

Influence of High Temperatures on Surface Cracking of Concrete Studied by Image Scanning Technique

Belkacem Toumi¹⁾ and Musa Resheidat²⁾

¹⁾ University Larbi Ben M'hidi, Oum El Bouaghui, Algeria, Email: tb_dz2001@yahoo.fr

²⁾ Jordan University of Science and Technology, Irbid, Jordan, Email: musaresheidat@yahoo.com

ABSTRACT

Surface concrete cracking is a visible type of damage that has significantly adverse effects on the mechanical properties and durability properties of concrete. This paper presents an experimental study on the identification and quantification of surface cracking of concrete heated to different temperatures ranging from 105 to 1250°C. In addition to the quantification of the residual compressive strengths of concrete after high temperature exposure, both initial surface absorption and total porosity were measured. The crack density was determined using a flat bed scanner and then images were treated using paint shop pro program. The total porosity was obtained using ASTM boiling. The mechanical properties of concrete were largely affected by temperatures beyond 500°C and were very feeble when temperatures exceeded 1000°C. The surface cracks' density, initial surface absorption and total porosity by boiling methods gave a rapid indication on concrete durability.

KEYWORDS: Temperature, Cracks, Surface absorption, Porosity, Image processing.

INTRODUCTION

The durability and performance of Portland cement concrete vary with its constituents (cement, sand, aggregates, additives and water) used in the concrete mixture, as well as with external exposure conditions during its service life. Elevated temperature is one extreme condition to which concrete structure could be exposed. Examples of such conditions are: concrete foundations for launching rockets carrying spaceships, concrete structures in nuclear power stations or those accidentally exposed to fire as the case of many tunnels registered in various countries as the fire of El-Akhdaria tunnel (Algeria) on February 28, 2008. Following the collision of two trains in the tunnel, 750 m³ of gas oil were burnt (Fig. 1). The temperature has reached 1200

°C and the duration of the fire was 48 hours. Interventions to extinct the fire were impossible and dramatic damages were observed in the tunnel's structure. The tunnel is closed until now.

Concrete structures subjected to fire have been studied in various aspects. When concrete is subjected to elevated temperatures, various physical (e.g., evaporation, condensation, water and vapour advection, vapour diffusion, heat conduction and advection, phase expansion), chemical (e.g., dehydration, thermochemical damage) and mechanical (e.g., thermo-mechanical damage, cracking, spalling) processes take place, resulting in the deterioration of the concrete (Heikal, 2000; Xu et al., 2001). This may result in undesirable structural failures (Kalifa et al., 2000; Cioni et al., 2001; Poon et al., 2004; Georgali et al., 2005; Janotka et al., 2005). Therefore, the properties of concrete retained after a fire are still of importance for

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determining its service life and for restoring fire-damaged constructions (Hertz, 2005). When exposed to

high temperature, the chemical composition and physical structure of the concrete change considerably.



Figure (1): The fire of El Akhdaria Tunnel (Algeria)



Figure (2): Specimens inside the furnace during heating

The first effects of temperature rise in concrete will occur between 100 and 200 °C when evaporation of free moisture, contained in the concrete mass, occurs. Instant exposure can result in spalling through generation of

high internal steam pressures. Spalling of concrete and surface cracking have been observed under laboratory and real fire conditions (Diederichs et al., 1995; Kodur et al., 2003; Bilodeau et al., 2004,). As the temperature

approaches 250°C, dehydration or loss of 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, the reduction in compressive strength would typically range from 55% to 70% of its original value (Gustafero, 1983). Temperatures in the

range of 550°C 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. Limestone aggregates also begin to deteriorate at about 750°C. At higher temperatures in the range of 1200°C, concrete specimens begin to melt.

Table (1): Physical properties of aggregates

Grain size (mm)	Sieve size (mm)							Specific weight	Unit weight (kg/m ³)	Water absorption ratio 24 h (%)
	12.5	8	4	2	1	0.5	0.25			
0 – 4	100	100	97	82	69	41	29	2.46	1705	1.62
4 – 12.5	99	46	2	1	0	0	0	2.75	1617	1.05

Table (2): Characteristics of cement

Physical test results		Chemical test results %		Composition %	
Initial setting time (h)	2:25	CaO	58.80	C ₃ S	61.19
Final setting time (h)	4:20	SiO ₂	21.70	C ₂ S	11.09
Specific surface (cm ² /gr)	2810	Al ₂ O ₃	6.10	C ₃ A	7.92
Specific gravity	3150	Fe ₂ O ₃	3.60	C ₄ AF	10.39
Residue on 200 μm (%)	1.0	MgO	3.60		
		SO ₃	3.00		
		K ₂ O	0.72		
		NaO	0.44		
		Loss of Ignition	1.50		

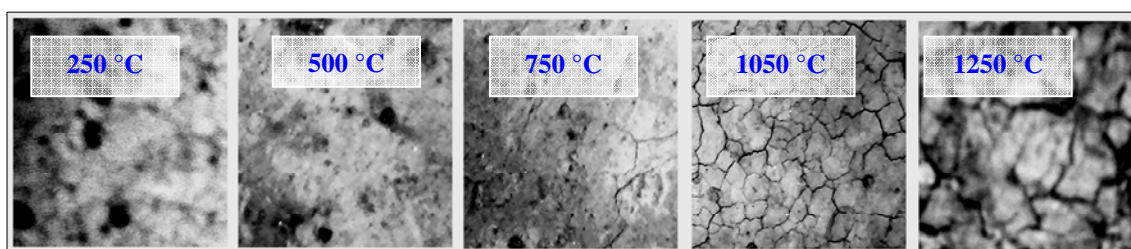


Figure (3): Surface state of concrete heated at different temperatures

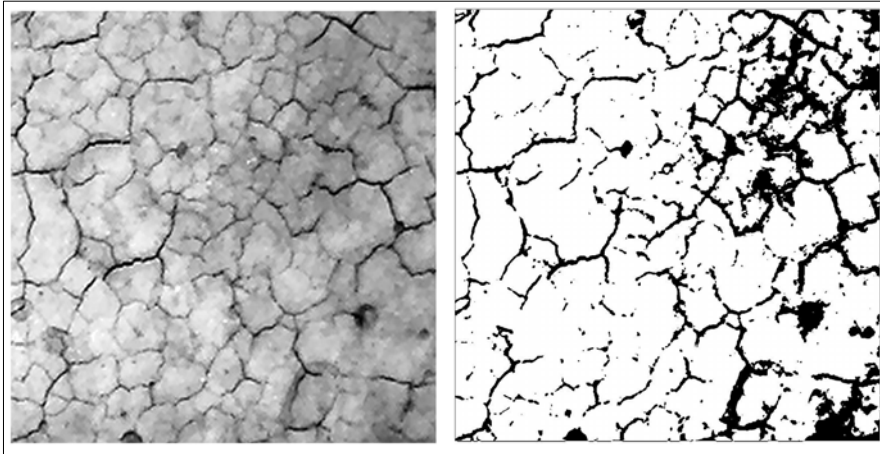


Figure (4): Crack extraction from scanned image

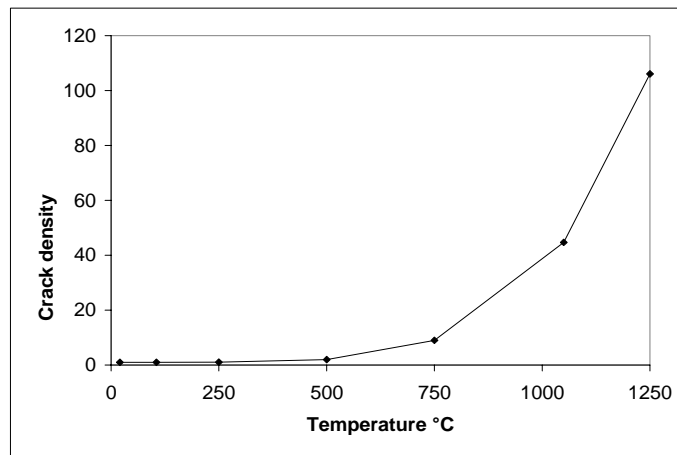


Figure (5): Surface cracks' density *versus* heating temperature

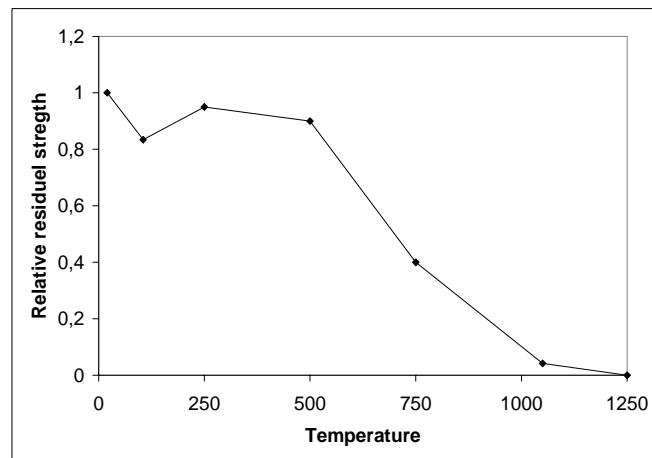


Figure (6): Residual relative compressive strength

Although visual observations of fired concrete provide a first idea on damage degree into concrete microstructure, quantitative information would be needed for such purposes as validation of theories of concrete failure and statistical analysis of damage and failure processes. Latest developed computer-based image analysis techniques (John et al., 1998; Dipayan, 2005) provide strong tools which can be adapted towards quantitative damage investigation of concrete. These techniques can be used to provide quantitative information of such structural phenomena as cracks' density in concrete under fire damage.

Image processing and image analysis are used to obtain quantitative information on the density of concrete surface cracks. Image processing can manipulate images and rearrange them with the intention of making them more useful; image processing is used to extract the cracks' topology from digitized images of the material. Image analysis of cracks involves mapping the cracks and manually measuring the lengths and areas of cracks (Konin et al., 1998).

Even as high temperatures increase the density of surface cracking, the ISAT (Initial Surface Absorption Tests) (Bungey, 1970; BS 1881-5) provide an additional rapid method to assess the concrete degradation caused by high temperatures. The permeation quality of surface concrete is assessed by this test, and the results are expressed in terms of a permeation index that is dependent on the pore and surface crack system of the concrete. Durability quality of concrete subject to high temperatures can be classified in terms of low, average or high permeability/absorption based on the value of measured permeation index (BS 1881-5).

EXPERIMENTAL DETAILS

The constituent materials were selected, tested for some physical properties and proportioned before starting the key operations of the experimental investigation. The initial surface absorption, total porosity as well as the slump and the compressive strength of the high strength concrete heated at different temperatures were determined.

Selection and Testing of Materials

Locally available crushed limestone coarse aggregate, sand fine aggregate, ASTM Type I Portland cement produced in Jordan, Silica fume (ASTM C-494) and tap water were used in preparing the concrete mixtures. Tap water was also used in curing the specimens and for conducting various tests. The materials were tested to determine the physical properties required for mixture proportioning of concrete. Physical aggregate properties are presented in Table 1, the chemical composition and physical properties of the cement are given in Table 2.

Concrete Mix Proportioning

High Strength Concrete (HSC) was designed with a water-cement ratio of 0.35. The mixture was designed based on the absolute volumes of the constituent materials in saturated surface-dry condition, but the proportions of materials were obtained on weight basis. In order to facilitate the batching process, the aggregates were used in air-dry condition and, therefore, extra water was required to account for absorption during mixing. Consequently, the proportions of coarse aggregate, fine aggregate and water were adjusted. The details of adjusted mixture proportions are shown in Table 3.

Table (3): Mixture proportions of concrete

Cement (kg/m ³)	500
Sand (kg/m ³)	1220
Gravel (kg/m ³)	1450
Silicate fume (kg/m ³)	50
Water (l)	175
Superplasticizer (%)	0.03

Mixing and Casting Details

Concretes were mixed in "Little Benford TIP-UP" concrete mixer. The coarse and fine aggregates were weighed and placed into the concrete mixer moistened in advance and mixed for 3 minutes with the addition of saturation water for 3 minutes with the addition of cement and silica fume. The superplasticizer was then

mixed thoroughly with the mixing water and added into the mixer. Fresh concrete was cast in cubic steel moulds (100 x 100 x 100 mm) and compacted on a vibrating table. After demolding at one day, specimens were cured in lime saturated water for 28 days (ASTM, 2003). Then, they were stored in the laboratory at 20 ± 2 °C and $60 \pm 5\%$ of relative humidity until the time of the experiment. The specimens were 90 days old at the time of conducting the tests.

Fire Exposure

To determine the effects of high temperatures on concrete properties, cubic specimens were exposed to six target temperatures, namely; 105, 250, 500, 750, 1050 and 1250 °C by using an electric furnace (Carbolite, Fig. 2) having a heating capacity of 2100 °C at a rate of 10 °C/min to target temperature. For each target temperature, the target temperature is maintained for the duration of 1 hour. Six specimens were used for each temperature and they were allowed to cool in air to the room temperature for 24 hours. After cooling, tests were performed to determine their residual physical and mechanical properties. The data obtained were compared with the results obtained for the control specimens which were stored at 20 ± 2 °C in the laboratory.

Image Acquisition and Processing

Surface Contrast Enhancement. The objective of the contrast enhancement was to produce a surface where the cracks in the concrete are collared black while the remaining phases (cement paste and aggregate) were tinted light grey. This contrast allows to clearly distinguish between the portions of the sample that are cracks and those that are non-cracks in the scanned image. The steps used in this study were as follows:

1. The surface of specimens was carefully polished with an adhesive backed fine grit fixed silicon-carbon paper. Polishing residues were removed by using a brush and by blowing with compressed air. This step is done in order to eliminate all irregularity and to obtain a smooth surface.

2. With a painting brush, a thick layer of black ink was carefully deposed on the smooth surface to ensure that all cracks were filled with ink and then left to dry.
3. After the ink dried, the concrete surface is cautiously cleaned with a cloth soaked in solvent ink to reduce the black level of the smooth surface that takes the colour grey to light brown while cracks stay black. Specimens are then ready to be scanned.

Digital Image Collection

A high resolution flatbed scanner was used for image acquisition. Images of the specimens were collected at 9600 x 9600 dpi (equivalent to a pixel resolution of 2.5 x 2.5 micron). Specimens were placed on a sheet of paper in which six square windows of 40 x 40 mm were pierced. This sheet of paper protects the glass surface of the scanner and provides landmarks around specimens for possible measures. Up to six specimens may be scanned together. Figure 3 gives a typical image of concrete heated at different temperatures.

Digital Image Processing

Digitized images (JPEG format) were stored in a computer and then analyzed via an image treatment software. The computer used was a laptop equipped with a processor Core 2 Duo 1.6GHz and running under windows, Vista Home edition. The software used for image processing was the JASC Paint Shop Pro version 7.04. The captured images were first encoded in grey scale then the function of histogram adjustment was used to enhance the black level. Finally, the images were segmented in two colours; black that represents cracks and white (Fig. 4) that represents the solid phase, and then the crack density was computed.

RESULTS AND DISCUSSION

Cracks' Density

Information on the density and the distribution of

cracks is useful in determining the minimum exposure temperature. Figure 5 shows the degree of cracking in connection to the temperature increase. Crack density is given in units of mm of crack length per cm^2 . Each point is an average of the crack length measured in 20 different squares of 40 mm x 40 mm. According to

Figure 5, the crack density increases strongly with temperature beyond 500 °C. The value of crack density at 1050 °C is 45 times greater than the reference, and at 1250 °C the value of crack density is 106 times greater than the crack density of unheated concrete.

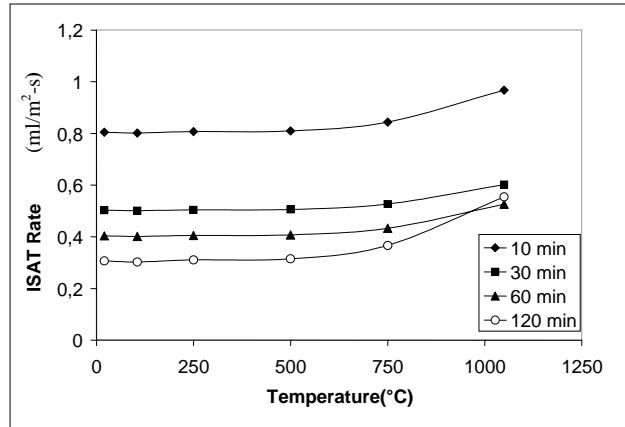


Figure (7): ISAT rate versus heating temperature

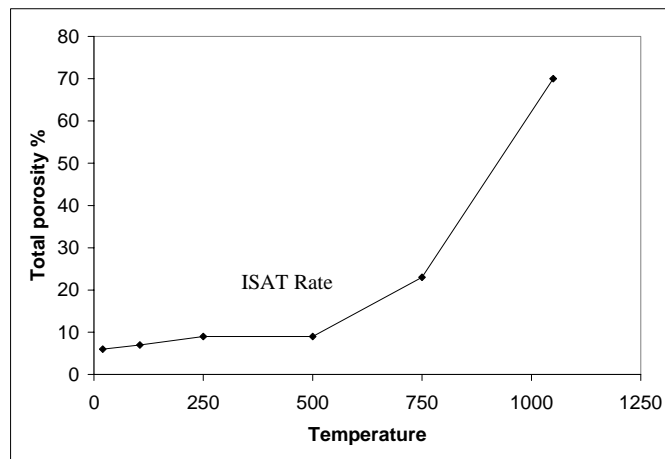


Figure (8): Total porosity versus temperature

Compression Test

The compression test was carried out according to ASTM C109 standard in order to determine the residual relative compressive strength of heated in comparison to reference concrete specimens. The ultimate strength of reference concrete at 28 days was 63 MPa. Figure 6

shows the results of this test.

From Figure 6, it can be seen that the compressive strength loss of HSC drops with temperature starting from 250°C. The retained compressive strength at 500 °C is 90% compared to the unfired strength, while after 750°C the strength is 40%. The compressive strength

value drops sharply to 0.4% after 1250°C compared to that of unfired specimens

Initial Surface Absorption Test (ISAT)

Initial surface absorption rate of water by concrete is the rate of flow of water into concrete per unit area at a stated interval from the start of the test at a constant applied head and temperature. The initial rate of absorption test was conducted on the concrete cube specimens based on the procedure laid in BS 1881: Part 5. The rates of absorption of water at 10, 30, 60 and 120 minutes from the start of the test were noted. The results of this test are presented in Figure 7.

For all testing intervals, the ISAT rate increases with the increase of heating temperature. This has proven the damage caused by high temperature in concrete specimens. The noticeable ISAT rate fast increase is for temperatures beyond 500°C. At these temperatures, concrete surface cracks are more visible.

Total Porosity

The porosity of concrete is an important characteristic which characterizes the durability of the concrete. High porosity is detrimental to the strength and permeability of concrete, particularly in cracked concretes. To determine the porosity of hardened concrete according to ASTM C642, the following properties need to be reported:

- Bulk density (dry);
- Bulk density (after immersion);
- Bulk density (after immersion and boiling);
- Absorption (after immersion);
- Absorption (after immersion and boiling);
- Volume of permeable voids evaluated by using the following formula:

$$P = \frac{1 - y_1}{y} \times 100 \quad (1)$$

where P = total porosity of concrete (%);

y_1 = concrete bulk dry specific gravity;

y = concrete apparent specific gravity.

Total porosity data (%) are summarized in Figure 8.

In general, up to 500 °C, the total porosity increases slightly and linearly (Eq. 2) with the heating temperature, and then a significant increase in porosity was observed. After heating at 500 °C, the increase of the total porosity follows a power law (Eq. 3) confirming a material degradation that can have an effect on the mechanical properties. In particular, with reference to undamaged concrete, the porosity values increased to three times with an exposure to 750 °C and to ten times at 1050 °C. At the temperature of 1250°C, concrete specimens were strongly cracked and the test was not possible.

$$P = 0.0131 \times T + 5.6929 \quad (R^2 = 0.99) \quad T \leq 500^\circ\text{C} \quad (2)$$

$$P = 1.3978 \times e^{0.0037 \times T} \quad (R^2 = 1.00) \quad T \geq 500^\circ\text{C} \quad (3)$$

CONCLUSIONS

Image processing was largely used as a new technique to investigate concrete properties as hydration degree and air voids. In this paper, this technique was used to evaluate the cracks' density in damaged concrete by high temperatures. The obtained results show that by using a high resolution flat bed scanner, this technique may be inexpensively used to assess the surface cracks' density and furthermore in investigations to evaluate the maximum temperatures at which concrete was subjected and the damaged layer of concrete to be removed for eventual repairs.

The mechanical properties of concrete (as compressive strength) are largely affected by temperatures beyond 500°C. In the case of a real fire, where temperatures exceed 1000 °C, the remaining compressive strength values are very feeble and concrete structures need special attention in the repairing case if not totally demolished.

The initial surface absorption and the total porosity by boiling methods give a rapid and good indication on

the durability of fired concrete as well as the temperature to which the concrete was subjected and at which it was damaged.

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