Indian Journal of Engineering & Materials Sciences
Vol. 15, February 2008, pp. 23-28

Effect of elevated temperatures and time on compressive and tensile properties of concretes

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Received 19 February 2007; accepted 30 January 2008

In this study, the effects of temperature level and time on the mechanical behaviour of concrete have been investigated. The concrete mixtures are produced using two different water/cement (w/c) ratios: 0.4, and 0.6. 288 cube (100 × 100 × 100 mm) specimens are prepared from these concrete mixtures and cured at 28 days. After standard curing period, specimens are dried in a furnace at 105°C for 4 h. Then the specimens are kept in loboratory for 1 day before exposing to 300, 600 and 900°C for 1, 3, and 5 h. Then compressive strength and split tensile strength are determined. It is concluded that, compressive strength and split tensile strength of the specimens are reduced after the high temperature exposure. Compressive strength losses of tested concretes are reduced with increasing w/c ratio. Remarkable effect is occurred in first 3 h in terms of strength losses.

Keywords: Elevated temperatures, temperature level, time, mechanical properties, concrete.

Subjecting concrete to high temperature as in fire leads to loss in compressive strength, cracking and spalling of concrete. It causes reduction of the bond between the cement paste and the aggregates and progressive breakdown of cement gel structure and consequent loss in its load-bearing capacity, reduced durability, and increased tendency of drying shrinkage, structural cracking, and associated aggregate color changes[1,2].

Deterioration of concrete which is exposed to elevated temperature may be attributed to some mechanical and environmental factors. Mechanical factors can be indicated as the physiochemical changes in the cement paste and aggregate, thermal disparity between them. Environmental factors also can be stated as temperature level, heating rate, applied load and heating time[3].

Fire-damage of concrete usually starts with color change, cracking and spalling of the surface. The initial effects of a slow temperature rise in concrete may occur between 100 and 200°C. Evaporation of the free moisture occurs in these temperature levels. At 300°C strength reduction is in the range of 15-40%. At 550°C reduction in compressive strength would range 55-70% of its original value. Calcium hydroxide dehydration takes place after the 400-550°C exposure temperature[4,5]. Aggregates may also deteriorate at this temperature level. But some aggregates can be deteriorated even at lower temperature levels. For example, quartz expansion is occurred at a higher rate about 300°C exposure condition and expands steadily up to 573°C[4,6,7]. Upon heating of concrete above 300°C, its color can change from normal to pink (300-600°C) to whitish gray (600-900°C) and buff (900-1000°C)[4,6].

However, concrete is a poor conductor, when it is rapidly heated, a thermal gradient is developing between the outer and inner layers of concrete and cause cracking. Besides, high internal steam pressure may be built up during exposure to high temperatures and cause cracking. This pressure varies depending on the temperature level, heating rate and size of specimens. The pore pressure induces tensile stresses which generally exceeds the tensile strength of concrete. Thus, it causes dramatic type of cracking of concrete[8,9]. Here, the effects of temperature level and time on the mechanical properties of concretes have been investigated.

Experimental Procedure

In this study, an ordinary Portland cement (CEM I 42.5) with specific gravity of 3.13 and Blaine fineness of 367 m^2/kg was used as a cementitious material. The aggregates were crushed limestone with maximum

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size of 15 mm. They were separated into two different size fractions as 0/5 mm fine aggregate (FA), and 5/15 mm coarse aggregate (CA). Then they were recombined to a specified uniform grading during mixing. The blend consisted of 40% FA, and 60% CA by weight. The agregates conform to ASTM C33 aggregate grading standard. Saturated surface dry (SSD) specific gravities and water absorption capacities of aggregates are 2.65, 2.70 and 1.21%, 0.64% for FA, and CA, respectively. A naphthalene-based super plasticizer (SP) was used to achieve the required workability (slump value 100 mm ± 20 mm) of the concrete mixes. Concrete mixtures were prepared using two different w/c ratios: 0.4 and 0.6. Cement content of 350 kg/m^3 were used in all concrete mixtures. The proportioning and description of the concrete mixtures are summarized in Table 1. The fresh concrete mixtures were prepared in a 65 liter pan mixer. The sequence of mixing procedure was as follows: (i) the aggregates were placed in the mixer and dry mixed for two min; (ii) half of the water + SP was added to mixture and the mixer is run for two min; (iii) afterwards, cement and the remainder of water + SP were added to the mixer and the mixer was run for an additional two minutes. Total mixing time was 6 min for all concrete mixtures.

100 mm cube specimens were prepared for uniaxial compressive strength and split tensile strength tests. Immediately after mixing and casting of concretes, the cube molds were stored in the humidity room for 24 h at 95% relative humidity and 20°C temperature. Then the cube specimens were removed from the molds and cured in 20°C water for 28 days. At the end of the curing period, all specimens were dried at 105°C in a furnace for 4 h. Except for the control samples, specimens were exposed to three temperature conditions (300, 600 and 900°C) in a ceramic furnace after one day. The furnace was heated up to inner temperature level in order to reach the prescribed temperature levels. After that, the heat was applied for an additional 1, 3, and 5 h before the samples were allowed to cool naturally to room temperature. The compressive strength and split tensile strength tests were performed on four heated and twelve unheated cube specimens for each temperature level and each concrete mixture. One of the well known indirect tests in order to obtain the tensile strength of concrete is split tensile strength test. Cylinder and cube specimens can be used for this test. For cube specimens, this test was performed as Fig. 1.

Table 1—Mix proportions of the concrete mixtures for 1 m^3 concrete

Mixture	w/c ratio	Cement (kg)	Water (L)	Aggregate (kg)		SP (kg)
				CA	FA	
Mix1	0.40	350	140	1168	779	7.0
Mix2	0.60	350	210	1056	704	3.5

Results and Discussion

Residual compressive strength

The uniaxial compressive strengths of heated and unheated specimens are shown in Table 2. In addition, the effects of exposure time and temperature on relative compressive strengths are graphically given in Figs 2 and 3. The relative compressive strength is expressed as the ratio of compressive strength at elevated temperatures to corresponding compressive strength at unheated condition.

The results revealed that the compressive strengths of all tested specimens were decreased dramatically with increase in temperature up to 900°C. Especially, significant loss in compressive strength was observed after exposure to the temperatures of 600 and 900°C. This is consistent with the observations of the previous studies[10,11].

The strength loss of the concretes with w/c ratio of 0.40 and 0.60 were calculated as 8-4%, 28-18% and 65-52%, which were exposed to 300, 600 and 900°C for 1 h, respectively. It shows that heating to a temperature up to 300°C does not have significant effect on the compressive strength of concretes. With increase in temperature up to 900°C, about 50%

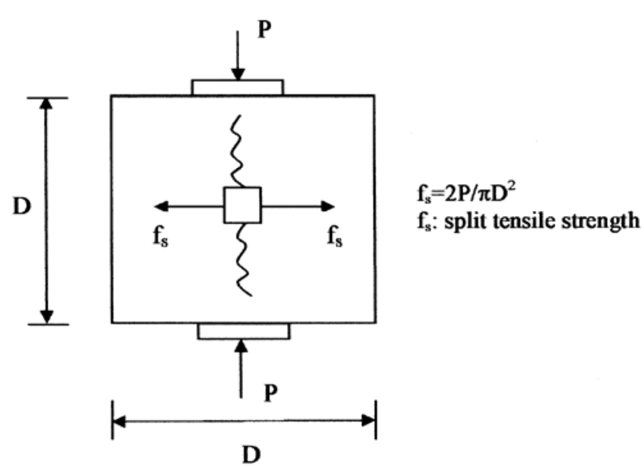

Fig. 1—Application of split tensile strength test on concrete cube specimen

Table 2—Experimental results of the specimens subjected to elevated temperatures

w/c ratio	Time, (h)	Average compressive strength after heat treatment (MPa)				
		20°C*	300°C**	600°C**	900°C**	Thermal resistance limit
	1	51.0	46.9	36.8	18.0	40.8
0.4	3	51.3	36.0	25.7	10.7	41.0
	5	50.9	35.3	23.8	6.8	40.7
	1	31.2	29.8	25.5	15.0	25.0
0.6	3	30.8	28.4	22.4	6.3	24.6
	5	30.9	26.2	20.9	5.4	24.7

w/c ratio	Time, (h)	Averege split tensile strength after heat treatment (MPa)				
		20°C*	300°C**	600°C**	900°C**	Thermal resistance limit
	1	4.89	3.75	2.90	1.87	3.91
0.4	3	4.87	3.19	2.40	0.63	3.90
	5	4.53	3.00	2.10	0.33	3.62
	1	3.26	2.67	1.80	0.93	2.61
0.6	3	3.23	2.20	1.47	0.37	2.58
	5	3.23	2.10	1.28	0.28	2.58

*Each value is the average of twelve specimens
**Each value is the average of four specimens

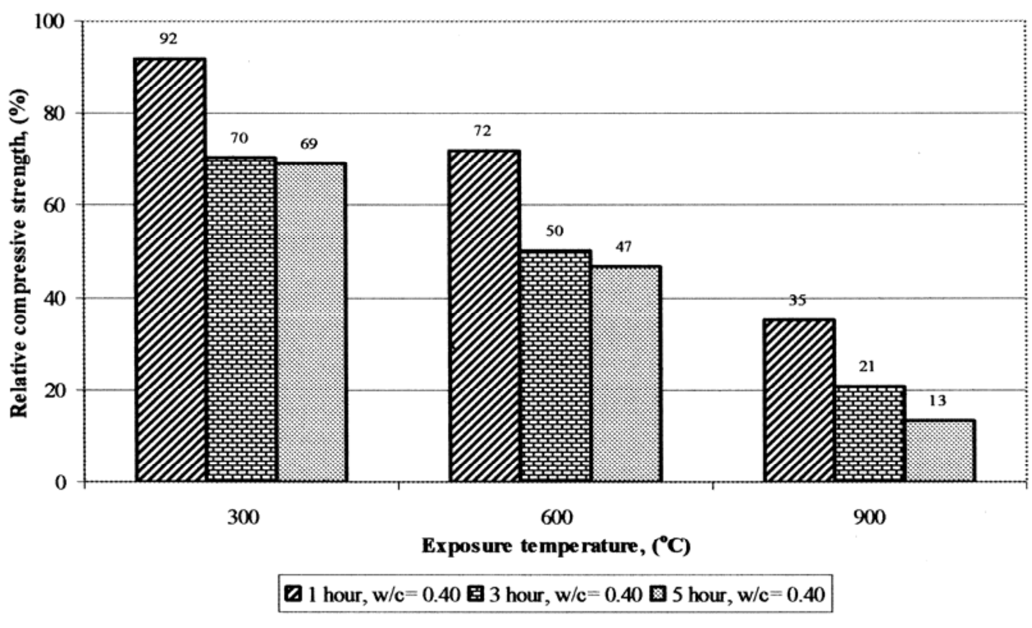

Fig. 2—Variation of relative compressive strength values for mixture with w/c=0.40

reduction in compressive strength was observed in heated specimen even at short exposure period.

The strength loss of the concretes with w/c ratio of 0.40 and 0.60 were evaluated between 30-8%, 50-27% and 79-80%, which were exposed to 300, 600 and 900°C for 3 h, respectively. Besides, under the same temperatures, 31-15%, 53-32% and 87-83% strength reductions were determined for 5 h exposures, respectively. Roughly same strength loss values were observed for 3 and 5 h temperature exposures. Consequently, increase in exposure time after 3 h have no significant effect on strength loss. 80% of compressive strength value at room temperature was used as the thermal resistance limit as recommended by Yeğinobalı *et al.*[12]. Thermal resistance limit is achieved at 300, 600 and 900°C as

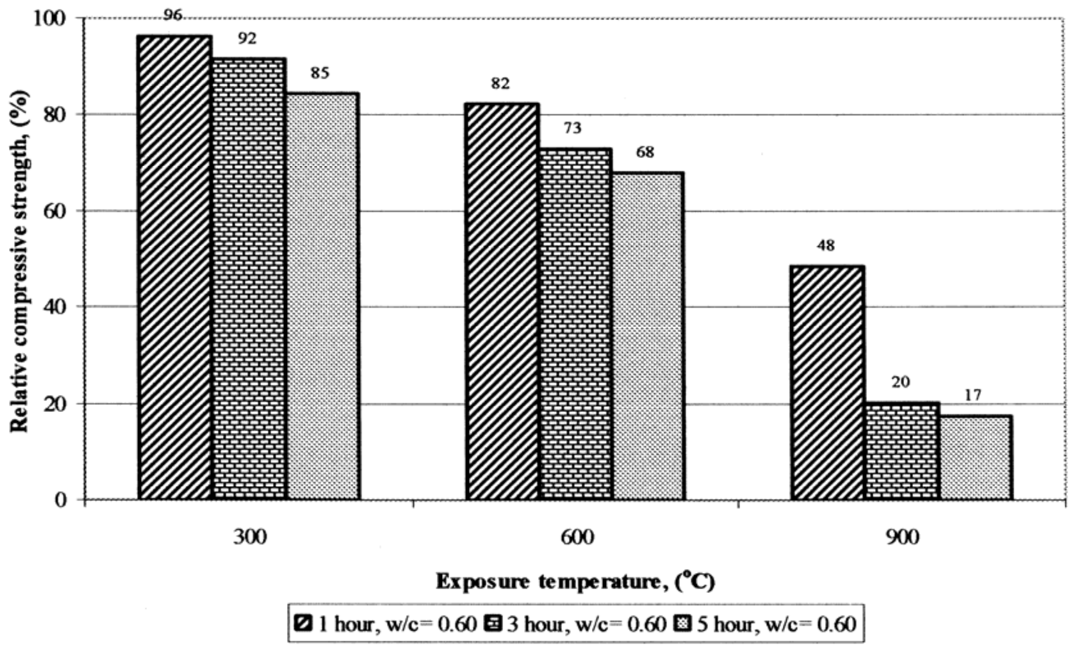

Fig. 3—Variation of relative compressive strength values for mixture with w/c=0.60

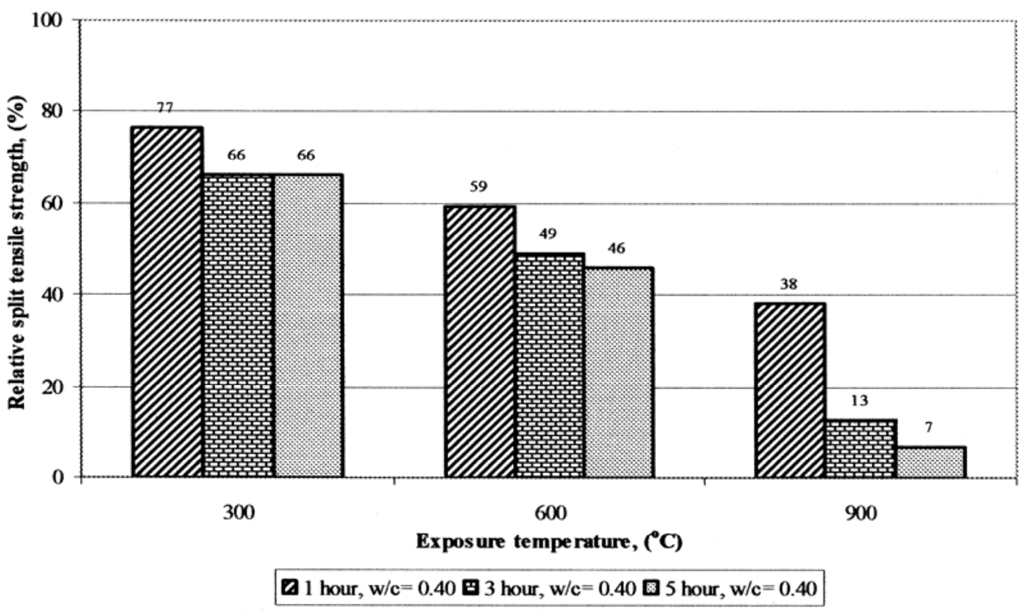

Fig. 4—Variation of relative split tensile strength values for mixture with w/c=0.40

46.9, 51.3 and 50.9 MPa for w/c of 0.40, respectively. In addition, the same limit is achieved at 300, 600 and 900°C as 25.5, 28.4 and 26.2 MPa for w/c of 0.60, respectively.

Reduction in compressive strength values of concretes with high w/c ratio were low compared to that of specimens with low w/c ratio. This can be attributed to the relatively more pores in high w/c ratio concrete mixture. These pores create a pathway for reduction of pore pressure. Besides, difference between strength reduction of high w/c ratio concrete and low w/c ratio concrete was higher at 300, 600°C than 900°C.

Residual tensile strength

The split tensile strengths of heated and unheated specimens are shown in Table 2. Also, the effects of exposure temperature and time on the relative split

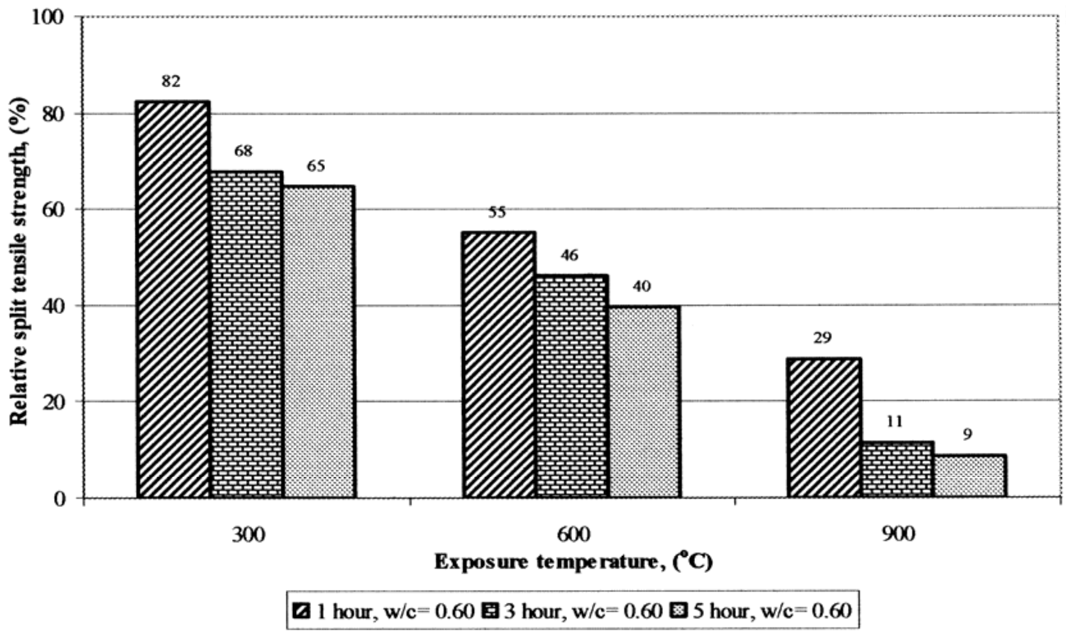

Fig. 5—Variation of relative split tensile strength values for mixture with w/c=0.60

tensile strength of concretes are illustrated in Figs 4 and 5. The relative tensile strength is expressed as the ratio of tensile strength at elevated temperatures to corresponding tensile strength at unheated condition.

It wasobseved that concretes with w/c ratio of 0.40-0.60 were lost 23-18%, 34-32% and 34-35% of their initial strengths after exposure to the temperature of 300°C for 1, 3 and 5 h, respectively. When temperature was elevated to 600°C, about 41-45%, 51-54% and 54-60% of the initial strength had been lost for 1, 3 and 5 h, respectively. With increase in temperature up to 900°C, the strength loss of the concretes was 62-71%, 87-83% and 93-91%. Roughly same tensile strength loss values were observed for 3 and 5 h temperature exposures as such in compressive strength values. Consequently, increase in exposure time after 3 h has not significant effect on strength loss.

Except for 300°C expose temperature for 1 h, in all temperature levels and exposure times, high strength losses were observed. Elevated temperatures affect the tensile strengths more than the compressive strength values. Besides, the rate of compressive strength losses was less than that of tensile strength losses at the elevated temperatures. This is due to the fact that tensile strength of concrete is more sensitive to cracks.[13,14]

Thermal resistance limits achieved at 300, 600 and 900°C are 4.89, 4.87 and 4.53 MPa for w/c ratio of 0.40, respectively. In addition, the same limits achieved at 300, 600 and 900°C are 2.67, 3.23 and 3.23 MPa for w/c ratio of 0.60, respectively. Split tensile strength of all specimens almost overcome thermal resistance limit at tested temperature of 300, 600 and 900°C.

Conclusions

The following conclusions can be drawn from this study:

(i) Heating to a temperature up to 300°C for 1 h did not have significant effect on the compressive and tensile strength of concrete. However, losses of compressive and tensile strength were observed at other temperature levels and exposure times.

(ii) Roughly same strength loss values were observed for 3 and 5 h temperature exposures either for compressive or split tensile strength. Consequently, increase in exposure time after 3 h had not significant effect on strength loss.

(iii) Elevated temperatures affect the tensile strength and rate of tensile strength loss more than that of compressive strength.

(iv) Reductions in compressive strength values of concretes with high w/c ratio were low compared to that of specimens with low w/c ratio.

(v) Regarding the thermal resistence limits, reasonable compressive strength loss of concretes with w/c ratio of 0.4 was occurred at 300°C for 1 h exposure. Beyond this temperature, strength losses are more serious. Reasonable compressive strength loss of concretes with w/c ratio of 0.6 was occurred at 600 °C. The corresponding temperature level for 3 and 5 h exposure times was 300°C.

(vi) Regarding the thermal resistence limits, reasonable split tensile strength loss was only observed in concretes with w/c ratio of 0.6 at 300°C for 1 h exposure. Tensile strength loss was serious for other temperature levels and times.

(vii) When temperature was elevated from 300 to 600°C, rate of strength loss was increased. Rate of strength loss was decreased between 600 and 900°C.

(viii) In terms of compressive strength, critical application temperature and time were observed as 300°C and 3 h respectively. In terms of split tensile strength, critical application temperature and time were observed to be below 300°C and 3 h in terms of split tensile strength, respectively.

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