

EFFECT OF FIBERS ON SELF-HEALING PROPERTIES OF MICROBIAL MINERALIZED CEMENT MORTARS

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Received: 10.09.2024

Received in revised form: 30.12.2024

Accepted: 12.03.2025

ABSTRACT

In this study, we selected cement mortar as the research object, used the expanded perlite (EP) which adsorbed bacteria as the self-healing agent, and mixed basalt fibers to improve the properties. The effects of different dosages and sizes of self-healing agent and basalt fibers on the mechanical properties and self-healing properties of cement mortar were investigated by compressive strength, SEM, EDS, XRD, and optical microscopy tests. The results of the study showed that under the perfect conditions for ideal bacterial activity, the bacteria were able to survive in cement mortar using expanded perlite as a carrier and induced the generation of calcium carbonate precipitates to fill the cracks. The healing agent can significantly improve the self-healing property of mortar, and the fibers can adsorb metabolic precipitates to improve the self-healing rate of mortar. The simultaneous addition of healing agent and basalt fibers can realize the complementary advantages. By adding a small amount of healing agent and a moderate amount of fibers, we achieve 100% self-healing performance, and at the same time improve the compressive strength of mortar. In this study, the addition of 10% self-healing agent and 0.1% volume fraction of 6mm long basalt fibers can not only achieve 100% self-healing performance, but also increase the compressive strength of the mortar by 7.96% when the curing age is 28 days.

KEYWORDS

Cement mortars, Bacteria; Basalt fibre, Self-healing, Mechanical property

INTRODUCTION

Concrete is one of the most widely used construction materials in the world, with applications ranging from infrastructure construction to high-rise buildings [1]. Despite its excellent compressive strength and durability, the brittle nature of concrete makes it susceptible to cracks when subjected to tensile stresses [2]. These cracks not only affect the overall strength of the concrete structure, but

also lead to the infiltration of water, chloride ions, and other corrosive substances, which accelerates the corrosion of the rebar and shortens the service life of the structure [3-5].

How to effectively repair concrete cracks and extend the service life of the structure has been an important research topic in the field of civil engineering. The traditional concrete crack repair methods mainly include physical and chemical methods, such as grouting and daubing repair materials [6,7]. However, these methods often have limitations such as high repair cost, unsustainable effect, and polluting the environment. In order to overcome these limitations, in recent years, academic circles and engineering circles have begun to explore the use of biotechnological means to repair concrete cracks, wherein, Microbially Induced Calcium Carbonate Precipitation (MICP) has become a hotspot of the research due to its unique advantages. The main principle of Microbially Induced Calcium Carbonate Precipitation (MICIC) is a bioremediation technique that utilizes microbial metabolic activities to precipitate calcium carbonate at cracks [8-12]. Compared with traditional repair methods, MICP technology has the following significant advantages: economy and environmental friendliness.

For MICP technology to repair cracks, the survival rate of microorganisms in cement mortar directly affects the level of repair rate of cracks. The hydration reaction of cement during the mixing process leads to a very high alkalinity within the concrete, with a pH value of approximately 11-13 [12]. At the same time, the continuous hardening of the concrete during the curing process also squeezes the living space of the internal bacteria and thus causes bacterial death. Therefore, the bacteria incorporated into the mortar must be able to adapt to the highly alkaline environment. *Bacillus* is an alkalophilic solitary anaerobic spore-producing bacterium that can produce spores and survive in highly alkaline environment, and it is the most widely used microorganism in related research at present [13]. However, some studies have also shown that placing bacteria in concrete for a long period of time leads to a decrease in the survival rate of spores [14-16]. This is due to the high alkalinity of the internal environment of the concrete, and the products of the hydration reaction compress the internal environmental space, resulting in the death of some bacteria. Therefore, the problem of bacterial survival should be considered when incorporating bacteria into geopolymer mortar. Fixing the bacterial spores in the protective carrier can significantly increase the survival rate of bacteria and enhance the self-healing ability of concrete. Expanded perlite (EP), limestone powder (LSP), ceramsite and their modified materials are common bacterial carriers that can increase the survival rate of bacteria, increase the ultimate self-healing width of cracks in concrete, and improve the self-healing efficiency of concrete [17-20]. Among them, fibers, as a common additive material in concrete, can also be used as a carrier for bacteria. The fibers were modified with high temperature or alkali solution, and the bacteria was adsorbed on the fiber surface and incorporated into the concrete [21]. This can not only effectively weaken deformation localization, reduce damage degree, enhance fracture bridging, and improve the mechanical properties and durability of concrete through prolonging plastic deformation and preventing breakage by fibers, but also be beneficial to the early repair of microcracks, and significantly improve the self-healing performance of concrete [21-25].

In this study, we selected the cement mortar as the research object, used the expanded perlite (EP) which adsorbed bacteria as the self-healing agent, and replaced the standard sand by equal volume. Meanwhile, we considered mix basalt fibers (BF) to improve the performance of the mortar. We tested the mechanical properties of cement mortar based on microbial mineralization by experiments, observed the self-healing properties of macroscopic cracks, and revealed the coupling

mechanism of incorporated microorganism and fibers to improve the properties of geopolymer mortars.

MATERIALS AND METHODS

Materials

Cement

The cement used in the test is P.042.5R ordinary Portland Cement produced by Ningguo Cement Factory of Anhui Conch Cement Co., Ltd. Its chemical composition is shown in Table 1.

Tab. 1 - Chemical Composition of the Cement

Chemical Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	SO ₃	MgO
Content (%)	64.84	20.14	4.94	3.83	0.25	0.88	3.02	1.34

Expanded perlite

The inorganic porous material used in the test is expanded perlite, which was purchased through Shanhe New Material Co., Ltd, Xinyang City, Henan Province. The basic parameters of expanded perlite are shown in Table 2. The diameter of the expanded perlite used in the test is in the range of 2~4mm, as shown in Figure 1, which is the morphological characteristics of the expanded perlite and its microscopic characterization under the electron scanning microscope. The adsorption rate of expanded perlite is low, but the open part of the pores absorbs solution faster than other aggregates, it is often used as a protective carrier for bacteria, and can protect the bacteria from the influence of cement hydration reaction in the mortar to ensure the survival capacity of the bacteria.

Tab. 2 - Basic Parameters of the Expanded Perlite

Chemical Composition	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	Fe ₂ O ₃	CaO	MgO	Others	Loss on Ignition
Content (%)	73.72	14.25	4.24	3.95	0.86	0.76	0.32	0.44	1.46



(a) Macroscopic Appearance

(b) Scanning Electron Microscopy Features

Fig. 1 - Expanded Perlite

The basalt fibers used in the test were produced by Changsha Ningxiang Building Materials Co., Ltd, with lengths of 6 mm and 12 mm respectively, diameters of 17 μm , specific gravities of 2.8~3.3 g/cm^3 , and elastic modulus of 100 GPa. The morphology of the basalt fibers is shown in Figure 2. In the concrete, basalt fibers tend to create agglomerates. In order to avoid such problems, basalt fibers should be fully separated before mixing.

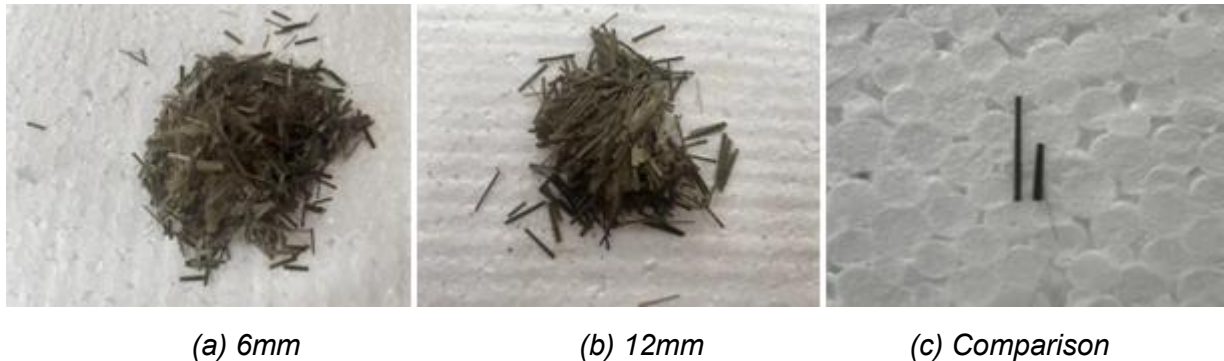
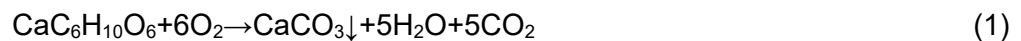


Fig. 2 - Basalt Fibers Morphology

Culture of Bacteria and Preparation of Self-healing Agents

The bacteria used in this study is *Bacillus Pseudofirmus* (CICC 10722), which was purchased from China Center of Industrial Culture Collection (CICC). It has the characteristics of high temperature resistance, strong ability of secreting enzymes, and high efficiency of spore transformation into bacteria. The reaction mechanism for the conversion of calcium lactate to calcium carbonate by *Bacillus Pseudofirmus* is as follows [26-28]:



The process of bacterial culture is as follows: Firstly, we prepared a solid medium for bacterial solution, and the main material was nutrient gravy agar. In addition, when cultivating *Bacillus*, it was also necessary to add an additional 5mg of $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ to promote the growth of *Bacillus*. Then, we sterilized the culture medium and adjusted the pH value of the culture medium to 9.7 using a sterile solution of 1mol/L sodium sesquicarbonate. Finally, we poured the adjusted medium and bacterial mixture into a conical flask and placed it on a constant temperature shaker to culture for 24 hours at a temperature of 30°C and an oscillation frequency of 120r/min. After the culture was completed, we centrifuged it at 8000rpm for 5 minutes, and collected bacterial spores and diluted them with distilled water to obtain the required bacterial concentration.

Expanded perlite cannot be used directly to adsorb bacteria. Firstly, we took out enough expanded perlite into a large beaker and poured enough water to fill the beaker to clean the expanded perlite. The low-density expanded perlite would float on the water surface and the impurities would be deposited to the bottom of the water. Then, we placed the cleaned expanded perlite on a filter screen to filter the water, evenly spread the expanded perlite in the rectangular tray after the water was filtered, and weighed and recorded the common weight of the tray and expanded perlite. Finally, we placed the expanded perlite in the drying box and adjusted the temperature for drying. In the process of drying, we took out and weighed a portion of the expanded perlite at regular

intervals until the weight of the expanded perlite remained constant. At this point, the dried expanded perlite could be used as a carrier for the solidified bacteria.

After preparing the expanded perlite, we took out the pre-configured bacterial solution and shook it well to ensure that the bacterial solution could be evenly distributed in the culture solution. We measured the required distilled water according to the demand of bacterial concentration, and mixed the distilled water with the bacterial solution to prepare the bacterial solution of specific concentration, and the bacterial solution could be evenly distributed in the water by continuing to stir. After completing the dilution of the bacterial solution, we poured the above-mentioned spare expanded perlite into the bacterial solution container to absorb the bacterial solution. There was a problem of the expanded perlite floating on the upper surface of the liquid due to its low density. Therefore, it was necessary to use a plastic film to cover the upper surface of the liquid and apply downward pressure with a heavy object so that all the expanded perlites could be suspended in the liquid to fully absorb the bacterial solution. After standing at room temperature for 24 hours, we removed the plastic film on the upper surface of the container, and poured the mixture of the expanded perlite and bacterial solution in the container into a funnel net to separate the outflow liquid. We evenly spread the expanded perlite adsorbed with bacterial solution on the tray for weighing, after adjusting the oven to 40°C, we placed the tray into the oven for drying. We removed and weighed the tray at regular intervals until the weight of the tray remained constant, indicating that the expanded perlite was completely dry. Compared with the weighing results of the expanded perlite before absorbing the bacteria, it could be seen that the weight of the expanded perlite increased by 8 grams per 100 grams, which indicated that the bacteria had been adsorbed to the interior of the expanded perlite. This result is consistent with the research result of Tziviloglou[29] et al.

Specimen Preparation

Cement mortar specimens were prepared using ISO standard sand, ordinary Portland cement, tap water and expanded perlite loaded with bacteria. According to the test purpose, the mix ratio was designed, and ten groups of cement mortar specimens with different mix ratios of admixtures were determined, as shown in Table 3. Among them, the expanded perlite (EP) specimens mixed with immobilized bacteria only were used as the control group, with the dosage of 10% and 30% equal volume instead of standard sand, respectively, and the codes were labeled as groups P1 and P6. The cement mortar with 10% expanded perlite was further added with 0.1% volume fraction of 6mm fibers and 12mm fibers, and 0.5% volume fraction of 6mm fibers and 12mm fibers, respectively, and the codes were labeled as P2, P3, P4, and P5. The cement mortar with 30% expanded perlite was further added with 0.1% volume fraction of 6mm fibers and 12mm fibers, and 0.5% volume fraction of 6mm fibers and 12mm fibers, respectively, and the codes were labeled as P7, P8, P9 and P10.

Tab. 3 - Mix Ratio of Cement Mortar Specimens

Group	Code	Water (g)	Cement (g)	Sand (g)	Expanded Perlite (g)	Basalt Fibers (g)
EP10	P1	175	350	630	4.7	—
EP6F10-0.1	P2	175	350	630	4.7	0.5
EP12F10-0.1	P3	175	350	630	4.7	0.5
EP6F10-0.5	P4	175	350	630	4.7	2.5
EP12F10-0.5	P5	175	350	630	4.7	2.5
EP30	P6	175	350	490	14.1	—
EP6F30-0.1	P7	175	350	490	14.1	0.5
EP12F30-0.1	P8	175	350	490	14.1	0.5
EP6F30-0.5	P9	175	350	490	14.1	2.5
EP12F30-0.5	P10	175	350	490	14.1	2.5

The preparation process of the cement mortar specimens is as follows:

- (1) We poured the weighed cement, standard sand, expanded perlite with solid bacteria, and fibers into the mixer, and the mixture was dried stir at low speed for 30 seconds to fully mix the raw materials.
- (2) We added water, and the mixture was continued to be stirred at low speed for 60 seconds, and then we used a shovel to treat the mortar bonded to the inner wall and the bottom layer of the mixing pot, and fully mixed the raw materials.
- (3) We stirred the mixture at high speed for 90 seconds, then stopped stirring.
- (4) We poured the mortar into the mold and vibrated it thoroughly. Then we used polyethylene film to wrap the surface of the mold to prevent the loss of water in the mortar, demolded after 24 hours of curing, and put it into $20\pm 1^{\circ}\text{C}$ water to continue curing.

Preparation and healing methods of cracks

In the process of studying the effect of bacteria-adsorbed expanded perlite and fibers on the self-healing ability of mortar, it was necessary to preform cracks on the specimens that have completed the curing. The preparation process of cracks is shown in Figure 3. Among them, the cement mortar specimens were maintained for 28 days. Firstly, we put the cube specimen with a side length of 40mm into the compressive test area of YAW-300H universal material testing machine, and placed a needle with a diameter of 1.5mm and a length of 1cm at the bottom of the specimen. Then, we turned on the pressure tester to apply pressure, and set the compression speed of the press to 2.4 kN/s. When the applied pressure reached about 7 kN, the specimen would crack. At this point, we stopped the continued application of pressure and the specimen formed a crack on both sides that was wider at the bottom and thinner at the top. To prevent the pre-cracked specimen from fracturing as a whole, we could wrap the specimen with black insulating waterproof tape to maintain the integrity of the specimen.

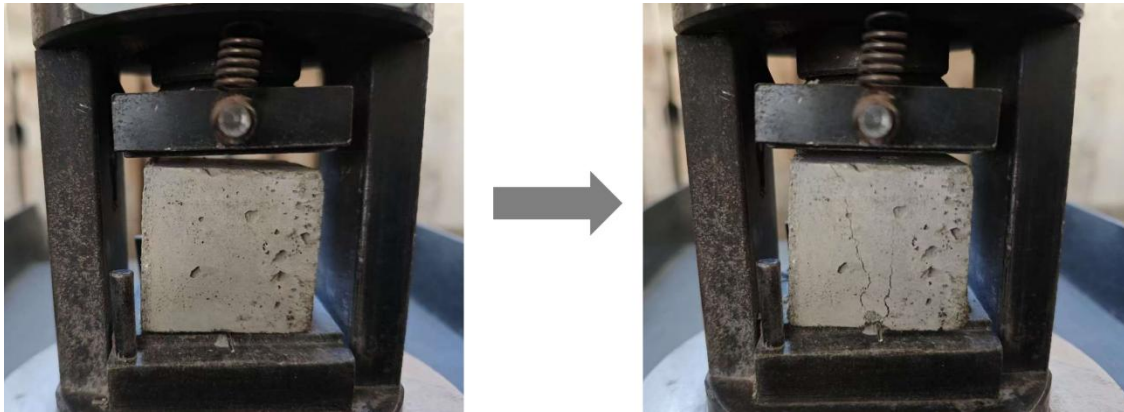


Fig. 3 - Preparation of Cracks

During the self-repairing process of mortar, bacteria required water and a calcium source. Therefore, during the self-repairing period, we placed the specimen in water, and added an appropriate amount of calcium lactate to the water, and stirred until uniform. According to the research report of Ryparová [31], the spores of *Bacillus pseudostrongylus* were able to survive in the temperature range from -20°C to 140°C and showed optimal reproductive and metabolic efficiency at 30°C . Therefore, in the process of self-healing curing of the specimen, we placed a constant temperature heater to keep the water temperature constant at 30°C . Since the mineralization process of *Bacillus pseudotoughii* required the involvement of oxygen, we used a small oxygenating pump to aerate the water to keep *Bacillus pseudotoughii* at its most metabolically active state. The results of this study were obtained based on the activity of bacteria under the above ideal perfect conditions.

Testing Process

Compression Experiment

We used YAW-300H universal material testing machine to carry out the compressive test, as shown in Figure 4. We put the maintained cube mortar specimen into the compressive test area of the testing machine. During the test, the compression speed was controlled to be 2.4kN/s . When the specimen reached the limit state and broke, we stopped the test and recorded the load value P at the time of failure. Formula (2) was used to calculate the compressive strength of the specimen.

$$\sigma = \frac{P}{b^2} \quad (2)$$

where P is the failure load, b is the side length of the cube specimen.



Fig. 4 - YAW-300H Universal Material Testing Machine

Crack Observation

(1) Pictorial representation

After the specimen completed pre-cracking, we marked both sides of the crack using a red waterproof neutral pen to facilitate observation of the healing progress of the crack. On day 0, 3, 7 and 28 of the healing of the specimen, we observed the crack using a GAOPIN GP-660V microscope, and measured the crack-marked areas using the software VPAPLatform, which is matched with the microscope, and took photos to record the results of the width of the cracks, as shown in Figure 5. We calculated the crack repair rate according to the crack widths measured at different repair ages. The calculation formula is shown in formula (3).

$$R_w = \frac{W_0 - W_t}{W_0} \times 100\% \quad (3)$$

where R_w is the crack repair rate, W_0 is average width of the initial crack, W_t is Average width of the crack at healing time t .



Fig. 5 - GAOPIN GP-660V Microscope

(2) Healing rate of the crack area

After using VPAPLatform software to photograph the specimen with crack, we imported the

image into ImageJ software and set the scale, then selected the crack area and used the analyze function to calculate the crack area. We calculated the healing rate of the crack area according to the area measured before pre-cracking and after 28 days of curing, and the calculation formula was shown in Formula (4).

$$\omega = \frac{S_0 - S_t}{S_0} \times 100\% \quad (4)$$

where ω is the healing rate of the crack area, S_0 is crack area at pre-cracking, S_t is crack area at repair age of t days.

Microscopic Analysis of Healing Products

After the pre-cracked mortar specimen was maintained in water for 28 days, we took out the specimen and wiped the surface moisture, put it into an oven at 50 ° C, took out and weighed at regular intervals until constant weight. Then, we collected the product at the crack of the specimen, and observed and analyzed the microstructure of the product by SEM, EDS and XRD tests.

RESULTS

Compressive Strength

Compressive strength is one of the basic mechanical properties of concrete, and it is also a common evaluation index of concrete properties. The cement mortar specimen with the size of 40mm×40mm×40mm was prepared for compressive strength test experiments. Figure 6 gives the results of compressive strength test of specimens at day 3, 7 and 28 with different mix proportions of admixtures in cement mortar. As shown in the figure, the cement particles continuously underwent hydration reaction during the curing process and the compressive strength of the cement mortar specimens increased with the increase of curing age. By comparing the test results in Figure 6 (a) and (b), it could be found that the compressive strength of the cement mortar specimens decreased with the increase of the expanded perlite dosage. This was due to the large amount of internal pores of expanded perlite and lower strength. Adding expanded perlite to the cement mortar specimens increased the porosity of the cement mortar and decreased the average strength of the cement mortar [32]. In addition, it could be seen from the figure that the effect of fibers on the compressive strength of cement mortar was not the same when expanding perlite with different dosages of solid-loaded bacteria was added to the cement mortar.

As shown in Figure 6 (a), when 10% bacteria-adsorbing expanded perlite was added to the cement specimens, with the increase of the dosage of basalt fibers, the compressive strength of the cement mortar specimens showed a trend of first increasing and then decreasing. This indicated that the moderate addition of fibers could improve the compressive strength of cement mortar, and excessive addition of fibers would reduce the compressive strength of cement mortar. This was because the fibers played a bridging role in the cement mortar, which could limit the formation and expansion of cracks and improve the compressive strength of the cement mortar. With the increasing dosage of basalt fibers, the fibers would agglomerate inside the cement mortar. The fibers were not only not embedded into the cement mortar to form a tight whole, but also formed pores in the cement mortar, which reduced the strength of the cement mortar [33]. Under the condition of low fibers dosage, with the increase of the length of the basalt fibers, the compressive strength of the cement

mortar specimens also showed the trend of first increasing and then decreasing; under the condition of high fibers dosage, with the increase of the length of the basalt fibers, the change of compressive strength of the cement mortar specimens was not obvious. This was because under the condition of low fibers dosage, short fibers were more easily embedded in the cement mortar to play a bridging role, improve the compressive strength of the cement mortar, while long fibers were easy to agglomerate in the cement mortar and reduce the compressive strength of the cement mortar. Under the condition of high fibers dosage, both short fibers and long fibers agglomerated inside the cement mortar, which reduced the compressive strength of the cement mortar.

As shown in Figure 6 (b), when 30% bacteria-adsorbing expanded perlite was added to the cement specimen, with the increase of the dosage of bacteria-adsorbing expanded perlite, the effect of basalt fibers dosage showed differences. With the increase of the dosage of basalt fibers, the compressive strength of the cement mortar specimens showed an increasing trend within a certain range. Compared with the control group (P6), the compressive strength of all the specimens showed increase to varying degrees. This was because the increase of expanded perlite dosage led to more pores in the specimens, and the bridging effect of basalt fibers was more obvious. By connecting the pores, the loss of compressive strength of the specimens was reduced, and the optimal dosage of basalt fibers was therefore increased. In addition, with the increase of the dosage of bacteria-adsorbing expanded perlite, the effect of the adding length of basalt fibers also showed differences. Under the condition of different fibers dosage, with the increase of the length of basalt fibers, the compressive strength of the cement mortar specimens all showed a tendency of increasing first and then decreasing. This was because short fibers were more easily embedded in cement mortar and played a bridging role to improve the compressive strength of cement mortar, while long fibers were more likely to agglomerate in cement mortar and reduce the compressive strength of cement mortar. Moreover, even under the condition of high fibers dosage, there were a large number of pore dispersed short fibers in the expanded perlite with high dosage, and short fibers would not agglomerate inside the cement mortar.

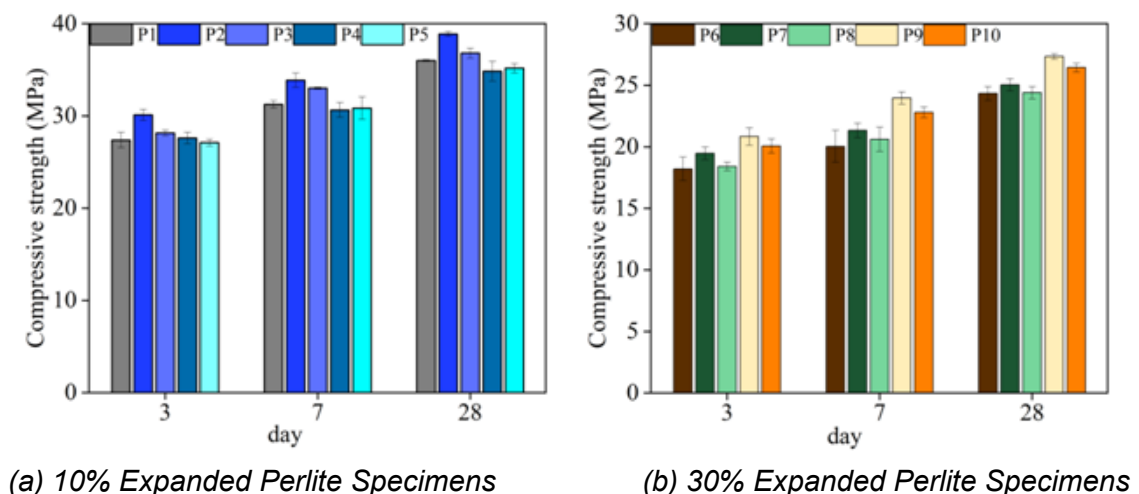


Fig. 6 - Column Charts of Compressive Strength Tests

Figure 7 gives the variation relationship between the compressive strength and the length of basalt fibers of specimens with 10% expanded perlite added at different curing ages. As shown in the figure, when the volume fraction of basalt fibers was 0.1%, the compressive strength of the

mortar specimens added with 6 mm (P2) and 12 mm (P3) long fibers improved to different degrees compared with the control mortar specimens (P1) without fibers. Among them, the mortar specimens added with 6mm long basalt fibers had the most significant compressive strength improvement effect, and the growth rate could reach 7.96% when the curing age was 28 days. When the volume fraction of basalt fibers was 0.5%, the change of compressive strength of the mortar specimens with 6mm (P4) and 12mm (P5) long fibers was not obvious. When the curing age was 28 days, the compressive strength of the mortar specimens even decreased, with a decrease rate of 3.24% and 2.31% respectively.

Figure 8 gives the variation relationship between the compressive strength and the length of basalt fibers of specimens with 30% expanded perlite added at different curing ages. As shown in the figure, when the volume fraction of basalt fibers was 0.1%, the compressive strength of the mortar specimens (P7) added with 6mm long fibers increased by about 2.87% in the curing age of 28 days compared with the mortar specimens (P6) of the control group. The compressive strength of the mortar specimens (P8) added with 12mm long fibers improved to some extent in the early curing period, but the compressive strength was basically the same as that of the control group at the curing age of 28 days. When the volume fraction of basalt fibers was increased to 0.5%, the compressive strength of mortar specimens added with 6mm (P9) and 12mm (P10) long fibers increased to different degrees. Among them, the mortar specimens added with 6mm long basalt fibers had the most significant compressive strength improvement effect, and the growth rate could reach 12.02% when the curing age was 28 days.

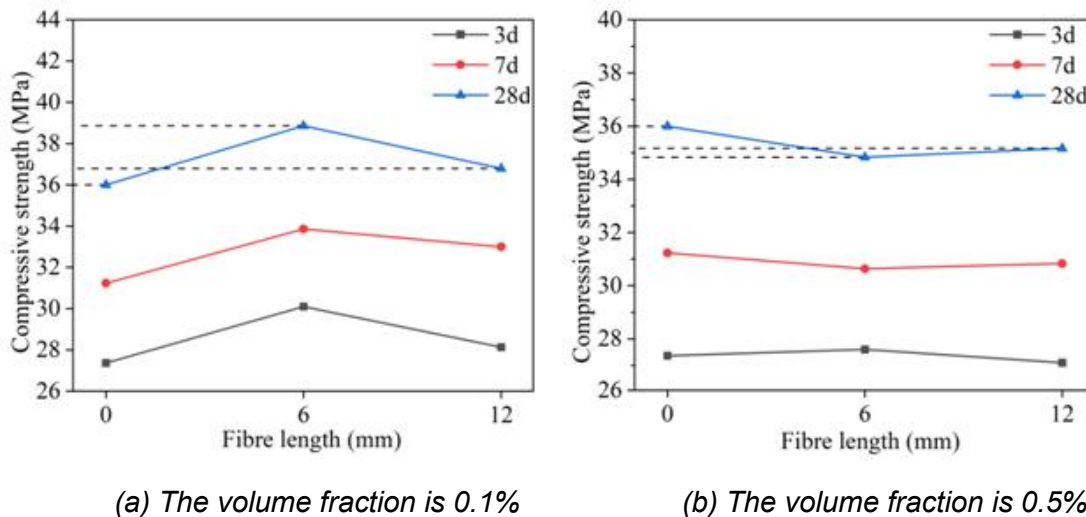


Fig. 7 - The relation between compressive strength and basalt fibers length of specimens added with 10% expanded perlite

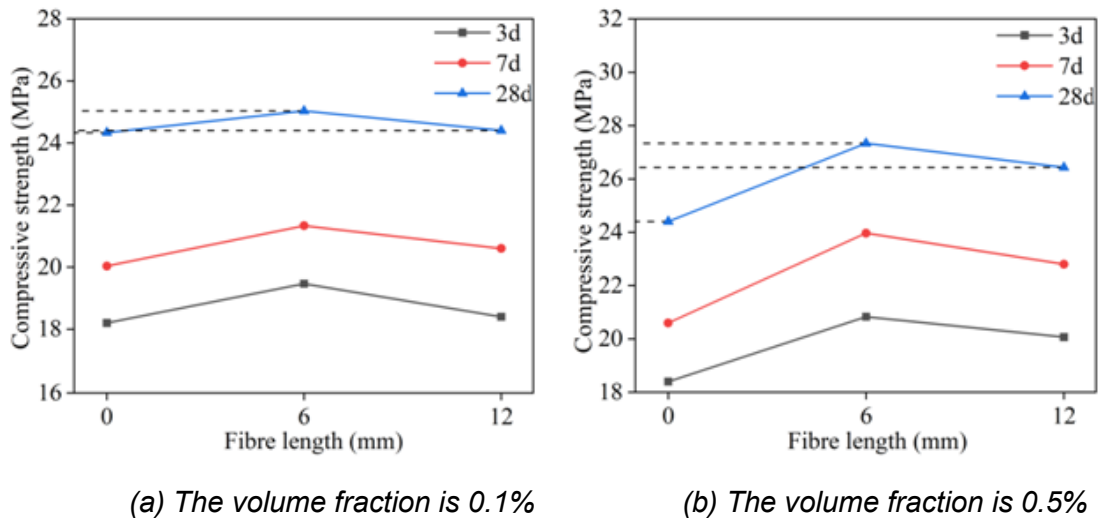


Fig. 8 - The relation between compressive strength and basalt fibers length of specimens added with 30% expanded perlite

Figure 9 and figure 10 respectively give the variation relationship between the compressive strength and the volume fraction of basalt fibers of the specimens with different dosages of expanded perlite at different curing ages. As shown in the figure, for the mortar specimens added with 10% expanded perlite, when 6mm and 12mm fibers were added, the compressive strength of the specimens showed an increase at low fibers dosage (0.1%) and a decrease at high fibers dosage (0.5%). For the mortar specimens added with 30% expanded perlite, the compressive strength of the specimens showed an increase with the increase of fibers dosages when 6mm and 12mm fibers are added.

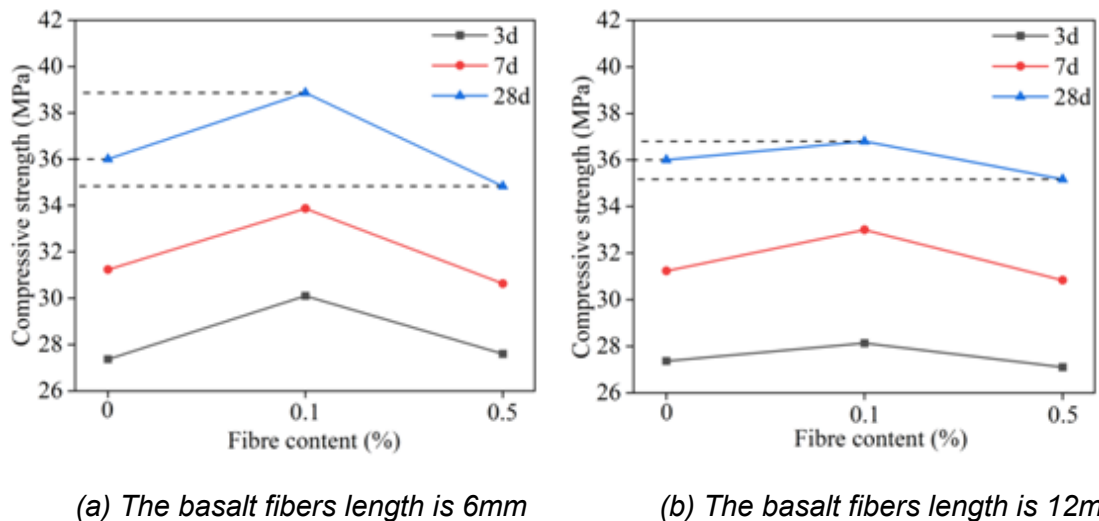
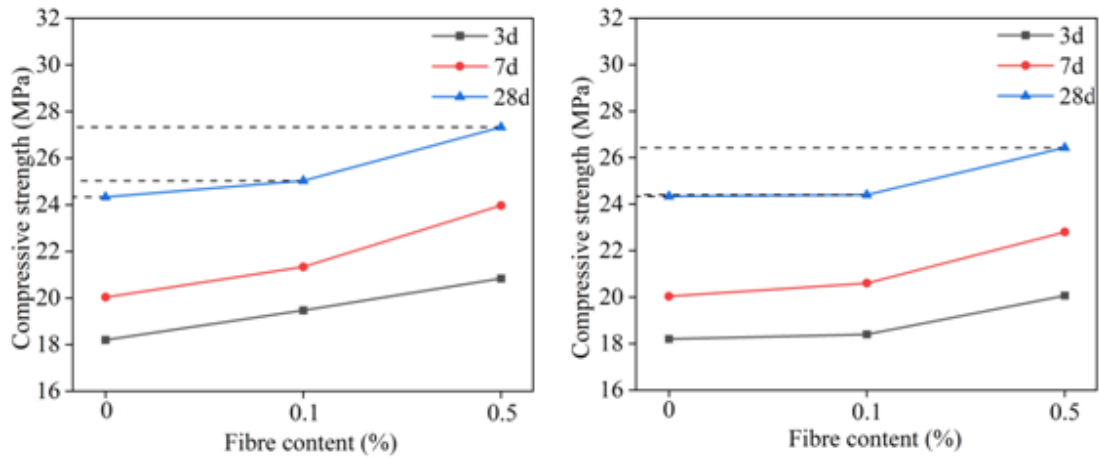


Fig. 9 - The relation between compressive strength and basalt fibers fraction of specimens added with 10% expanded perlite



(a) The basalt fibers length is 6mm

(b) The basalt fibers length is 12mm

Fig. 10 - The relation between compressive strength and basalt fibers fraction of specimens added with 30% expanded perlite

In summary, different dosages of expanded perlite had different effects on the internal pores of mortar specimens. With the increase of the expanded perlite dosage, the pores in the mortar specimens increased, the optimal dosage of basalt fibers increased, and the bridging effect of fibers became more obvious. Under the condition that the size of the mortar specimens was 40mm×40mm×40mm, the spacing between the internal pores of the specimens was very small, and the fibers with a length of 6mm could always play a role without negatively affecting on the compressive strength of the mortar specimens to the maximum extent, while the fibers with a length of 12mm were easy to agglomerate, which reduced the compressive strength of the mortar specimens.

Self-healing Performance

The crack self-healing property of cement mortar has an important influence on the overall property of the material, and the healing rate and healing degree determine the influence degree to which the internal material is affected by the external environment. The crack self-healing property of cement mortar can be evaluated by observing the healing conditions of cracks on the surface of specimens under different curing age conditions. Figure 11 gives the self-healing results of the cement mortar specimens added with 10% expanded perlite at 0, 3, 7 and 28 days after pre-cracking. As shown in the figure, with the increase of curing days, the width of the cracks gradually decreased, and the healing rate of each group could reach 100% at 28 days of self-healing curing. This was due to the fact that after cracks appeared in the mortar specimens, the spores in the cracks germinated, generated white precipitate through their own metabolism, and could completely fill the crack.

The self-healing efficiency of cracks could be effectively improved by adding fibers to cement mortar, and the self-healing efficiency of cracks increased gradually with the increase of fibers dosage. Figure 12 shows the self-healing results of cement mortar specimens added with self-healing agent and fibers at day 0, 3, 7 and 28 after pre-cracking. For the cement mortar specimens added with 0.5% fibers, the healing rate of the cracks could reach nearly 100% at 7 days of curing after pre-cracking. This was because the basalt fibers bridged on both sides of the cracks, providing

landing points for the white precipitate generated by bacterial metabolism, which improved the efficiency of crack healing. Compared with the cement mortar specimens added with 12 mm fibers, the cement mortar specimens added with 6 mm fibers had a higher self-healing efficiency, but the advantage was not obvious.

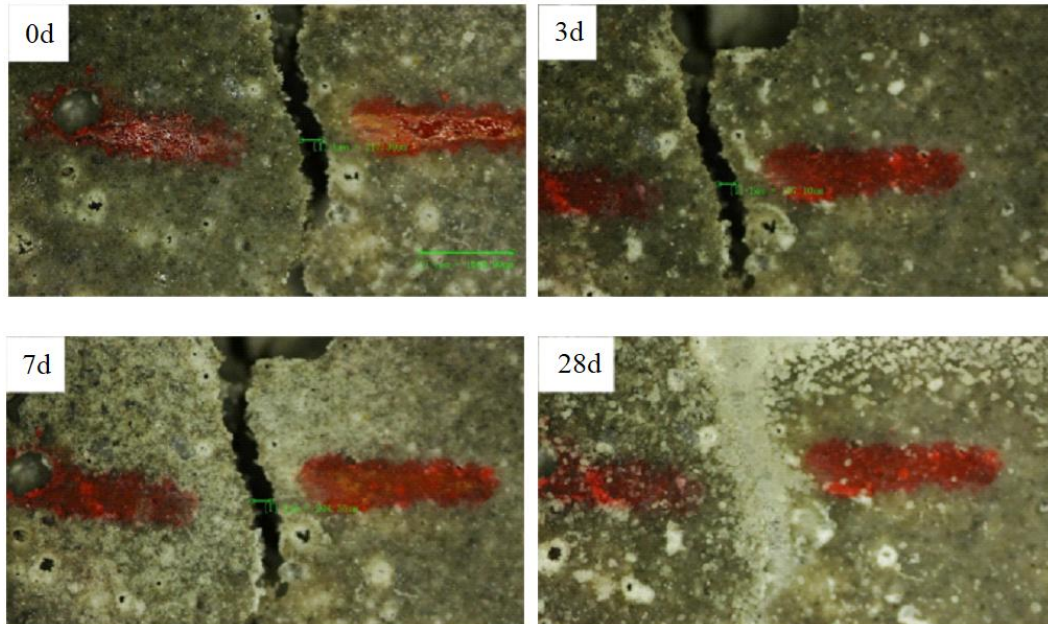
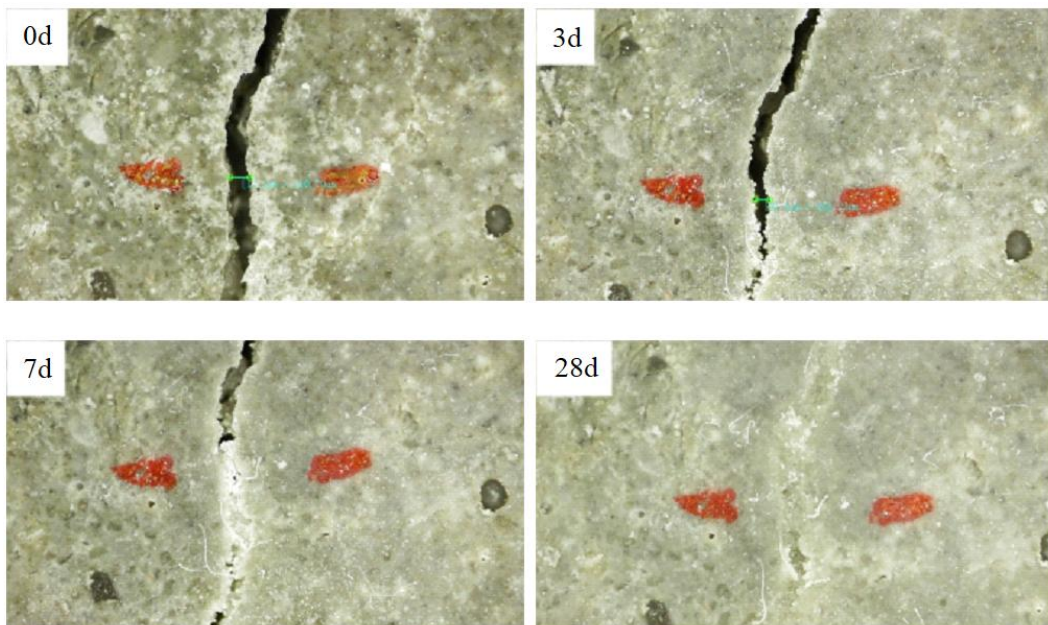
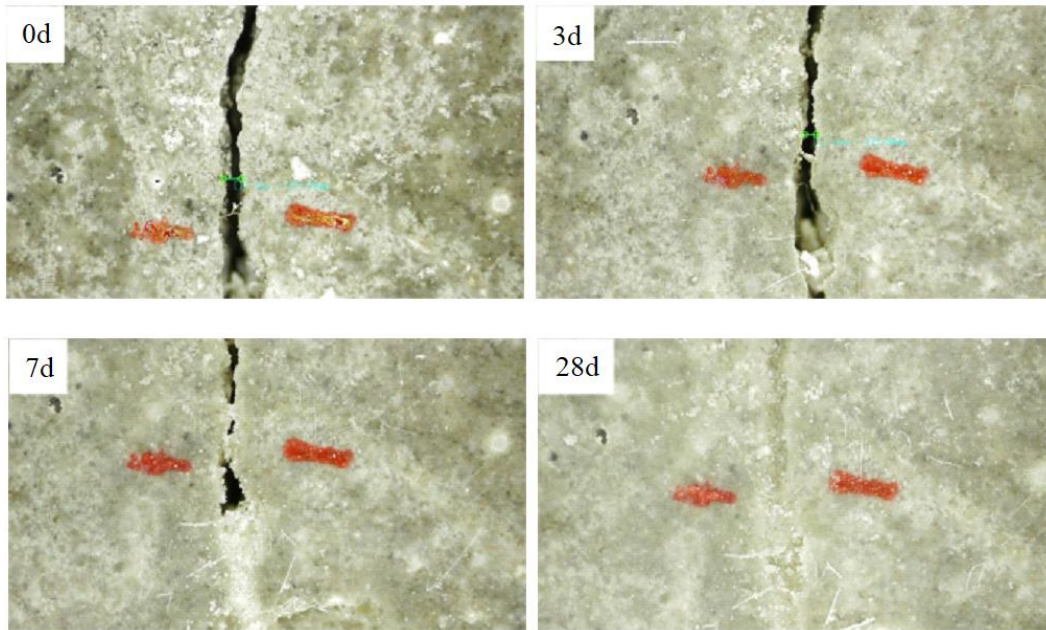


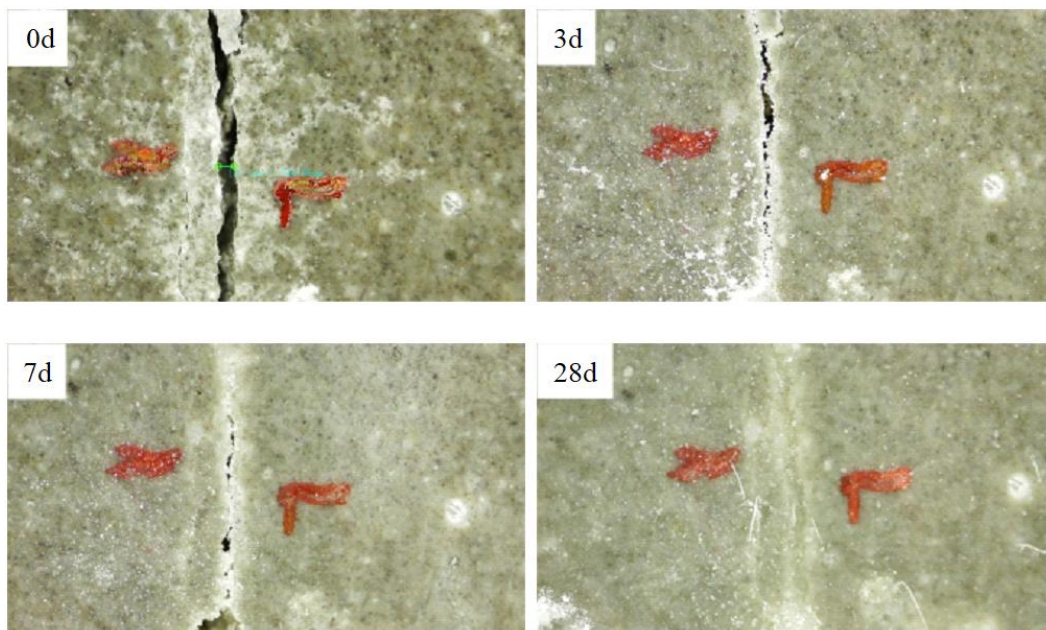
Fig. 11 - Self-healing results of cracks at days 0, 3, 7 and 28 in specimens doped with 10% expanded perlite under microscope



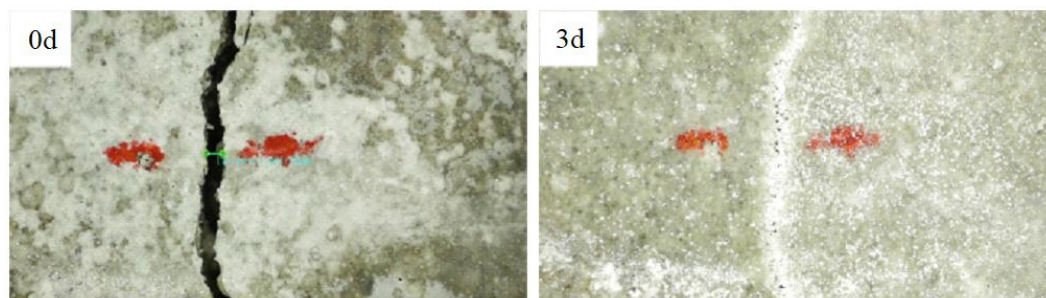
(a) Specimens containing 0.1% 6mm fibers and 10% expanded perlite

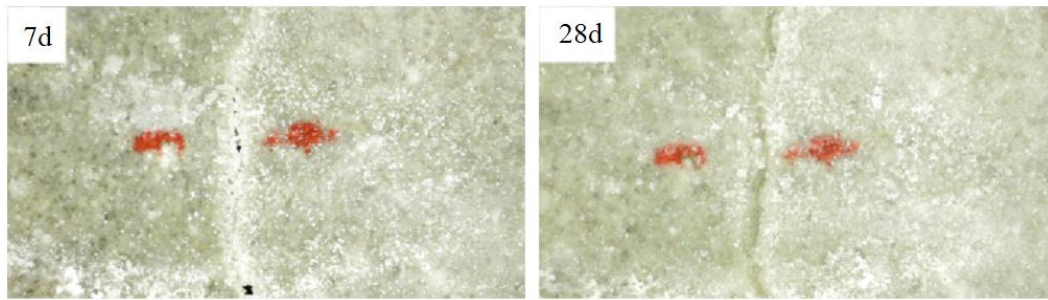


(b) Specimens containing 0.1% 12mm fibers and 10% expanded perlite



(c) Specimens containing 0.5% 6mm fibers and 10% expanded perlite





(d) Specimens containing 0.5% 12mm fibers and 10% expanded perlite

Fig. 12 - Self-healing results of cracks at day 0, 3, 7 and 28 under the microscope

Figure 13 shows the self-healing results of the cement mortar specimens added with 30% expanded perlite at 0 and 3 days after pre-cracking. As shown in the figure, the self-healing efficiency of the cement mortar specimens added with 30% self-healing agent was significantly improved compared to the cement mortar specimens added with 10% expanded perlite. For the specimens without basalt fibers, the healing rate of the cracks could also reach 20% at the curing age of 3 days.

Figure 14 shows the self-healing results of cement mortar specimens added with self-healing agent and fibers at day 0, 3, 7 and 28 after pre-cracking. As is shown in the figure, for the specimens added with fibers, the healing rate of the cracks could all reached 100% at the curing age of 3 days. This indicated that the basalt fibers in the mortar specimens could control the width of the cracks and play a bridging role at the cracks, providing a adsorption space for the comfortable landing points of the precipitate of bacterial metabolic reaction, which was conducive to improving the self-healing efficiency of the crack, as shown in Figure 15. However, under the condition of a large number of self-healing agents were added, the effect of the dosage and length of basalt fibers on the self-healing performance of cement mortar specimens was not very obvious.

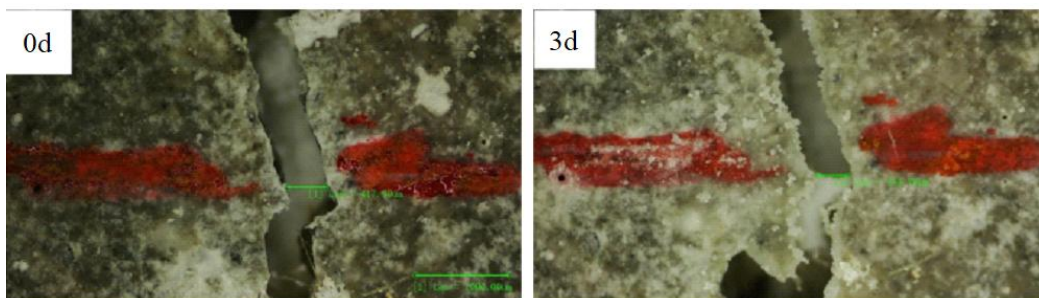
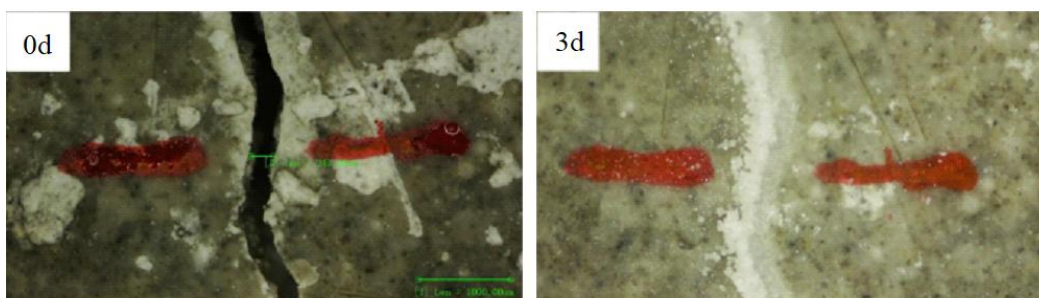
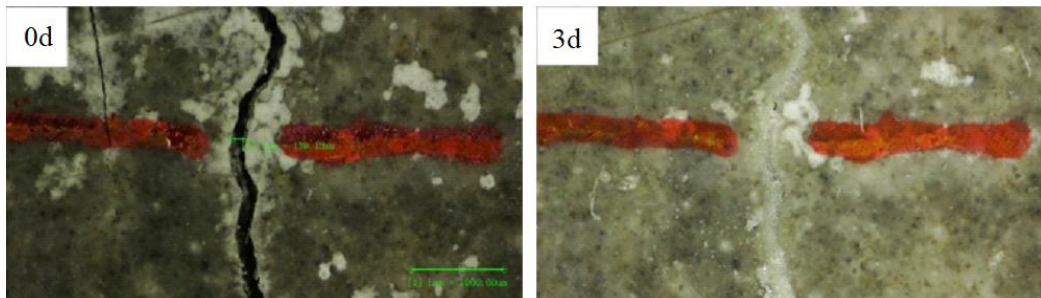


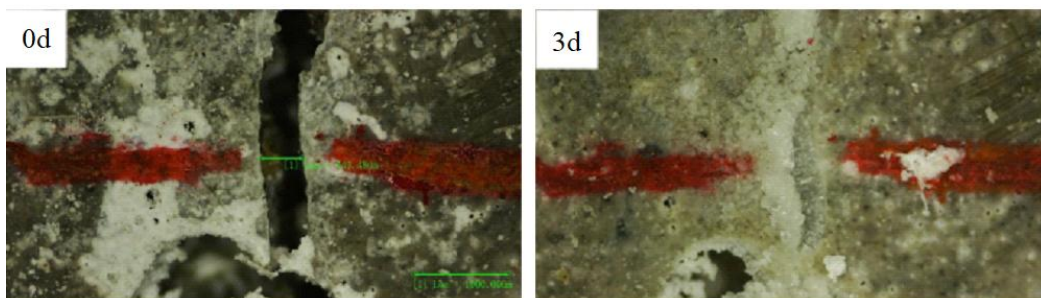
Fig. 13 - Self-healing results of cracks at day 0 and 3 in specimens doped with 30% expanded perlite under microscope



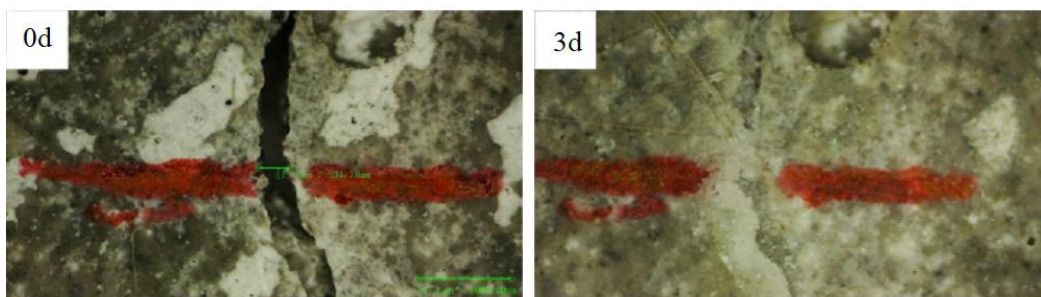
(a) Specimens containing 0.1% 6mm fibers and 30% expanded perlite



(b) Specimens containing 0.1% 12mm fibers and 30% expanded perlite



(c) Specimens containing 0.5% 6mm fibers and 30% expanded perlite



(d) Specimens containing 0.5% 12mm fibers and 30% expanded perlite

Fig. 14 - Self-healing results of cracks at day 0 and 3 under the microscope



Fig. 15 - Calcium carbonate attaches to the surface of fibers

In order to further study the effects of self-healing agents with different dosages and different sizes and dosages of fibers on the self-healing performance of mortar specimens, the maximum

healing efficiency diagram of cracks with different widths was drawn. As shown in Figure 16, the crack width was divided into five intervals for statistics.

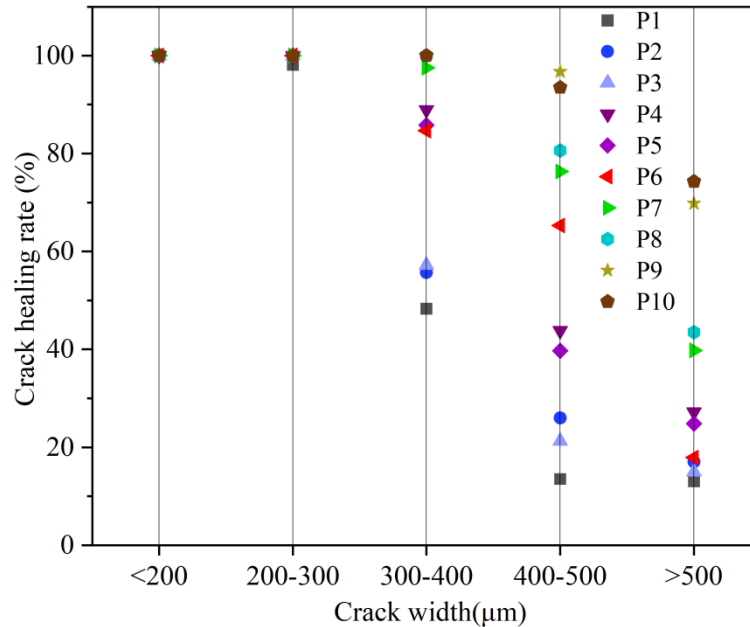


Fig. 16 - The healing rates of different crack widths at 28 days of self-healing

It can be seen from Figure 16 that when the crack width was less than 300μm, the mortar specimens could basically heal completely, and the healing rate of specimens of each group was all above 95%. However, when the crack width increased to 300-400μm, the self-healing efficiency of the specimens with 10% self-healing agent dosage began to decline, among which P1, P2 and P3 decreased the most, which was due to the fact that when the crack width was too large, the precipitate produced by the bacterial mineralization could not connect the two sides of the cracks, resulting in the poor final repair effect. Although the self-healing agent dosage of P4 and P5 specimens was 10%, the internal fibers dosage was enough to provide a large number of precipitation anchor points at the cracks, which could improve the self-healing efficiency.

For cracks larger than 500μm, only P9 and P10 could maintain a healing rate of more than 50%, which was because the crack width was too large, exceeding the self-healing limit of the remaining groups. Only P9 and P10 showed better healing rates under the coupling of self-healing agents and fibers.

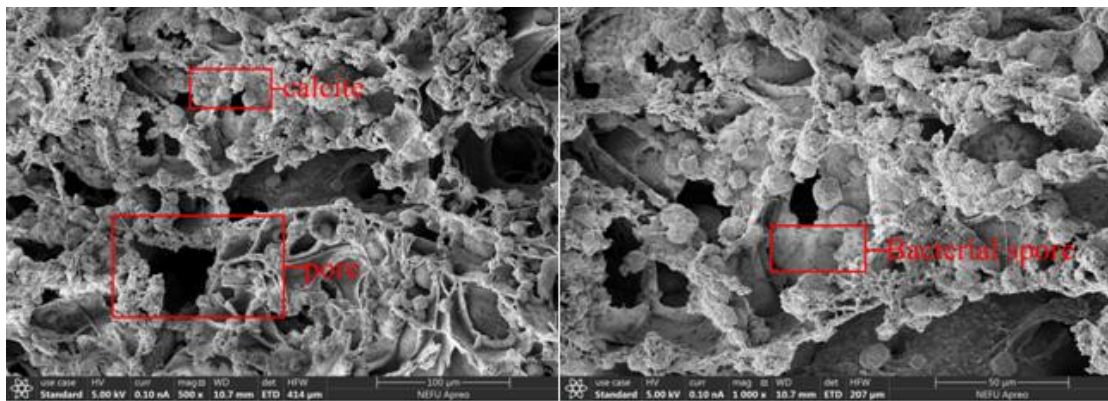
Microscopic and Phase Analysis

SEM Microscopic Analysis

In order to further clarify the self-healing mechanism of the cracks, this paper observes the morphology of the healing products in the cracks by SEM test. More healing products could be obtained by choosing to extract healing products from P10 specimens. Figure 17 shows the microscopic morphology of the expanded perlite at the cracks. As can be seen in Figure 17(a), calcium carbonate precipitate was generated around the holes on the surface of expanded perlite. This indicated that bacteria could survive in expanded perlite and fill the cracks by germinating and

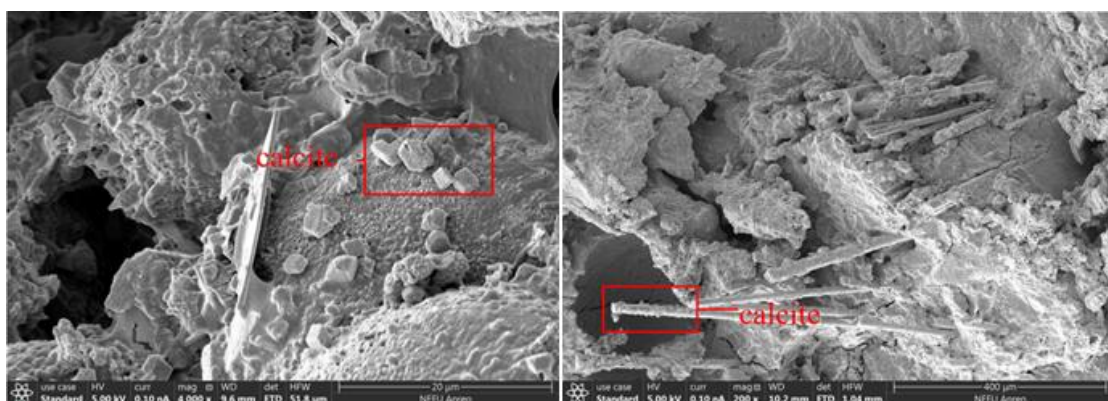
generating calcium carbonate precipitate when cracks appeared in the cement mortar specimens. As can be seen in Figure 17(b), the bacterial spores were fixed in the pores inside the expanded perlite, but the distribution was not uniform. This also indicated that the repair efficiency at different locations of the same crack was not the same.

Figure 18 gives the microstructure of the product at the crack healing site. As can be seen in Figure 18 (a), a large amount of cube-shaped calcite was generated at the crack, indicating that the metabolic product of bacteria at the crack was calcium carbonate [34]. From Figure 18(b), it could be seen that a large amount of calcium carbonate was attached to the surface of basalt fibers, which indicated that the contact area of bacterial mineralization deposition could be increased by mixing basalt fibers, and the deposited calcium carbonate filling the pores inside the cement mortar improved the mechanical properties and impermeability of the mortar. The fibers at the cracks both bridged and anchored the deposits, controlling the crack width and providing deposition anchor points for calcium carbonate precipitation.



(a) Calcium carbonate on expanded perlite (b) Bacterial spores on expanded perlite

Fig. 17 - The surface microstructure of expanded perlite under SEM



(a) Cubic calcite

(b) Calcium carbonate on fibers

Fig. 18 - The microstructure of CaCO₃ produced by cracks under SEM

XRD Phase Analysis

Figure 19 gives the XRD results of healing products at cracks in the cement mortar specimens added with 30% expanded perlite. As shown in the figure, CaCO₃, SiO₂ and other substances were

detected in the XRD spectra of specimens of all the 5 groups. Among them, calcite peaks were found at 29.4 and 39.4. This indicated that the bacteria could survive in cement mortar using expanded perlite as the carrier and generate calcium carbonate through metabolism [35]. From the figure, we could also find that the more fibers dosage, the higher the calcite peak. This indicated that the addition of fibers was beneficial to adsorbing the calcium carbonate precipitation generated by bacterial metabolism, and the dense bonding could improve the self-healing performance of cement mortar.

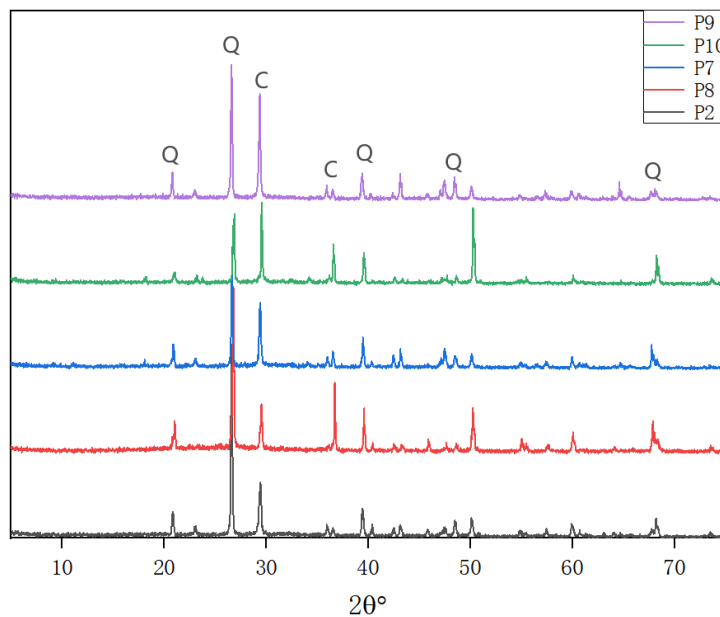


Fig. 19 - XRD results, Q-quartz, C-calcite of self-healing products of the specimens at 28 days of healing

CONCLUSION

- (1) Adding an appropriate number of basalt fibers has no negative effect on the compressive strength of cement mortar. For the cement mortar specimens added with 10% expanded perlite, basalt fibers added with 6mm and 0.1% volume fraction had the highest compressive strength. For the cement mortar specimens added with 30% expanded perlite, basalt fibers added with 6mm and 0.5% volume fraction had the highest compressive strength.
- (2) The number of self-healing agents added to cement mortar was proportional to the number of healing products generated after mortar cracking. Under the perfect conditions for ideal bacterial activity, increasing the dosage of self-healing agents could significantly improve the self-healing property of cracks in cement mortar, but at the same time, it also reduced the compressive strength of cement mortar. By adding basalt fibers to cement mortar at the same time, the mechanical properties of the material could be improved, and the complementary advantages with the effect of self-healing agents could be achieved. By adding a small number of healing agents and a moderate number of fibers at the same time, not only could achieve 100% self-healing performance, but also benefit to the compressive strength of cement mortar.
- (3) Through XRD analysis, it was found that the healing product at the cracks was calcium carbonate. Through SEM observation tests, it was found that bacteria could survive in cement mortar

with expanded perlite as carriers, and further determined that the healing products were cubes and amorphous calcite.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

ACKNOWLEDGEMENTS

This work is supported by the Fundamental Research Funds for the Central Universities (No. 2572022DX07).

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