Reducing High Temperature Effect on Concrete by Changing Concrete Mixture

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***Abstract*—Mechanical properties of concrete decrease when subjected to high temperatures. It is desired to reduce concrete surface temperature when it is subjected to high temperature. In this study, different proportions of glass beads (10%, 20%, 30%) and blast furnace slag (+10%, +20%, -10%, -20%) were added into C30/37 strength class concrete samples to reduce the concrete surface temperature when it is subjected to 3000 ℃ flame for a short time. Mechanical properties of concrete samples were also measured. It was determined that lower surface temperatures can be obtained by regulating concrete mixture with optimum proportions of glass beads and blast furnace slag when the concrete is subjected to high temperature. In this study, the easy, cheap and time consuming test is also presented to find the better concrete mixture when subjected to high temperature.**

***Index Terms*—glass bead, blast furnace slag, high temperature, concrete**

I. INTRODUCTION

Many cases of fires taking place in buildings, tunnels and drilling platform structures. During a fire, the temperature may reach up to 1100 ℃ in buildings and even up to 1350 ℃ in tunnels, leading to severe damage in concrete structure [1]. Concrete generally provides the best fire resistance properties of any building material [2]. This is due to its low thermal conductivity, high heat capacity and slower strength degradation with temperature. This slow rate of heat transfer and strength loss enables concrete to protect itself from fire damage. The behavior of a concrete structural member exposed to fire is dependent on thermal, mechanical and deformation properties of concrete. These properties vary as a function of temperature and depend on the composition characteristics of concrete. Although concrete has a high resistance to fire, its mechanical properties decrease when subjected to high temperatures. When concrete is heated under conditions of fire, significant temperature gradients are observed between the concrete surface and the deeper layers. The surface temperature becomes significantly higher than the inner parts. High temperature damages concrete structure and alterations of its physical, thermal and mechanical properties occur. As temperature is increased, the water on the surface of concrete and the capillary water is lost, and this process is accelerated by the reduced cohesive forces between water molecules due to water expansion [3]. When temperature increases beyond 400 ℃, the concrete strength decreases rapidly due to the degradation of calcium–silica–hydrate (C–S–H) [3]. At a temperature of 900 ℃, the C–S–H breaks down completely. Therefore, the critical temperature for concrete ranges from approximately 400 to 900 ℃. In this range concrete loses most of its strength [4].

Fire resistance of structural members used to be evaluated mainly through standard fire tests [5]. In recent years, the use of numerical methods for the calculation of the fire resistance of structural members is gaining acceptance because of their cheaper and time consuming properties [6]. In this study, different range of proportions of glass beads (10%, 20%, 30%) and blast furnace slag (+10%, +20%, -10%, -20%) were added into the C30/37 strength class concrete samples. The mechanical properties of the mixtures were examined. The temperatures of top and bottom surfaces of these mixtures measured after heating the concrete under about 3000 ℃ flame for a short time. These easy and time consuming test results evaluated with the help of studies in literature.

II. CONCRETE UNDER HIGH TEMPERATURE

Aggregates normally occupy 50–75 % of the volume in concrete, therefore, the behavior at elevated temperatures is strongly influenced by the type and properties of the aggregate used [4]. The term “thermal stability of aggregates” is employed to describe aggregate effect on concrete performance at high temperatures [7]. The suitable aggregate for a concrete under high temperature is the one with a low thermal strains coefficient as well as negligible residual strains. Mineralogical composition determines aggregate thermal strains, since all minerals differ in their thermal expansion properties. The type of minerals governs the chemical and physical changes that take place during heating.

The heating of cement paste results in drying. Water gradually evaporates from the material. Free water evaporates first, then capillary water and finally physically bound water. The process of removing water that is chemically bound with cement hydrates is the last to be initiated. Evaporation of water between C-S-H gel sheets strongly affects the mechanical properties of the cement paste [8].

Concrete expands during heating. The heating of concrete makes its aggregate volume grow and at the

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same time it causes the counteraction of the cement paste which surrounds it. As a result, cement paste-aggregate bond is the weakest point in heated cementitious material. Figure 1 is an example of thermally damaged concrete, which is made of silico-calcareous aggregates and heated to 600°C [9]. The SEM photo shows cracks crossing the cement paste and proceeding through the interfacial transition zone. Also cracks passing through siliceous aggregate are present.

The main factor dominating the extent of concrete expansion is the mineralogical character of the aggregate. For example concrete containing basalt aggregate has a lower thermal expansion coefficient than concrete containing calcareous aggregate. Thermally stable aggregates with low thermal expansion are favorable for the reasons of durability in fire conditions.

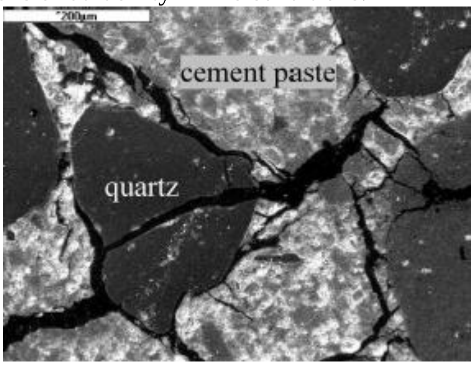

Figure 1. The microstructure of concrete heated to 600 ℃.

Spalling is defined as the breaking up of layers (pieces) of concrete from the surface of a concrete member when it is exposed to high and rapidly rising temperature. The spalling of concrete is one of the more interesting phenomenon occurring in conditions of fire. The literature describes it both from the experimental [10], [11] and the theoretical side [12]. The mechanisms of spalling of concrete at high temperature can be explained from vapor pressure in pores and thermal stresses [13]. When the concrete is heated due to thermal gradient, the inner part of concrete becomes cooler than the surface and the vapor is condensed. Saturated layer is gradually formed with the accumulation of the condensed water and the spalling process starts. If the tensile stress of concrete could not resist the pore pressure, spalling of concrete would occur [14]. As it is seen from the explanation of spalling, the main reason that induces the process is concrete surface high temperature. It is needed to reduce this temperature to avoid harmful effect of spalling.

A. Supplementary Cementing Materials

The incorporation of pulverised fly ash (PFA) and slag in Portland cement can generally remain the mechanical properties of concrete at a higher level after heating to high temperature up to 900 ℃ and 1050 ℃, respectively [15]. Portland cement blended with PFA and slag also exhibits a high resistance to spalling at high temperatures [16], [17]. Karakurt and Topcu [18] determined that thermal cracking did not ocur in PFA and slag blending samples and that the degradation of C-S-H decreased compared to PC sample by using SEM analysis. Besides, the incorporation of slag significantly reduces the amount of portlandite in PC so that decreasing the degradation of porlandite at high temperatures [19]. As a result of these aspects, the total porosity and the average pore diameter of PCs blended PFA and slag are smaller than those of PC at high temperatures [16]. The higher resistance of PCs blended PFA and slag to high temperature can be explained by this result.

B. Mixture Design and Mechanical Properties of Concrete

Eight different types of mixtures were designed to study the effects of glass bead (10%, 20%, 30% proportions by total weight of aggregate) and blast furnace slag (BFS) (+10%, +20%, -10%, -20% proportions by weight of cement) on compressive strength of the concrete. One of these mixtures was a control mixture and the glass bead used in this study was smaller than 1 mm in size. All coarse and fine aggregates were limestone in control mix design. Fine aggregates are more effective in thermal conductivity than coarse aggregates. Due to this reason, glass beads which are used for road marking and which have a density of 1.6 gr/cm ^{3}(Figure 2) were used as a fine aggregate to obtain lower surface temperatures in this study.

Figure 2. Glass beads used as a fine aggregate.

Chemical properties of glass bead, blast furnace slag and cement used in this study are in Table 1.

TABLE I. CHEMICAL PROPERTIES OF GLASS BEAD AND CEMENT

Oxide	Glass Bead	Blast Furnace Slag	Cement
SiO_2 (%)	69.80	34.2	20.81
Al_2O_3 (%)	1.45	10.31	5.41
CaO (%)	9.52	35.73	62.3
MgO (%)	4.20	10.84	0.97
Fe_2O_3 (%)	0.15	0.52	3.72
K_2O (%)	0.72	-	0.28
Na_2O (%)	13.85	-	0.15

If the difference of coefficient of thermal expansion (CTE) between coarse aggregate and hydraulic cement paste becomes too large, a breakage of the bond between coarse aggregate particles and the surrounding paste may cause due to the differential movements. Aggregates used in this study were limestone and Portland-limestone cement (PLC) CEM II/A-LL 42.5 N was used in all mixtures to prevent the breakage of the bond between coarse aggregate and the cement.

The mixtures were named using the percentage of recycled glass and BFS in concrete mixtures. For example G10 represents the concrete mixture that consists of %10 proportion of glass bead by total weight of aggregate. BFS (+20) represents the concrete mixture that consists of +%20 proportions of BFS by total weight of cement added to total cement. BFS (-20) represents the concrete mixture that consists of +%20 proportion of BFS by total weight of cement replaced with same amount of cement. Mixture designs and compressive strengths of eight different types of concrete after 28 days are in Table II. It was desired to get at least 37MPa at the end of 28 days to obtain C30/37 strength class concrete. It was determined that all mixture designs used in this study met the compressive strength requirement of C30/37 type of concrete, except G30 mixture.

TABLE II. MIXTURE DESIGNS AND COMPRESSIVE STRENGTHS OF SAMPLES

Mixtures	Cement PLC 42.5 (Kg)	Water (lt)	BFS (Kg)	Recycled glass (Kg)	0-5 mm fine aggregate (Kg)	7-15 mm coarse aggregate (Kg)	15-25 coarse aggregate (Kg)	Admixture (gr)	28 day Comp. Strength (MPa)
Standard Mixture	3	1.86	-	-	9.49	4.66	4.3	0.036	48.06
G10	3	1.86	-	1.85	7.64	4.66	4.3	0.0036	42.48
G20	3	1.86	-	3.69	5.80	4.66	4.3	0.0036	39.67
G30	3	1.86	-	5.54	3.95	4.66	4.3	0.0036	36.53
BFS(+10)	3	1.86	0.3	-	9.49	4.66	4.3	0.0036	51.04
BFS(+20)	3	1.86	0.6	-	9.49	4.66	4.3	0.0036	51.42
BFS(-10)	2.7	1.86	0.3	-	9.49	4.66	4.3	0.0036	50.11
BFS(-20)	2.4	1.86	0.6	-	9.49	4.66	4.3	0.0036	49.22

C. *ASR Measurements*

Thermal expansion and contraction behavior of concrete varies primarily with aggregate type, cementitious material content, w/c ratio, temperature range, concrete age, and ambient relative humidity, and of these factors, aggre- gate type was found to have the greatest influence on the expansion and contraction of concrete [20]. In a temperature range from 100 to 1000°C, the coefficient of thermal expansion decreases with increasing porosity of aggregates, therefore, a lower expan- sion is observed in concretes with lightweight (porous) aggregate in comparison to those that contain normal weight aggregates [21].

Under high temperature, the strength of cement pastes is reduced due to dehydration and decomposition. This in turn reduces the stress threshold for crack generation and propagation. These cracks generate new surfaces that are directly exposed to high temperatures, hence the temperature gradient may significantly change and the cracking deterio- ration could accelerate [4].

The potential ASR expansion of the prepared mortar bars (25x25x285 mm) with a water to cement ratio of 0.47 was assessed in accordance with ASTM C1260. Seven series of mortar bars were prepared in total. In these series, different proportions (10-20-30%) of glass bead and blast furnace slag were prepared with control mixture. The test period was 14 days. ASR expansion need to meet the requirements prescribed in ASTM C1260 (<0.1% within 14 days). Some mixture proportions of mortar bars are in Table III. It was observed that all glass bead and blast furnace slag proportions used in this study were able to meet the ASR expansion requirements.

TABLE III. MIXTURE PROPORTIONS OF MORTAR BARS

Mixtures with glass bead proport.	Cement (gr)	Water (gr)	Fine aggregate (gr)	Glass bead (gr)
Control mixture	440	207	990	-
10%	440	207	900	90
20%	440	207	800	200
30%	440	207	600	300

D. *Surface Temperatures*

All eight mixtures were heated by a flame, which was about 3000℃, from 10 cm distance for 15 seconds. Concrete samples with 3.5 cm in thick were prepared for all these mixtures. The heated top surface and unheated bottom surface temperatures were measured. The aim of this test was to get lower top surface temperatures and lower surface temperature differences. Figure 3 shows the process of heating and measuring the surface temperatures.

Figure 3. Measuring heated concrete surface temperature.

Table IV represents the surface measurements of top and bottom surfaces of samples after heating by a flame. It was determined that using glass bead or blast furnace slag, significantly affects concrete surface temperature and temperature differences of both sides. In this study glass beads used in the mixture with proportion of %10, 20, 30 reduced top surface temperature from 52.4°C to 38.3°C, 37°C and 36.2°C respectively. The surface temperature difference decreased from 15.8°C to 3.0°C by using %30 proportion of glass bead. Blast furnace slag in the mixture with proportion of %+10, +20, -10, -20 reduced top surface temperature from 52.4°C to 44.7°C, 40.2°C, 42.3°C and 51.5°C respectively. The surface temperature difference decreased from 15.8°C to 8.2°C by using %+20 proportion of blast furnace slag. Spalling occurred for all mixtures during heating process. The size of the spalling decreased with the reduced surface temperature. G30 mixture doesn't meet the compressive strength requirement of C30/37 type of concrete. Due to this reason, G20 mixture with a 3.6°C surface temperature difference is the best alternative against high temperature for the mixtures used in this study.

TABLE IV. TOP AND BOTTOM SURFACE TEMPERATURES

Mixtures	Top surface temperature (℃)	Bottom surface temperature (℃)	Surface temperature difference (℃)
Standard Mixture	52.4	36.6	15.8
G10	38.3	30.0	8.3
G20	37.0	33.4	3.6
G30	36.2	33.2	3.0
BFS(+10)	44.7	30.2	14.5
BFS(+20)	40.2	32.0	8.2
BFS(-10)	42.3	33.5	8.8
BFS(-20)	51.5	33.3	18.2

III. CONCLUSION

The first concern of this study was to obtain lower surface temperature when the concrete is subjected to a very high temperature. There are some methods in literature to evaluate the concrete response to high temperature. The easy, cheap and time consuming test would be better to compare different mixtures under high temperature. Due to this reason, an alternative method was used to determine the effects of using glass bead or blast furnace slag on concrete surface temperature after heating procedure. The effect of blast furnace slag was as expected from studies in the literature. Using blast furnace slag reduces heated surface temperature and adding it to existing cement or replacing it with the cement, gives different results for surface temperatures. Using glass bead in concrete for fire resistance hasn't been searched before. It was obtained that concrete with glass bead in its mixture design is very effective under high temperature. Besides spalling, thermal cracks which occur by big surface temperature differences are also important problems for the concretes. It was obtained that using %20 proportion of glass bead in concrete is desirable when compared with other mixtures used in this study after examining compressive strength measurements, top and bottom surface temperature differences after heating concrete by a flame. Standard mixture heated surface temperature was measured 52.4°C while heated surface temperature of G20 was measured 37°C under same condition. The top and bottom surface temperature difference was 15.8°C for standard mixture while this difference was 3.6°C for G20 mixture under same condition. G20 type of concrete mixture is a good alternative to be used in tunnels where fire can take place. This type of mixture can also be used as a concrete road to decrease temperature gradients which cause thermal cracks on road.

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