# SELF-HEALING BEHAVIOR OF ENGINEERED CEMENTITIOUS COMPOSITES UNDER DIFFERENT NUMBER OF WET-DRY CYCLE

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## INTRODUCTION

This paper describes self-healing phenomenon of Engineered Cementitious Composites (ECC) at early age subjected to wetting and drying cycles. ECC is a fiber reinforced cementitious composites characterized by ductile behavior with multiple fine cracks under uniaxial tensile stress. In previous researches, it has been found that these fine cracks are beneficial in self-healing under wet-dry cycle (Yang et al. (2009)). The aims of this study were to clarify the effect of number of wet-dry cycles on self-healing in uniaxially loaded ECC. Throughout the wet-dry cycle, resonant frequency was measured to confirm the recovery level non-destructively. After undergoing wet-dry cycle, ECC specimens were reloaded in order to investigate the effect of wet-dry cycle on uniaxial tensile property.

## EXPERIMENTAL PROCEDURES

### Experiment flow chart

Fig. 1 is a flow chart which shows the test program. As shown in Fig. 1, test program is composed of three major tests: uniaxial tensile test, environmental conditioning regime and resonant frequency test. They will be described step by step below.

### ECC Specimen preparation

The dimensions of specimen are illustrated in Fig. 2. The mix proportion of ECC is shown in Table 1. After casting, the specimens were covered with plastic sheets and demolded after 24 hours. Thereafter, the specimens were air cured at laboratory temperature (21±1 °C) and humidity (RH 45%) for 48 hours.

### Uniaxial tensile test

Before uniaxial tensile test, aluminum plates were glued both sides at the ends of specimens as shown in Fig. 2. This is intended to protect specimens from damage by being gripped directly by tensile machine. Specimens were uniaxially loaded in displacement controlled mode and the loading speed was 0.0025mm/s. Load and axial displacement of specimens were respectively measured using load cell and two external linear variable displacement transducers. Fig. 3 shows the actual set up for the uniaxial tensile test. As previously described in Fig. 1, uniaxial tensile tests were conducted before and after environmental conditioning cycles. Hereinafter, they were referred to as “pre-loading” and “reloading”. In pre-loading tests, 0.3% or 0.5% tensile strain was induced and residual strain was recorded on unloading. All crack widths were investigated along three lines shown in Fig. 2 in the unloaded state with a microscope. Table 2 describes crack characteristics of pre-loaded ECC. On reloading, specimens were loaded to 0.3% or 0.5% of the original test length considering the residual strain introduced on preloading.

### Environmental conditioning regime

After the pre-loading test, specimens were subjected to any of the following two cyclic environments which have 48 hours cycle length. One is wet-dry cycle, which is consisted of submersion in water at 20 °C for 24 hours and drying in laboratory air at 21±1 °C for 24 hours. This is for simulating the rainy and fine day which turns every other day. The other is drying cycle (“Lab Conditioned”), drying in laboratory air 48 hours to duplicate the fine days. In this investigation, ECC specimens were subjected to 10 or 20 conditioning cycles. As explained above, setting the three parameters, tensile strain, type and number of environmental conditioning regime, a total of 16 specimens were prepared as summarized in Table 3. 0, 0.3 or 0,5% which appears first in specimen names indicate the applied strain (0 means virgin (non-damaged) specimen), A or WD means Air or Wet-Dry, that is the type of environmental regime which specimens went through, 10 or 20 is number of environment conditioning regime. In order to confirm strain-hardening behavior of ECC at early age, 3 specimens (Fracture (No1-3)) were loaded to failure.

**Resonant frequency test**
In order to qualify the damage and healing level before and after uniaxial tensile test and environmental conditioning, longitudinal resonant frequency was measured based on ASTM C215.

## RESULTS AND DISCUSSIONS

**Resonant frequency test**
Fig. 4 represents the change of resonant frequency throughout this study. Regarding the data obtained from specimens that underwent the wet-dry cycle, the average value of two specimens is shown. From this figure, it can be said that resonant frequency dramatically recovered after just one wet-dry cycle and shows a tendency to subsequently recover bit at a time. To evaluate this self-healing rate quantitatively, normalized resonant frequency, which was obtained by dividing resonant frequency of pre-loaded specimens by

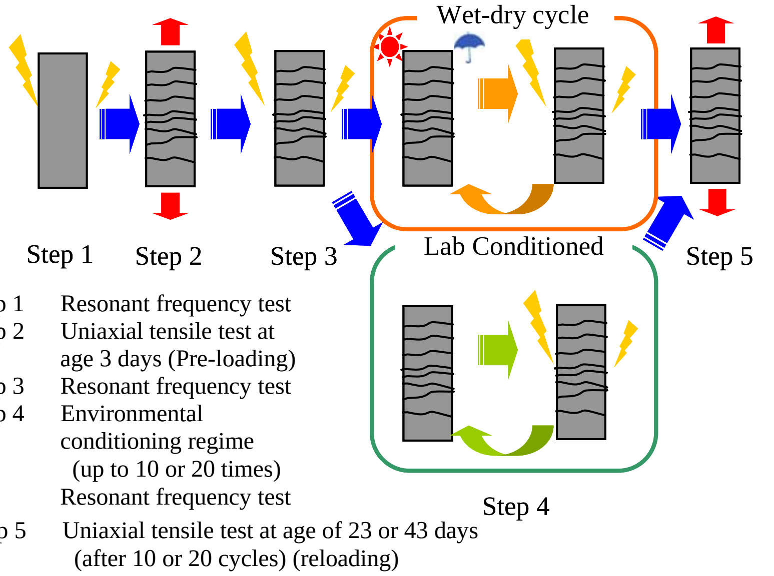


Fig. 1 Experiment flow chart

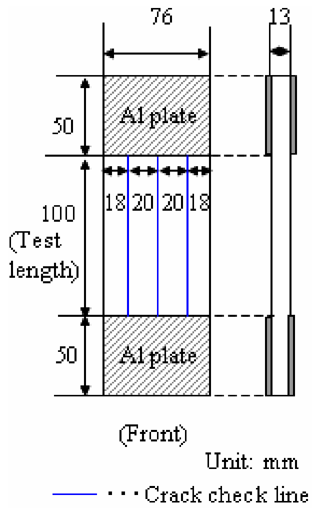


Fig. 2 Specimen size

Table 1. Mix proportion of ECC

| W/C | W/B | C*1 | FA*2 | S*3 | W*4 | Ad*5 | PVA fiber*6 |
|---|---|---|---|---|---|---|---|
| (%) | | (kg/m$^3$) | | | | | (vol. %) |
| 57.1 | 26.0 | 574 | 689 | 459 | 328 | 7 | 2.0 |

*1 Ordinary Portland Cement, *2 Fly Ash (Class F) *3 Silica sand, average grain size=110μm, *4 Water *5 High range water reducer (Polycarboxylate-based), specific gravity=1.1 *6 PVA Fiber, length=12mm, nominal tensil strength=1600MPa, diameter=39μm

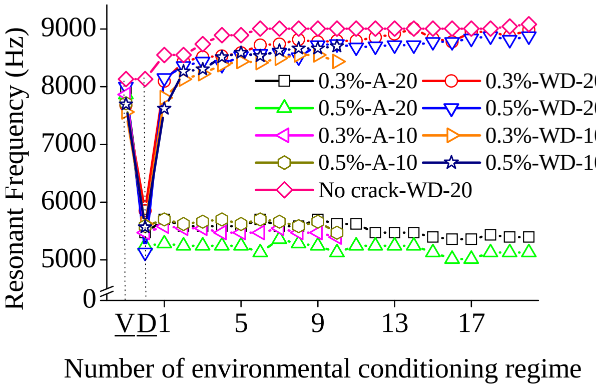

Fig. 3 Loading condition

Table 2. Crack characteristics of pre-loaded ECC

| | 0.3% | 0.5% |
|---|---|---|
| Average crack width (μm) | 12 | 16 |
| Maximum crack width (mm) | 30 | 50 |
| Crack number | 4 | 6 |

Table 3. Specimen type and numbers

| Name | No. | Name | No. |
|---|---|---|---|
| 0.3%-A-20 | 1 | 0.3%-A-10 | 1 |
| 0.3%-WD-20 | 2 | 0.3%-WD-10 | 2 |
| 0.5%-A-20 | 1 | 0.5%-A-10 | 1 |
| 0.5%-WD-20 | 2 | 0.5%-WD-10 | 2 |
| 0%-WD-20 | 1 | Fracture (No1-3) | 3 |




V-virgin specimen (before pre-loading test)
D-damaged specimen (after pre-loading test)

Fig.4 Change of resonant frequency

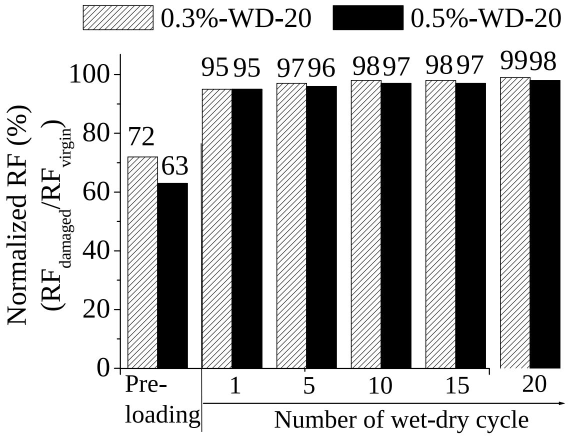



Fig. 5 Normalized resonant frequency

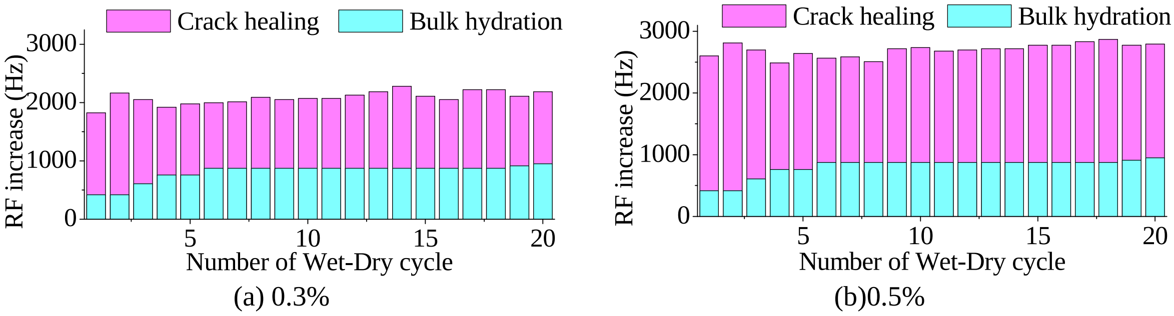
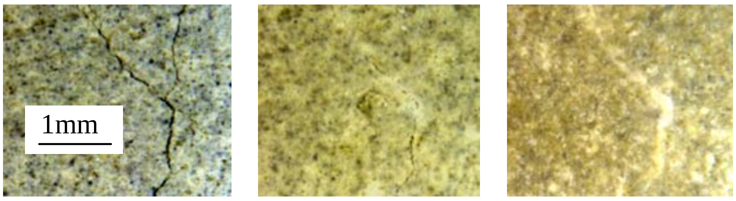



Fig. 6 Breakdown of resonant frequency increase (20 wet-dry cycle)




(a) After pre-loading (b) 1 wet-dry cycle (c) 20 wet-dry cycle

Fig. 7 Self-healing of crack (20μm) with wet-dry cycles

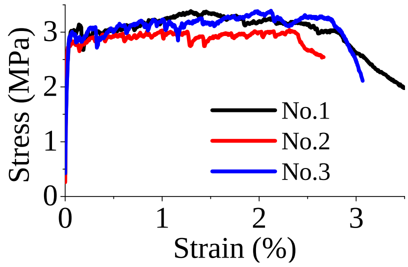



Fig. 8 Tensile tress-strain curve of ECC

the resonant frequency of virgin specimen which went through the same number of wet-dry cycle, was computed as shown in Fig. 5. After pre-loading, the normalized resonant frequency decreases to 63~72%, however, it can rally recover up to 95% after one wet-dry cycle and thereafter approach to nearly 100%. This resonant frequency increase is thought to be due to 1. bulk hydration and 2. crack healing. Here the breakdown of the resonant frequency increase after pre-loading by each contributor is shown in Fig. 6 on the assumption that the resonant frequency increase due to bulk hydration corresponds to that in virgin specimens which underwent the same number of wet-dry cycles. The resonant frequency increase due to crack healing is calculated by deducting the one due to bulk hydration from the whole resonant frequency increase in pre-loaded specimen. From Fig. 6(b) and Table 2, even in specimens which were pre-loaded to 0.5% tensile strain and have greater number of cracks and wider cracks, resonant frequency recovery due to crack healing is confirmed. And it also can be said that the drastic recovery after 1 wet-dry cycle is mainly ascribable to crack healing and after that only slight change was observed. Fig. 7 shows self-healing of crack with wet-dry cycles. In Fig. 7(b), white self-healing product considered as calcite can be observed inside the crack and this is corroborative of the resonant frequency recovery (Edvardsen (1999)). This white self-healing product can be confirmed more prominently in Fig. 7(c).

**Uniaxial tensile test**

Fig. 8 shows the results of uniaxial tensile tests of three specimens loaded to failure. The characteristic ductile behavior of ECC can be seen and the average uniaxial tensile strain was 2.6%. Stress-strain curves of ECC specimens underwent the environment conditioning cycle 10 or 20 times are shown in Fig. 9 and Fig. 10. Regardless of the magnitude of imposed strain and the number of environment conditioning cycle,

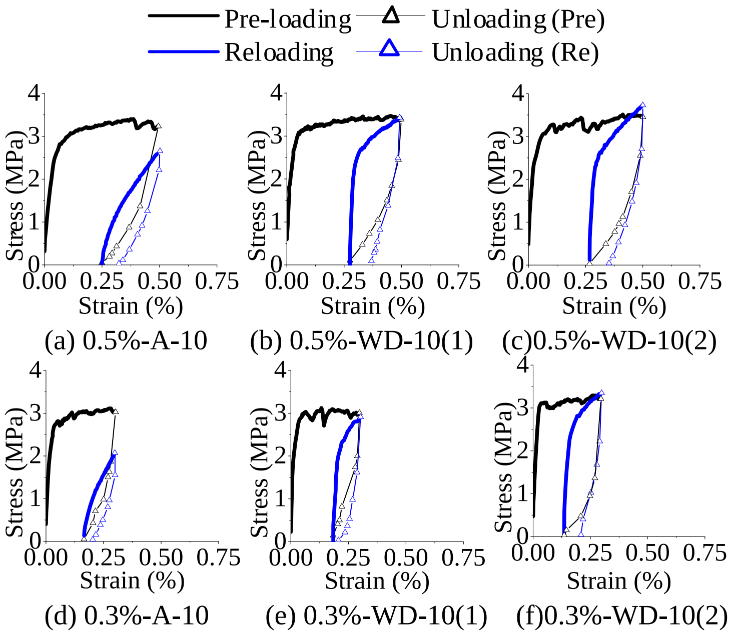



Fig. 9 Stress-strain curve (10 conditioning regime series)

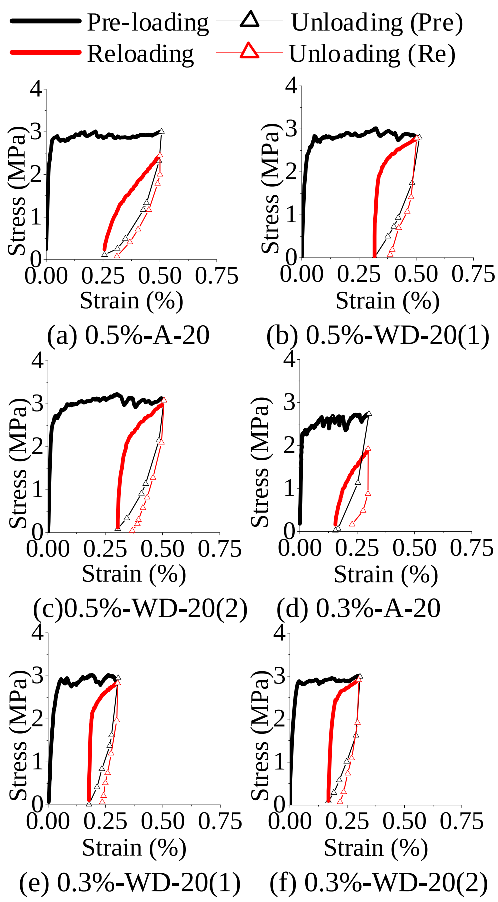



Fig. 10 Stress-strain curve (20 conditioning regime series)

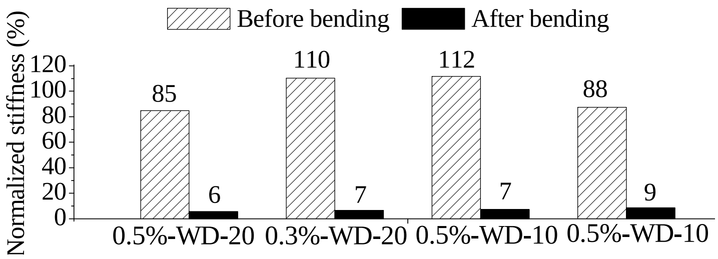



Fig.11 Normalized stiffness of ECC specimens on reloading

the stiffness of specimens that underwent wet-dry cycles recovers to that of the virgin specimen on reloading, but the stress-strain curves bend over after the tensile stress reached 2~2.5MPa. Further investigation will be required to clarify the mechanism of this stiffness change. However, possible causes include 1. Lower tensile strength of self-healing products assumed to be calcite, 2. poor bonding between self-healing products and crack flank surface, or both. Fig. 11 shows the normalized stiffness calculated by dividing stiffness on reloading by stiffness on pre-loading. Stiffness before and after bending of stress-strain curve on reloading was considered separately. From this figure, it can be found that stiffness before stress-strain curve bends can be recovered to 85~112% of stiffness obtained on pre-loading.

## CONCLUSIONS

From this study, it was clarified that wet-dry cycle is beneficial to encourage self-healing in ECC at early age. A drastic recovery of resonant frequency was favorable even just after 1 cycle and self-healing product which can be anticipated as calcite was confirmed by images. Stiffness of ECC specimens which underwent wet-dry cycle on reloading was 85~112% of stiffness on pre-loading and that was unaffected by the number of the wet-dry cycle and the magnitude of imposed strain. However, it was found that stress-strain curves on reloading bend over when stress goes above 2~2.5MPa. Further studies will be needed to clarify the cause of the lower first crack strength compared to the virgin material.

## REFERENCES

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