Experimental Study on the Performance of Self-Healing Concrete Based on Temperature Response

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Abstract: In construction engineering, new building materials exhibit unique properties, with self-healing concrete drawing significant attention for addressing issues such as water leakage through fine cracks in concrete. This thesis investigates the healing performance of self-healing concrete based on ceramsite carrying Bacillus subtilis under various temperature conditions, conducting repair tests on self-healing concrete within a temperature range of 10°C to 40°C. It was found that the volume fraction of ceramsite carrying bacteria significantly impacts the mechanical properties of self-healing concrete. For the mix proportion in this study, the optimal replacement volume fraction of ceramsite in self-healing concrete was determined to be 45%. Additionally, environmental temperature noticeably affects the healing performance of self-healing concrete, with the crack healing rate showing a trend of initially decreasing and then increasing with rising temperature. The best healing effect was observed at an environmental temperature of 40°C, achieving a healing rate of 81.8%.

Keywords: Self-Healing Concrete; Bacillus Subtilis; Temperature Effect; Ceramsite

1. Introduction

Self-healing concrete is a unique type of concrete that has the capability to automatically repair small cracks and damages [1-3]. Special materials such as microorganisms and polymers are incorporated internally, enabling self-healing concrete to autonomously sense cracks and release healing agents to fill them, thereby restoring structural integrity and durability. Currently, research on self-healing concrete is in a rapid development phase and has been validated and applied in various laboratories and practical projects. With further research, it is expected that the performance and application scope of self-healing concrete will expand [4-7].

In recent years, the application of biotechnology in the field of building materials has gradually emerged as a research hotspot. Unique biological activity and environmental adaptability of biomaterials enable self-repair and regeneration under specific conditions. The application of biotechnology to concrete materials can endow them with self-healing capabilities, thereby enhancing the durability and reliability of concrete. As infrastructure construction continues to advance, the self-healing properties of concrete have received widespread attention. Self-healing concrete can automatically repair damage after it occurs, extending its service life. Currently, microbial repair technology, which utilizes calcium carbonate precipitates produced by microbial metabolism to fill cracks, has become a research focus. The study of self-healing concrete performance is influenced by many factors and is developing relatively slowly, with many technical bottlenecks still to be resolved [8-10]. In this study, the impact of temperature factors on the healing effect is explored by utilizing the mineralization effect of Bacillus subtilis to repair cracks in concrete.

2. Preparation of Self-Healing Concrete Specimens

2.1 Mix design of Self-Healing Concrete

The design of concrete mix proportions is an essential aspect of civil engineering material application, directly impacting the performance and quality of concrete. Optimal proportions of cement, aggregate, water, and admixtures are determined through precise calculations and experiments to meet the strength and durability requirements of the structure. A reasonable mix proportion ensures the safety of the structure while also enhancing construction efficiency and reducing costs. In practical applications, various factors such as environmental conditions, usage requirements, and economic considerations need to be considered in mix proportion design. With the advancement of technology, the requirements for concrete performance are becoming increasingly stringent, thereby making mix proportion design more significant. The mix proportion design for this experiment is presented in Table 1.

Table 1. Mix Proportions of Self-Healing Concrete at Different Repair Temperatures

Specimen Number	Water (kg)	Cement (kg)	Sand (kg)	Crushed stone (kg)	Ceramsite (%)	Temperature ℃	Bacterial solution concentration (mol/L)
1	0.54	1.38	1.53	2.067	45	10	2.15*10^3
2	0.54	1.38	1.53	2.067	45	20	2.15*10^3
3	0.54	1.38	1.53	2.067	45	30	2.15*10^3
4	0.54	1.38	1.53	2.067	45	40	2.15*10^3

2.2 Determination of Standard Compressive Strength of Self-Healing Concrete

The determination of the compressive strength of concrete using ceramsite as aggregate is conducted through experiments. The compressive strength test is depicted in Figure 1. Standard specimens of self-healing concrete with ceramsite content ranging from 0% to 65% are prepared, having dimensions of 100*100*100mm standard cubes. Standard compressive strength tests of concrete are conducted under standard testing conditions. The standard compressive strength values of the various specimens are presented in Table 2.

Table 2. Compressive Strength of Specimens Different Ceramsite Contents

Ceramsite content (%)	Compressive strength (kpa)
40	25
45	24
50	25
55	25
60	29
65	22
0	25

Figure 1. Compressive Strength Test of Standard Self-Healing Concrete Specimen

2.3 Preparation of the Bacterial Strains

As a common Gram-positive bacterium that has a wide range of habitats, Bacillus subtilis can survive in various environments, including soil, water bodies, plant surfaces, and animal intestines. Being able to adapt to different temperature conditions, with its optimal growth temperature typically being between 30°C and 37°C, this bacterium can survive under low nutrient conditions and can form spores, a dormant form that resists harsh environments such as high temperatures, dryness, and chemicals. In the spore state, Bacillus subtilis can withstand extreme temperature variations and even survive for years in dry environments, which can also rapidly reproduce and regain activity under suitable conditions. The bacterial strain used in this experiment is Bacillus subtilis, which is cultured using a liquid medium.

2.4 Ceramsite Water Absorption at Different Temperatures

In this experiment, ceramsite is used as the coarse aggregate, and its water absorption characterizes the absorption performance of ceramsite as a carrier for Bacillus subtilis. Table 3 presents the water absorption of ceramsite under various temperature conditions.

Table 3. Water Absorption Rate of Ceramsite under Different Temperature Conditions

Specimen	Temperature			
	10℃	20℃	30℃	40℃
1	1.145	0.845	0.759	0.823
2	1.334	0.985	0.834	0.943
3	1.489	1.107	0.904	0.967
4	1.494	1.112	0.913	0.978
5	1.502	1.115	0.921	0.983

Table 3 indicates that the water absorption of ceramsite remains relatively stable under conditions of 10°C to 40°C, demonstrating its capability to effectively absorb the bacterial solution. This series of experiments confirms the feasibility of using ceramsite as a carrier for Bacillus subtilis in the production of concrete specimens.

3. Test on Healing Performance of Self-Healing Concrete under Different Temperature Conditions

3.1 Healing Test of Self-Healing Concrete under Different Temperature Conditions

Initially, a hydraulic press was used to create cracks in standard concrete specimens and bacterial concrete specimens, dividing them into four groups and placing them in curing boxes at 10°C, 20°C, 30°C, and 40°C for seven days to observe the healing of the specimens. Since the healing of self-healing concrete is significantly correlated with factors such as bacterial solution concentration, environmental conditions, crack width, and ceramsite content, this thesis conducted 48 sets of healing experiments focusing on the impact of environmental temperature on the healing effect of self-healing concrete. Different widths of artificial cracks were randomly formed on the formed specimens, and after 7 days of curing, the degree of crack healing was determined using a water permeability test, with the healing rate characterizing the healing effect. Table 4 lists the initial crack width values of the specimens in different groups. The crack healing conditions of the specimens under different temperature conditions are shown in Table 5.

Table 4. Initial Crack Width of Specimens under Different Temperature Conditions

Temperature (°C)	Initial crack width of specimens at different temperatures (mm)														
10	0.11	0.11	0.12	0.17	0.20	0.20	0.24	0.29	0.32	0.36	0.39	0.45	0.48	0.53	0.55
20	0.11	0.12	0.13	0.15	0.18	0.22	0.24	0.30	0.32	0.36	0.38	0.44	0.48	0.53	0.58
30	0.11	0.12	0.13	0.15	0.18	0.22	0.23	0.28	0.33	0.35	0.38	0.46	0.48	0.50	0.50
40	0.12	0.12	0.13	0.13	0.14	0.21	0.27	0.29	0.28	0.33	0.39	0.42	0.48	0.53	0.53

Table 5. Healing Rate of Self-Healing Concrete Cracks under Different Temperature Conditions

Temperature (°C)	Specimen crack healing rate (%)		
	0.1-0.3 (mm) crack	0.31-0.5 (mm) crack	0.51-0.7 (mm) crack
10	89	75	0
20	89	75	60
30	78	75	80
40	100	71	100

3.2 Analysis of Test Data

From the experimental data on the reaction of Bacillus subtilis in self-healing concrete tests, a significant effect on the healing of concrete cracks is shown. The tests show that under certain conditions, Bacillus subtilis produces $CaCO_3$, which fills the original cracks, thereby promoting the healing of the cracks. By comparing the test results, it was found that concrete samples with added Bacillus subtilis had a significant improvement in compressive and tensile strength compared to specimens with cracks that were not repaired, indicating that the filling of cracks can enhance the mechanical properties of concrete. Furthermore, a large number of experimental results show that the self-healing effect of Bacillus subtilis is compatible with cement-based materials and can maintain activity in an alkaline environment. All 48 sets of self-healing concrete specimens exhibited varying degrees of crack healing. The concrete specimens under different healing temperature conditions were classified in line with the width of the healed cracks, with the aim of filling 80% of the crack surface area, to evaluate the healing of the cracks. The tests found that when the temperature was 10°C, the healing rate gradually decreased with the increase in crack width, especially for cracks of 0.51-0.7mm, which could not be filled. The healing rate of wide cracks in self-healing concrete significantly increased as the environmental temperature increased. When the temperature reached 40°C, the healing rate of cracks with a width of 0.51-0.7mm reached 100%, indicating that the increase in temperature has a significant promoting effect on the mineralization of Bacillus subtilis. When the temperature increased from 10°C to 30°C, the healing rate of cracks with a width of 0.31-0.5mm in self-healing concrete almost did not change according to the experimental data. This could be due to the limitation of crack space, which causes a shortage of other chemical reaction elements for the mineralization effect, even though the temperature conditions are good, the effect is still not significant. For the optimal survival temperature of Bacillus subtilis, when the temperature is above 40°C, the survival amount in the bacterial solution will decrease sharply, so there is no need to further analyze its healing conditions. The experimental data in Table 5 shows that at an environmental temperature of 40°C, most cracks can be healed, with a total healing rate of 81.8%. Therefore, the optimal temperature for the Bacillus subtilis self-healing concrete prepared in this thesis, based on temperature response, is determined to be 40°C.

4. Conclusion

This thesis investigates the feasibility of using ceramsite as a carrier for Bacillus subtilis in self-healing concrete, as well as the study of the healing effects of Bacillus subtilis self-healing concrete based on temperature response, through 48 sets of healing experiments. The following conclusions were drawn from a large number of experiments:

1. A stable water absorption rate of ceramsite within the temperature range of 10°C to 40°C was observed, indicating that ceramsite is suitable as a carrier for Bacillus subtilis. The design of the concrete mix ratio directly impacts the performance and quality of the concrete, ensuring structural safety and durability while improving construction efficiency and reducing costs.
2. In the standard strength test of ceramsite concrete, it was found that the ceramsite content has a certain impact on the strength of the concrete for the mix ratio design in this thesis. The water absorption rate of different ceramsite contents is highly correlated with the degree of bacterial solution absorption.
3. The healing effect of ceramsite-loaded Bacillus self-healing concrete has certain differences under different healing temperature conditions. As the temperature increases, the crack healing rate exhibits a trend of first decreasing and then increasing. For the self-healing concrete studied in this thesis, the healing effect of concrete is best at an environmental temperature of 40°C, with a healing rate of 81.8%.

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