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Effects of re-curing on residual mechanical properties of concrete after high temperature exposure

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HIGHLIGHTS

- Deterioration of concrete continues at the post heating stage.
- Mechanical recovery of concrete is seen possible by applying water re-curing.
- Air entrainment improves the spalling resistance of fiber reinforced concrete.
- Steel fibers survive after heating and resist to excessive cracking of concrete.

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ABSTRACT

Physical and mechanical changes in concrete continue in subsequent days of heating since some chemically active products in concrete give reactions with water and carbon dioxide in air and new formations determine the fate of concrete. Therefore, this study was conducted to understand the effects of mineral admixtures, fiber reinforcement, air entrainment and different re-curing regimes (after heating) on residual properties of concrete. Concrete specimens were heated to 1000 °C then water and air re-curing processes were applied on heated specimens and further deterioration and recovery of concrete were evaluated. New cracks occurred on the heated surfaces during air re-curing period and reduction in mechanical properties was observed while water re-cured specimens kept their stabilities and regain in their mechanical properties was obtained. Moreover, micro level investigations were conducted on heated surfaces of air re-cured and water re-cured concrete specimens for understanding the reasons of changes observed in mechanical properties.

1. Introduction

During fire or high temperature exposure deteriorations in concrete can be observed such as color change, surface delamination, cracking, spalling etc. [1–9]. Thermal gradients, evaporation of free water and chemical changes in concrete are the main reasons of these deteriorations [1,3,8,10,11]. Thermal gradients are dependent upon thermal conductivity of concrete which varies according to thermal characteristic of materials used and porosity of concrete [12–14]. High amount of water evaporation causes increase in internal pore pressure [15]. Combined stress level of thermal stresses and pore pressure can exceed tensile strength of concrete in some cases and explosive spalling may occur [10,15]. Most common way to prevent concrete from spalling is adding polypropylene (PP) fibers in concrete mixes since they melt above 180 °C and form micro channels which may facilitate the evacuation of water vapor [1,3,10,16–18]. Extra reservoirs in concrete like entrained air voids can also be beneficial to improve spalling resistance of concrete [1].

Another reason of deteriorations is the chemical changes occurring in concrete due to excessive temperature increases [1–3,5,9,19–21]. Weakened bonds and increased voids as results of crystal water evaporation and decarbonation of carbonates cause reduction in mechanical properties of concrete [19–21]. Research showed that chemical activity was still high after cooling, causing changes in physical and mechanical properties of concrete [21–24]. Water vapor and carbon dioxide in air can react with some oxides and calcium silicate phases after cooling and resulting products determine the final state of concrete [21,23,25]. For example, disintegration and further deterioration of concrete can be observed due to CaO rehydration since $Ca(OH)_2$ is produced at the end of

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the rehydration and its volume is 44% higher than CaO [21,23,25,26]. Due to this expansion, size and numbers of existing cracks can increase and mechanical performance of concrete further decrease after cooling [1,7,23]. In literature it was reported that using mineral admixtures in concrete could eliminate or reduce the negative effect of CaO rehydration since slag consumed $Ca(OH)_2$ after rehydration [25]. Using high melting point fibers in concrete can be another way of decreasing damage, since high melting point fibers can survive after heat exposure and resist to tensile stresses occurred due to CaO expansion after rehydration.

On the other hand, when concrete come in contact with water after cooling, healing and recovery of concrete can be possible in case of regeneration of C-S-H and carbonates phases and filling micro pores in concrete [21,26–28]. However, water re-curing is a debated application since some of researches inferred that water re-curing after cooling could be beneficial for the recovery of concrete and many other researchers found water re-curing application detrimental for concrete [27–32].

Unfortunately, there are very limited numbers of study about water re-curing after heat exposure and also curing techniques of some of them are not easily applicable on full scale structural concrete members. For example, most of the related studies apply heat from all faces of the specimens which may not simulate real conditions during fire. In this study, experimental approaches and methods used were selected such that to mimic real conditions during and after fire exposure as much as possible by using the available facilities. A comprehensive research was designed in order to understand disintegration and recovery process and concrete groups were subjected air and water re-curing processes after heating up to 1000 °C. One face heating was applied by using a fire scenario similar to ISO curve. For after fire curing conditions again two possible scenarios to represent real life cases as possible as could be done were selected. Some of the specimens were left in ambient conditions while some of them were cooled from the heated face by using water.

Important changes in the microstructure was observed and thorough chemical analyses were carried out to understand and explain the reason why the concrete material exposed to water after high temperature exposure shows different residual properties when compared to concrete left as it is after fire. While doing these examinations effects of using different mineral/chemical additives and different types of fibers and their combinations were also evaluated by means of contributions to spalling performance, microstructural changes, residual strength, etc. Ground granulated blast furnace slag (GGBFS) and pulverized fly ash (PFA) as mineral admixtures were added into concrete mixes in order to evaluate their possible effects on deterioration and recovery of concrete at the post heating stage. Hooked end steel fibers as high melting point fibers were used in some concrete groups to understand their efficiency to resist crack growth during heating especially during air re-curing period. Spalling resistance of PP fiber reinforced and air entrained concrete were evaluated in previous research of authors. Moreover, in this study influences of PP fiber reinforcement and air entrainment on disintegration and recovery of concrete were investigated.

It should be remembered that a sustainable approach covers all the steps from mix design to manufacturing and from maintenance during lifetime to following hazardous events. Therefore concrete resistant to fire should be examined such that from mix design and used materials to after fire curing conditions by considering what events may occur in real life during the lifetime of the structures.

2. Experimental study

2.1. Materials and specimens

CEM I type Portland cement (PC), ground granulated blast furnace slag (GGBFS) and F type pulverized fly ash (PFA) were used in concrete groups as cementitious materials. Cement replacement ratios of GGBFS and PFA were 40% and 30%, respectively since these ratios were found to be optimum in previous researches [2,33]. Total amount of cementitious materials in 1 m^3 of concrete was 450 kg in every concrete group and all concrete groups had a water to binder ratio of 0.45. Water contents were determined according to TS EN 206-1 and TS 13515 since cement equivalence factors for GGBFS and PFA are given to be 0.8 and 0.4, respectively. Table 1 shows mix proportions of concrete groups. As chemical admixtures, oil alcohol and ammonium salt based air entraining admixture (AEA) and modified polycarboxylate based superplasticizer were used in concrete mixes. AEA content was the same and 0.3 kg (0.7% of total weight of binder.) in all concrete groups. Super plasticizer amount changed in order to obtain slump levels in S4 limits given in TS EN 206-1. Steel fibers were used as high melting point fibers and PP fibers were used as low melting point fibers to reinforce concrete groups. In PP fiber reinforced groups, PP fibers were used 0.2% of volume of concrete and in steel fiber reinforced groups steel fibers were used 0.5% of volume of concrete. PP fibers and steel fibers were added at contents of 0.1% and 0.25% per volume in hybrid fiber reinforced concrete groups, respectively. River sand and siliceous gravel were used in all concrete groups as aggregates. Depending on cementitious materials and fiber types and also presence of air entraining agent 24 different concrete groups were designed as can be seen in Table 2.

15 cubic specimens with dimensions of 15 × 15 × 15 cm were produced for each concrete group. One day after production, specimens were demolded and placed in curing water for 27 days. Then they were conditioned in laboratory environment for additional 2 months before tests [2,4,8]. Three cubic specimens were used to determine initial properties of concrete before heating. Remaining 12 cubic specimens were heated to 1000 °C. Three of them were

Table 1
Mix proportions.

Materials	PC groups (kg/m^3)	PC + GGBFS Groups (kg/m^3)	PC + PFA groups (kg/m^3)
Portland cement	450	270	315
GGBFS	–	180	–
PFA	–	–	135
Water	203	186	167
Aggregate No1	484	493	496
Aggregate No2	484	493	496
Crushed Sand	564	574	577
River sand	225	229	230
Super Plasticizer (min–max)	5.3–6.7	6.9–8.3	8.6–10.4
In PP fiber reinforced groups	1.8 kg PP fiber		
In SF reinforced groups	40 kg Steel fiber		
In HF reinforced groups	0.9 kg PP fiber and 20 kg Steel fiber		
In air entrained groups	0.3 kg Air entraining admixture		
Density (kg/m^3) (min–max)	2285–2402	2280–2411	2296–2430