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Microstructure of fire-damaged concrete. A case study

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Abstract

Concrete is a poor conductor of heat, but can suffer considerable damage when exposed to fire. Unraveling the heating history of concrete is important to forensic research or to determine whether a fire-exposed concrete structure and its components are still structurally sound. Assessment of fire-damage concrete structures usually starts with visual observation of color change, cracking and spalling. On heating, a change in color from normal to pink is often observed and this is useful since it coincides with the onset of significant loss of concrete strength. This paper presents results of cores strength, as well as, optical microscopy investigations of fire-damaged concrete. Samples were taken from concrete that had been exposed to fire. Optical microscopy has focused on microstructure of cement paste, aggregates, microvoids and cracks, as well as, on quantification the crack patterns found in heated concrete samples. The physical condition of concrete sample in combination with the microscopic examination, enable a petrographer to make a reasonable estimation of the minimum exposure temperature and its relative impact to the depth of damage in concrete.

Keywords: Concrete; Fire-damage; Microstructure

1. Introduction

When reinforced concrete is subjected to high temperature as in fire, there is deterioration in its properties. Of particular importance are loss in compressive strength, cracking and spalling of concrete, destruction of the bond between the cement paste and the aggregates and the gradual deterioration of the hardened cement paste.

Assessment of fire-damaged concrete usually starts with visual observation of color change, cracking and spalling of the surface. Concrete color provides a broad, general guide of temperatures, whether the color represents the original surface or one resulting from spalling. Crazing, cracking popouts caused by quartz or chert aggregate particles, spalling and dehydration (crumbling and powdering of paste) are general indications of temperatures to which concrete has been exposed as shown in Fig. 1. On heating above 300 °C the color of concrete can change from normal to pink (300–600 °C) to whitish gray (600–900 °C) and buff (900–1000 °C). The pink discoloration results from the presence of iron compound in the fine or coarse aggregates [1–3].

The first effects of a slow temperature rise in concrete will occur between 100 and 200 °C when evaporation of the free moisture, contained in the concrete mass, occurs. Instant exposure can result in spalling through generation of high internal steam pressures. As the temperature approaches 250 °C dehydration or loss of the non-evaporable water or water of hydration, begins to take place. The first sizable degradation in compressive strength is usually experienced between 200 and 250 °C. At 300 °C strength reduction would be in the range of 15–40%. At 550 °C reduction in compressive strength would typically range from 55% to 70% of its original value [3–5].

Temperatures in the 550 °C range are critical because calcium hydroxide dehydration takes place. Calcium hydroxide is a hydration product of most Portland cement, the amount being dependent upon the particular cement being used. Aggregates also begin to deteriorate at about 550 °C. For example quartz expands at a higher rate around 300 °C [6,7].

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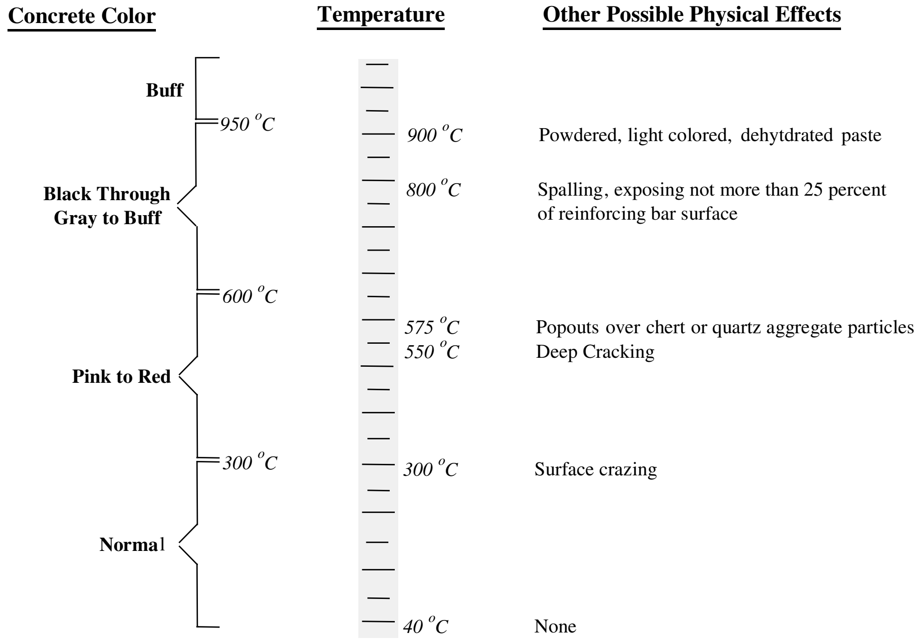

Fig. 1. Visual evidence of temperature to which concrete has been heated.

Two main types of spalling occur during fire. Explosive spalling and sloughing off of concrete surface layers. Explosive spalling looks like a series of popouts and usually occurs within the first 30 min of fire-exposure. Sloughing off is a gradual non-violent separation of the concrete that occurs primarily at the edges of columns and beams. When concrete spalls, deeper layers of concrete are exposed to the maximum fire-temperature, speeding the transmission of heat to the reinforcement. As the temperature within a member rises, steel reinforcement expands more than concrete. This can lead to further spalling and cracking around the steel. Such cracks often develop where incipient cracks (due to drying shrinkage, flexural loading or other factors) were present. Also, differing thermal expansion between aggregates and cement paste can create surface crazing, which can lead to deeper cracking [4,7].

Except the visual observation and the tests on concrete cores, optical microscopy applied to petrographic thin section has been used in investigations of concrete microstructure and has recently been applied to fire-damaged concrete. Results suggest that the nature and extent of cracking may be correlated with the actual temperatures attained in the concrete and a form of quantification of the crack patterns found was attempted [3,4].

The aim of the present research is to take advantage of the optical microscopy results on thin sections, and carry out a study to determine the microstructures of concrete-pastes/aggregates, microvoids/cracks, and separation of cement paste from aggregates in fire-exposed concrete samples, as well as the quantification of the crack patterns.

2. Experimental procedure

The ten test specimens examined were concrete cores from the first floor of a reinforced concrete building (age: 15 years old) which had been exposed to fire on 5th February 2000.

Five cylinder cores (cyl. 1–5) were subjected to compressive strength test according to method ASTM C-39, and three cylinder cores (cyl. 6–8) were subjected to “tensile splitting test” according to method ISO 4108 (Brazilian test). The other two cores (cyl. 9–10) were used for the petrographic analysis based on ASTM C-856: “petrographic examination of hardened concrete” was carried out on two thin sections from each core. Their construction was made in such a way, that the observation of the phenomena escalation due to fire-exposed would be feasible (Fig. 2).

The thin section were manufactured by vacuum impregnation, of the selected sample (cut from the core,

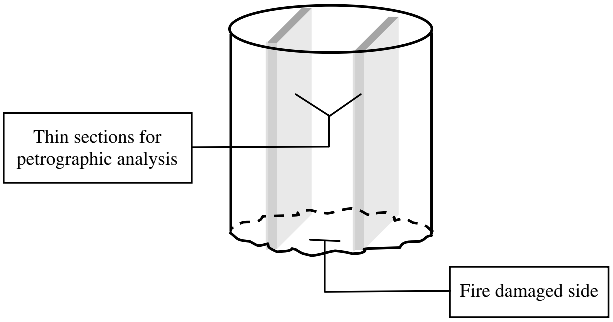

Fig. 2. Specimens for (thin section) microscopic observation.

size 50 mm × 50 mm × 10 mm) with epoxy resin, followed by cutting, grinding, and polishing until a final thickness of 20 μm is reached. During the process the thin section is mounted upon an object glass.

The thin sections were analyzed by polarization microscopy. The concrete constituents, and its microstructure—pastes/aggregates, microvoids/cracks, and separation of the cement paste from aggregates—in fire-exposed concrete samples, were examined and signs of the deterioration process were noted. The quantification of the crack patterns was carried out by measuring the crack density of concrete, in units of "mm" of crack length per "cm^2", correlating the extent of cracking, because of temperature increase, with the depth from the surface exposed to fire. The examination was carried out in filtered transmitted light, at a magnification of 32× so that the cracks present in an area of 3.2 mm × 3.2 mm could be observed.

3. Results and discussion

3.1. Macroscopic observation

All of the ten concrete cylinders examined, sustained significant damage caused by exposure to heat. The damage in all cases confined, especially, to the surface side near to the fire origin. The surface crazing was due to dehydration, which starts at 100 °C and ends at 540 °C, resulting in the removal of free water. Cracking and softening, following by decrepitation of the concrete surface is caused first by expansion and then by shrinking of the cement paste due to transformation of $Ca(OH)_2$ to CaO in the temperature of 450 and 500 °C.

Though the remainder cylinder cores appeared with fewer damages, significant parallel cracking was observed toward the core axis. The existence of cracking perpendicular to face (parallel to the axis concrete core) in significant depth (bigger than 3 cm) indicates large scale internal cracking because of internal shrinkage, which is caused by overheating following by rapid cooling (due to fire-extinguishing). Obviously, this cracking does not have the ability of self-restoration. Spalling and popouts of concrete are confined to surface close to areas exposed to fire, an indicator of heating at 573 °C. Deeper cracking beyond the depth of the reinforcement indicates that temperature has exceeded 700 °C [3,4].

Because the aggregates used in concrete, was mostly limestone, heat transmission in the internal part of the reinforced concrete was greater. The presence of red aggregates around reinforcement indicates that temperatures up to 590 °C must have been attained. Furthermore, in bigger depth pink aggregates can be observed (heating at 300 °C) which is a result of transformations in the composition and/or structure of hydrated iron oxides present in the aggregate. Taking into account that the reinforcement had been set in the depth of 3 cm and that the surface, exposed to fire, color has been changed to gray, temperature is believed to exceed 800 °C [1,6].

The absence of macroscopically visible glassy layer, at the location close to fire origin, indicates that there was not any concrete melting and, as a result, temperature is believed not to exceed the limit of 1000 °C [1–3].

3.2. Effect on compressive strength

Although a compendium of indirect information about the structural capability of individual elements can be obtained, it may still become necessary, and is indeed frequently desirable, to determine the actual loading capacity of an integrated system of elements. Furthermore, the most important effect of fire on concrete structure is the reduction of its compressive strengths due to heating. As a result, to estimate the strength of the fire-damaged concrete, in the affected building, five cylinder cores were subjected to compressive load test. The results are given in Table 1. Moreover, three of the extracted cylinder cores were subjected to "Brazilian test" according to method ISO 4108: "tensile splitting test" and the results are given in Table 2.

From the results of Table 1, it can be seen that the residual compressive strengths of fire-exposed concrete were very low, whose reduction has reached 70% of initial compressive strength. This indicates that temperature exposure exceeded 700 °C [1,6,7].

According to the results of "Brazilian test" (Table 2) the tensile strengths of the examined cores specimens were, also, too low, a fact that was predictable given that, random and radial microcracks were observed in the load axis.

Table 1
Compressive strengths of fire-damaged concrete

Core no.	Diameter (mm)	Height (mm)	Strength (MPa)
Cyl. 1	100	102	7.55
Cyl. 2	100	101	7.64
Cyl. 3	100	101	7.36
Cyl. 4	100	100	7.78
Cyl. 5	100	101	7.23

Table 2
Tensile splitting test of fire-damaged concrete

Core no.	Diameter (mm)	Height (mm)	Strength (MPa)
Cyl. 6	100	103	2.04
Cyl. 7	100	104	1.04
Cyl. 8	100	104	1.65

3.3. Petrographic examination

All samples received from the fire-damaged concrete cores were studied microscopically giving the following results:

1. At the surface near to the fire origin carbonate aggregate in concrete have been transformed to CaO, a fact that indicates the temperature must have reached 900 °C (Fig. 3a, 32×). The rest of the aggregates—in greater depth—are seemed to have been preserved relatively harmless.
2. The carbonation reaction has been completely developed in the cement paste, at the surface near to the fire-exposed side, contrary to the inner side of the specimen, where crystals of $Ca(OH)_2$ has been detected (Fig. 3b, 200×).
3. Large amount of gaps has been observed in the whole area of examined specimens, which are related with, either because of the pulverization of the aggregates, or because of the cement paste fragmentation, by reason of its structure collapse (Fig. 3c, 32×).
4. Large amount of heavy cracking has been detected in the cement paste–aggregates interface (Fig. 3d, 2×) in the whole area of examined specimens. Moreover, in the main area of the cement paste microcracking, of various orientation, has been observed which obviously, are not placed among these of self-restored. The absence of a microscopically visible glassy layer, underlain by thin layers of altered paste and aggregate, indicated that temperature exposure did not exceed 1000 °C.

3.4. Crack density

Information on the density and the distribution of cracks is useful in determining not only the minimum exposure temperature, but the thickness of concrete (from the spalled surface) that may eventually be removed in the case of repair work. It is also important in determining whether fire-attacked elements and its components, such as steel reinforcement, are still structurally sound and that the local loading conditions, in the long term would not adversely affect the mechanical properties and the durability of the elements.

Fig. 4 shows the extent of cracking, due to the temperature increase, in connection with the depth from the surface exposed to fire. Crack density is given in units of

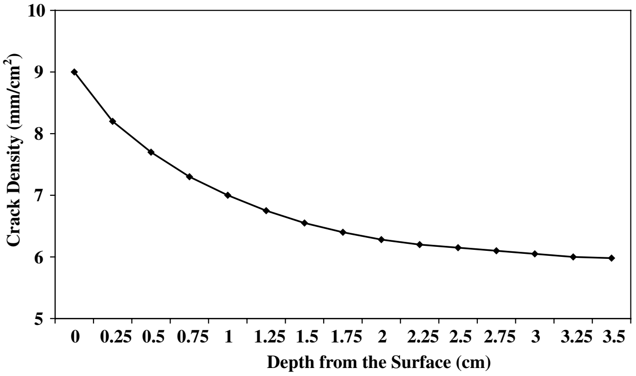

Fig. 4. Crack density vs the depth from the surface of the examined concrete.

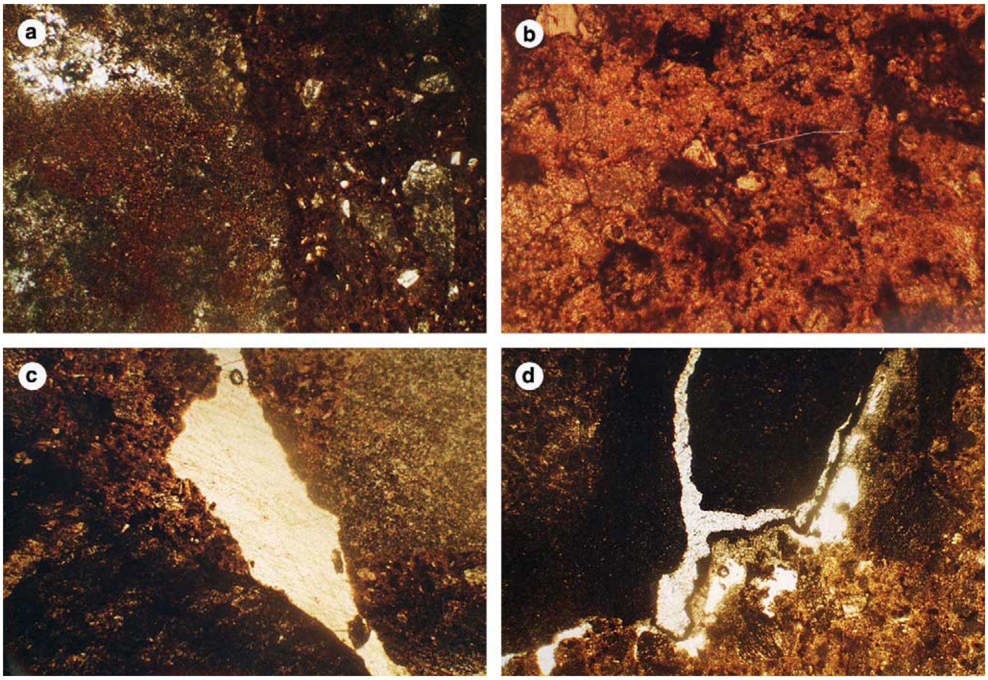

Fig. 3. Representative thin section photos of the examined fire-damaged concrete samples.

mm of crack length per cm^2. Each point is an average of the crack length measured in 15 different squares of 3.2 mm × 3.2 mm covering the wide of the 50 mm × 50 mm thin section.

According to Fig. 4, the temperature in the inner side of the core (at 3 cm depth) near to the reinforcement bar, did not exceed 800 °C, whereas in the outer side reached 950–1000 °C [3].

4. Conclusions

Measurements, such as microscopically-petrographic examination and loading tests, together with the macroscopically observation, were used in order to determine the thermal history of a fire-damaged concrete and to provide information regarding the maximum temperature at the surface exposed to fire.

Macroscopically observation showed significant parallel cracking toward to the core axis, a fact that indicated large scale internal cracking because of internal shrinkage, which is caused by overheating following by rapid cooling (due to fire-extinguishing). Spalling and popouts are confined near surface exposed to fire, an indicator of heating at 575 °C. Deeper cracking beyond the depth of the reinforcement indicates that temperature has exceeded 790 °C. Taking into account that the surface, exposed to fire, color has been changed to gray, temperature is believed to exceed 800 °C.

The results of compressive test showed that the concrete's fire residual compressive strengths were very low, whose reduction has reached the 70%. This fact indicates that the temperature exposure exceed 700 °C.

According to crack density measurements, the temperature in the inner side of the core near to the reinforcement bar, did not exceed 800 °C, whereas in the outer side reached 950–1000 °C.

Microscopic observation at the surface near to the fire origin showed that carbonated aggregates have been transformed to CaO, a fact that indicates the temperature reached 900 °C. The carbonation reaction has been completely developed in the cement paste, at the surface near to the fire-exposed side, contrary to the inner side of the specimen, where crystals of $Ca(OH)_2$ has been detected. The large amount of gaps observed is related with, either because of the pulverization of the aggregates, or because of the cement paste fragmentation at the temperature around 900 °C. Finally, the absence of a microscopically visible glassy layer, underlain by thin layers of altered paste and aggregate, indicated that temperature at the surface exposed to fire did not exceed 1000 °C.

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