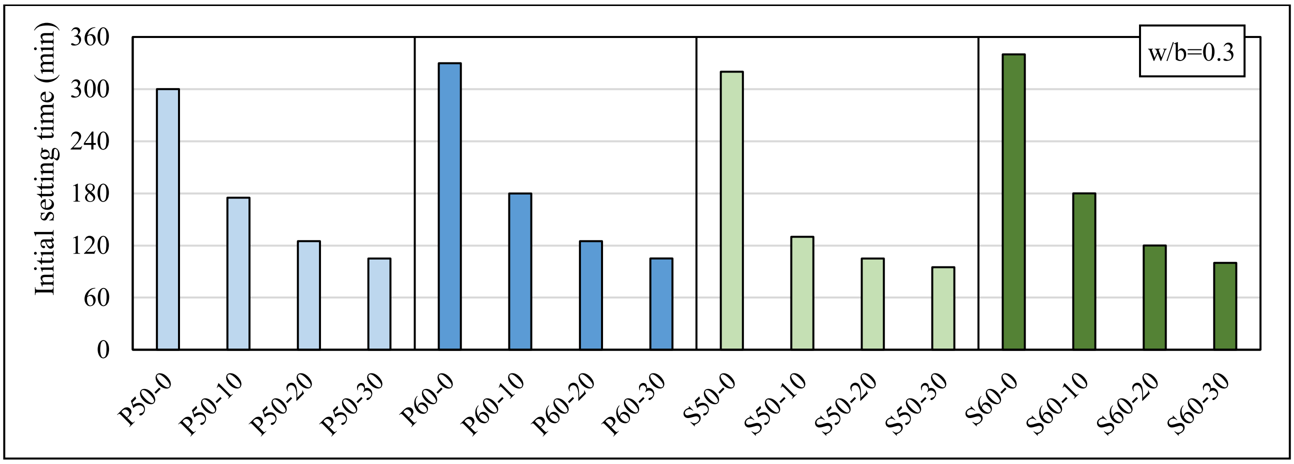


**Fig. 3.** Initial setting time of HVFA mortar mixes.

### 3.3 Compressive strength development

The effects of calcium hydroxide addition on the compressive strength development of the mortar and concrete mixture, specifically on class C fly ash from Paiton and class F fly ash from Sudimoro, are presented in Fig. 4 and Fig. 5, respectively. The compressive strength data shown in these figures is an average of three samples. Adding calcium hydroxide to HVFA mortar and the concrete mixture could increase the later-age compressive strength, with the highest strength obtained when calcium hydroxide was added up to 30% by mass of fly ash to the HVFA mixture. The lower strength of the HVFA concrete mixture was expected since it used a higher water-to-binder ratio of 0.4 for concrete. However, the influence of calcium hydroxide addition on the mixture is similar.

In mortars and concretes using Paiton fly ash (Fig. 4), the resulting compressive strength increased up to 30% of calcium hydroxide addition, but the increase was minor compared to mortar and concrete without calcium hydroxide. This trend could be due to the fly ash originating from the Paiton power plant, which is class C fly ash with high calcium oxide content. The results indicate that when the fly ash has sufficient active calcium compound in the mixture, the positive influence of calcium hydroxide is not extensive.

However, calcium hydroxide addition significantly affects the compressive strength development of HVFA mortar and concrete mixture with class F Sudimoro fly ash. Sudimoro fly ash is classified as intermediate calcium fly ash while Paiton fly ash is classified as high calcium fly ash. The high calcium content in Paiton fly ash verifying that Paiton fly ash has self-cementing properties [28].

Adding calcium hydroxide up to 30% increases the compressive strength compared with the control mixture. The compressive strength gain was especially noticeable from the 7 to 28-day compressive tests. A substantial strength increase was observed for both fly ash replacement ratios, although the final strength is still lower for mixtures with 60% fly ash replacing the Portland cement. The highest compressive strength produced was 71.33 MPa at 56 days for a 50% fly ash replacement ratio with 30% of calcium hydroxide addition.

Contrary to the study's hypothesis, the addition of calcium hydroxide did not affect the early-age compressive strength. In some mixtures with calcium hydroxide, the 7-day compressive strength was lower than that of the control HVFA mortar and concrete due to decreased workability because of the addition of calcium hydroxide. However, the later-age compressive strength remained comparable to the control HVFA mixture.

At a 60% mass of fly ash replacing the Portland cement, it was found that the class C fly ash could still produce a comparable compressive strength to the 50% mixture. This result showed that the class C fly ash has a hydraulic reaction besides the pozzolanic reaction. The class F fly ash showed that the compressive strength was reduced with the higher percentage of fly ash replacement to the Portland cement. The 60% HVFA mixtures have consistently lower strength than the 50% ones for the Sudimoro fly ash, and the impact of calcium hydroxide addition was shown more on the class F Sudimoro fly ash mixture.

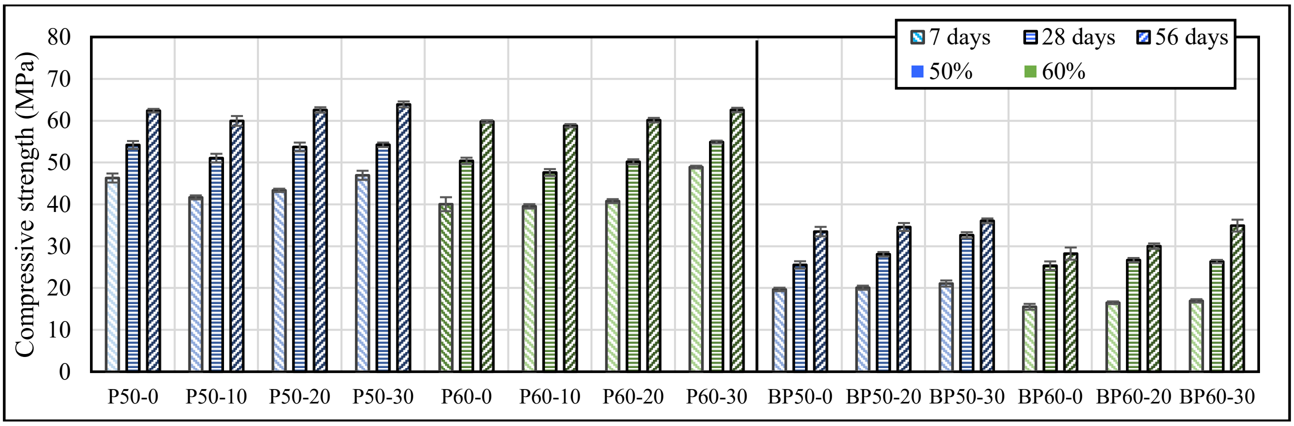


**Fig. 4.** Compressive strength of the Paiton fly ash for the HVFA mortar and concrete specimens.

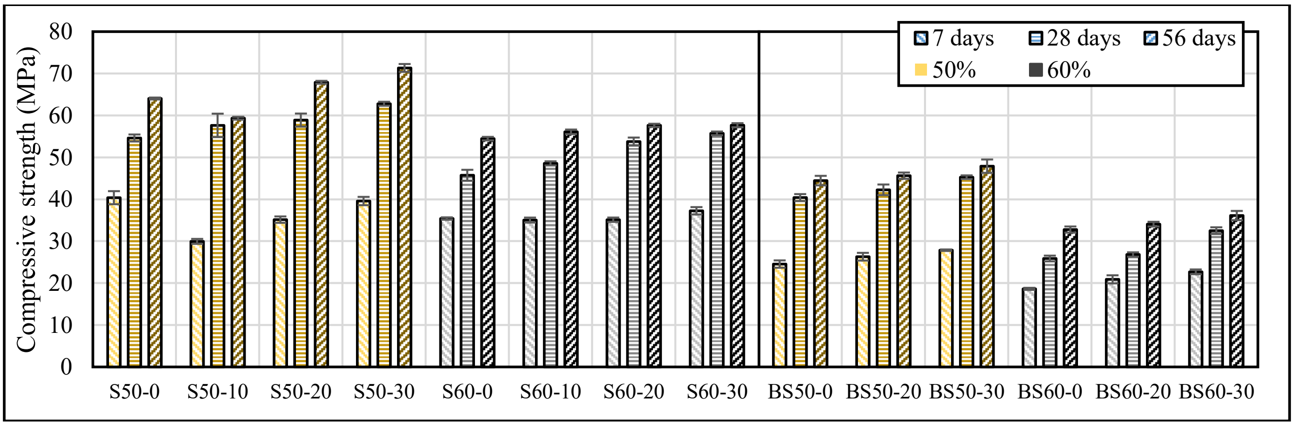


**Fig. 5.** Compressive strength of the Sudimoro fly ash for the HVFA mortar and concrete specimens.

## 4 Conclusions

- Integrating calcium hydroxide into the High Volume Fly Ash (HVFA) mortar and concrete formulations demonstrates the potential to enhance their long-term compressive strength relative to the control HVFA mixture. With the addition of calcium hydroxide at a level of 30%, an appreciable increase in compressive strength was observed, ranging between 7 to 10%.
- While the early-stage compressive strength at seven days remained unaffected with the addition of calcium hydroxide due to the relatively slower pace of the pozzolanic reaction compared to the hydration reaction, a substantial surge was noted in the compressive strength of HVFA mortar and concrete within the 7 to 28-day interval, directly attributable to the inclusion of calcium hydroxide.
- The implementation of calcium hydroxide proved especially beneficial for class F fly ash, given its inherently low calcium content. Class C fly ash, on the other hand, already possesses a sufficient calcium hydroxide supply stemming from the hydration of Portland cement and the inherent content of the fly ash, thereby rendering the rate of strength development increment less noticeable.
- The introduction of calcium hydroxide into the mixture led to a reduction in the workability of both mortar and concrete, as evidenced by an increased demand for superplasticizer commensurate with the calcium hydroxide content.
- Calcium hydroxide addition was found to significantly hasten the initial setting times for both mortar and concrete. A higher proportion of calcium hydroxide corresponded to accelerated initial setting times. Thus, in field applications where a faster setting time for the concrete mixture is a prerequisite, the use of calcium hydroxide could be considered an advantageous strategy.

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