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Microstructural examination of concrete exposed to elevated temperature by using plane polarized transmitted light method

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HIGHLIGHTS

- Microstructure of concrete exposed to high temperature was examined by PPTL method.
- The compressive strength decreased depending on increasing temperature.
- The aggregate–cement matrix adherence decreased depending on high temperature.
- The quartz aggregate was more affected from high temperature and cooling regime.

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ABSTRACT

In this study, the influence of elevated temperature on the residual compressive strength and ultrasonic wave velocity of the concrete specimens has been investigated. In addition, the effect of elevated temperature on the aggregate–cement paste interface and aggregate microstructure of the concrete specimens was also has been examined by plane polarized transmitted light (PPTL) method. Investigation was carried out by using one concrete mixture which was produced by normal Portland cement (PC), quartzitic natural sand and crushed basaltic coarse aggregate. The water–cement (w/c) ratio used in the mixtures was 0.50. The produced concrete specimens were exposed to 200, 400, 600, 800 and 1000 °C. Test results indicated that the residual compressive strength and ultrasonic wave velocity values of the concrete specimens decreased depending on increase in elevated temperature. In addition PPTL examinations showed that, increasing temperature caused weakening of the adherence of aggregate and cement matrix. Film layers and discontinuities observed in the aggregate–cement matrix depend on increasing temperature. Fast cooling (FC) method resulted in strength losses when compared to slow cooling (SC) method.

1. Introduction

Fire is one of the serious potential risks to most of the buildings and structures [1] Concrete construction materials offer good resistance to fire because they are incombustible (in comparison to wood) and have low thermal conductivity (in comparison to steel), however they suffer from a certain degree of strength loss [2,3]. Due to composite nature of concrete and different thermal characteristics of constituents, its performance is greatly affected by high temperature [4,5]. The type of aggregate and cement used in its composition, the porosity and moisture content of concrete, its thermal properties, and sizes of structure members and their construction type are the other factors that determine the level of fire resistivity of the material. An increase in the size of structural members increases fire resistance [6]. The extensive use of concrete as a structural material has led to the demand to fully understand the effect of fire on concrete [4].

When concrete is subjected to high temperatures, physical properties changes and chemical transformations take place resulting in deterioration of its mechanical properties [7–9]. The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced during these exposures [10]. The free water in the pores and some chemically bonded water in the hydrated cement paste are released and a large amount of energy is consumed, because of exposing high temperatures [11]. Free water evaporates at around 100 °C and is completely removed at 120 °C. Above approximately 150 °C, there is a loss of the water chemically bound in hydrated calcium silicate, with a peak rate of loss at 270 °C [11–13]. Because of the difference between the thermal expansion coefficients of the cement paste and aggregate, thermal stresses are induced between the expanding aggregate and shrinking cement paste. The induced stress results in breakdown of the interfacial bond between the aggregate

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and the surrounding cement paste, that results in strength loss of concrete specimens [14]. From 300 °C microcracks are induced through the material and mechanical strength and thermal conductivity are degraded at this stage with some associated expansion taking place [12,15]. Temperatures in the 550 °C range are critical because calcium hydroxide dehydration takes place. Aggregates also begin to deteriorate at about 550 °C [16]. This result causes the shrinkage of concrete [10]. If the water is sprayed in order to extinguish fire in this stage, calcium oxide turns into calcium hydroxide and flows through the pores and forms white spots on the surface after the fire. This leads to a volume increase. During these processes, some cracks occur and concrete is crumbled and becomes porous material [17,18]. C–S–H gel decomposes further, and spalling behavior is observed above 600 °C. At 800 °C, concrete is usually crumbled and the cement paste is transformed into a glass phase above 1150 °C [12,13]. As a result, severe microstructural changes occur and some deterioration is observed in strength and durability properties of concrete.

Not only the cement paste, but also the aggregates suffer from physicochemical degradations [3]. Because of aggregates represent a considerable proportion of volume in the concrete, the type and properties of aggregate also play an important role on the properties of concrete exposed to elevated temperatures. The aggregate selection is important, since various types of aggregates exhibit different resistances to elevated temperatures. According to their mineralogical composition and their internal microstructure, it is quite likely that aggregates have very different values of thermal conductivities. For instance, thermal conductivity values of quartz, limestone and basalt aggregates are about 5.17, 2.95 and 2.66 W/mK, respectively. The thermal conductivity of aggregates influences the thermal conductivity of concrete [19,20].

The use of ultrasonic wave velocity for assessment of concrete residual strength is one of the nondestructive testing concrete after exposure to high temperatures [8]. Ultrasonic wave propagation speed in a material depends on the porosity of that material; therefore it depends on the density and elastic properties [21]. While the compactness and density of concrete decreases, the ultrasonic wave velocity and strength of concrete decreases together [22,23]. In addition the ultrasonic wave velocity values of the concrete decrease depending on increasing exposure temperature [8,15,24].

Plane polarized transmitted light (PPTL) method is one of the microscopical examinations to use determining fire damage of concrete. In this method, thin-section specimens are prepared through which light will pass to allow microscopical observation. Thin-sections are examined in PPTL method using a high quality, medium to high-power petrological microscope at magnifications typically up to 600× [2].

The aim of the present research is to investigate the effect of elevated temperature on the residual compressive strength and ultrasonic wave velocity of the concrete specimens and examine the aggregate–cement paste interface and microstructures of the aggregates of concrete specimens exposed to elevated temperatures by using PPLT method.

2. Materials

Ordinary Portland cement CEM I 42.5 R (PC) conforming to requirements of TS EN 197-1 [25] was used for concrete mixture preparing. The specific surface area of PC measured with Blaine method was 3150 cm^2/g, and the specific weight of the PC was 3.13 g/cm^3. The initial and final setting times of the cement were 156 and 201 min, respectively. The 28-day cube compressive strength of PC according to TS EN 196-1 [26] was 52.7 MPa. The chemical oxide composition of PC is presented in Table 1.

Table 1
Chemical properties of PC.

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
PC	19.87	4.62	3.11	62.45	2.23	2.78	0.72	0.45	3.69

Table 2
Aggregate grading with standard limit.

Sieve size (mm)	Passed (%)			
	TS 706 EN 12620+A1 lower limit	TS 706 EN 12620+A1 medium limit	TS 706 EN 12620+A1 upper limit	Aggregate used
31.5	100	100	100	100.0
22.4	98	99	100	100.0
16	85	92	99	94.0
11.2	68	79	90	74.0
8	48	63	77	55.7
4	33	49	64	40.0
2	22	37	52	26.4
1	15	28	41	20.3
0.5	10	20	30	14.2
0.25	6	13	20	8.1
0.15	3	7	11	5.0
0.063	1	3	5	2.0

Uncrushed, quartzitic natural sand with maximum size of 4 mm and crushed basaltic coarse aggregate with maximum size of 16 mm in accordance with TS 706 EN 12620+A1 [27] were used in the mixture. The specific weights of fine and coarse aggregates at saturated surface dry condition were 2.45 g/cm^3 and 2.57 g/cm^3, respectively. The water absorption values of fine and coarse aggregates were 2.5% and 2.0%, respectively. The grading of aggregates is presented in Table 2 with the standard specification.

Polycarboxylic ether based superplasticizer (SP) according to TS EN 934-2 [28] was incorporated in the concrete mixture to improve workability. The specific weight of superplasticizer was 1.043 g/cm^3.

3. Mixture properties and testing methods

Mixture design was made with according to absolute volume method given by TS 802 [29]. The water–cement (w/c) ratio used in mixtures was 0.50. Cement content was kept constant for per cubic meter, 400 kg/m^3. The approximate air content of fresh concrete mixture was 2% estimated by TS 802 [29] using total aggregate granulometry. After the volume of total aggregate was determined, weights of aggregate were calculated by using unit weight of aggregates. Approximate concrete composition for concrete mixture of a cubic meter is given in Table 3.

Cubic specimens with 71 × 71 × 71 mm dimensions were cast and de-molded after 24 h and then cured in lime saturated water at 20 ± 2 °C for 28 days. In this investigation, cubic specimens with 71 × 71 × 71 mm dimensions were used, since most appropriate area to obtain thin sections was typically 75 × 50 mm [2]. The specimens were left in the oven under temperature of 105 °C at 24 h before exposure to elevated temperatures in order to dry the specimens completely. The specimens were placed in an electric furnace (maximum temperature of 1400 °C) in which temperature was increased to 200, 400, 600, 800 and 1000 °C. The heat

Table 3
Approximate concrete mix design for a cubic meter.

PC concrete	
Portland cement (kg/m^3)	400
Quartzitic natural sand 0/4 (kg/m^3)	655
Basaltic coarse aggregate 4/16 (kg/m^3)	983
Water (kg/m^3)	200
Superplasticizer (kg/m^3)	2
w/c	0.5
Slump (mm)	110
Air content (%)	2