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EFFECT OF POST-FIRE CURING ON THE RESIDUAL MECHANICAL PROPERTIES OF FIRE-DAMAGED SELF-COMPACTING CONCRETE

MAHSA MIRMOMENI [*], AMIN HEIDARPOUR [*], ERIK SCHLANGEN [†] AND SCOTT SMITH [††]

[*] Monash University
Clayton, VIC, Australia
e-mail: mahsa.mirmomeni@monash.edu
amin.heidarpour@monash.edu

[†] Delft University of Technology
Delft, Netherlands
e-mail: erik.schlangen@tudelft.nl

[††] Southern Cross University
Lismore, NSW Australia
e-mail: scott.smith@scu.edu.au

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Abstract: Concrete is recognized for being a fire-resistant construction material. At elevated temperatures concrete can, however, undergo considerable damage such as strength degradation, cracking, and explosive spalling. In recent decades, reuse of fire-damaged concrete structures by means of developing techniques to repair the degraded material has gained interest amongst researchers. Autogenic self-healing methods such as re-curing in water has proven to partly restore the strength of concrete. The extent of restoration is dependent upon various parameters such as concrete type, exposure temperature, and post-fire curing conditions for example. The use of self-compacting/consolidating concrete (SCC) has become common in the construction industry due to its high workability and low permeability. This paper presents the results of an experimental study aimed at investigating the improved mechanical properties of high temperature exposed SCC concrete by the autogenic self-healing phenomenon resulting from water re-curing. The residual mechanical properties including strength, modulus of elasticity and ultimate strain of the material upon application of different post-fire curing regimes are presented herein with special emphasis on the effect of thermal profile including exposure time, temperature and cooling rate. The experimental results confirm that the recovery of material properties in fire-damaged SCC concrete is contingent on the post-fire water curing conditions.

1 INTRODUCTION

Concrete is recognized as a fire-resistant construction material due to its low thermal conductivity. However, it can endure considerable damage such as degradation of strength, cracking, shrinking and explosive spalling at elevated temperature. Mechanical, physical and chemical properties of concrete are influenced if subject to fire conditions. Bisby et al. [1] demonstrated that the compressive strength of plain concrete specimens diminish if exposed to elevated temperature.

In the recent years, there has been increased interest amongst researchers to develop techniques for salvaging fire-damaged concrete structures [2]. Poon et al. [3] reported that concrete can recover up to 93% of its original mechanical properties without special repairs if exposure temperatures are kept below 600 degrees.

Based on the research of Kadam and Chakrabarti [4], common methods to heal degraded concrete structures include: polymer injection, external pre-stressing, geomembranes and polymer wraps. These approaches restore concrete from out-side to inside by using additional repair material to concrete. Kadam and Chakrabarti [4] also designed a self-repair technique for concrete which involved adding an admixture (namely chemical resins) inside the concrete in order to repair internal cracks

According to the investigation of Lv and Chen [5], self-repair technology can be classified as autogenous healing and autonomous healing, respectively. Autogenous healing refers to situations in which concrete is self-healing as the damage can be naturally sealed. The autogenous healing method such as re-curing in water has proven to partly restore the strength of concrete. Schlangen et al. [6] researched the reaction products of autogenous self-healing procedures and concluded that autogenous self-healing was caused by further hydration of unhydrated cement clinker.

The main mechanisms of autogenous self-healing are: (1) further hydration of unhydrated cement; (2) recrystallization of portlandite leached from the bulk paste; (3) formation of calcite [7].

For autonomous healing, the self-healing abilities are obtained by the release of encapsulated repair-admixture due to cracking from the onset of damage. Besides, the extent of restoration is dependent upon various parameters such as concrete type, exposure temperature, and post-fire curing conditions [5].

In this study, an experimental investigation is carried out to study the alteration in mechanical properties (including strength, elastic modulus and ultimate strain) of high temperature exposed concrete, by autogenic self-healing phenomenon resulting from water re-curing. Concrete specimens undergo different thermal and curing conditions which are presented herein with special emphasis on the effect of thermal profile including exposure time, temperature and cooling rate.

2 METHODOLOGY

2.1 Concrete Mixture

In this project, Self-Compacting Concrete (SCC), a high performance concrete developed in Japan in 1988, has been chosen for the investigation [8]. Due to the fact that SCC has the advantage of excellent deformability and segregation resistance, the need for vibration can be eliminated during the placing process. SCC has been verified as an economical concrete since adoption of this type of concrete has the merit of saving labour costs and shortening the construction period [8]. It has become a popular construction material, especially for large scale civil construction.

Unconfined self-compacting concrete specimens with nominal dimensions of 40mm diameter and height/diameter ratio of 1, with target strength grade of C37 (ie. 37 MPa) have been utilized for the experiments. The mixture proportion of self-compacting concrete used by Mirmomeni et al. [9] is adopted here and is presented in Table 1.

The SCC concrete samples are cast in PVC tubes and cured for 28 days as follows:

1) Curing the fresh concrete at room temperature in plastic covered conditions for the first 24 hours;
2) Concrete specimens are taken out of the PVC tubes and cured in a water tank for 7 days;
3) Specimens are taken out of the water tank and cured at room temperature for the remainder of the curing period.

2.2 Testing scheme

The effect of water re-curing on the behavior

Table 1: The mixture proportion of self-compacting concrete

Ordinary Portland cement ($\mathbf{kg/m^3}$)	Water ($\mathbf{kg/m^3}$)	Class F Fly ash ($\mathbf{kg/m^3}$)	Coarse aggregate ($\mathbf{kg/m^3}$)	Fine aggregate/Sands ($\mathbf{kg/m^3}$)	Superplasticizer /BASF (**ml**)
2.133	1.121	0.533	4.008	4.341	13

of partially damaged concrete induced by exposure to elevated temperatures up to 600°C is investigated in this study. The experimental procedures adopted for conducting the tests are as follows:

The experimental program commences by heating 28-day old concrete specimens to the target temperature inside an Instron environmental chamber with a capacity of 600°C.

The chosen target temperatures are **300**°C, **450**°C, and **600**°C. The surface temperature of a specimen is measured by five type *K* thermocouples placed inside the chamber so that the temperature of the sample can be recorded regardless of the position of the specimen inside the chamber, as shown in Figure 1. Three of the thermocouples are used for measuring the surface temperatures of the specimen and 2 for the inside temperatures. A fine hole with the dimensions of the tip of thermocouple have been designated in some of the samples to measure the internal temperature gradient of the samples.

Figure 1: Concrete specimens in an environmental chamber.

Holding time as one of the test parameters refers to the duration temperature is maintained at the target temperature after reaching this target. Two different holding times of **15 minutes** and **2 hours** have been chosen here. The time-temperature graph for the different holding times for each temperature has been presented in Figure 2. The data on this figure are based on the readings of the thermocouples placed inside the samples.

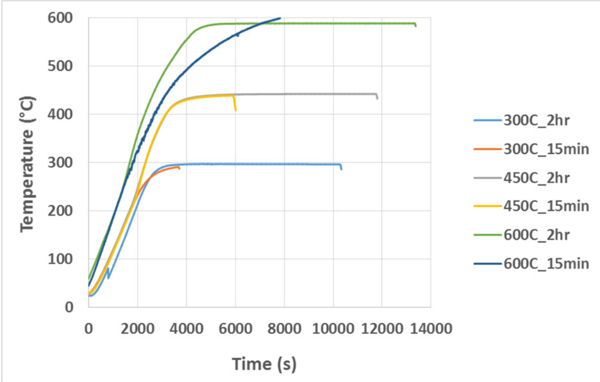


Figure 2: Temperature gradient for 15 minutes and 2 hour holding times

Once the temperature exposure requirements are met, the chamber is turned off. The first group of specimens are taken out and quickly placed inside a water tank at room temperature for 5 minutes (until surface temperature measurements using a digital thermometer indicate a temperature below 30°C). This process is to simulate the **quenching** (denoted as **Q** herein) process in which water is sprayed on concrete structures as fire is put out. The second group of specimens are taken out of the chamber and left to cool down to the ambient temperature which is classified as **slow cooling** (denoted as **S** herein) rate condition.

Subsequently, these heat exposed specimens are categorized into four separate autogenic curing groups:

- "**No curing**" left overnight (approx. 12 hrs.) at room temperature
- "**2 days curing**" water cured in a water tank for 2 days. Water tank is maintained at ambient temperature.
- "**7 days curing**" water cured for 7 days in a water tank
- "**28 days curing**" water cured for 28 days in a water tank,

As the fifth parameter, for the "28 day curing" conditions, there are two further different curing methods. One is curing the samples by **submerging in water** and the other is curing the specimens at **60% humidity**. The designated humidity is maintained via curing the samples inside a C150 WEISS temperature and climate test chamber.

Once the curing process is complete, a quasistatic compression test at the rate of 0.1 mm/min is conducted using a 100kN Instron 5982 testing machine.

3 RESULTS AND DISCUSSION

In order to investigate the effect of post-fire curing on the residual mechanical properties of fire damaged self-compacting concrete, the average ultimate compressive stress (UCS) for different classifications of the concrete specimens are illustrated in Figure 3. Note that in the horizontal axes labels, the first number implicates the temperature exposure and the number directly after the letter "C" is the number of post-fire curing days. Hence, "300C0" denotes specimen which are heated up to 300°C and tested with no post curing while "25C0" denotes the control sample.

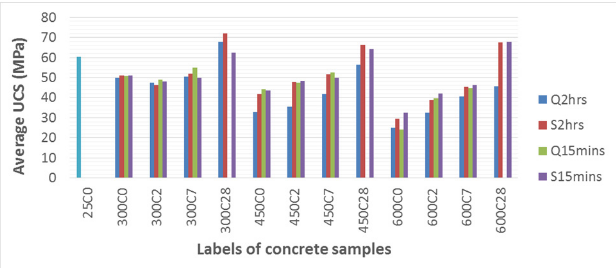


Figure 3: Average UCS of concrete under different post-fire curing conditions.

Data presented in this paper are based on the average value obtained from a minimum of 4 and a maximum of 6 repeat tests. It must be mentioned that Figure 3 reflects the results of specimen cured under 100% humidity conditions.

The overall trend of Figure 3 indicates that with an increase in temperature, concrete undergoes damage and strength is decreased. The rate of strength degradation is not linear, that is, while at 300°C material maintains as much as 85% of its capacity. With a temperature elevation to 600°C, up to 60% of the concrete strength is lost. With the adoption of a specific post curing condition, there is evident restoration in the ultimate strength of the material for high temperature exposed materials while those exposed to lower fire temperature do not experience much change in their behavior. It can clearly be observed from this figure that for 600°C, with the increase in the duration of post-curing, the concrete gains considerable strength.

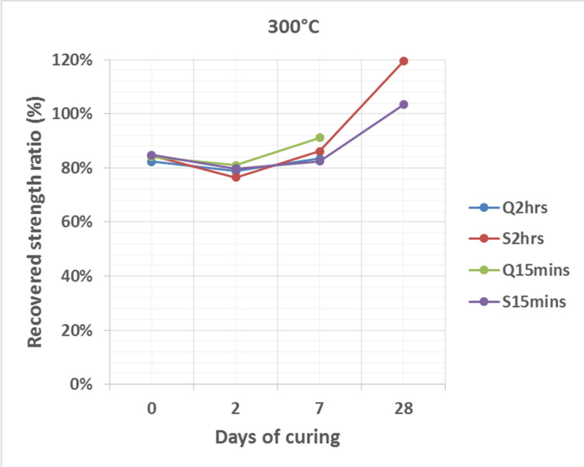
For the purpose of comparing the residual strength of post-fire cured SCC concrete, the percentage of recovered strength has been reported here by normalizing the average ultimate compressive strength of specimen re-cured under various conditions to that of the average 28 day stress of undamaged concrete ($\acute{f}_c$). This relative stress parameter used for analysis is as follows:

$$Recovered\ strength\ (\%) = \frac{Post\_curing\ UCS}{\acute{f}_c} \quad (1)$$

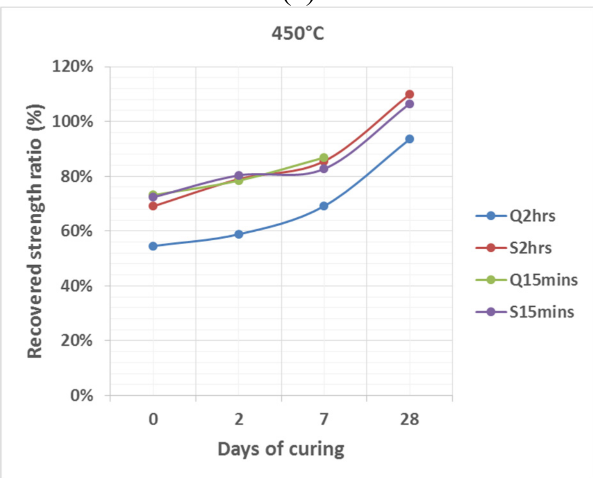
In this paper, the average stress of the control samples ($\acute{f}_c$) is estimated as 60.4MPa. It should be reiterated that results presented herein are ratios of material strength post curing, to $\acute{f}_c$. This emphasizes how much strength is lost as a result of fire exposure (hence zero days of curing strengths are below 100%) and how much of the original compressive capacity of the material is recovered using the autogenous self-healing procedures.

3.1 Effect of post-fire curing duration

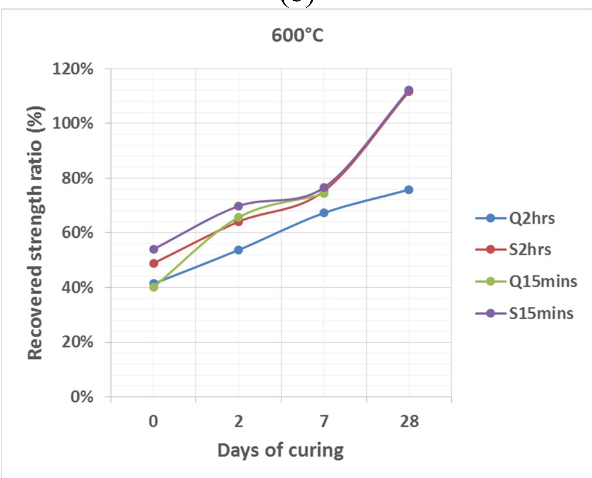
Figure 4 (a-c) illustrates the restored strength of the material with respect to duration of curing for three different temperatures. Based on these figures, it can be observed that, at the same elevated temperature, the trend line simulated in the graphs are similar. Although the 300°C temperature induced partially damaged specimen do not gain any strength after being cured for 2 days in water tank, after 7 days, the introduced micro-cracks are recovered to some extent and there is a slight increase in the UCS. However, for higher temperatures of 450°C and 600°C in which more temperature damage are introduced and more cracks have formed in the material, after 2 days the material strength has already had a considerable recovery. Hence, the increasing trend of strength restoration is demonstrated within the curing durations considered in this study.



(a)



(b)



(c)

Figure 4: Compressive strength recovery of SCC concrete exposed to a) 300°C, (b) 450°C, (c) 600°C with respect to different curing conditions.

3.2 Effect of temperature exposure duration

The longer the fire exposure time, the more damage is caused in the concrete microstructure. The extent of damage caused by the duration of fire and the effect it has on the post-curing outcome are investigated here and results are presented in Figure 5.

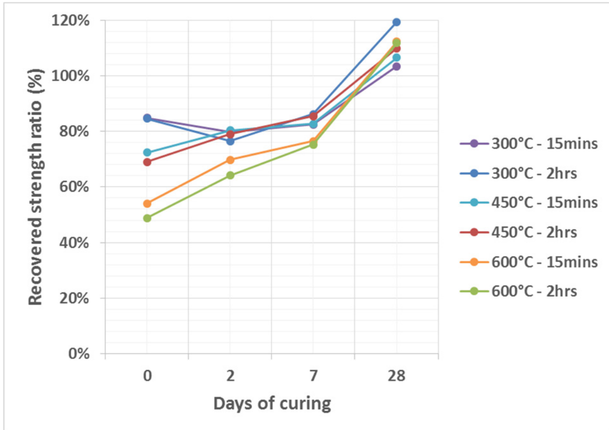


Figure 5: Restored strength of concrete exposed to different holding times (with slow cooling rate)

During the first days of curing, regardless of what the target temperature is, the restored strength of specimens with 15 minutes additional exposure time post temperature stabilization are marginally higher than those maintained for 2 hours. However, with the increase of curing days, the restored strength of more damaged samples surpasses those with a lower pre-damage at temperatures up to 450°C. However, following the long term curing of specimens undergoing very high temperatures (600°C), the variation in exposure time does not affect the restored strength of the material.

3.3 Effect of temperature cooling rate

In this project, two different cooling methods (namely quenching cooling and slow rate cooling) are adopted for simulating possible post-fire scenarios in case of an actual fire. In order to compare the effect of these two approaches on the residual mechanical properties of fire-damaged concrete, Figure 6 presents the restored strength against the days of curing for different curing methods.

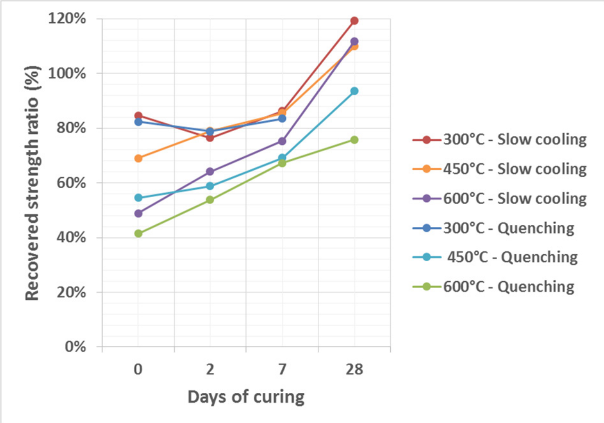


Figure 6: Effect of cooling rate on post-fire curing strength restoration (2 hours holding time)

When the concrete is exposed to lower fire temperature around 300C, whether or not the temperature is lowered suddenly or restored to ambient temperature in a natural pace, the subsequent compressive strength of the material stays constant. With an increase of temperature, the abrupt alteration to the material properties due to quenching of concrete in cold water results in a much slower healing process. Overall, slow rate cooling can result in higher restored strength and higher UCS compared with that of quenching cooling. The reason is that quenching causes large internal stress that leads to micro-cracking due to excessively rapid volume changes.

3.4 Effect of relative humidity condition

A conventional water curing procedure in laboratory is to submerge concrete specimen in a temperature controlled tank. This provides sufficient moisture supplementation for the hydration of concrete. However, in civil engineering projects, where repair of fire-damaged concrete structures is needed, the extent of humidity applied to the concrete for re-curing purposes might be of question.

In order to investigate the possibility of a more economical practice to repair fire-damaged concrete, two humidity conditions (namely 100% humidity and 60% humidity) have been considered here. In this case, 100% humidity is the case where that the concrete specimens are fully submerged in water tanks. Results of the effect of relative humidity on material strength restoration are presented in Figure 7.

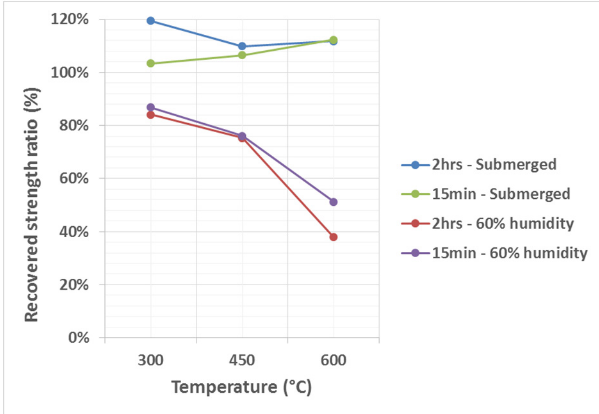


Figure 7: Recovered material strength under different humidity conditions (slow cooling rate - 28 days post-fire-curing)

The recovery of material properties of fire-damaged concrete has mostly been observed in high humidity conditions due to rehydration of the constituent materials in concrete. These rehydration products refill the fire-induced micro-cracks in the interfacial zone between the cement paste and aggregates. Hence, under sufficient moisture supplementation (100% humidity) curing condition provides much better improved effect on the residual mechanical properties of fire damaged concrete.

It is worth noting that given the application of adequate humidity, and given the strength loss is not crucial, if the damaged concrete is post-fire cured for a duration of 28 days, not only can the material strength be restored to its original state but it has the potential to regain more. The reason is that $\acute{f}_c$ is the strength of a non-damaged specimen cured for 7 days in water and tested on the 28th day of casting. When the material is re-cured for an additional 28 days in a water, it has a potential for hydrating the unhydrated cement constituent. Hence, not only healing the damage but surpassing the original compressive strength.

3.5 Failure mode

Macro failure modes of the tested specimen with various curing conditions have been investigated. Results indicate that the mode of failure is mainly dependent on the maximum temperature the material is exposed to and less on the cooling rate or the level of re-curing humidity. Figure 8 shows the failure modes of 7 days cured specimens subjected to different temperatures. As it can be seen from these pictures, at 300°C, the material exhibits a diagonal splitting failure. This is an abrupt collapse accompanied with a large breaking noise. With an increase of temperature to 450°C, the failure changes into a combined vertical splitting and shear failure. At 600°C, material has gained an extensively large ductility and fails in shear.

Figure 8: Failure mode of SCC concrete exposed to different fire temperatures and post-fire-cured for 7days (2hr exposure time, quench cooling)

4 CONCLUSIONS

This paper presents an experimental investigation into the effects of post-fire curing conditions on the residual material properties of fire-damaged concrete. The test results are summarized as follows:

- The longer fire damaged concrete is cured the more strength it will gain. This strength increase is not significant in lower fire temperatures around 300C.
- For long term curing of specimens that have undergone very high temperatures (600°C), the variation in exposure time does not affect the restored strength of the material.
- The rate at which material is cooled from fire temperatures is a dominant factor on how much strength is able to be regained as a result of re-curing.
- Recovery rate of compressive strength of concrete is small at low relative humidity conditions. This gain is gradually increased at higher humidity, which appears to occur according as a result of recovery of micro-cracks in the presence of sufficient water for hydration.
- Failure modes are mostly temperature dependent.
-The gradients and stresses that develop in the material due to the restraining are highly size dependent. This means that no general conclusions regarding the concrete in a structures can be deducted from these experiments.

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