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Self-Healing Effects of Silica Fume and Quicklime on Microcracks in Cement-Based Materials

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ABSTRACT

To improve the self-healing ability of microcracks in cement-based materials, this study took fly ash mortar designed according to the mix ratio of C35 hydraulic concrete as the reference, added silica fume and quicklime, and conducted multi-factor experiments. Focusing on two environments: standard curing and water immersion curing, it explored the effects of mineral admixtures on the microcrack repair, mechanical properties and impermeability of cement-based self-healing materials, analyzed the repair mechanism, and focused on the role of 7-120-day curing ages. The results show that environmental water content is the core influencing factor, and the effect of water immersion curing is significantly better. The specimens mixed with 10% silica fume and quicklime have the best effect: after 90 days of water immersion curing, the crack healing difference is about 0.19 mm (healing rate >50%); after 120 days of curing, the water seepage time exceeds 360 minutes, and the compressive strength recovery coefficient is >1, achieving complete recovery. Under standard curing, the coefficient is 0.74-0.80, with water seepage time over 245 minutes at 90 days but poor overall effect. A sufficient water environment can promote the secondary synergistic hydration of fly ash, mineral admixtures and cement hydration products, generating calcium carbonate and calcium silicate hydrate to fill cracks. The limitation of this study is that mortar specimens are used, and the effect of this admixture ratio in actual mass concrete needs further verification.

INTRODUCTION

Cement-based materials have been the most widely used materials in civil engineering and have played an important role in national economic development (Ma, 2026). Cement-based materials are prone to microcracks, which, if not repaired in time, would continue to extend and expand under the action of loads or environmental factors, eventually leading to the failure of components or even the entire project and causing serious damage (Yu, 2026; Wang et. Al., 2026). Cement-based materials themselves have had the ability to spontaneously heal microcracks, and this repair method has been referred to as intrinsic self-

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healing. The intrinsic self-healing property of cement-based materials has been able to promote automatic crack closure in the early stages of microcrack formation in concrete structures (Wang et. al., 2026; Sha, 2026). Additionally, studies have found that the addition of mineral admixtures could provide the possibility of improving the workability, volumetric stability, and durability of concrete. The age at which cracking occurred and the curing environment could also have certain effects on the durability performance of concrete structures (Yao et al,2026; Yang et. al., 2026).

At present, the self-healing technology of mineral additives has become a research hotspot at home and abroad, and many mineral admixtures have been proven to have a certain impact on the performance of concrete (Wang, 2026; Zhang et. al., 2026). Among them, Liu (2025) pointed out that the main action mechanisms of silica fume applied in concrete included the pozzolanic effect and the micro-aggregate effect. Shang et. al. (2025) found through experimental research that silica fume exhibited strong self-healing ability for cracks at the 28-day cracking age, and the addition of silica fume could significantly improve the impermeability of concrete. Chang et. al. (2022) explored the influence law of different dosages of quicklime on the mechanical properties of concrete through experiments and found that concrete mixed with quicklime generated more calcium-silicate-hydrate gel substances, thereby enhancing the mechanical properties of concrete, and the compressive strength of concrete was the best when the quicklime content was 10%. Wang et al. (2022) used silica fume, metakaolin, quicklime, expansive agent and sodium carbonate to replace 10% of cement by double mixing to study the effect of dual mineral additives on the self-healing performance of cement-based materials. The results showed that the specimens with double mixing of quicklime and silica fume had the best crack repair effect, with a 28-day crack repair rate of up to 80%. Although existing studies have confirmed that the single incorporation and partial compound incorporation systems of silica fume and quicklime have had positive effects on the self-healing of cement-based materials, and the 10% dosage has had a good effect, there are still clear unsolved problems: first, there has been no systematic analysis of the regulatory effect of curing age and curing environment on the self-healing effect for the silica fume-quicklime compound incorporation system, making it impossible to determine the optimal curing parameters; second, most existing studies took pure cement mortar as the benchmark, which was disconnected from the mix ratio of concrete in actual engineering, and its engineering application effect was still unclear, making it difficult to support practice.

Therefore, based on the research gaps, this study took mortar with a fixed content of fly ash as the benchmark (adapting to C35 hydraulic concrete), prepared self-healing cement-based material specimens by single and combined incorporation of mineral additives (silica fume and quicklime), and carried out crack width healing tests, mechanical property tests and permeability tests under two conditions of water immersion curing and standard curing to explore the influence law of different mineral additives on the self-healing performance of cement-based materials.

EXPERIMENTAL MATERIALS

Raw materials

This experiment used P·C42.5 ordinary Portland cement as the base material, with a density of 3132 kg/m³. Fine aggregate was natural river sand from Region II, medium sand, with a fineness modulus of 2.47 and an apparent density of 2680 kg/m³. Mixing water was sourced from the tap water. Fibers used were cylindrical 8mm polyoxymethylene fibers. Quicklime was construction-grade quicklime that met the standards of Construction Quicklime (JC/T 479-2013) (China Building Materials Federation, 2013). Silica fume used was SF90 type.

Basic mortar mix

This study took the actual working conditions of Chinese dam face slabs as the engineering background, conducted the mix proportion design of C35 hydraulic concrete, and provided experimental basis and technical references for similar projects combined with the research on crack resistance and durability

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performance. The mix proportion design was strictly carried out in accordance with the Code for Mix Proportion Design of Hydraulic Concrete (DL/T 5330-2015) (National Energy Administration, 2015) and Design Code for Concrete Face Rockfill Dams (NB/T 10871-2021) (National Energy Administration). The fly ash content was determined as 80 kg/m³ to satisfy the strength and various performance requirements of C35 concrete. Meanwhile, 4 kg/m³ polyoxymethylene fiber was added to enhance the toughness and crack resistance of mortar. The specific basic mortar mix proportion is shown in Table 1.

Table 1. Basic Mortar Mix Proportions

Water-cement ratio /%	sand content/%	Amount of each type of mortar material(kg)				Water reducer dosage/%	Fiber content/(kg/m^3)
		water	cement	sand	Fly ash		
0.36	64.2	115	240	573	80	1.1	4

Self-healing mortar sample group

The self-healing mortar sample group used basic mortar as the base material, with single or composite admixture of silica fume and quicklime, and the total internal admixture was set to 10% of the cement mass (the single admixture group was 10% silica fume or 10% quicklime, and the composite admixture group was 5% silica fume + 5% quicklime). The basis for selecting this admixture dosage was as follows: first, it complied with the requirements of the Silica Fume for Mortar and Concrete (GB/T 27690-2023) and relevant literatures; the total admixture of 10% was within the effective action range of silica fume and quicklime, which could ensure the generation of self-healing products and avoid problems such as poor workability and increased early shrinkage caused by excessive admixture. Second, existing studies had shown that this admixture dosage had a significant effect on improving crack self-healing. Third, the equal-proportion composite admixture could fix the total admixture, control test variables, and facilitate the comparison of self-healing effects between single and composite admixtures as well as reveal the synergistic mechanism.

In this paper, JZ was the control group without any mineral additives; S10 meant 10% silica fume (by cement mass) was added into the base material; L10 meant 10% quicklime (by cement mass) was added into the base material; SL10 meant 10% silica fume + quicklime (by cement mass) was added into the base material (the mass ratio of silica fume to quicklime was 1:1, and the total admixture was 10% of the cement mass).

Self-repair mortar test program

Under standard curing and water immersion curing conditions, different self-healing mortar specimens were prepared by incorporating silica fume and quicklime into the reference mortar system, and the influences on the crack self-healing performance of various self-healing mortars were investigated. By adopting different mineral admixtures, this study compared the crack width repair rate, compressive strength recovery rate, permeability coefficient and other performance indicators of cement mortar at different curing ages (7 d, 28 d, 56 d, 90 d and 120 d) and under two curing regimes including standard curing and water immersion curing. The detailed experimental scheme is presented in Table 2.

Standard curing conditions consist of a temperature of 20±2°C, relative humidity above 95%, and uniform indoor humidity. Water-immersion curing involves immersing the samples underwater at a temperature of 20±2°C.

Table 2. Self-Healing Slurry Self-Repair Test Plan

Group Number	Mineral Additive Dosage (%)	Type of Mineral Additive	Test Indicator	Curing Environment	Curing Age

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JZ	—	—	Crack width	Standard curing Water curing	7d 28d 56d 90d 120d
S10	10	Silica fume	Compressive Strength		
L10	10	Quicklime			
SL10	10	Silica fume + Quicklime	Impermeability coefficient		

Sample size and preparation process

The preparation and curing of samples were strictly carried out in accordance with the Standard for Testing Long-term Performance and Durability of Concrete (GB/T 50082-2024) (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2024).

Sample preparation process: The specimens were mixed using a forced mixer. The aggregates, cement, fibers, and mineral additives were dry-mixed for 60 seconds in sequence, followed by the addition of water for wet mixing for 180 seconds to produce fiber-reinforced concrete. Then, the mixture was cast into molds, vibrated, and demolded after 24 hours, followed by curing in a curing room (temperature 20±2°C, relative humidity above 95%). The test items and sample sizes for crack self-healing tests of cement-based materials are shown in Table 3.

Table 3. Test Items and Sample Sizes

Testing Items	Sample size/mm	Number of sample /group
Crack Width	40×40×160	3/8
Compressive Strength	70.7×70.7×70.7	3/40
Impermeability Coefficient	Φ70/80×30	6/48

TEST METHODS

Method for measuring cracks in cement mortar

All pre-cracks of specimens in each test group were uniformly fabricated using a pressure servo loading device. The crack sizes were accurately regulated by setting standard loading parameters. After forming, the cracks were measured and verified one by one with microscopic observation instruments, and the widths of pre-cracks of all specimens were strictly controlled within the range of 0.2 to 0.4 mm to eliminate the interference caused by the difference in initial crack width on test results. The crack width of three specimens was measured for each group, and the arithmetic mean value was taken as the representative crack width of the group to avoid the influence of initial crack width difference on experimental outcomes.

The method for measuring crack width in mortar specimens referred to the Standard for Test Methods of Basic Performance of Building Mortar (JGJ/T 70-2009) (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2009). Cracks were pre-formed and measured on 40mm × 40mm × 160mm prism specimens, with each test group including three specimens. Cracks were pre-formed using a flexural test device. After cracking, six fixed lines were drawn on the same crack as shown in Fig. 1. At different ages, an electronic crack observation instrument was used to observe and record the crack width.

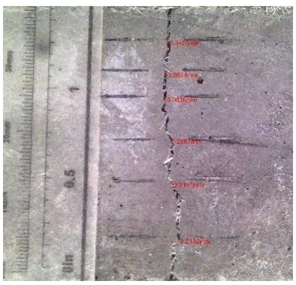

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Fig. 1: Crack measurement point fixation

The difference in the specimen before and after crack repair was determined using Equation (1).

$$\Delta D = D_m - D_{\mathrm{i}} \tag{1}$$

where

D_m Average Initial Crack Width，mm

D_i Average Width of Cracks After Repair，mm

In this study, the average values of test data from each group were calculated, and significant difference analysis was conducted to complete systematic statistical demonstration of the data.

Test method for compressive strength recovery performance of cement mortar

In accordance with the Standard for Test Methods of Basic Properties of Building Mortar (JGJ/T 70-2023) issued by the China Academy of Building Research in 2023, cubic mortar specimens with dimensions of 70.7 mm × 70.7 mm × 70.7 mm were adopted in this test, with three specimens arranged in each group for testing. Initial damage prefabrication was first performed on the specimens. Loading was implemented via a pressure servo control system and terminated when the stress development of specimens entered the fourth stage, so as to complete the prefabrication of initial compressive damage of specimens, and the residual load at this moment was recorded. Afterwards, the damaged specimens were cured for 28 days under different environmental conditions, and the reference compressive strength of damaged specimens in each group was determined.

The arithmetic mean value of compressive strength of three specimens in each group was taken as the representative strength value. Mathematical statistical methods were used for mean value analysis and difference test to establish a standardized data statistical analysis system.

The degree of mechanical property recovery was determined by Equation (2).

$$\xi_{ra} = \frac{F_{ra}}{F_{fa}} \tag{2}$$

F_{ra} represents the peak load of a self-healing mortar specimen with initial damage after a certain curing age; F_{fa} represents the residual load of the original specimen. The mechanical property recovery coefficient (ξ_{ra}) characterizes the degree of mechanical property recovery of the self-healing mortar after different curing ages.

Testing method for the impermeability of cement mortar

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In accordance with the Standard for Test Methods of Basic Properties of Building Mortar (JGJ/T 70-2023) issued by China Institute of Building Standard Design & Research in 2023, standard cylindrical mortar specimens were used in this test, with an upper diameter of 70 millimeters, a lower diameter of 80 millimeters and a height of 30 millimeters. Each test group consisted of six specimens. Firstly, through cracks were prefabricated on the specimens with blades. After crack preparation was finished, the specimens were cured for 28 days in a standard curing room and then demoulded, followed by the Impermeability test conducted on a mortar impermeability tester.

The impermeability performance of mortar was tested following standard test procedures. The maximum pressure corresponding to four specimens without water seepage out of six specimens in each group was adopted as the final impermeability pressure result. The test procedure was strictly controlled in line with water seepage judgment criteria for specimens to standardize test operations. All measured experimental data were subjected to mean value analysis and difference test via mathematical statistical methods. A standardized data statistical analysis system was established to ensure scientific and consistent processing of test data.

RESULTS ANALYSIS

Analysis of the mortar crack healing effect

Table 4 lists the measured data of crack width and crack repair rate of four groups of specimens including JZ, S10, L10 and SL10 at different curing ages under standard curing (B-series) and water immersion curing (J-series).

Table 4. Sample Crack Width and Crack Repair Rate

Number	Repair Environment	Crack width/mm					Crack Repair Rate /%			
		0d	7d	28d	56d	90d	7d	28d	56d	90d
B-JZ	Standard Environment	0.220	0.218	0.214	0.210	0.206	0.91	2.73	4.55	6.36
B-S10		0.287	0.274	0.245	0.202	0.174	4.53	14.63	29.62	39.37
B-L10		0.291	0.271	0.243	0.201	0.172	12.57	25.45	35.33	41.02
B-SL10		0.295	0.267	0.233	0.191	0.167	9.49	21.02	35.25	43.39
J-JZ	Water-Immersed Environment	0.259	0.253	0.248	0.240	0.235	2.32	4.25	7.34	9.27
J-S10		0.343	0.318	0.262	0.214	0.171	7.29	23.62	37.61	50.15
J-L10		0.367	0.326	0.261	0.221	0.178	11.17	28.88	39.78	51.50
J-SL10		0.313	0.265	0.193	0.148	0.118	15.34	38.34	52.72	62.30

It could be preliminarily observed from the Table 4 that regardless of the curing environment, the crack widths of the three groups of specimens mixed with silica fume and quicklime (SF10, QL10, SQ10) gradually decreased with the increase of curing age, and their crack repair rates increased steadily, presenting obviously better repair effects than those of the reference group R0 without mineral admixtures.

In general, all specimen groups achieved better crack repair performance under water immersion curing than under standard curing, and the composite admixture group SQ10 possessed favorable repair potential in both curing environments. This variation law was consistent with findings from previous studies. Relevant researches had also verified that the combined incorporation of mineral admixtures exerted a

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superior effect on concrete crack repair compared with single incorporation, and the crack repair effect improved with the extension of curing age (Wang et al., 2022; Bai et. al., (2026). The specific variation trends, rate differences and synergistic mechanism of crack repair rates of all groups would be further analyzed in detail combined with the line chart of crack repair rate.

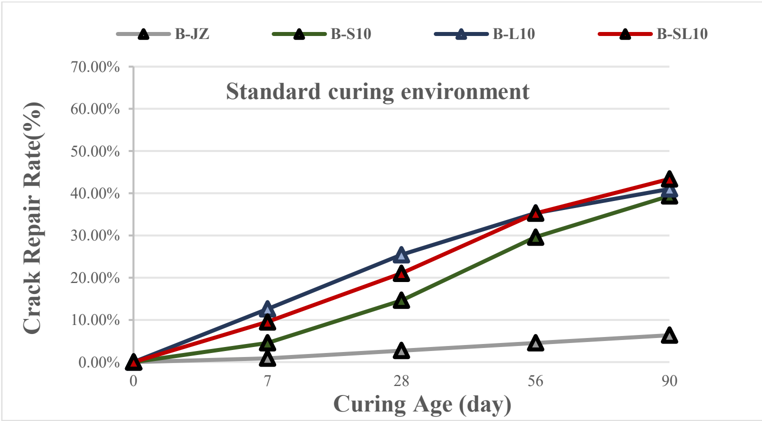

Fig. 2: Variation of average crack healing rate of specimens under standard curing environment

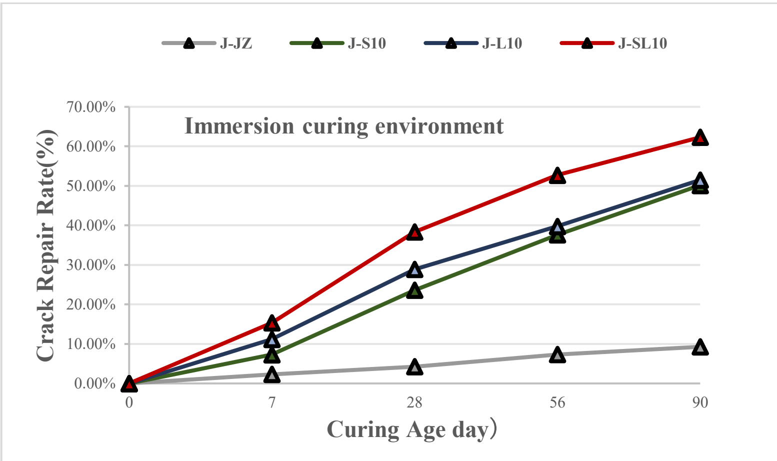

Fig. 3: Variation of average crack healing rate of specimens under water immersion curing environment

By comparing Fig. 2 and Fig. 3, it was found that under the two curing environments, the crack repair rate of each group of mortar specimens containing a fixed amount of fly ash had increased with the curing age. The line chart showed that the line of the water immersion curing group had an overall steep upward trend, while that of the standard curing group had a gentle upward trend. The overall repair effect of water immersion curing was significantly better than that of standard curing, and the repair rate of each group had improved significantly at 90 days. Among them, the repair rate of the SQ10 group under water immersion curing at 90 days had reached 58.3%, which was 32.1% higher than that under standard curing at the same period. This was consistent with the overall trend reported by Feng et. al., (2026); Bai et. al.(2026) that water immersion environment can improve the self-healing effect of cement-based materials", but the composite admixture system based on fly ash in this study had shown more prominent repair advantages.

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There were significant differences in the repair characteristics of each group: the reference group (containing fly ash) had increased gently throughout the whole period and remained at the lowest level, with a repair rate of only 31.7% at 120 days, and its line was almost in a horizontal state; the growth rates of SF10, QL10 and SQ10 under water immersion curing were significantly better than those under standard curing, and the overall trend was consistent with the existing literature, but the full-age repair performance of the composite admixture group SQ10 in this study had been more stable. Among them, the growth rate of QL10 had dropped sharply in the later stage under standard curing but had continued to increase steadily under water immersion curing; SQ10 had performed the best in both environments and maintained a leading position in the full age under water immersion curing, and its synergistic repair effect had been better than that of similar systems reported in the existing literature.

The core difference between the two environments lies in the role of water regulation. Under standard curing, insufficient water had not only restricted the progress of the repair reaction, but also slowed down the hydration of fly ash, which was consistent with the mechanism analysis in the existing literature; water immersion curing had provided sufficient water, fully stimulated the activity of mineral admixtures, and promoted the continuous hydration of fly ash, making the repair process of each group more sufficient. The repair advantage of SQ10 had been particularly obvious (Xia et al., 2021).

In summary, water immersion curing has been more conducive to exerting the repair potential of mineral admixtures. The SQ10 system had performed the best in both environments, and its repair performance and stability had been better than those of related systems reported in the existing literature, providing a reference for the optimization of the self-healing system of cement-based materials.

Analysis on recovery coefficient of compressive strength

As shown in Table 5, it has presented the corresponding compressive strength recovery coefficients of various pre-damaged specimens after being subjected to different healing environments and healing ages.

Table 5. Compressive Strength Recovery Coefficient of Initially Damaged Self-Healing Mortar

Repair Environment	Sample Number	Mineral Additive	Compressive Strength Recovery Coefficient of Self-Healing Slurry				
			7d	28d	56d	90d	120d
Standard Environment	B-JZ	/	0.74	0.76	0.78	0.79	0.79
	B-S10	Silica fume	0.76	0.78	0.79	0.80	0.82
	B-L10	Quicklime	0.77	0.79	0.82	0.84	0.84
	B-SL10	Silica fume + Quicklime	0.79	0.80	0.85	0.86	0.87
Water-Immersed Environment	J-JZ	/	0.80	0.81	0.84	0.86	0.86
	J-S10	Silica fume	0.81	0.83	0.87	0.92	1.00
	J-L10	Quicklime	0.81	0.85	0.88	0.95	1.01
	J-SL10	Silica fume + Quicklime	0.82	0.88	0.92	1.01	1.05

It has been concluded from Table 5 that the compressive strength recovery coefficients of mortar specimens under the two curing environments have all risen with the increase of healing age, and obvious differences have existed in the growth patterns of specimens with different mixing ratios. The strength recovery effect of specimens with single quicklime incorporation has outperformed that of specimens with single silica

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fume incorporation, and composite mineral admixture systems have shown better overall performance than single admixture systems.

This rule has been consistent with findings from previous studies. Relevant researches have verified that composite admixtures have achieved better effects in improving strength recovery performance, and the self-healing capacity has continuously increased along with the extension of curing age (Wang et al., 2022; Wei et. al., 2026). The specific variation trends have been elaborated in combination with the line charts.

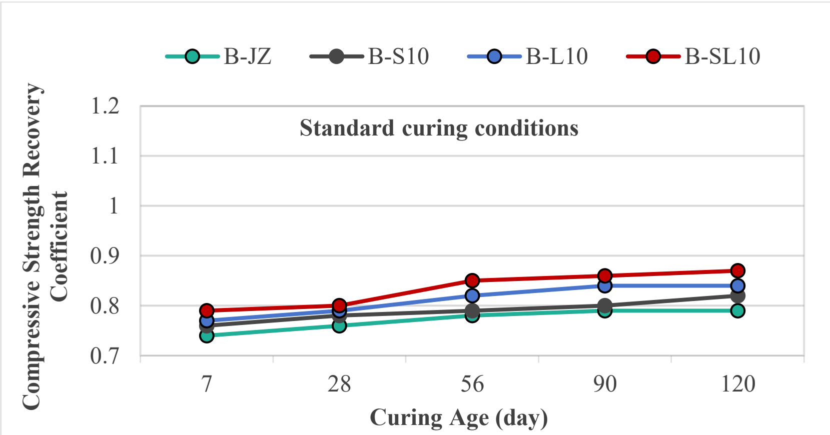

Fig. 4: Variation of compressive strength recovery coefficient under standard curing environment

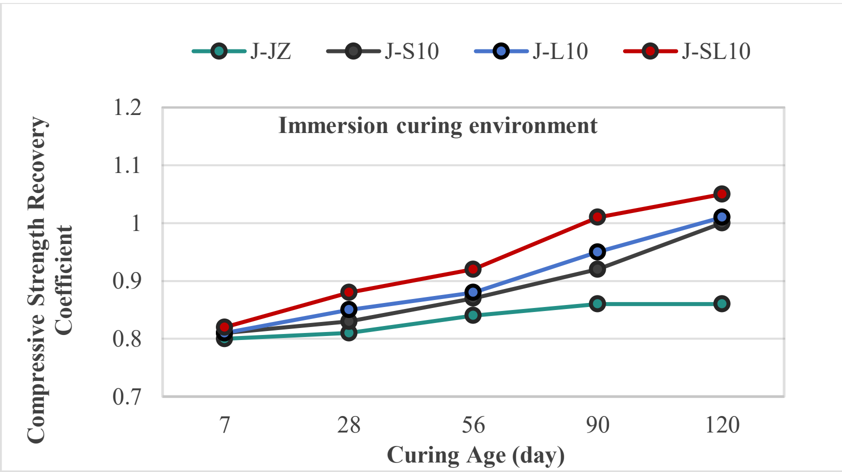

Fig. 5 Variation of compressive strength recovery coefficient under water immersion curing environment

By comparing Fig. 4 and Fig. 5, it was observed that the compressive strength recovery coefficient of each group of mortar specimens had shown an upward trend with the extension of curing age under both curing environments, and the repair effect under water immersion curing had been significantly better than that under standard curing. The line chart trend showed that the curve of the composite admixture group (J-SL10) under water immersion curing had presented a continuous steep upward trend, while the curve of the

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same group (B-SL10) under standard curing had slowed down significantly in the later stage; the 120-day age data showed that the recovery coefficient of each group had improved obviously, among which the composite admixture group under water immersion curing (J-SL10) had reached a recovery coefficient of 1.05, being the only group that had exceeded 1.0. The reference group had grown gently with the lowest repair level, while the single silica fume group, single quicklime group and composite admixture group had shown differentiated growth. Water immersion curing had accelerated the self-healing rate in the middle and later stages, and the composite admixture system had achieved the optimal final repair effect.

The above rules had been basically consistent with the research conclusions of Wang et al. (2022) and Wei et. al. (2026), both of which had confirmed that the water-rich environment of water immersion was conducive to the self-healing of cement-based materials, the repair effect of composite mineral admixtures was better than that of single admixtures, and the repair performance had been optimized with age. The main difference lay in the test substrate: the specimens in this study had taken fly ash as the substrate, which had provided a basic environment for the reaction of admixtures; while the above-mentioned literature had used pure cement mortar as the substrate and had not involved the regulation of fly ash on repair performance.

At the mechanism level, the cognition of this study had been consistent with that in the literature, both holding that water supply was the core of regulating hydration, alkali activation and carbonation reactions. Under standard curing, insufficient water had not only inhibited the activity of silica fume and quicklime, but also slowed down the hydration of fly ash, leading to the decline of the repair power of quicklime in the later stage, which had been consistent with the conclusion in the literature that "humidity restricts self-healing"; water immersion curing had optimized the reaction environment, activated the activity of admixtures and promoted the continuous hydration of fly ash, thus strengthening the repair effect, which had been in line with the view of high humidity strengthening repair in the literature (Li et al., 2021).

The fly ash substrate had enabled the composite admixture system to improve the matrix compactness and optimize the later mechanical properties with the help of the micro-aggregate effect and continuous hydration of fly ash on the basis of early crack sealing. Compared with previous studies on pure cement mortar substrates, the introduction of fly ash had enriched the synergistic mechanism of admixtures, improved the research dimension of the self-healing system of mineral admixtures, and provided a new reference.

Analysis of mortar impermeability

As shown in Table 6, the listed data represent the average water seepage time of each specimen group under different curing environments and different healing ages. In this test, the initial water seepage time under the water pressure of 0.5 MPa was adopted to evaluate the impermeability performance. Water seepage occurring within 5 minutes was recorded as 0 minutes, and no water seepage within 6 hours was recorded as 361 minutes. A longer water seepage time indicated a higher closure degree of prefabricated micro-cracks with a width of 0.3 millimeters.

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Table 6. Water penetration time of self-healing paste samples under different environments and different repair ages

Repair Environment	Sample Number	Mineral Additive	Permeation time of samples with different curing ages/min					
			0d	7d	28d	56d	90d	120d
Standard Environment	B-JZ	/	0	0	0	0	0	0
	B-S10	Silica fume	0	0	10	15	20	25
	B-L10	Quicklime	0	10	15	20	25	30
	B-SL10	Silica fume + Quicklime	0	15	20	25	30	40
Water-Immersed Environment	J-JZ	/	0	0	0	0	0	0
	J-S10	Silica fume	0	110	190	225	245	265
	J-L10	Quicklime	0	125	215	245	280	300
	J-SL10	Silica fume + Quicklime	0	155	300	335	361	361

It can be seen from Table 6 that the reference group R0 had a water seepage time of 0 minutes at all ages under both curing conditions, showing poor impermeability and no obvious self-healing effect. Under standard curing, the seepage time of mixed specimens rose slowly with age, with composite group performing best, quicklime group second and silica fume group worst. Under water immersion curing, all groups had much longer seepage time with rapid growth. The composite group reached 361 minutes at 90 days and realized complete waterproof crack healing. This trend conforms to existing studies, and detailed variations will be analyzed via line charts.

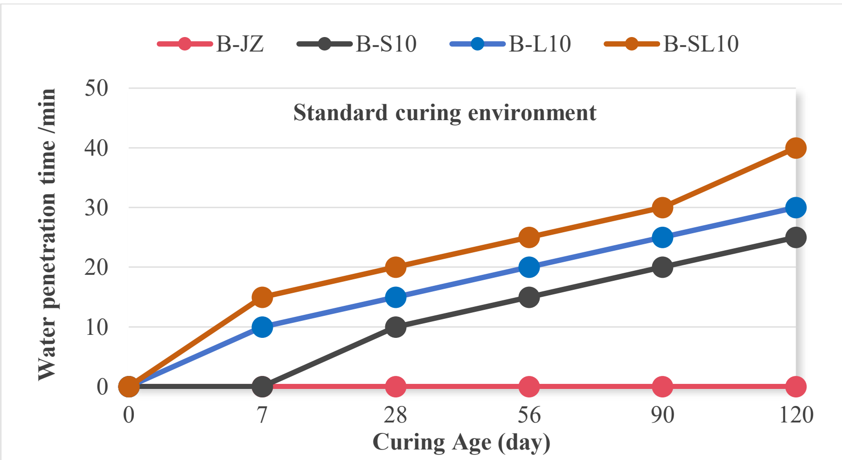

Fig. 6. Change of Mortar Water Permeation Time with Curing Age under Standard Conditions

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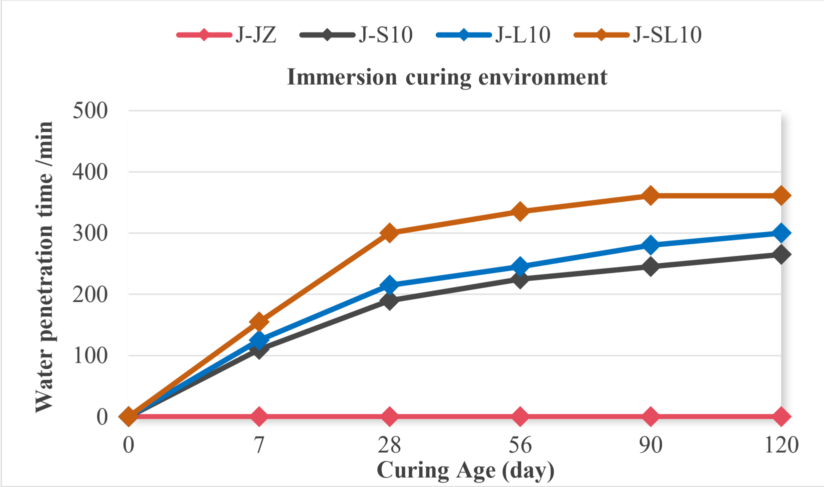

Fig. 7. Variation of mortar water seepage time with repair age in waterlogged environment

By comparing Fig. 6 and Fig. 7, it was found that for each group of mortar specimens containing a fixed amount of fly ash under the water immersion environment, the growth rate and final level of water penetration time were significantly higher than those under standard curing. There were obvious differences in the trend of the line charts: under standard curing, the curves of all groups had grown gently, while the curve of the composite admixture group under the water immersion environment had shown a rapid rise in the early stage and then stabilized at a high level in the later stage. There were obvious differences in the stage growth characteristics of each group. For example, the water penetration time of the composite admixture group under the water immersion environment at 120 days had reached 361 minutes, which was 9 times that under the standard curing environment (40 minutes). This was consistent with the overall trend reported by Wang et. al. (2022) and Wu et. al. (2026) that "the water immersion environment can significantly improve the self-healing effect of cement-based materials". However, based on the fly ash substrate, each group of specimens in this study, especially the composite admixture group, showed more prominent advantages in impermeability repair.

At the mechanism level, the core difference in repair between the two environments lay in the role of water regulation, which was consistent with the mechanism cognition in the existing literature. However, due to the presence of the fly ash substrate in this study, unique characteristics had been presented: insufficient water under standard curing had not only limited the pozzolanic reaction and quicklime digestion reaction, but also slowed down the hydration of fly ash itself, leading to limited impermeability repair effect of each group; sufficient water in the water immersion environment had not only provided conditions for various reactions, but also promoted the continuous hydration of fly ash, strengthened the filling effect of hydration products, and greatly improved the impermeability repair level (Chen et. al., 2026). Based on the fly ash substrate, this study had found that although the crack repair rate of the composite admixture group was slightly lower in some stages, better impermeability effect had been achieved due to the synergy of the micro-aggregate effect of fly ash and dense hydration products.

In summary, water had been the key factor in impermeability repair, and the fly ash substrate had enriched the repair mechanism. The impermeability repair performance of the composite admixture group in this study was better than that of similar systems in the literature, providing a reference for the optimization of impermeability self-healing of cement-based materials.

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CONCLUSION

This study has taken fly ash mortar as the reference group (designed according to the mix ratio of C35 hydraulic concrete) and focused on two common curing environments, namely standard curing and water immersion curing. It has explored the effects of mineral admixtures on the microcrack repair effect, mechanical properties and impermeability of self-healing cementitious materials, and systematically analyzed the internal repair mechanism of mineral admixtures on cementitious materials. The research results have shown that environmental moisture content is the core factor affecting the crack self-healing effect; the higher the moisture content, the more significant the crack self-healing effect of the specimens. The reference specimens without mineral admixtures (fly ash reference group) have shown no obvious improvement in crack self-healing effect under both curing environments. The compressive strength recovery performance of self-healing mortar has been mainly regulated by the repair environment, curing age and type of mineral admixtures. Under standard curing conditions, the water seepage time of the specimens has only increased slightly with the extension of curing age; after the curing age reached 90 days, the water seepage time of cement mortar specimens mixed with mineral admixtures has been more than 245 minutes. For the specimens prepared by compounding 10% silica fume and quicklime, after 120 days of curing under water immersion conditions, the water seepage time has exceeded 360 minutes, which has fully proved that the prefabricated microcracks inside the specimens have achieved complete closure and repair.

In conclusion, the water immersion curing environment has been the key driving condition for ensuring the efficient self-healing of cracks in cementitious materials. Sufficient water environment has effectively promoted the secondary synergistic hydration reaction between mineral admixtures, fly ash and cement hydration products. Among them, the continuous hydration of fly ash has helped improve the activity of the system and promoted the reaction between mineral admixtures and cement hydration products, generating high-quality cementitious products such as calcium carbonate and calcium silicate hydrate, which have densely filled the internal gaps of cracks and strengthened the interfacial bonding density. Among them, the synergistic effect of composite mixing of silica fume and quicklime has been the most prominent: silica fume has excellent activity and has been able to quickly accelerate the overall hydration reaction process; the hydration of quicklime has continuously precipitated calcium ions, which have coupled with carbon dioxide in the environment to form stable calcium carbonate precipitates. The dual physical and chemical synergistic effects have greatly improved the compactness of crack filling. Water immersion curing has effectively extended the duration of the hydration reaction; with the continuous increase of curing age, the cementitious hydration products have continuously accumulated, which has not only steadily improved the degree of crack closure and healing, but also simultaneously optimized the compressive strength and long-term impermeability and durability of the matrix.

RESEARCH RECOMMENDATIONS

Based on the research results of this paper, aiming at the microcrack self-healing performance of mineral admixture-modified cement-based materials (prepared according to the mix ratio of C35 hydraulic concrete), the following directions for further research are proposed. It should be noted that this study did not discuss relevant research limitations, such as the single specimen size specification, single dosage level, lack of microscopic image observation and analysis, and uncertainty in long-term performance. Future research needs to be improved in a targeted manner.

First, the dosages of fly ash, silica fume and quicklime in this test were all fixed values, corresponding to the research limitation of a single dosage level. In the future, gradient dosage combinations can be set to systematically explore the optimal dosage range of the above mineral admixtures, improve the mix ratio parameter system of the mineral admixture composite system, and make up for the deficiencies caused by the single dosage setting.

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Second, this paper only set standard curing and water immersion curing conditions, which did not combine the actual service conditions of hydraulic structures, nor did it fully consider the uncertainty in long-term performance. In the future, it is necessary to combine the actual service scenarios of hydraulic structures, simulate complex environments such as dry-wet cycles, flowing water scouring and low temperature, explore the self-healing stability of the mineral admixture composite system under harsh conditions, and clarify the reliability of its long-term performance.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Li Mei Ying conceptualized the central research idea and provided the theoretical framework, carried out the research, wrote and revised the article. Norul Wahida Kamaruzaman designed the research, supervised research progress, anchored the review, revisions and approved the article submission.

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