

Mix Design and Performance Study of Early-Strength Concrete based on Orthogonal Experiment

Linchuan Li¹, Xiang Wang²

¹ School of Linchuan, Liaoning Petrochemical University, Fushun, Liaoning, China

² School of Xiang Liaoning Petrochemical University, Fushun, Liaoning 113001, China

Abstract

To investigate the influence mechanism of C-S-H nano-nuclei on the early strength of high-performance concrete in which fly ash partially replaces cement, this study employed an orthogonal experimental method to systematically explore the synergistic effects of three key factors-fly ash content, nano-C-S-H nuclei content, and curing age-on the mechanical properties of early-strength concrete. A four-level, three-factor orthogonal experimental design (L16(4³)) was adopted, with a total of 17 groups of concrete specimens prepared. Their compressive strength, splitting tensile strength, and elastic modulus were tested at different ages ranging from 4 hours to 7 days. Through range analysis and mean comparison, the primary and secondary influence order of each factor on the performance indicators, as well as the variation patterns, were clarified. The results indicate that curing age is the most significant factor affecting the compressive strength, splitting tensile strength, and elastic modulus of early-strength concrete, followed by the content of nano-C-S-H nuclei, while the influence of fly ash content is relatively weaker. As the fly ash content increases (10%–40%), the early compressive strength of concrete shows a slow declining trend. The appropriate incorporation of nano-C-S-H nuclei (2%–4%) can significantly enhance early strength, but excessive addition may lead to a reduction in strength. With the extension of curing time, all mechanical properties improve markedly. Based on comprehensive performance analysis, the optimal mix proportion for early-strength concrete is determined as 20% fly ash content, 2% nano-C-S-H nuclei content, and 7 days of curing. Verification shows that, compared to the reference group without supplementary materials, the optimized group exhibits increases of 19% in compressive strength, 33.3% in splitting tensile strength, and 8% in elastic modulus, demonstrating excellent early-strength performance and engineering applicability. This study quantitatively analyzes the effects of material proportioning and curing regime on the early mechanical behavior of concrete under a dual-admixture system through orthogonal experiments, providing experimental evidence and theoretical references for the mix design and performance regulation of early-strength concrete.

Keywords

Orthogonal Experiment, C-S-H Crystals, Concrete, Compressive Strength, Splitting Tensile Strength, Elastic Modulus.

1. Introduction

Improving the early strength of concrete not only shortens curing time and accelerates construction progress but also effectively enhances construction quality and saves costs, making it a key performance target for many concrete projects[1]. Currently, methods such as steam/autoclave curing can be employed to improve early strength; however, these methods consume significant thermal energy, emit harmful gases causing pollution[2], and are not

suitable for cast-in-place concrete in low-temperature environments. Adding hardening accelerators to shorten setting time is another common technical approach.

Existing research shows[3-4] that calcium silicate hydrate (C-S-H) crystal seeds, as a cement hardening accelerator, can not only accelerate cement hydration and effectively improve the early strength of cement paste but also ensure the development of later-age strength, with pronounced effects. Domestic and international studies also indicate that fly ash[5-12], as a silico-aluminous inorganic mineral material, can improve the internal structure of cement paste when incorporated in appropriate amounts, thereby influencing its engineering properties. However, excessive fly ash content reduces cement quantity and the generation of hydration products, severely impacting the early strength of cement paste. Nano C-S-H crystals can compensate for the slow early strength development caused by fly ash incorporation. The key to achieving early strength characteristics lies in the optimal proportion and synergistic optimization of the two materials. Organization of the Text.

Given this, this study adopts a dual-incorporation approach, using orthogonal experiment to investigate the effects of different mineral admixture contents, specifically crystal nuclei (0%, 2%, 4%, 10%), fly ash content (10%, 20%, 30%, 40%), and curing age (4h, 1d, 3d, 7d), on the compressive strength, splitting tensile strength, and elastic modulus of early-strength concrete, and identifies the optimal mix proportion.

2. Experimental Overview

2.1. Raw Materials

Cement: P042.5R grade cement, apparent density 3000 kg/m³.

Fly Ash: Grade II fly ash, loss on ignition 2.7%, moisture content 1%, SO₃ content 2.6%, fineness (residue on 45 μm sieve) 18%, water demand ratio 93%, apparent density 2448 kg/m³.

Hardening Accelerator: Nano C-S-H crystals.

Fine Aggregate: River sand, fineness modulus 2.52, silt content 1.9%, bulk density 1530 kg/m³.

Coarse Aggregate: Crushed stone, particle size 5-25 mm, bulk density 1550 kg/m³.

Water Reducer: Polycarboxylate-based high-performance water reducer, water reduction rate 30%.

Water: Tap water.

2.2. Mix Design

This experiment employed an orthogonal experimental design L₁₆/4-7/ (4³) to investigate crystal nuclei (0%, 2%, 4%, 10%), fly ash content (10%, 20%, 30%, 40%, by mass of binder materials), and curing age (4h, 1d, 3d, 7d), resulting in a total of 17 experimental groups, including one control group. The factor levels for the orthogonal experiment are shown in Table 1, and the experimental plan is in Table 2. After trial mixing and adjustments, the reference concrete mix proportion was designed according to JGJ 55-2011 "Specification for Mix Proportion Design of Ordinary Concrete", details are shown in Table 3.

Table 1. Orthogonal test factor level table

Level	Factor		
	Fly Ash A/%	Crystal B/%	Curing Age C/d
1	10%	0	4h
2	20%	2%	1d
3	30%	4%	3d
4	40%	10%	7d

Table 2. Orthogonal text program

No.	Fly Ash A/%	Crystal B/%	Curing Age C/d
A ₁ -B ₁ -C ₁	10%	0%	4h
A ₁ -B ₂ -C ₂	10%	2%	1d
A ₁ -B ₃ -C ₃	10%	4%	3d
A ₁ -B ₄ -C ₄	10%	10%	7d
A ₂ -B ₁ -C ₂	20%	0%	1d
A ₂ -B ₂ -C ₁	20%	2%	4h
A ₂ -B ₃ -C ₄	20%	4%	7d
A ₂ -B ₄ -C ₃	20%	10%	3d
A ₃ -B ₁ -C ₃	30%	0%	3d
A ₃ -B ₂ -C ₄	30%	2%	7d
A ₃ -B ₃ -C ₁	30%	4%	4h
A ₃ -B ₄ -C ₂	30%	10%	1d
A ₄ -B ₁ -C ₄	40%	0%	7d
A ₄ -B ₂ -C ₃	40%	2%	3d
A ₄ -B ₃ -C ₂	40%	4%	1d
A ₄ -B ₄ -C ₁	40%	10%	4h

Table 3. Basic mix proportions of concrete

Exp. No.	Cement /(kg·m ⁻³)	Fly Ash /(kg·m ⁻³)	Crystals /(kg·m ⁻³)	Water /(kg·m ⁻³)	Coarse Agg./ (kg·m ⁻³)	Fine Agg./ (kg·m ⁻³)	Water Reducer /(kg·m ⁻³)
A ₀ -B ₀ -C ₀	324	0	0	130	1200	655	3.6
A ₁ -B ₁ -C ₁	324	36	0	130	1200	655	3.6
A ₁ -B ₂ -C ₂	324	36	0.048	130	1200	655	3.6
A ₁ -B ₃ -C ₃	324	36	0.120	130	1200	655	3.6
A ₁ -B ₄ -C ₄	324	36	0.240	130	1200	655	3.6
A ₂ -B ₁ -C ₂	288	48	0	130	1200	655	3.6
A ₂ -B ₂ -C ₁	288	48	0.048	130	1200	655	3.6
A ₂ -B ₃ -C ₄	288	48	0.120	130	1200	655	3.6
A ₂ -B ₄ -C ₃	288	48	0.240	130	1200	655	3.6
A ₃ -B ₁ -C ₃	252	108	0	130	1200	655	3.6
A ₃ -B ₂ -C ₄	252	108	0.048	130	1200	655	3.6
A ₃ -B ₃ -C ₁	252	108	0.120	130	1200	655	3.6
A ₃ -B ₄ -C ₂	252	108	0.240	130	1200	655	3.6
A ₄ -B ₁ -C ₄	216	144	0	130	1200	655	3.6
A ₄ -B ₂ -C ₃	216	144	0.048	130	1200	655	3.6
A ₄ -B ₃ -C ₂	216	144	0.120	130	1200	655	3.6
A ₄ -B ₄ -C ₁	216	144	0.240	130	1200	655	3.6

2.3. Testing Equipment and Methods

Compressive strength, splitting tensile strength, and elastic modulus of concrete: Tests were conducted in accordance with JTG 3420-2020 "Test Methods of Cement and Concrete for Highway Engineering". Specimen dimensions were 100mm×100mm×100mm for compressive

strength, 100mm×100mm×100mm for splitting tensile strength, and 150mm×150mm×300mm for elastic modulus. A total of 17 groups were prepared, with 6 specimens per group, totaling 102 specimens. After standard curing, mechanical property tests were performed using a TAW-2000 pressure testing machine with a maximum load of 2000 kN, employing stress-controlled loading. Loading rates were 0.8 MPa/s for compressive strength, 0.08 MPa/s for splitting tensile strength, and 0.4 MPa/s for elastic modulus. Considering that the compressive test specimens did not meet standard size specifications, the measured compressive strength was multiplied by a conversion factor of 0.95, as shown in Figure 1.



(a) Concrete Mixing



(b) Concrete Vibration



(c) Compressive Strength Test



(d) Splitting Tensile Strength Test

Figure 1. Schematic Diagram of Concrete Test Specimen Preparation and Testing

3. Results and Analysis

Table 4 shows the performance test results of early-strength concrete.

Table 4. Test results

No.	Comp. Strength /MPa	Split. Streng /MPa	Elastic Modulus /GPa
A ₀ -B ₀ -C ₀	20	1.4	24.5
A ₁ -B ₁ -C ₁	1.1	0.1	0.3
A ₁ -B ₂ -C ₂	8.5	0.6	0.4
A ₁ -B ₃ -C ₃	12.1	0.8	4.1
A ₁ -B ₄ -C ₄	22	1	22.8
A ₂ -B ₁ -C ₂	3.6	0.5	1.8
A ₂ -B ₂ -C ₁	2.7	0.2	1.0
A ₂ -B ₃ -C ₄	18	1.3	26.9
A ₂ -B ₄ -C ₃	9.4	0.8	3.8
A ₃ -B ₁ -C ₃	8.8	1.1	2.7
A ₃ -B ₂ -C ₄	23.8	1.7	17.8
A ₃ -B ₃ -C ₁	1.6	0.2	1.3
A ₃ -B ₄ -C ₂	1.9	0.3	2.4
A ₄ -B ₁ -C ₄	13.2	1.7	15.3
A ₄ -B ₂ -C ₃	15.2	0.8	14.7
A ₄ -B ₃ -C ₂	2.5	0.3	2.5
A ₄ -B ₄ -C ₁	0.3	0.2	0.2

3.1. Range Analysis of Compressive Strength

The range analysis results for compressive strength of early-strength concrete are shown in Table 5.

From Table 5, it can be seen that the order of influence of factors on the compressive strength of early-strength concrete is: Curing Age C > Crystal Nuclei B > Fly Ash A. The optimal combination is $A_1B_2C_3$.

Table 5. Range analysis results of compressive strength

Item	Fly AshA	Crystal NucleiB	Curing AgeC
k1	10.925	6.675	1.425
k2	8.425	12.550	4.125
k3	9.025	8.550	11.375
k4	7.800	8.400	19.250
R	2.500	5.875	15.125

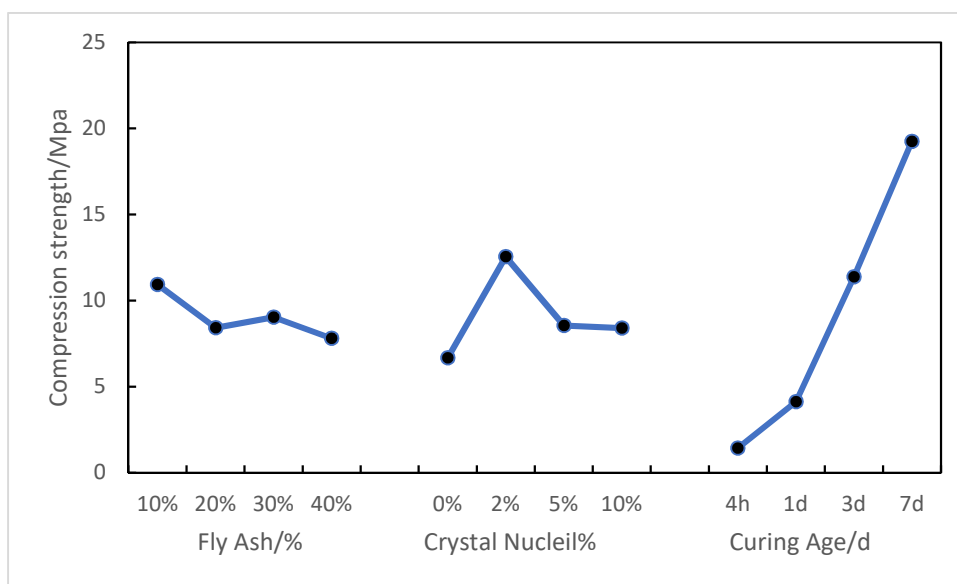


Figure 2. Mean compressive strength by factor level

From Figure 2, it can be observed that as the fly ash content increases from 10% to 40%, the compressive strength of early-strength concrete decreases, albeit slowly. With increasing crystal nuclei content, the compressive strength initially increases slightly and then decreases. This is because, at an appropriate dosage, crystal nuclei can compensate for the adverse effects of fly ash on compressive strength. As the curing age increases from 4h to 7 days, the compressive strength of early-strength concrete increases significantly. Analysis: (1) Fly ash has low early-age activity (slow pozzolanic reaction) and cannot effectively contribute to strength in the early stages (several hours to 7 days). It replaces part of the cement, effectively diluting the binder system, leading to reduced early hydration products and therefore slower strength development. However, its benefits may include improved workability, reduced heat of hydration, and enhanced long-term strength. (2) Crystal nuclei provide a "template" or "seed" for the formation of cement hydration products (e.g., C-S-H gel), significantly accelerating the hydration process. At appropriate dosages, this acceleration can compensate for or even surpass the strength loss caused by adding fly ash.

3.2. Range Analysis of Splitting Tensile Strength

The range analysis results for splitting tensile strength of early-strength concrete are shown in Table 6.

Table 6. Range analysis result of flexural strength

Item	Fly AshA	Crystal NucleiB	Curing AgeC
k1	0.625	0.850	0.175
k2	0.700	0.825	0.425
k3	0.825	0.650	0.875
k4	0.750	0.575	1.425
R	0.200	0.275	1.250

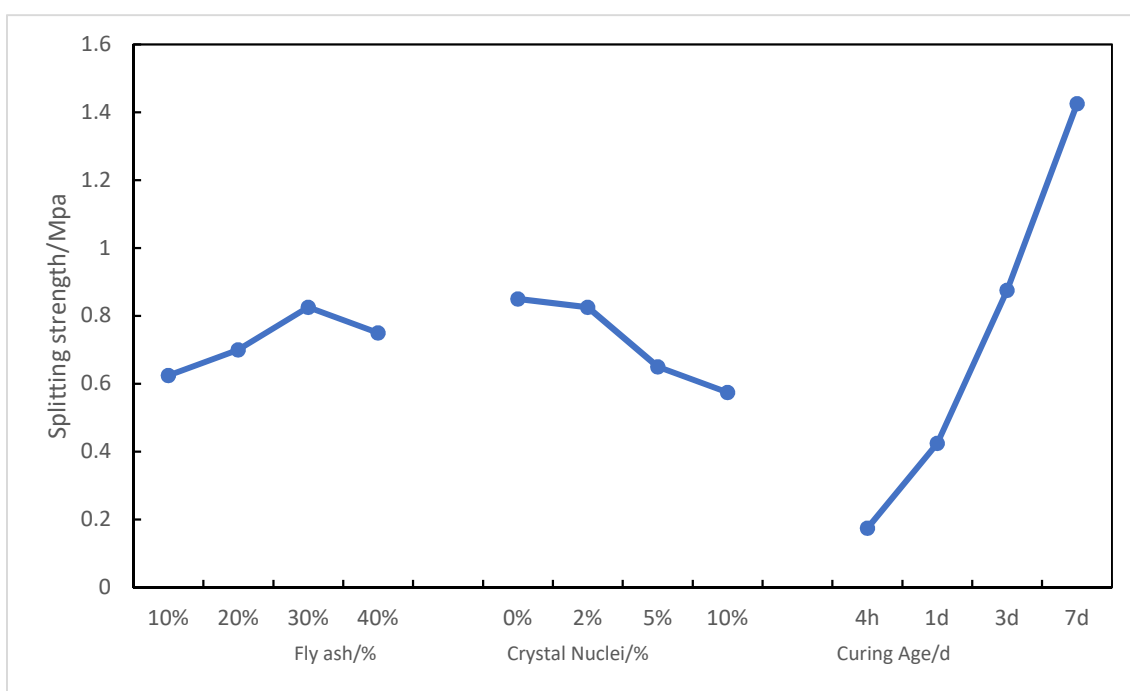


Figure 3. Mean splitting strength by factor level

From Table 6, it can be seen that the order of influence of factors on the splitting tensile strength of early-strength concrete is: Curing Age C > Crystal Nuclei B > Fly Ash A. The optimal combination is A₃B₁C₃.

From Figure 3, it can be observed that as fly ash content increases from 10% to 40%, the splitting tensile strength of early-strength concrete first increases and then decreases. This is because, at an appropriate dosage, the contribution of fly ash to splitting tensile strength outweighs the negative impact of reduced cement content. With increasing crystal nuclei content, the splitting tensile strength gradually decreases, albeit slowly. This suggests that a small amount of crystal nuclei has a minor effect on the splitting tensile strength of concrete. As curing age increases from 4h to 7 days, the splitting tensile strength of early-strength concrete increases.

3.3. Range Analysis of Elastic Modulus

The range analysis results for elastic modulus of early-strength concrete are shown in Table 7.

Table 7. Range analysis results of elastic modulus

Item	Fly AshA	Crystal NucleiB	Curing AgeC
k1	6.900	5.025	0.700
k2	8.375	8.475	1.775
k3	6.050	8.700	6.325
k4	8.175	7.300	20.700
R	2.325	3.675	20.000

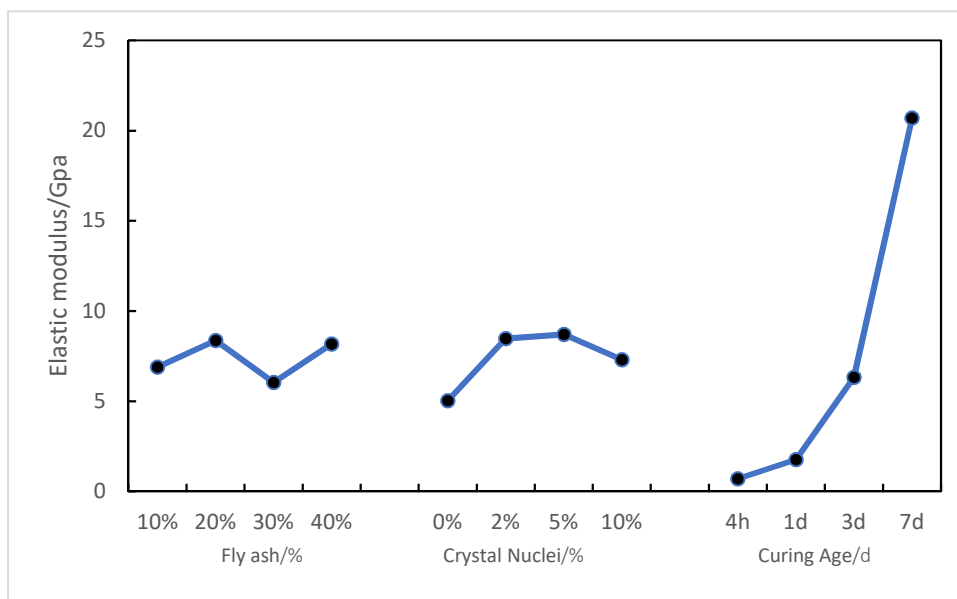


Figure 4. Mean elastic modulus by factor level

From Table 7, it can be seen that the order of influence of factors on the elastic modulus of early-strength concrete is: Curing Age C > Crystal Nuclei B > Fly Ash A. Generally, a smaller elastic modulus indicates greater deformation under external force. The optimal combination is A₂B₃C₄.

From Figure 4, it can be observed that as fly ash content increases from 10% to 40%, the elastic modulus of early-strength concrete fluctuates. With increasing crystal nuclei content, the elastic modulus first increases and then decreases. As curing age increases from 4h to 7 days, the elastic modulus of early-strength concrete increases.

In summary, considering both strength and toughness comprehensively, this experiment recommends the optimal mix proportion combination for early-strength concrete as A₂B₂C₄ (curing age 7 days), corresponding to crystal nuclei 2% and fly ash content 20%.

3.4. Validation of Optimized Solution

A comparison of performance test results between optimized and non-optimized early-strength concrete formulations is shown in Table 8.

Table 8. Performance comparison between optimized and non-optimized early-strength concrete formulations based on experimental results

No.	Comp. Strength /MPa	Split. Strength /MPa	Elastic Modulus /GPa
A ₀ -B ₀ -C ₀	19.25	1.4	20
A ₂ -B ₂ -C ₄	23.8	2.1	26.9

From Table 8, it can be seen that for the $A_2B_2C_4$ group of early-strength concrete specimens cured for 7 days, the compressive strength was 23.8 MPa, splitting tensile strength was 2.1 MPa, and elastic modulus was 26.9 GPa. Compared to the non-optimized group, these values represent improvements of 19%, 33.3%, and 8% respectively, indicating good strength and toughness, meeting the requirements for early-strength performance concrete.

4. Conclusion

Based on orthogonal experiment, this study quantified the synergistic effects of C-S-H crystal nuclei and fly ash content on the early-age mechanical properties of concrete, ultimately optimizing an ideal mix proportion that balances early strength and supplementary cementitious material utilization. The main conclusions are as follows.

- (1) The order of influence of factors on the compressive strength of early-strength concrete is: curing age > crystal nuclei > fly ash. The order for splitting tensile strength is: curing age > crystal nuclei > fly ash. The order for elastic modulus is: curing age > crystal nuclei > fly ash.
- (2) As fly ash content increases from 10% to 40%, the compressive strength of early-strength concrete decreases slowly. The splitting tensile strength first increases and then decreases, while the elastic modulus fluctuates. With increasing crystal nuclei content, the compressive strength and elastic modulus initially increase slightly and then decrease; the splitting tensile strength gradually decreases slowly. As curing age increases from 4h to 7 days, the compressive strength, splitting tensile strength, and elastic modulus of early-strength concrete all increase.
- (3) Considering both strength and toughness comprehensively, this experiment recommends the optimal mix proportion combination for early-strength concrete as $A_2B_2C_4$ (curing age 7 days), corresponding to crystal nuclei 2% and fly ash content 20%. After optimization, the compressive strength is 23.8 MPa, splitting tensile strength is 2.1 MPa, and elastic modulus is 26.9 GPa. Compared to the non-optimized group, these represent improvements of 19%, 33.3%, and 8% respectively, demonstrating good toughness and meeting the requirements for early-strength performance concrete.

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