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Acoustic Emission behavior of thermally damaged Self-Compacting High Strength Fiber Reinforced Concrete

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HIGHLIGHTS

- High temperature effects were investigated on SC-High Strength and Fiber-Reinforced Concrete.
- Steel fibers played a beneficial role in bridging the expansion of heat-induced cracks.
- Acoustic Emission (AE) measurements allow scrutinizing thermal damages in cementitious composites.
- AE activity was monitored for analyzing bridging fiber mechanisms in SCHSFRC.

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ABSTRACT

This paper investigates the effect of high temperature on two different Self-Compacting (SC) cementitious composites. SC-High Strength (SCHSC) and Fiber-Reinforced Concrete (SCHSFRC) samples were tested in three-point bending after having been exposed to high temperature at 300 and 600 °C. Besides the conventional force-displacement response, Acoustic Emission (AE) activity was monitored during the bending tests with the aim to investigate the possible correlation between the fracture behavior, the rate of AEs and the influence of high temperature exposure. The tests clearly pointed out the effects of heat exposure. More specifically, SCHSC specimens showed a significant decay in mechanical properties as a result of thermal treatments. Then, a lower degradation was observed for the SCHSFRC after heat exposure at 300 °C, whereas the specimens exposed to 600 °C exhibited a tougher response than the corresponding SCHSC. The results showed that the effect of fibers played a beneficial role in bridging the expansion of heat-induced cracks developed in the concrete matrix during the exposure of specimens at high temperature. This bridging effect of fibers was observed also in terms of the AE activity: much less AE events were systematically registered for SCHSFRC specimens with respect to SCHSC ones, for a given value of the imposed Crack-Mouth-Opening-Displacement (CMOD). Therefore, AE measurements confirm their potential in scrutinizing the damage level in cementitious composites.

1. Introduction

Over the last decades, the use of Self-compacting High-Strength Concrete (SCHSC) in the construction industry has been expanding considerably. Significant advances in new materials, quality and mixture proportioning, e.g. chemical admixtures and mineral binders, have led to both obtaining outstanding flowability at the fresh state and increasing compressive strength at the hardened state. As a result of the lower water-cement ratio, the microstructure of SCHSCs has less permeability and porosity, with enhanced durability against harmful actions of the environment, hence, a longer service life. However, strength increase implies a less ductile mechanical behavior [1,2]. The addition of amounts between 30 and 80 kg/m^3 of steel fibers in concrete improves its energy absorption capacity and limits the propagation and width of cracks [3]. SCHSC is also characterized by a higher content of cement paste and a more compact microstructure than those of

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Normal-Strength Concrete (NSC). Consequently, SCHSC could develop higher internal vapor pressure gradients under high-temperature exposure which allows to trigger microcracking and, sometimes, explosive detachment of parallel parts to the heated concrete surface. This phenomenon is called "spalling" and, although it can also occur in NSCs, it is more frequent and pronounced in High-Strength Concretes (HSCs) [4]. However, it was demonstrated that the incorporation of small amounts of polypropylene microfibers can partially mitigate this drawback [5–7].

The interest for investigating the behavior of concrete exposed to high temperatures has been motivated by two main reasons: fire resistance of tunnels and/or buildings and the nuclear facilities behavior. The design of new concrete demands to know their behavior under several environmental conditions, including for temperatures ranging between 20 °C and 800 °C [8,9]. Concrete exposed to high temperatures suffers chemical and physical changes, such as loss of moisture content, microstructure modification and aggregates decomposition which are mainly related to the reached maximum temperature of exposure [10]. Up to 200 °C no important changes take place in concrete mechanical properties due to the evaporation of the free and adsorbed water. Conversely, with increasing temperature (up to 500 °C), the average pore size grows up due to the loss of water and dehydration of hydrated calcium silicates (C-S-H). Specifically, reaching 450 °C, the calcium hydroxide ($Ca(OH)_2$) of the cement paste decomposes into calcium oxide (CaO_2) and water. Up to these temperatures, the aggregates are more or less stable, excepting the siliceous aggregates. Furthermore, over 500 °C, concrete chemical and physical changes become very important and irreversible: at 573 °C, the aggregates α-quartz crystalline phase transforms into β-quartz, resulting in deleterious expansions. A further increase in temperature up to 600 °C leads to the initiation of chemical decomposition in C-S-H, which is the main strengthening compound of cementitious matrix. Between 600 °C and 800 °C calcium carbonate ($CaCO_3$) dissociates. Moreover, after 800 °C all the hydration or chemically combined water has already been lost and the strength capacity becomes very low. Finally, at 1200 °C the solid compounds begin to melt [11]. However, concrete behavior subjected to high temperature does not only depend on the maximum temperature, but it is also affected by many environmental conditions, such as heating rate, temperature permanence time, cooling and humidity level, among others [9,10,12].

Several investigations have shown that thermal actions induce substantial modifications in cohesion and strength of concrete, which reduce both Young's modulus and Poisson's coefficient [13–17]. Concrete behaves in a more ductile manner increasing peak compressive strength deformation as temperature rises [18]. In addition, a slight increase in fracture energy released up to 400 °C has been observed, which decreases at higher temperature due to excessive thermal damage and the strong loss of tensile and compression strength [19,20]. Specifically, the experimental evidence for Self-Compacting Concrete (SCC) at high temperature shows that their mechanical properties are more seriously thermally degraded than traditionally-vibrated ones [17,21–24].

The actual state of damage of concrete can be scrutinized by means of non-destructive techniques, among which Acoustic Emission (AE) testing is gaining consensus within the scientific community [25]. In fact, AE is known as the spontaneous release of elastic energy in the form of transient elastic waves that occurs within the materials when stressed [26]. Hence, the waves contain information about internal behavior of the material [27]. Structural modifications such as cracks growth and friction are generated as the fracture process of concrete is progressing, which are associated with acoustic emissions. These elastic waves propagate from their sources to the surface where piezoelectric sensors convert them into electrical signals which can be subsequently processed by a specific electronic equipment. A set of relevant signal parameters can be calculated in order to characterize the digitalized AE waveforms. Therefore, AE technique has been used to monitor in real time laboratory mechanical tests of concrete specimens due to it great sensitivity to detect damage evolution from the very beginning [28–32]. Many investigations have been carried out in order to quantify the global damage level of reinforced concrete elements using AE-based parametric approaches. For this purpose, new indexes derived from conventional AE parameters have been defined: e.g., Calm ratio [33,34], Cumulative Signal Strength ratio [35,36], Relaxation ratio [37], b-value [38–40] and Improved b-value [41], among others. Moreover, AE can deliver useful information to detect, locate and infer the origin of the sources [30,42,43]. In this regard, several experimental results have been reported evidencing the close relationship between the AE features with the source cracking mode [44–47]. It has been pointed out that tensile fracture mode, characterized by opening mode I movements of the crack, results in AE signals with higher frequency and shorter rise time (defined as elapsed time from the first arrival to the peak amplitude). On the other hand, shear fracture mode waveforms, represented by a sliding mode II movement of the crack faces, show lower frequency and longer rise time and duration. Thus, AE events can be plotted in a bi-dimensional representation defined by the combined features of RA value (rise time over amplitude) and Average Frequency (AF) (counts over duration) to assess the cracking mode corresponding to the AE source.

This work reports the results obtained from three-point bending tests carried out on both SCHSC and SCHSFRC with the aim to investigate the influence of heat-induced damage on their cracking and post-cracking behavior. Both force-displacement relationship and AE activity were monitored during those tests. Thermal treatments were performed in an electric furnace at maximum temperatures of 300 and 600 °C. Steel macrofibers (0.76% in volume) and polypropylene microfibers (0.1%) were dispersed within the concrete matrix of the SCHSFRC mixture. It is important to remark that the adopted methods followed in this work mainly investigated the high temperature exposure at the material level and thus, the structural response at a fire scenario is out of the scope of this paper.

In the Authors' best knowledge, no experimental researches are available in the scientific literature reporting the fracture behavior of thermally damaged SCHSFRC specimens, tested in bending and related to AE activities. Indeed, the exiguous related results currently available refer to either Fiber Reinforced Concrete (FRC) [48–51] or thermally-treated concrete without steel fibers reinforcement [52–55]. Therefore, the results presented in this paper could be useful to researchers interested at studying the AE applicability limits as valuable tool in Structural Health Monitoring (SHM) for high responsibility structures, such as spent nuclear fuel storage facilities.

2. Materials and methods

This section summarizes the experimental activities related to the AE tests executed at the Laboratory of Materials and Structures of the University of Buenos Aires, Argentina. Further details on the extended experimental program and results of complementary mechanical tests can be found in [56]. The specimens for this experimental program were prepared adopting a unique dosage for the concrete matrix characterized by a water-to-binder ratio of 0.35. This mixture was designed to achieve an adequate flowability at the fresh state and, at the same time, a high-strength in hardened state.

2.1. Materials

The selected concrete constituents were early age high-strength Portland cement, finely Ground Granulated Blast Furnace Slag (GGBFS), three different fractions size of siliceous aggregates and a very high range polycarboxylate-based superplasticizer admixture. The mixture composition is detailed in Table 1. The