Pergamon

Compressive strength–color change relation in mortars at high temperature

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Abstract

Changes in materials' physical, chemical and mechanical properties have to be known to decide whether the buildings exposed to high-temperature effect will be repaired or demolished. In order to carry out the effects of fire and extinguishing on the properties of concrete, mortars with and without silica fume were exposed to different temperatures, such as 100, 200, 300, 600, 900 and 1200 °C, and cooled slowly in the air and fast in water in two groups. Flexural and compressive-strength tests were performed on the samples which were cooled up to room temperature and changes in color were determined by using the Munsell Color System. High temperature has caused damages in mechanical properties of mortars with or without silica fume, especially samples which were cooled in water, which showed significant decrease in mechanical strengths at 600 °C. In this study, it was observed that the changes in color's hue component and the compressive strength have similarities. Test results show that residual color changes in mortar can give an idea about the effect of high temperatures on the mechanical properties of mortar during a fire.
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1. Introduction

When reinforced concrete is subjected to high temperatures, compressive strength and elastic modulus of concrete, yield stress, ductility and tensile stress of steel decrease. As a result, the bond between them decreases [1,2].

Because concrete is an important material, which protects steel from high temperature, the behavior of concrete and mortar must be well known. Although there are different approaches to explain the occurrences, causing loss of compressing strength when exposed to high temperature, the problem in forming a model is investigated by taking thermal incompatibility between cement paste and aggregate, contact between aggregate and cement paste interface, the pressure of evaporated water during heating, and chemical structure changes in cement paste and aggregates into consideration [3].

Shrinkage caused by evaporation of water and steam pressure occurring in concrete causes cover concrete to crack and break off. As a result of the destruction of concrete, steel contacts with hot gas at the beginning of fire. $Ca(OH)_2$, one of the most important compounds in cement paste, turns into CaO at 530 °C. During this process, an almost 33% shrinkage happens. When the water is sprayed in order to extinguish fire, CaO turns into $Ca(OH)_2$ and flows through the pores and forms white spots on the surface after the fire. This leads to a volume increase of 44%. During these processes, some cracks occur and concrete is crumbled and becomes porous material [4]. It is clearly seen that extinguishing is an important factor.

Aggregate's effect on concrete at high temperatures is related to their mineral structures. Quartz in siliceous aggregates changes polymorphically at 570 °C and quartz α turns into quartz β. This process results in volume increase and damage [5]. In limestone aggregates, $CaCO_3$ turns into CaO at 800–900 °C, and expands with temperature. Shrinkage starts with the decomposition of CO_2 into CaO. During this process, volume changes cause destructions [6]. Aggregate's mineral structure is an important factor in damage ratio in concretes exposed to high temperature.

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Nowadays, in order to get the different properties expected from the concrete, pozzolan materials, such as slag, fly ash, silica fume, etc., and additives are used. Silica fume, which is a product of Ferro silica and silica metal industry, fills the pores in cement paste and interface between cement paste and aggregate, and decreases permeability of concrete [7]. The effect of silica fume used to produce high-performance concrete exposed to high temperatures is being researched in different aspects [8–11].

In experimental studies, it is observed that when concrete is exposed to high temperatures, some changes in color occur [12,13]. In previous studies, it has been mentioned, especially for concretes produced with siliceous aggregates, that if the residual color is pink or red, it indicates that the temperature is raised up to 300–600 °C; if it is gray, it shows that temperature is raised up to 600–900 °C. When the temperature reaches 600 and 800 °C, concrete loses 50% and 80% of its strength, respectively, which gives an idea about which temperature the concrete was exposed to by determining its color [14]. According to Short et al. [13], the actual colors observed depend on the types of aggregate used to make the concrete and it might be better to only analyze the mortar matrix. As a result, concrete strength can be predicted according to the surface color.

The visual determination of surface color is carried out by color-appearance systems. One of the most widely used systems is the Munsell Color System. In this system, the attributes hue, value and chroma of color are divided into equal perceptual intervals and denoted through the use of decimals. Hue is the dimension which distinguishes one color family from another, as red from yellow, or green from blue. All the hues are arranged in a circle and indicated with the numbers between 1 and 100. The hue circle is divided into five principal hues, which are perceived in equal intervals; red (5 or 5R), yellow (25 or 5Y), green (45 or 5G), blue (65 or 5B) and purple (85 or 5P). Five intermediate hues are also designated in the Munsell System as yellow-red (15 or 5YR), green-yellow (35 or 5GY), blue-green (55 or 5BG), purple-blue (75 or 5PB) and red-purple (95 or 5RP). Each of the 10 hues is then subdivided into 10 hues and in this way, a system based on decimals is designed. Value, the second quality of color, indicates the lightness of a color, and there are 10 main steps in the value scale. Absolute white and absolute black are given the notations 10 and 0, respectively. Intermediate grays are given notations ranging between 10 and 0. Every hue can be constituted in different values. Chroma, the third attribute of color, can be defined as the degree of departure of a color from a grey having the same Munsell value, expressed on a scale extending from 0 for neutral samples, by steps of approximately equal visual importance, to about 20 for the strongest colored specimens producible. Thus, an ultimate limit for chroma cannot be set. The highest chromas achieved depend on the hue and the Munsell value of the samples [15–17].

By taking all the explanations above into consideration, before deciding whether a building exposed to high tem-

perature is to be demolished or to be repaired, the actual situation of the building should be well examined. For this, destructive and nondestructive test methods are used [18]. The aim of the present study is to investigate the effect of silica fume usage and the type of cooling regime on mortar's strength and color under high-temperature effect.

2. Experimental procedure

In this study, effects of high temperature and cooling regime on physical and mechanical properties of normal and silica fume replaced mortars were studied. Experimental study was carried out in three steps, as sample production, heating and cooling processes, and tests on physical and mechanical properties. Four main groups of mortars were produced. These are control mortars (PC), mortars with silica fume (PC + SF), mortars cooled in air (PC-A) and (PC + SF-A), and mortars cooled in water (PC-W) and (PC + SF-W). For each of these groups, effect of temperature at 100, 200, 300, 600, 900 and 1200 °C was investigated and the samples at 20 °C were considered as control samples. For each temperature, three prismatic samples of $40 \times 40 \times 160$ mm, 78 in total, were produced. For production of samples, sand with silica of maximum aggregate size of 2.0 mm, density of 1.47 g/cm^3 and specific gravity of 2.3 g/cm^3, ordinary Portland cement, silica fume and water reducer admixture was used. Cement and silica fume properties are reported in Table 1.

An ordinary Portland cement, siliceous sand according to the Rilem guidelines and silica fume was used for the mortar mixtures. The sand/cement was 3, and water/cementitious material was 0.5. Silica fume was replaced in 10% of the cement by mass for the PC + SF mortars. Test specimens were demolded 24 h after production and stored in lime-

Table 1
Chemical analyses and physical properties of Portland cement and silica fume

	Portland cement	Silica fume
Chemical composition (%)		
Loss on ignition	1.42	2.37
SiO$_2$ (soluble)	20.60	90.54
Al$_2$O$_3$	6.14	0.89
Fe$_2$O$_3$	3.72	0.61
CaO	63.65	1.60
MgO	1.29	0.76
SO$_3$	2.55	1.16
Specific weight (g/cm^3)	3.05	2.11
Specific surface (cm^2/g)	3204	–
Setting time (min)		
Initial	110	–
Final	215	–
Mineralogical components (%)		
C$_3$S	40.18	–
C$_2$S	28.83	–
C$_3$A	9.98	–
C$_4$AF	11.32	–

Table 2
The color components and mechanical test results of the specimens prior to high-temperature exposure

Mortar type	Compressive strength (MPa)	Flexural strength (MPa)	Hue	Value	Chroma
PC	30.25	6.32	25	4	1.25
PC + SF	34.30	7.96	25	4	1

saturated water at 20 ± 2 °C for 27 days. On the 28th day, the strengths of the control group were determined by flexural and compressive-strength tests. The six remaining groups of samples removed from water were dried up to fix the weight in oven at 105 °C, and then three samples from each group were placed in a furnace having a heating rate of 6–10 °C/min in such a way that all the surfaces of the samples would be heated, and then heated up to mentioned temperatures without loading. When the furnace reached the expected temperature, all the samples were taken out and cooled.

Cooling was performed in two groups where it was slow in air and fast in water. For cooling in air, samples were taken out from the furnace and placed on bagets so that all surfaces of samples could contact with air and cooled down to room temperature. For cooling in water, samples were placed in test tubs containing standing water at room temperature, and as the water in the test tub was heated, another test tub was used and samples were cooled down to room temperature [10]. After the cooling process, mechanical tests were performed and color changes were determined visually by using the Munsell Book of Color. Visual determination/evaluation using a Book of Color should be realized by an observer whose color matching ability is nearly equal to the CIE (International Commission on Illumination) standard colorimetric observer. In this study, color measurements were conducted by an observer having the mentioned ability. The samples and the glossy color chips in the Munsell Book of Color are compared on a middle gray background considering the appropriate angular relationship between light source, samples/color chips, and observing direction. In order to compare the color changes and strengths, compressive and flexural-strength tests were

performed on the same samples. Flexural-strength test was carried out on three $40 \times 40 \times 160$ mm prismatic specimens, whereas compressive-strength test was carried out on six pieces of prisms. The results obtained from the experiments are given in Table 2 and Figs. 1–4. Relative values shown in figures are determined by dividing the test results of the specimens exposed to high temperature into the control samples.

3. Results and discussion

Serious changes were observed in mortars' mechanical properties and color components under high-temperature effect. Silica fume usage and cooling regime has also effected this change. According to the flexural-strength results, in normal mortars, n increase of up to 100 °C and a decrease after 200 °C were observed according to the initial value. For example, at 600 °C, mostly known as critical temperature, 40% strength loss in PC-A group of normal mortars (Fig. 1 and 70% strength loss in PC-W groups (Fig. 2) were observed. Initial strength (20 °C) in silica-fume-added mortars was 20% higher than normal mortars (Table 2), and it was constant up to 100 °C. After this temperature, a decrease in strength was observed. At 600 °C, the strength of silica-fume-added PC + SF-A and PC + SF-W groups decreased 50% and 70% according to the initial values, respectively (Figs. 3 and 4). These losses in flexural strength show the occurrence of micro- and macro-cracks in concrete due to the decrease of tensile strength with high temperature. During the inspection of fire-damaged buildings, ultrasonic pulse velocity, which gives an idea about porosity, should be measured besides compressive strength. Chan et al. [11] also show that the changes in pore structure could be used to indicate the degradation of mechanical properties of high-performance concrete subjected to high temperature.

Test results show that decreases in compressive strength started at 600 and 300 °C for PC-A and PC-W groups of normal mortars, respectively (Figs. 1 and 2). Strength losses
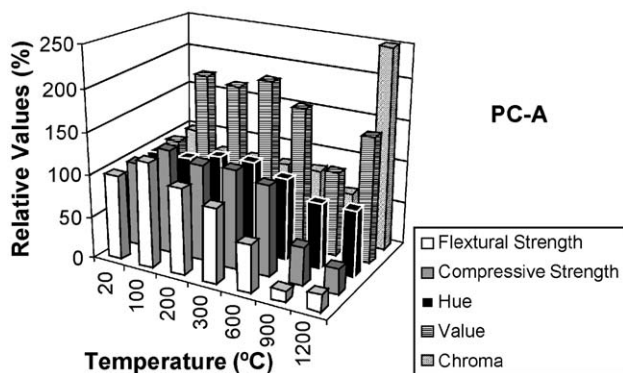

Fig. 1. Relation between strength and color change in air-cooled specimens under high-temperature effect.
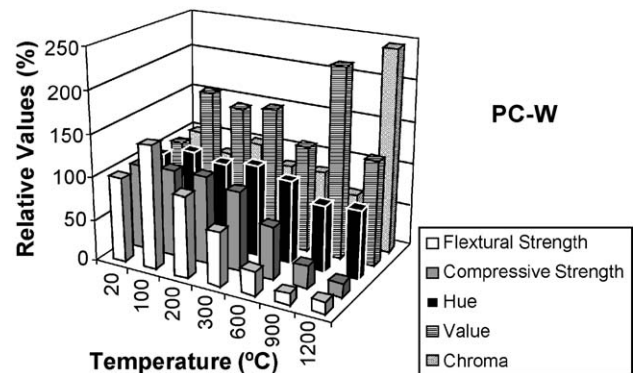

Fig. 2. Relation between strength and color change in water-cooled specimens under high-temperature effect.

of these mortars at 900 °C are 55% for PC-A and 75% for PC-W groups. Mortars with silica fume, such as PC + SF-A groups, had an increase in compressive strength of up to 600 °C and a decrease started after this temperature. Strength loss at 900 °C is about 65% (Fig. 3). There are no significant changes in PC + SF-W groups until 300 °C, but at 900 °C, 75% strength loss was observed (Fig. 4). According to the test results, there are no significant changes at 1200 °C compared with 900 °C. Water cooling caused more decrease in strength compared with air cooling. Similar results were obtained in a study performed by Luo et al. [19] by observing the compressive strength and the variation of pore structure of concrete.

Before the high-temperature effect, as seen in Table 2, the hue component of all samples is yellow—25 (5Y), value is medium dark—4, chroma is very weak, and is 1.25 for PC and 1 for PC + SF, respectively.

For all groups, when the temperature increased from 20 to 600 °C, the hue of color changed a little from yellow into greenish yellow, at 600 °C again, yellow—25 (5Y), when increased from 600 to 1200 °C, it became reddish yellow. The change in hue between 100 and 300 °C is approximately 2.5 steps and at 1200 °C, 5.5 steps. The relative values of the change in color's hue component are given in Figs. 1–4.

The value component of the color changes in great amounts according to the increase in temperature. The temperatures that correspond to the maximum and minimum values of this change show difference for mortar properties and cooling regime. For example, the temperatures that the maximum changes in value observed for PC-A is light at 300 °C—7.75, very light for PC-W—9 at 900 °C, very light for PC + SF-A—9 at 900 °C, middle dark for PC + SF-W—6.25 at 200 °C. The maximum and minimum changes in value are 4 steps and 0.75 steps, respectively. The relative values of the change in color's value component are given in Figs. 1–4.

When the chroma component, whose relative values are given in Figs. 1–4, is examined, the change is very low in all groups from 20 to 900 °C. The maximum and minimum change for these temperatures is 0.5 steps, but there occurs a
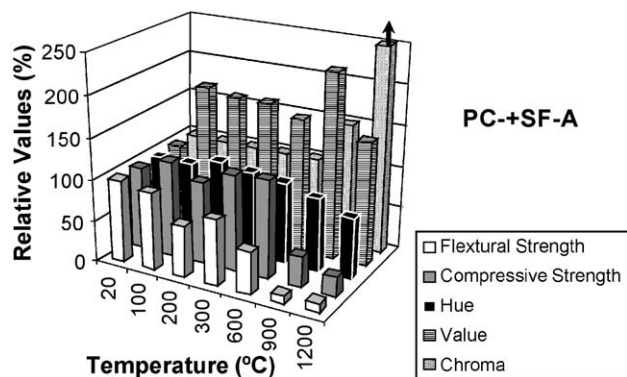

Fig. 3. Relation between strength and color change in air-cooled specimens with silica fume under high-temperature effect.
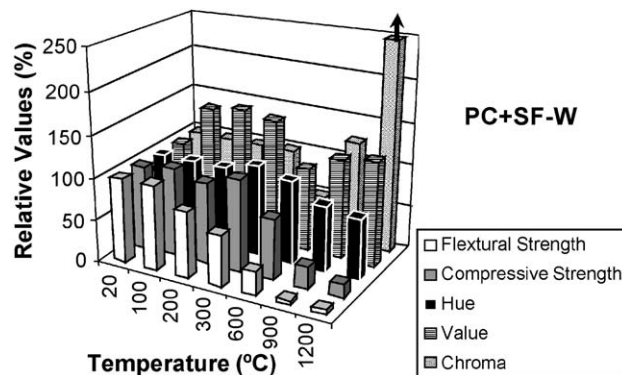

Fig. 4. Relation between strength and color change in water-cooled specimens with silica fume under high-temperature effect.

bigger increase at 1200 °C. The average value of chroma is 3.5 at 1200 °C.

The change in concrete's flexural and compressive strength according to temperature showed similarities with the changes in hue components of color. This similarity is also valid for the silica-fume-added samples and different types of cooling regime. It can be said that in buildings damaged by fire, by examining the color of concrete surface and evaluating the hue component, we can have some ideas about the change in concrete strength.

4. Conclusions

According to the test results, effects of high temperature and cooling regime on strength and color of mortar are given below:

(1) Compressive strength does not change up to 300 °C in all groups. The strengths of specimens with and without silica fume cooled in water and air decreased above 300 and 600 °C, respectively. Critical temperature is 300 °C for the strength loss of mortars. Losses are more rapid after this temperature. The loss in compressive strength for mortar with silica fume is more than normal mortars above 600 °C.

(2) Flexural strength decreased in all groups starting from 100 °C and the loss in water-cooled groups was observed as 40% at 300 °C. Thus, it is not enough to evaluate only concrete's compressive strength under the effect of high temperatures.

(3) Cooling in water has more harmful effects compared to cooling in air. Therefore, instead of water, alternative extinguishers should be used, but their effects on concrete must be examined.

(4) Color changes were observed on concrete surface under the effect of high temperature. These changes may give an idea about the temperature that concrete was exposed to. This result is valid for the samples with silica fume and different cooling regimes.

(5) Strength loss can be determined by drilling cores out of concrete specimens exposed to high temperature and color changes can be examined to have an idea about the depth of the concrete exposed to high temperature.

Acknowledgements

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