Proceedings of the 5th International Conference on Civil Engineering for Sustainable Development (ICCESD 2020), 7~9 February 2020, KUET, Khulna, Bangladesh (ISBN-978-984-34-8764-3)

PERFORMANCE OF CONCRETE UNDER ELEVATED TEMPERATURE

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ABSTRACT

In this study, the variation of different mechanical properties of high strength concrete at elevated temperatures was investigated. The mechanical properties such as compressive strength and splitting tensile strength under different temperatures (200°C, 400°C and 600°C) were determined following three various cooling conditions (immediately after heating i.e. no cooling, 24 hours cooling and water cooling). Concrete cylindrical specimens (100 mm dia. and 200 mm height) were prepared by maintaining a mix ratio of 1:1.8:1.95 among binder, Fine Aggregate, Coarse Aggregate and with water to cement ratio of 0.4. After completing 28 days of curing period, the compressive and tensile strength of 6 nos. of specimens were tested at room temperature (32°C) and rest of them were heated in a laboratory furnace for 1 hour at 200°C, 400°C, 600°C temperature, following 3 hours of preheating at 105±5°C temperature. After that, the strength tests of the heated specimens were completed at the three different cooling conditions. Compressive and tensile strengths were found as 44.7 MPa and 4.04 MPa respectively at room temperature. From the results of this study, it was observed that no remarkable changes in compressive and tensile strengths of concrete were observed between 200°C and 400°C heating temperature. Whereas, gradual decrease in the mechanical properties were found at 200°C and rapid reduction was observed after 400°C due to explosive spalling. Maximum reduction in compressive and tensile strengths were observed as 55.5% and 63.6% respectively at 600°C for testing after water cooling condition when compared to the controlled specimens. Moreover, the tensile strength of concrete decreased more promptly than compressive strength after 400°C temperature.

Keywords: High strength concrete, Compressive strength, Tensile strength, Elevated temperature.

1. INTRODUCTION

Concrete is the most widely used construction material in the world. The main functional elements of concrete are cementing medium, fine aggregate, and coarse aggregate. Based on the strength requirements, there are mainly two types of concrete, such as, normal strength concrete (NSC) and high strength concrete (HSC). According to American Concrete Institute (ACI 363R, 1997), concrete having 28 days compressive strength above 41 MPa, can be considered as HSC. The demand of high strength concrete is increasing day by day as the performance (in terms of strength and durability) of high strength concrete is superior than NSC (Neville & Brooks, 2010). Fire accident in concrete structures has become one of the most unavoidable hazards in the world. Though it is thought that high strength concrete has a good fire resistance, its exposure to fire affects badly the mechanical properties (Malhotra, 1956; Neville, 2012). In the past, extensive investigations have been conducted to examine the behavior of NSC exposed to fire (Lea, 1920; Kim, Han, & Song, 2002; Shoukry, William, Downie, & Riad, 2011); however, very limited studies are found regarding brick aggregate based HSC.

Earlier at 20th century, Lea (1922) outlined in a review report that concrete prepared with ground brick and cement, gain strength up to 650°C heating temperature. Chan, Peng, & Chan (1996) carry out an extensive research regarding compressive and tensile strength of HSC in comparison with NSC. Fire exposure for the samples were varied from 400°C to 1200°C. Finally, it was found that the strength reduction of HSC occurred with a higher rate than NSC. Similar trend regarding calcareous aggregate based HSC and NSC was observed from the experiment conducted by Noumowe, Clastres, Debicki, & Costaz (1996). Again, the effect of high temperatures and cooling regimes on regarding high performance concrete (HPC) and NSC, was investigated (Chan, Luo, & Sun 2000). In that case, rapid cooling caused more strength loss than gradual cooling.

Husem (2006) had examined the variation of flexural and compressive strength of high-performance micro-concrete (HPMC) and ordinary micro-concrete (OMC) at elevated temperatures following different cooling regimes. The results showed that rapid reduction in flexural and compressive strength was observed at 200°C when compared to the reference specimens. After 600°C heating temperature, both the strengths decreased, showing a little increasing trend between 200° and 400°C. Moreover, Bastami, Chaboki-Khiabani, Baghbadrani, & Kordi (2011), examined the performance of HSC, prepared with varying water to cement ratio, fine aggregate ratio and silica fume ratio under elevated temperature exposure. Most of the researches were regarding limestone aggregate based concrete.

In the recent years, several fire incidents, are frequently occurring in Bangladesh due to various reasons. Most of them broke out in industries, factories, shopping complexes, residential buildings, etc., which not only caused significant loss of valuable lives, livelihoods, and equipment but also seriously affected the structures. Moreover, burning was not the only reason behind the life loss as well as injury. In fact, the structural failure of the building was also responsible for the life loss (Wadud, Huda, & Ahmed, 2014). On the other hand, the structure is required to be rebuilt or repaired to allow the structure functional again after a fire incident has happened. In that case, it is required to investigate the residual capacity of the structure after being exposed to fire hazard. Being a major construction material of reinforced concrete structures, the residual capacity of concrete at high temperatures, can give a very important indication about the structural strength. So, it is required to investigate the residual capacity of the structure. Besides, brick aggregate is one of the most commonly used coarse aggregate for concrete in Bangladesh. Furthermore, a few research works are available on HSC with brick aggregate as coarse aggregate. Thus, the objectives of this study are to determine the mechanical properties (compressive strength and tensile strength) of HSC after being heated to high temperatures (200°C, 400°C and 600°C) and to compare the effect of different cooling regimes on the residual strength of HSC with respect to the strength at room temperature.

2. EXPERIMENTAL PROGRAM

2.1 Materials and Mix Proportions

Portland Cement Composite (PCC) confirming to ASTM C595/C595M as a binder material, coarse sand as fine aggregate (FA), 19 mm downgrade 1st class brick aggregate as coarse aggregate (CA) were used to prepare the concrete mix. The material properties of the binder and aggregates are tested in the laboratory according to ASTM standard procedure and tabulated in Table 1 below. The mix ratio among binder, FA and CA was 1 : 1.8 : 1.95, maintained to prepare the test specimens.

Table 1: Material Properties of binder and aggregate

Materials	Properties	Unit	Value	Test Standards
Binder (PCC)	Initial Setting Time	min	170	ASTM C191
	Final Setting Time	min	295	ASTM C191
Fine Aggregate (Coarse Sand)	Specific Gravity (SSD)	-	2.44	ASTM C128
	Absorption	%	2.4	ASTM C127
	Fineness Modulus	-	2.91	ASTM C136
	Unit Weight	Kg/m³	1605	ASTM C29
Coarse Aggregate (Brick Aggregate)	Absorption	%	13.7	ASTM C127
	Unit Weight	Kg/m³	1130	ASTM C29

2.2 Preparation of Concrete Specimens and Curing

70 nos. of cylindrical specimens (100 mm diameter and 200 mm height) were cast using the mix ratio. For each batch of mixing, slump test was performed and the value was recorded 80 ~ 90 mm. The top surface of the specimens was finished with 1 (cement): 1 (fine sand) rich mortar mix by using a straight edge before reaching to initial set. Then the samples were placed at a moist place to avoid the unexpected surface moisture loss. After 24 hours, the samples were demolded and placed in a curing chamber to promote the hydration process. The samples were cured for 28 days.

2.3 Heating

After completion of the curing period the samples were removed from the chamber and kept in air to drying up the surface water. A preliminary drying process was carried out for 3 hours at a temperature of 105±5°C in an electric oven as shown in figure 1 below. Preheating was necessary to reduce the internal water content of the specimens.

(a) (b) (c)

Figure 1: (a) Specimens placed in the oven for preheating, (b) Electric oven for preheating, (c) Specimen after preheating in oven at

After that the samples were placed in a laboratory furnace for heating the samples at 200°C, 400°C and 600°C temperature following the ASTM E 119 standard time-temperature curve. The maximum heating capacity of the furnace was 1200°C temperature. The samples were heated for 1 hour after being reached to the desired temperature.

(a) (b)

Figure 2: (a) Placement of the specimens in the furnace, (b) Furnace during heating process

2.4 Test Methods

The Compressive and splitting tensile strength tests were carried out according to ASTM C 39 and ASTM C496 respectively. Both of the tests were performed in a Compression Testing Machine with a capacity of 1000 kN. After completing the heating of the specimens, compressive and splitting tensile strength tests were performed for three different cooling conditions. The cooling conditions were: (i) No cooling (i.e., test immediately after heating), (ii) water cooling and (iii) cooling for 24 hours after heating. The compressive and tensile strength of the controlled specimens were also determined at room temperature. Three samples were tested to get the average experimental results.

Figure 3: (a) Compressive strength test, (b) Tensile strength test

3. RESULTS & DISCUSSION

3.1 Compressive strength at different elevated temperature

The test results of compressive strength of concrete specimens at room temperature and several exposed temperatures (200°C, 400°C and 600°C), based on three separate cooling conditions, are presented in figure 4. At ambient temperature the average compressive strength of concrete specimens was found to be 44.7 MPa. The compressive strength decreased rapidly with increasing temperature up to 200°C. No remarkable change was observed between 200°C and 400°C temperature for the specimens tested after 24 hours of heating and immediately after heating. This slow decreasing rate attributed to the removal of crystalline water from the samples (Lie, 1992). After 400°C rapid reduction in the concrete compressive strength occurred for all the cooling conditions. The minimum compressive strength was found to be 24.47, 23.05 and 19.08 MPa for the test after 24 hours of heating, immediately after heating and water cooling respectively. However, spalling, especially explosive spalling is the major reason behind the strength reduction of high strength concrete. Spalling of concrete from surface of the cylindrical specimens were noticed at 600°C heating temperature. In high strength concrete, less amount of pore spaces exists inside due to high density. So, there is less scope for vapor pressure to escape from concrete when subjected to high temperatures, causing explosive spalling of concrete and accordingly the compressive strength of concrete may also decrease (Chan et al., 2000).

The test results show that compressive strength reduction rate is affected by the cooling conditions considered in this study. The maximum reduction was found for the specimens tested after water cooling as the water spray on heated specimens caused cracking and crumbling of concrete due to conversion of calcium oxide to calcium hydroxide (Arioz, 2007). However, there is a slight reduction of concrete compressive strength for the test immediately after heating than that of for the test after 24 hours of heating, which may occur due to the partial recovery of concrete strength.

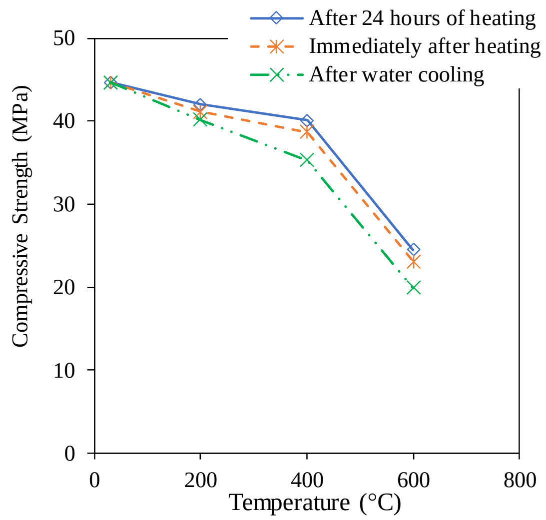

Figure 4: Compressive strength at different elevated temperatures

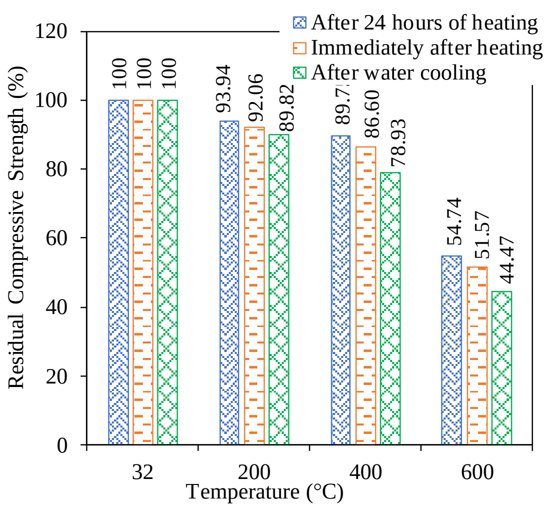

Figure 5: Residual compressive strength at different elevated temperatures

In figure 5 the relative residual compressive strengths as a percentage of average strength obtained by testing control specimens, were presented against various high temperatures, for different cooling conditions. About 7~10% of compressive strength reduction was observed at 200°C. Subsequently, showing a little decrease at 400°C temperature, the compressive strength rapidly decreased when the samples were heated at 600°C. At 600°C temperature, maximum of 45.26%, 48.43% and 55.53% strength reduction were observed with respect to the control specimen for the test after 24 hours of heating, immediately after heating and after water cooling respectively. Similar trend with little different reduction in compressive strength were obtain from Chan, Peng, & Anson (1999), Husem (2006).

3.2 Splitting Tensile Strength at Different Elevated Temperature

The splitting tensile strength test was performed for all of the test conditions and the average results of the specimens are presented in figure 6 below. From the figure, it can be shown that the slope of the tensile strength vs temperature curve showed distinct nature with increasing temperature which behaves similar to the trend followed by compressive strength. A significant decrease in the tensile strength observed when the specimens were exposed to temperature between 400°C and 600°C. The maximum tensile strength was found to be 4.04 MPa at ambient temperature and the minimum tensile strength was found to be 1.47 MPa for the test after water cooling and 1.65 MPa for the test immediately after heating. Moreover, due to regain of strength after 24 hours of cooling phase the tensile strength was found to be 1.88 MPa. All the minimum values of tensile strength were observed at the maximum temperature 600°C.

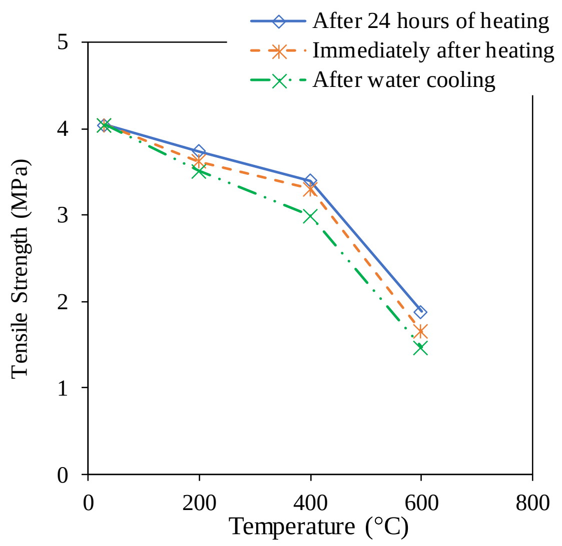

Figure 6: Tensile strength at different elevated temperatures

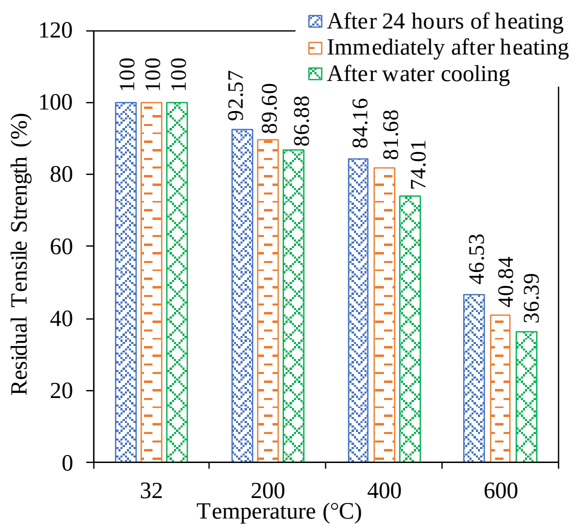

Figure 7: Residual tensile strength at different elevated temperatures

The relative residual tensile strength of concrete was calculated as the percentage strength of unheated specimens and presented in figure 7. The residual tensile strengths of concrete with respect to the control specimens were obtained as 46.53%, 40.84% and 36.39% for the specimens tested after 24 hours of heating, immediately after heating and after water cooling respectively at 600°C temperature. Among these three cooling conditions, maximum tensile strength reduction of 63.61% was occurred due to water cooling of the samples.

The splitting tensile strength to compressive strength ratio at different elevated temperatures are shown in Figure 8. The tensile strength to compressive strength ratio of concrete remained almost identical up to 400°C heating temperature. But in case of heating the samples at 600°C temperature, the ratio was 15.0%, 20.8% and 18.3% lower than that of control specimens for three different cooling conditions respectively. The observations showed that the tensile strength decreased more promptly than compressive strength. Hence, the concrete strength depends on the load resisting area of concrete which decreased with increasing crack in concrete. Besides, the cracks approaching closer when subjected to compressive load and contrarily, they become more prominent under tensile load. Therefore, the effect of crack coalescence in concrete is more pernicious to tensile strength (Behnood and Ghandehari 2009; Peng *et al*. 2006; Chen 2007).

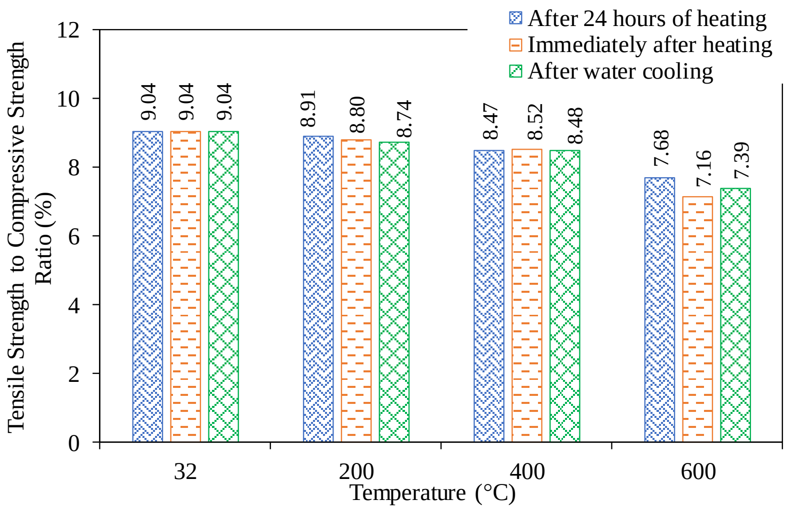

Figure 8: Ratio of splitting tensile strength to compressive strength of concretes at different temperatures

4. CONCLUSION

In this study the different mechanical properties of high strength concrete at high temperatures (200°C, 400°C, 600°C) were determined and the following conclusions may be outlined from the experimental results:

- The average compressive and tensile strength of HSC were found to be decreased with increasing temperature. The decreasing rate was not significant between 200°C and 400°C temperature.
- A severe strength reduction as well as explosive spalling of the concrete specimens were observed at 600°C exposure temperature.
- Relative strength reduction at different elevated temperatures are affected by the cooling conditions. When the samples were subjected to the peak temperature of 600°C, the residual compressive strength of HSC relative to the control specimen dropped to approximately 54.74%, 51.57% and 44.47% for after 24 hours cooling process, immediately after heating and after water cooling respectively.
- Moreover, the residual tensile strength of HSC relative to the control specimen dropped to approximately 46.53%, 40.84% and 36.39% for the three different cooling conditions respectively.
- Therefore, the rate of decrease in both the mechanical properties of HSC is maximum for the specimens tested after rapid water cooling following the high temperature exposure.
- Tensile strength is more sensitive to high temperature than compressive strength. Thus, the rate of decrease of compressive strength is higher than that of tensile strength at high temperature.

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