Self Healing Behavior of Engineered Cementitious Composites

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ABSTRACT: Normal concrete is brittle and tends to crack, resulting in a lack of durability and frequent repair needs. In order to combat this problem, the self-healing behavior of pre-cracked engineered cementitious composites (ECC) was investigated in this paper. Specifically, the influence of precracking time on the self healing behaviour of ECC was studied. Four-point bending tests were used to precrack ECC beams at different age. Two curing regimes were adopted in the study, i.e. water immersion and air curing. For both curing regimes, the magnitude of the deflection capacity after self-healing can recover and even exceed that from virgin samples. While the recovery level of flexural stiffness decreases with the precracking time, no clear trend can be seen for the recovery level of deflection capacity with the precracking time. The addition of nanosized clay in the mixture may have positive effect on the self-healing behavior of ECC even without the presence of external water, i.e. water immersion curing. Further demonstration is needed for this preliminary finding via ESEM and/or NMR.

1 INTRODUCTION

Self-healing phenomenon has been observed in cement-based material for many years. Under certain circumstances (e.g. when rainwater and carbon dioxide is available) concrete was able to heal its own damage (e.g. microcracks) with chemical products by itself. Furthermore, some researchers (Edvardsen, 2006; Reinhardt and Joos 2003) noted a gradual reduction of permeability over time in the study of water flow through cracked concrete under a hydraulic gradient. The main cause of self-healing was attributed to the formation of calcium carbonate, a result of reaction between calcium ion in concrete and carbon dioxide dissolved in water.

As suggested by many previous studies (Edvardsen, 2006; Reinhardt and Joos 2003; Clear 1985), the crack width of the concrete material was found to be critical for self-healing to take place. The requirement of crack width to promote self-healing falls roughly below 200 µm, preferably lower than 50 µm (Li and Yang 2007). This is particularly the case for continuous hydration based self healing phenomena. Yet in practice, such small crack width is very difficult to achieve consistently in normal concrete structures, if not possible at all.

To achieve controlled tight crack width, a new class of fiber reinforced concrete material, termed as Engineered Cementitious Composites (ECC) has been developed by Li and continuously evolved over the last 15 years (Li et al 2002). ECC has been deliberately engineered using micromechanics theory to possess self-controlled crack width that does not depend on steel reinforcement or structural dimensions (Li 2003). Instead, the fibers used in ECC are tailored (Li et al 2002) to work with a mortar matrix in order to suppress localized
brittle fracture in favor of distributed microcrack damage, even when the composite is tensioned to several percent strain. ECC with crack width as low as 30 micron have been made. The ability of ECC to maintain extremely tight crack width in the field has been confirmed in a bridge deck patch repair (Lepech and Li 2006) and in an earth retaining wall overlay (Kunieda and Rokugo 2006).

In an effort to develop green ECC with local waste material, Zhou et al (2008) have developed a number of ECC mixtures with blast furnace slag (BFS) and limestone powder, all characterized with 2-3% tensile strain capacity and tight crack width (typically below 60 μm). With these green ECC mixtures, Qian et al (2009) have demonstrated it is possible to achieve self-healing behaviour if the precracked samples were saturated with water for certain period. In this paper, the self healing behaviour of ECC with different precracking time will be investigated in order to reveal the effect of timing of damage on the self healing behaviour of ECC.

In the following sections, the experimental program of this investigation will be introduced in details, including material preparation, four point bending test. Furthermore, experimental results will be presented followed by brief discussions. Finally, overall conclusions will be drawn based on the experimental works.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement (CEM-I 42.5 N)</th>
<th>Lime stone powder</th>
<th>Blast Furnace Slag</th>
<th>Clay</th>
<th>Water</th>
<th>Superplasticizer</th>
<th>Fiber (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>1</td>
<td>0.8</td>
<td>1.2</td>
<td>0.025</td>
<td>0.9</td>
<td>0.028</td>
<td>2%</td>
</tr>
<tr>
<td>M1</td>
<td>1</td>
<td>0.8</td>
<td>1.2 (Fly ash)</td>
<td>-</td>
<td>0.69</td>
<td>0.033</td>
<td>2%</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>1.5</td>
<td>1.2</td>
<td>-</td>
<td>0.98</td>
<td>0.023</td>
<td>2%</td>
</tr>
<tr>
<td>M3</td>
<td>1</td>
<td>2.0</td>
<td>1.2</td>
<td>-</td>
<td>1.09</td>
<td>0.018</td>
<td>2%</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>3.0</td>
<td>1.2</td>
<td>-</td>
<td>1.33</td>
<td>0.018</td>
<td>2%</td>
</tr>
</tbody>
</table>

2 EXPERIMENTS

2.1 Material proportion and specimen preparation

In table 1 only Mix M0 was used in this investigation, while the rest M1-4 from Qian et al (2009) is shown here for comparison purpose. Portland cement CEM I 42.5 N was used in the mixture along with BFS, limestone powder and clay. The clay is a purified Na-montmorillonite with a small particle size (ca 500 nm). The purpose for introducing small amount of clay is to investigate the feasibility of utilizing the water retaining capacity of clay to enhance the self-healing behavior of ECC, without relying on external supply of water. The polyvinyl alcohol (PVA) fibre with a length of 8 mm and a diameter of 40 μm was used in the content of 2% by total volume.

The solid materials, CEM I 42.5, BFS, limestone powder and clay were first mixed with a HOBART mixer for 2 minutes thoroughly. Water and superplasticizer were then added and the mixture was mixed at low speed for 1 minute, followed by high speed for 2 minutes. Finally, fibres were added at low speed and the mixture was mixed at high speed for another 2 minutes. Coupon specimens with the dimension of 240 mm × 60 mm × 10 mm were cast for four-point
After 1 day curing in moulds covered with plastic paper, the specimens were cured under sealed condition and a temperature of 20 °C for another 27 days before testing.

After 28 days curing, the coupon specimens were evenly cut into 4 pieces with the dimension of 120 mm × 30 mm × 10 mm. These specimens were used in four-point bending test. The support span of four-point bending test set-up was 110 mm and the middle span was 30 mm. The deflection capacity was calculated based on the average results of at least four measurements. The deflection capacity was defined as the deflection at which point the bending stress reaches maximum (MOR).

2.2 Four Point Bending

The overall program for FPBT includes 3 precracking ages (14 days, 28 days and 56 days) and 3 curing schemes (A, B and C), resulting in 9 combinations. All bending samples were first cured under sealed condition (RH 98%) at 20 °C until time of precracking, i.e., 14, 28 or 56 days.

In the scheme A, four samples of each mixture were bent until final failure to derive the flexural stress-deflection relation. The results from this scheme form a reference value for determining how much healing, especially in terms of deformation capacity, has occurred. In fact for scheme A, time of precracking has no meaning since all samples were tested until final failure.

In case of scheme B and C, three samples from each mixture were bent (precracked) up to 1.5 mm and unloaded. The deflection of 1.5 mm is well below ultimate deflection of the mix at different precracking ages. Afterwards the precracked samples were further cured in air (RH 30% at 20°C, scheme B) or water (scheme C) respectively for 28 more days before testing to final failure.

These two schemes are to compare the effect of air and water curing on the self-healing behavior of pre-damaged samples. The water curing is used to simulate the transportation infrastructure scenario where abundant water is readily available. In the FPBT, the sample was tested under deformation control at a constant rate of 0.01 mm/second.

![Figure 1 Development of deflection capacity with time](image1)

![Figure 2 Comparison of deflection capacity for different curing schemes and precracking time](image2)
3 RESULTS AND DISCUSSION

The deflection (deformation) capacity is of major concern for ECC type material since its structural application mainly requires high deformation and energy dissipation capacity. In the experiment program, three schemes have been carried out to investigate the influence of water and air curing on the recovery of deformation capacity. In scheme A, the sample was tested until final failure, which provides a reference for the other two schemes B and C, both of which have the potential to reheal their deformation capacity.

As can be seen from Figure 1, the deflection capacity for virgin samples (scheme A) first increases from 14 days to 28 days and then decreases afterwards. This is in agreement with findings of Lepech and Li (2006). Their results indicated a stable ductility after about one or two months.

Figure 2 indicates both air and water cured samples can fully recover its deflection capacity; in many cases even exceed the reference deflection capacity. This is very significant especially considering these air and water cured samples have been precracked to 1.5mm deflection.

Figure 3 shows the same trend as Figure 2, but in a normalized manner, where the deflection capacity of schemes B and C is normalized by scheme A (100%). It can be seen that that air cured sample can reach about 80-120% of its reference deflection capacity, while water cured sample can reach about 120-140% of its reference deflection capacity. This recovery level is significantly higher than that of M2-4 in Figure 4 (Qian et al (2009)). This can be explained that the M2-4 has much less cementitious material compared with M0 and M1. Therefore the self-healing potential of M0 due to continuous hydration is much greater than that of M2-4.

Furthermore, it should be noted that the air cured sample shows quite decent recovery with different precracking time, which seems to indicate that the water retaining capacity of clay provide alternative water supply (internal vs. external) for further hydration to occur. While this statement needs to be further proved, Valcke et al (2009) did indicate that the clay (the same type as used in this investigation) can absorb water of about 100% of its own weight between layered structures and requires about 7 times more water to have a homogeneous water/clay mixture. The extra water is free water and can potentially be utilized for cement hydration.

![Figure 3 Comparison of normalized deflection capacity for different curing schemes and precracking time](image)
Figures 4-7 show bending stress-deflection curves for precracking age of 14, 28 and 56 days under different curing schemes, which shows the same trend of deflection capacity recovery as shown in Figures 2-3.

The comparison of flexural stiffness for different curing schemes is shown in Figures 8 and 9, indicating a decreasing recovery level of flexural stiffness with precracking time. The flexural stiffness is calculated from the slope of bending stress-deflection initial stage when the stress is
rising from 1 to 6 MPa, when the linearity is generally valid. The flexural stiffness of precracked samples is generally governed by how well the microcracked is healed. The decreasing recovery level of flexural stiffness with precracking time may suggest that it become less likely to have high level of healing inside microcrack as sample ages. This however is not the case for the recovery of deflection capacity with precracking time, where no such trend can be found.

Figure 8 Comparison of flexural stiffness for different curing schemes and precracking time

Figure 9 Comparison of normalized flexural stiffness for different curing schemes and precracking time

4 CONCLUSIONS

This paper investigates the influence of precracking time on the self-healing behavior of ECC. While the recovery level of flexural stiffness decreases with the precracing time, no clear trend can be seen for the recovery level of deflection capacity with the precracking time.

It has been shown that the recovery level of deflection capacity can be as high as 140% of its reference value, significantly higher than that of the previous mixtures due to higher amount of cementitious materials. The addition of nanosized clay has positive effect on the self-healing behavior of ECC even without the presence of external water, i.e. water immersion curing. This suggests it may be possible to utilize the water retaining capacity of clay to internally cure and heal the damage along the microcracks. The next step for study is to further demonstrate the above preliminary findings with ESEM and NMR, etc.

References


