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# BOND STRENGTH RECOVERY OF FIRE-DAMAGED CONCRETE AFTER POST-FIRE-CURING

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The effects of post-fire-curing on the bond strength recovery of fire-damaged concrete were investigated in this study. Normal strength concrete (NSC) and high-strength concrete (HSC) specimens with deformed steel bars were prepared respectively. We measured the bond strength of unheated NSC and HSC, and exposed other NSC and HSC specimens to high temperatures of 300℃, 400℃, and 500℃, respectively for 120 minutes. Following by rapid cooling with water, the bond strengths of heated NSC and HSC were measured instantly without re-curing, the remains were cured in water for 28 days, or further in the air of 20℃, 60% R.H. for 56 ~62 days. After the re-curing, the pull-out tests were conducted. The test results indicate that the post-fire-curing contributes to a substantial bond strength recovery of heated concrete. The longer the re-curing in water, the greater the recovery extent. At 90 days of re-curing age, the bond strength rose up to around 77% for NSC, and around 70% for HSC, respectively.

*Keywords*: Elevated temperature, Re-curing, Compressive strength, Repair, Heat.

## 1 INTRODUCTION

Concrete is possibly exposed to elevated temperatures during fire or when it is near to furnaces and reactors. The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced during these exposures (Arioz 2007) as a result of damage to the pore structure and chemical degradation. This may result in undesirable structural failures. Hence, according to exposure temperature, compressive strength and width of cracks after heated, fire-damaged concrete should be strengthened or re-cast (AIJ 2015). If the compressive strength of fire-damaged concrete is smaller than the design strength, the concrete should be removed and newly constructed.

If fire-damaged concrete is re-cured in water, its properties would recover to some degree due to rehydration (Poon *et al.* 2001, Li 2011). The rehydration can save time and money, as well as minimize space lost, making it a financially attractive repair option. Therefore, inspection and repairing of fire-damaged concrete should consider the property recovery ability of fire-damaged concrete, and put it to practical use. There have been many studies on the compressive strength recovery of fire-damaged concrete, but we have not yet found the investigation on the bond strength recovery.

This work is intended to further understand the property recovery ability of fire-damaged concrete. We investigate the bond strengths of concrete with different strength grades before heated, right after exposed to different high temperatures, and after re-cured for different durations. Based on the test results, we discuss the influencing factors of bond strength recovery of fire-damaged concrete.

## 2 EXPERIEMTAL PROGRAM

### 2.1 Materials

The mix proportions of concrete are shown in Table 1. Ordinary portland cement with the specific gravity of 3.15 g/cm$^3$, crushed stone, sea sand, and standard type AE water reducer (WRA) or retarding type high range AE water-reducer (HRWR) were used to mix the concretes. The crushed stone was hard sandstone with 2.73g/cm$^3$ of density in saturated surface - dry state, and 0.47% of water absorption. The solid content and the fineness modulus of the crushed stone were 59.2% and 6.68, respectively. The density in saturated surface-dry state, water absorption, solid content, and fineness modulus of the sea sand were 2.57 g/cm$^3$, 1.36%, 66.7%, and 2.90, respectively. Deformed steel bar was used, of which mechanical properties are shown in Table 2.

### 2.2 Pull out Specimen Fabrication

After the concrete was mixed, slump and air content were measured, and cylindrical specimens with $\phi$10cm $\times$ $h$ 20cm were prepared for measuring the 28-days compressive strength. Test results of the properties of two series of concrete are shown in Table 1.

Table 1. Concrete mixture proportions and properties.

| Series | *W/C* (%) | Unit mass (kg/m$^3$) | | | | | *Sl*(cm) | Air content (%) | $F_c$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|
| | | W | *C* | *S* | G | Admixture (*C*×%) | | | |
| No.1 | 60 | 179 | 298 | 825 | 980 | WRA, 0.5 | 15.0 | 6.5 | 38.1 |
| No.2 | 38 | 165 | 434 | 688 | 1048 | HWRA, 1.0 | 21.0 | 8.0 | 54.3 |

[Notes] *W* is water, *C* is ordinary potland cement, *S* is sea sand, *W/C* is water-cement ratio by mass, *s/a* is fine aggregate-aggregate ratio by volume, *Sl* is slump, $F_c$ is 28 days compressive strength.

Table 2. Properties of deformed reinforcing steel bar used.

| Type | Nominal diameter (mm) | Yield stress (N/mm$^2$) | Tensile strength (N/mm$^2$) | Maximum deformation (%) |
|---|---|---|---|---|
| D16 (SN490) | 15.9 | 384.5 | 557.6 | 22.3 |

A total of 22 pull-out cubic specimens with the side length of 10cm were also fabricated for the two series of concretes. The specimens were compacted for 10 seconds by a table vibrator. The deformed steel bars with the length of 170 mm were embedded into the cubic specimens, of which 36mm in the loading side didn't contact the concrete by fitting up with a polyvinyl chloride (PVC) pipe for equalizing the compressive stress on the surface of concrete in the loading side, as shown in Figure 1.

The exposure length of the bar in the loading side was 60 mm with screwy extremity, at which a steel bar was connected for griping in the pull-out test. The opposite side was 10mm, joining a deformation meter for measuring the bar's slip.

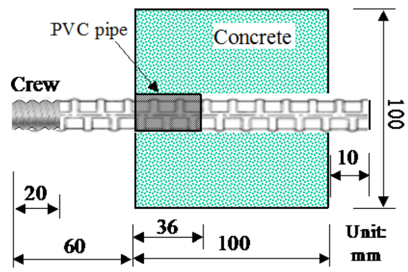


Figure 1. Geometry of the specimen.

## 2.3 Test Program

The bond strength specimens were cured in 20±2℃ water for 28 days, then the reference bond strengths before heated (BH) were measured. 20 remained specimens were heated by an electric furnace at 300, 400, 500℃. Because if elevated temperature is over 500℃, the residual compressive strength is lower than its design strength, or many wide cracks forms, thus the fire-damaged concrete has to be removed. Therefore, in this study, the maximum heating temperature was set up to be 500℃. After inside temperature of the electric furnace rose up to the planned temperature in one hour, it was kept for 2 hours once the inside temperature of the concrete specimen also reached to the planned temperature, then cooled suddenly by water. 6 specimens were used to measure the bond strengths of the two series of concrete on the next day (1D re-curing age). The others were first re-cured in 20±2℃ water for 28 days, further in the atmosphere of 20℃, 60%R.H. for 56~90 days.

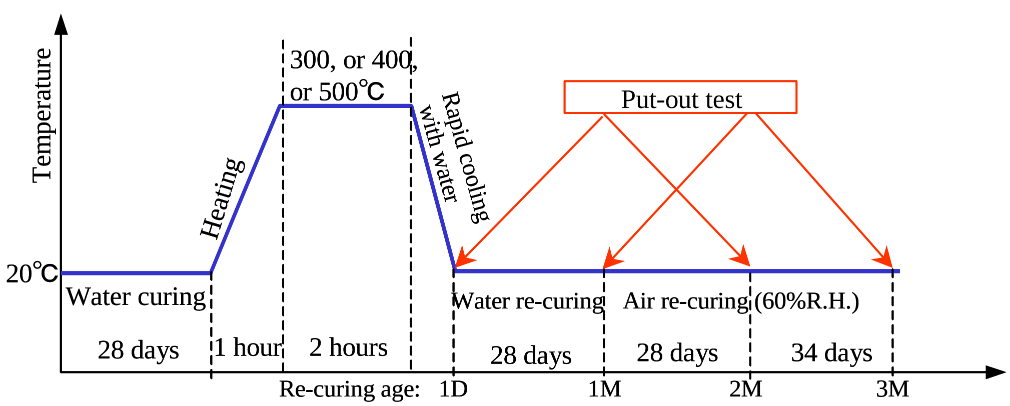


Figure 2. Regime of heating, curing and pull-out test.

The bond strengths of re-cured concrete specimens were measured after they were re-cured for the planned durations (1M ~ 3M re-curing age). The regime of heating, cooling, re-curing, and pull-out test are shown in Figure 2. The pull-out test method is shown in Figure 3. The pull-out load versus slip was recorded.

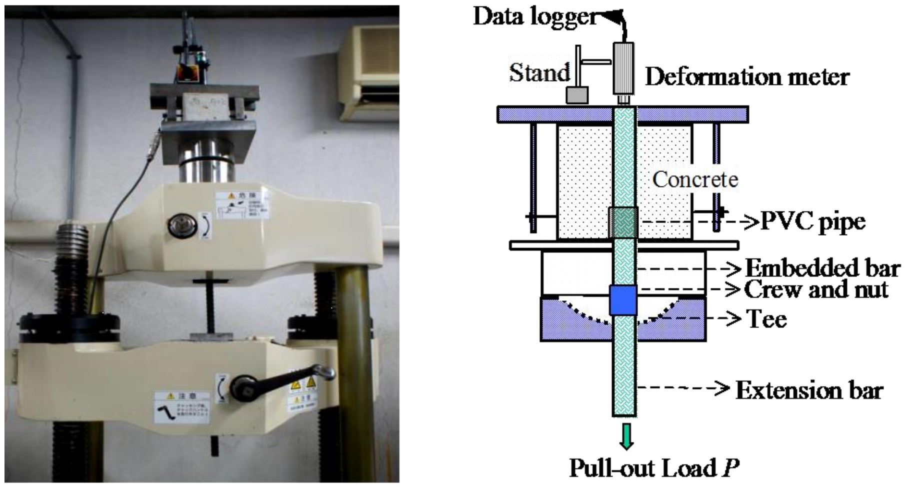


Figure 3. Pull-out test for bond strength measurement.

### 2.4 Bond Stress Calculation

In general, the bond stress corresponding to the max. pull-out load can be regarded as the bond strength. For uniform bond, the average bond strength (*S*) is calculated by Eq. (1), which is well-known expression (Hadi 2008). Eq. (1) was employed in present calculation of bond strength *S*.

$$S = \frac{P_{\max}}{\pi \times L \times D} \tag{1}$$

Where $P_{max}$ is maximum pull-out load, *D* is diameter of rebar (=15.9 in this study), *L* is effective embedded bar length.

## 3 TEST RESULTS AND DISCUSSION

### 3.1 Pull-Out Load – Slip Relationship

Figure 4 and Figure 5 show the pull-out load-slip relationships of the two series of concretes. As shown in these figures, the $P_{max}$ of heated concretes decreased, compared to the unheated specimens, no matter how great the compressive strength before heated.

A tendency can be seen that the higher the heating temperature, the lower the $P_{max}$ of concrete directly after heated, though several test results were in disorder. The sip corresponding to the $P_{max}$ of heated concrete decreased in case of No.1 series that was ordinary concrete, but increased in case of No.2 series that was high strength concrete, compared to each unheated concrete.

Though the test results were in disorder for some re-curing ages and heating temperatures, we can conclude that re-curing with water improved the bond between the concrete and the rebar; The $P_{max}$ increased due to the re-curing for any of the two series of concrete; The longer the re-curing duration, the greater the $P_{max}$. There are many factors influencing the bond characteristic of concrete, including distributions of porosity and coarse aggregate, and bleeding, etc. (Soylev and Francois 2006). It is considered that the disorder of the test results shown in Figure 4 and Figure 5 was caused by the inconsistency of specimens.

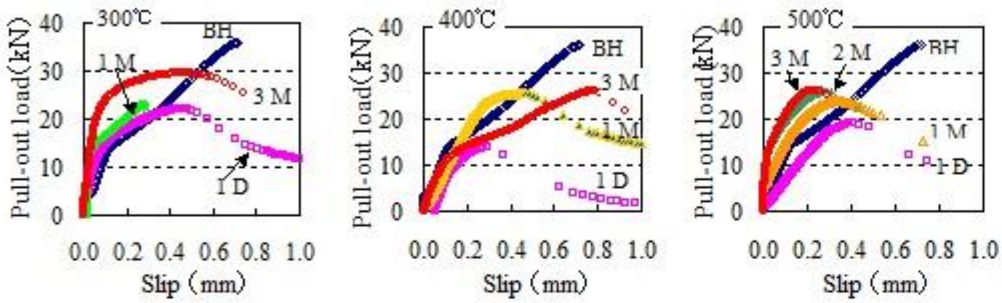


Figure 4. Effects of heating temperature and re-curing duration on the pull-out load – slip relational curve (Series of concrete: No.1).

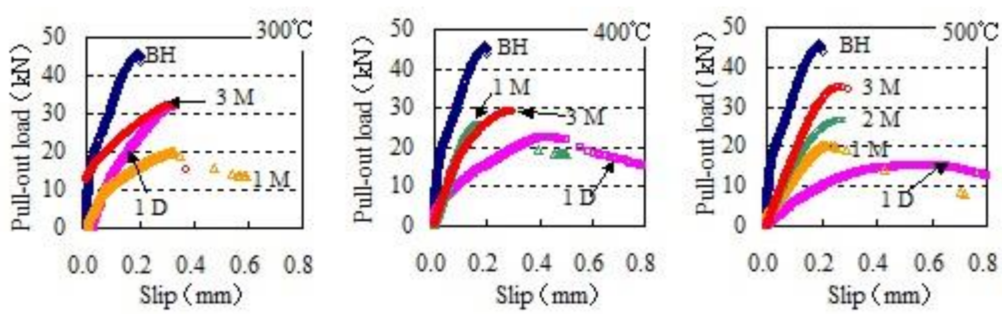


Figure 5. Effects of heating temperature and re-curing duration on the pull-out load – slip relational curve (Series of concrete: No.2).

### 3.2 Variation of Residual Bond Strength with Re-curing

Figure 6 shows the residual bond strength of two series of heated concretes. Since there was only a single specimen for a test condition, there is a relatively greater error due to the inconsistency of specimens as stated above. But from this figure, we can observe that the residual bond strength ($S_r$) just after heated was different from heating temperature ($T$). When $T$ was 300℃, $S_r$ was above 60% of that of unheated concrete. But if $T$ was 400 or 500℃, $S_r$ was around 40%.

Also, with the increase of re-curing duration, the $S_r$ increased. At 90 days of re-curing age, $S_r$ was around 77% for NSC, and around 70% for HSC, respectively. That is to say, the lower the initial strength, the greater the recovery degree of $S_r$ caused by the re-curing. Moreover, in the case of NSC, the recovery degrees of $S_r$ of concretes exposed to 400 and 500℃ were almost the same, but in the case of HSC, the higher the heating temperature, the greater the recovery degree of the bond strength. This maybe is because that the bond strength loss of the concrete exposed to lower $T$ is smaller.

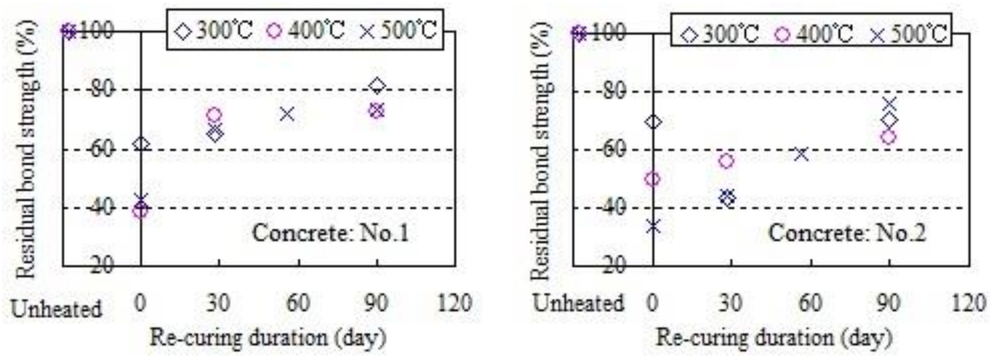


Figure 6. Residual bond strength of concrete exposed to elevated temperature.

## 4 CONCLUSIONS

In this study, we investigated the bond strength recovery of (NSC) and (HSC), which were exposed to 300℃, 400℃, and 500℃ for 2 hours, and then rapidly cooled down with water, following by re-curing in 20℃ water in the first 28 days, or further stored in the air of 20℃, 60%R.H. for 28~62 days. The pull-out tests before and after high temperature exposure and the re-curing were performed. Obtained main conclusions are as follows: (1) The bond strength (*S*), just after heated, was above 60%, when heating temperature *T* was 300℃. But if *T* was 400 or 500℃, *S* was around 40%, compared to unheated concrete. (2) With the increase of re-curing duration, the *S* increased. At 90 days of re-curing age, *S* recovered to be around 77% for NSC, and around 70% for HSC, respectively. (3) In case of HSC, the higher the heating temperature, the greater the recovery degree of the bond strength. (4) Re-curing would improve *S* for about 20~30%.

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