THE SELF-HEALING OF ULTRA-HIGH PERFORMANCE CEMENT BASED COMPOSITES

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Abstract: The self-healing of ultra-high performance cement based composites (UHPCC) was researched. Multi-scale fibers and different reactive powders were used to improve the self-healing of UHPCC. The static mechanical properties and ultrasonic wave velocity of UHPCC were measured before and after loading. The damaged UHPCC specimens subjected to different static loads were re-cured in different conditions. The mechanical behaviour and ultrasonic wave velocity of re-cured specimens were compared with those of intact specimens. Results show obvious self-healing of UHPCC and the self-healing is improved with increasing of curing time and temperature. Longer fiber reinforced UHPCC shows better self-healing than short fiber reinforced one. The damaged specimens with binary or ternary reactive powders recover more than those with single powders.

Key words: UHPCC, self-healing, fiber, reactive powders, curing condition

1. INTRODUCTION

The damage of concrete usually has a cumulative process. Not all initial micro-cracks develop into harmful cracks or unstable cracks. If the micro-cracks can be healed once it formed, then the further development of concrete damage can be avoided. The safety of structures can be improved and the maintenance costs can be greatly reduced.

Many researchers have researched this interesting phenomenon of concrete. Hannant et al. [1] studied the self-healing process of micro-cracks in concretes. Stefan et al. [2] found that there were crystals of ettringite and Ca(OH)2 seen traversing the cracks at several location through scanning electron microscope (SEM) when concretes deteriorated by freeze and thaw. Stefan et al. [3] studied the deterioration and self-healing on chloride transport in OPC concretes. Nataliya [4] talked about the differences of self-sealing, autogenous healing and continued hydration. Liu et al. [5] carried out experiments to distinguish the influences of cement particles diameter on self-healing performance of concretes. Waterproof concrete structures cracked and leaked gently at the beginning. But after a period of time, Li et al. found that the cracks closed completely and did not leak at all [6]. Reinhardt et al. [7] researched self-healing behavior of cracked concrete as a function of temperature and crack.
width. They found that the average crack width measured at the surface showed the fastest self-healing. Romildo et al. [8] studied the crack self-healing tendency after plastic shrinkage cracking of cement mortar and sisal fiber mortar composite. They got the results that both cracks of two different mortars could be self-healed and different initial crack width showed different self-healing tendencies. Above mentioned researches discovered that concrete after deterioration could heal by itself indeed. The mechanisms and influence factors must be further studied.

Ultra-high performance cement based composites (UHPCC) have excellent mechanical properties and it is found to be consistent with the direction of future development of the new materials in civil engineering [9,10]. In this paper, UHPCC was prepared by removing coarse aggregates, replacing cement with reactive powders and reducing water cement ratio. The strength and toughness of UHPCC were improved by fibers reinforcement.

Although experts have done many works on the self-healing of concrete, there are still many problems to be solved. In this paper the self-healing of UHPCC was investigated under different healing conditions to sum up its major influencing factors. The damage of UHPCC was measured using the ultrasonic pulse velocity (UPV) method. The effects of reactive powders, different fibers and healing conditions were researched on the self-healing of UHPCC.

2. EXPERIMENT

2.1 Material preparation

Three cementitious materials were used in the preparation of UHPCC including Portland cement, silica fume (SF), and blast-furnace slag. The strength grade of the cement is P·II 52.5 according to the relevant Chinese standard. Ground fine quartz sand used for normal UHPCC was totally replaced with natural sand. The maximum particle size of natural sand is 2.5mm with a fineness modulus of 2.6. The polycarboxylate based superplasticizer (SP) was produced by the Grace Company in Shanghai China with a water-reducing ratio of more than 40%. Two types of fibers shown in Fig.1 were used, including steel fibers and PVA fibers. The steel fibers used in this experiment are 13 mm or 20mm in length, 0.2 mm in diameter and 210 GPa in elastic modulus. The PVA fibers used in this experiment are 12 mm in length, 0.04 mm in diameter and 43 GPa in elastic modulus. The mix proportions of UHPCC are given in Table 1. The cubic specimens (70×70×70 mm) were cured in standard conditions(20°C±2°C, R.H.>90%).

![Steel fibers](image-a) ![PVA fibers](image-b)

Fig.1. Pictures of two types of fibers.
Table 1. Mix proportions of UHPCC

<table>
<thead>
<tr>
<th>Series</th>
<th>Binder (wt.%)</th>
<th>Sand/Binder</th>
<th>Superplasticizer/Binder</th>
<th>Water/Binder</th>
<th>Fiber volume fraction (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
<td>Silica fume</td>
<td>Slag</td>
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<td>Steel fiber</td>
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<tr>
<td>A</td>
<td>50</td>
<td>20</td>
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<td>1.2</td>
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<td>20</td>
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<td>I</td>
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<td>1.2</td>
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</tr>
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</table>

2.2 Testing method

The intact concrete specimens were cured in standard conditions for two different ages (28 days and 90 days). After the compressive loading, the damaged specimens were cured in two different conditions: (1) 20°C±2°C, R.H.>90%, cured for 28 days; (2) in 95°C hot water, cured for 48h. The steps of tests are as follows:

1. Test the UPV of the original UHPCC specimens.
2. Test the compressive strength of the original UHPCC specimens.
3. Test the UPV of the damaged specimens.
4. Curing the damaged specimens under different healing conditions.
5. Test the UPV of the self-healing specimens.
6. Test the compressive strength of the self-healing specimens.

3. RESULTS AND DISCUSSION

3.1 The results of compression strength testing

The ability of strength recovery is determined by many factors, such as the mixture of concrete, the damaged age, damage degree, conditions of self-healing (humidity, temperature) and curing ages etc. Among these factors, this paper focused on the mixture proportion and the conditions of self-healing.
3.1.1 The effects of fibers on the self-healing of UHPCC

In order to define the self-healing capability, self-healing ratio was introduced and signed as \( k \). \( k \) represented the ratio of the compression strength after self-healing (\( P_0 \)) to the original compression strength (\( P \)) of UHPCC.

\[
k = \frac{P}{P_0}
\]

Fig. 2. Self-healing ratio \( k \) and strength of the UHPCC with different fibers

Fig. 2 shows \( k \) and the strength of UHPCC with different fibers. It appears that the compression strength of all specimens is from 120MPa to 160MPa. It can be obviously discovered the specimens reinforced by longer steel fibers have better effect on the self-healing compared with those reinforced by shorter steel fibers. The self-healing ratio \( k \) of longer fibers reinforced specimens approaches 0.9 and the self-healing ratio \( k \) of shorter fibers reinforced specimens is below 0.6. The longer fiber was hard to be pulled out and it restrained the development of cracks. The specimens with hybrid fibers shows better mechanical property, but the self-healing ratio of concrete will increase with the increasing of damage degree.

3.1.2 The effects of reactive powders on the self-healing of UHPCC

Fig. 3. Effects of reactive powders

Fig. 3 shows that UHPCC specimens with single reactive powder have lower...
self-healing ratio than the specimens with two kinds of reactive powders. The reactive powders used in this project were slag and silica fume. Slag and silica fume are reactive materials which can improve the self-healing of concretes. Although each kind of these materials can improve the healing effects, the synergy of two materials can produce much better results.

3.1.3 The effects of curing age on the self-healing of UHPCC

In order to distinguish the effects of the curing ages on the self-healing of UHPCC, the specimens were cured for different time before loading. Parts of them were cured for 28d, and others were cured for 90d as showing in Fig.4. Results show that the series that cured for 90d have a stable self-healing ratio and it changes from 0.6 to 0.77 with the changing of the steel fiber content. The series cured for 28d have a self-healing ratio increasing with the increasing of fiber content and it changes from 0.42 to 0.86. The self-healing effect is good for both curing ages when the fiber volume fraction is 3.0%.

3.1.4 The effects of healing conditions on the self-healing of UHPCC

The hydration speed of reactive powders is different in different healing conditions. The healing temperature affects the self-healing performance of the specimens for the hydration of cement and other powders can be accelerated by high temperature. Time is another important factor on self-healing. Enough time can make unhydrated cement hydrate thoroughly. The damaged specimens was cured at 20°C for 28d or at 95°C for 48h. It can be seen that the damaged specimens cured at
95 °C healed less in compressive strength for the curing time is short. The self-healing ratio can reach 0.4 at 95 °C. The damaged specimens cured at 20 °C for 28d have a much higher self-healing ratio than that of concretes cured for short time.

3.2 THE RESULTS OF UPV TESTING

3.2.1 Testing method

As shown in figure 6, there are 10 labels marked on two adjacent aspects of the specimen. The first five are on the loading surface and the others are on free surface. Ultrasonic concrete tester is shown in figure 7. It includes the emission and the receiver of ultrasonic. By testing the elapsed time (T) and distance (L) of the ultrasonic propagation through the concrete matrix, finally calculate the ultrasonic pulse velocity (UPV).

\[ \text{UPV} = \frac{L}{T} \]  

Fig.6. Labels on concrete specimen  
Fig.7. Ultrasonic concrete tester

Fig.8 shows the UPV of d. It is obviously that the results of UPV are according to the results of strength test. The direction vertical to loading surface has less cracks than other direction. So the UPV of the same specimen is not all the same, and it reflects the destroy form in different specimens and different direction.
Figure 9 shows the average UPV of each concrete specimen. It obviously that after self-healing, not only the mechanical properties of concrete have been recovered, but also the UPV has been regained in a great deal. So that damage degree could be inferred from the UPV decrease of concrete at loading. Theoretically, concrete has been classified as a composite material which includes three phases, such as macro-cracks, discrete unstable micro-cracks and matrix filled with stable micro-cracks. The UPV of concrete is a comprehensive effect of macro-cracks, micro-cracks and matrix. So the two curves are not totally the same.

According to studies of other researchers [12], the UPV decrease to a large extent depending on the secant modulus reduction during uniaxial compressive loading. So Wenhui Zhong and Wu Yao defined a damage degree as:

$$D = 1 - \frac{v}{v_0}$$

Where D is the damage degree of concrete, v is the UPV before self-loading and \(v_0\) is the UPV before loading. So the microstructure changes in concrete could be inferred from the decrease of UPV by D.

The relationship between D and k is shown in Fig.10. The D-k of series D, a, b and c have a good corresponding relationship, and the self-healing ratio k is following with
the damage degree \( D \). But the others’ relationship is messy. So we know, the damage degree could influence the self-healing performance of the concrete, but it is not the only factor.

4. CONCLUSIONS

(1) When the fiber volume fraction is 3.0\%, the compression strength of hybrid fibers reinforced UHPCC is weaker than steel fiber reinforced one. Longer steel fiber reinforced UHPCC has the best self-healing effect.

(2) The results obtained from mechanical and ultrasonic properties show that self-healing of UHPCC is improved with the increasing of curing ages and temperature.

(3) The damaged specimens with binary or ternary reactive powders recover more than those with single powders.

(4) The UPV of the same specimen is not all the same. It reflects the destroy form in different specimens and different direction.

(5) After self-healing, the UPV has been regained in a great deal and the damage degree could be inferred from the UPV decrease of concrete at loading.

(6) The damage degree could influence the self-healing performance of the concrete, but it is not the only factor.

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