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Various Factors Influencing on Thermal Behaviors of High Strength Concrete (HSC) Columns under Fire

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Abstract

The objective of this study is to investigate behaviors of high strength concrete (HSC) columns at elevated temperatures including temperature distributions and spalling. Toward this goal, seven short HSC columns having different design parameters are fabricated and placed in a heating chamber for fire tests. The design parameters are cross sectional areas, cover thicknesses, and arrangements of reinforced bars. The columns are heated using temperature control system following ISO 834 time-temperature curve. Temperature distributions are obtained from temperature gauges located inside the columns during the fire tests, and the spalling depths of the columns are measured after the fire tests in order to examine loss of cross sectional area due to spalling. Experimental results show that the design parameters, such as cross sectional areas, cover thicknesses, and reinforcement arrangements, affect on the temperature distributions and spalling of HSC columns, and are important factors of fire safety design.

Keywords: Fire, high strength concrete, RC column, temperature distribution, spalling

1. Introduction

For many years, experimental studies have been performed in order to investigate the thermal and mechanical behaviors of High Strength Concrete (HSC) at elevated temperatures including spalling and pore pressure. Experimental studies reported by Kodur et al.(2003) and Kodur and Sultan(1998; 2003) reveal thermal material behaviors of high strength concrete at elevated temperature. From their studies,

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temperature dependent thermal material properties of HSC, such as conductivity, specific heat, thermal expansion and mass loss are examined. Experimental studies for the effect of elevated temperatures on behaviors of full scale HSC columns are reported by Kodur and McGrath(2003). During the fire tests, spalling and crack propagations that occurred at the columns were observed, and the time to failure was measured to quantify fire resistance of HSC columns. From their study, it is found that the fire resistance of HSC columns is lower than that of NSC columns. However, an HSC column is able to resist against fire for up to four hours if sufficient confinement is provided. For the tie configurations, 135° bent ties, cross ties, and the closer tie spacing show beneficial effects on the fire resistance of HSC columns. Later, Kodur and Phan(2007) examine the factors that influence the fire performance of HSC structural members. The factors are classified into three categories; fire, material and structural characteristics. Fire characteristics include fire intensity, fire size, heat output, and heating rate, while material characteristics include concrete strength, fiber reinforcement, and aggregate type. In structural characteristics, tie spacing, confinement, tie configuration, load levels, and size of the member are considered. Phan(2007) studies the effect of various factors on pore pressure build up and degradation of the mechanical material properties in normal and high strength concrete. These factors include water/cement ratios, curing conditions, heating rates, test methods, and polypropylene (PP) fibers. As a result of the experiments, HSC added with PP fiber shows a significant reduction in pore pressure, thus prevents explosive spalling in specimens. In addition, studies of process and causes of spalling are reported by Kalifa et al.(2000) and Phan et al.(2000), which reports that pore pressure is the main cause of the spalling.

The existing experimental studies have revealed thermal and mechanical behaviors including spalling of HSC at elevated temperatures. For further studies, this study aims at investigating the effect of various parameters on the temperature distributions and spalling of HSC columns at elevated temperatures. The parameters are cross sectional areas, cover thicknesses, and reinforcement arrangements of HSC columns. The columns are exposed to high temperatures following ISO time-temperature curve, and temperature distributions are measured from the thermocouples installed within the cross section of the columns. Spalling of the column is quantified by measuring depth of damaged surfaces at the end of the fire tests. The results from the experiment indicate that cross sectional areas, cover thicknesses, and reinforcement arrangements play important roles on the thermal behaviors of the HSC columns.

2. Experimental method

2.1. Tested specimens

The experimental study includes fire resistance tests on seven HSC columns. The lengths of the columns are 1500mm, while the cross sections of the column vary from 350×350mm to 550×550mm. The summary of specimens is listed in Table 1 and details of a specimen along with the locations of thermocouples are illustrated in Figure 1. All the specimens are fabricated to have same compressive strength, and the mixture ratios of the high strength concrete are listed in Table 2. Compressive tests are performed on cylindrical specimens in order to measure the material properties of the HSC. From the material tests, the 28-day compressive strength and elastic modulus of the concrete are found to be 52.97MPa and 3.1×10^4 MPa, respectively. After demolded, concrete columns are cured at room temperature for about 6 months to reduce moisture of the concrete and avoid the effect of moisture on the thermal response of the concrete. In order to measure temperature distributions of the columns during fire tests, five thermocouples are installed within the cross section of the column prior to concrete pouring. Figure 2 illustrates the locations of the installed thermocouples in cross section of the column. Five thermocouples from C1 to C5 are placed at distances of 25, 100, 175mm from the surface of the cross section.

Table 1: Summary of specimens

Specimen name	Dimensions (mm)	Cover (mm)	Reinforcement	Ratio of reinforcement (%)
C11	350 x 350	40	4-D22	1.26
C12	350 x 350	60	4-D22	1.26
C21	450 x 450	40	4-D29	1.27
C22	450 x 450	40	8-D19	1.13
C23	450 x 450	40	12-D16	1.18
C31	550 x 550	40	4-D32	1.05
C41	350 x 550	40	6-D22	1.21

Table 2: Mixture ratios of the HSC

Compressive strength (MPa)	W/C (%)	s/a (%)	Weight per unit vol. (kg/m^3)					
			W	C	FA	S	G	AD
50	30.8	44	170	469	83	702	900	5.52

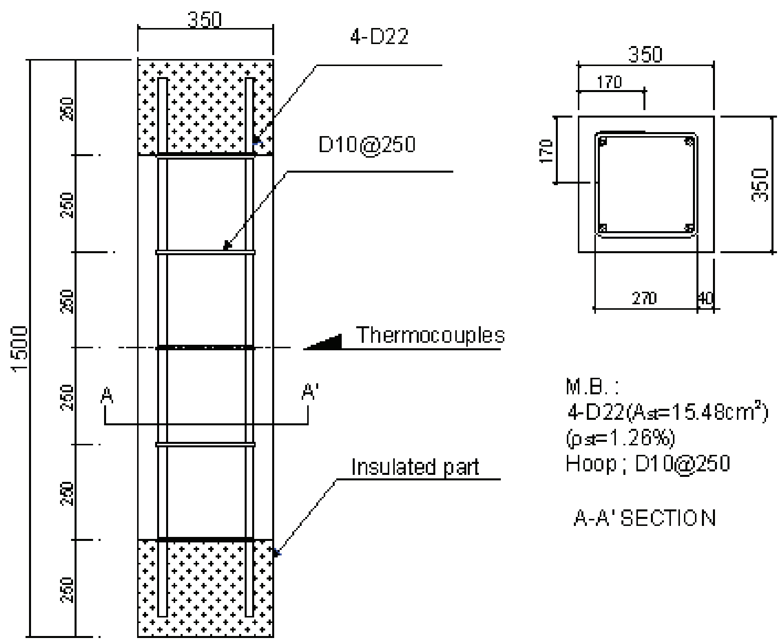


Figure 1: Elevation and cross sectional details of C11 column

2.2. Test setup

The fire tests for the HSC columns are performed in a horizontal heating furnace sized 3×4m. The columns are exposed to high temperature for 3 hours. Gas is used as the heating source and passes flames through the furnace for maximum internal temperature uniformity. The temperature inside the furnace is monitored by ten thermocouples installed in the furnace and controlled to follow the ISO 834 time-temperature curve as shown in Figure 3.

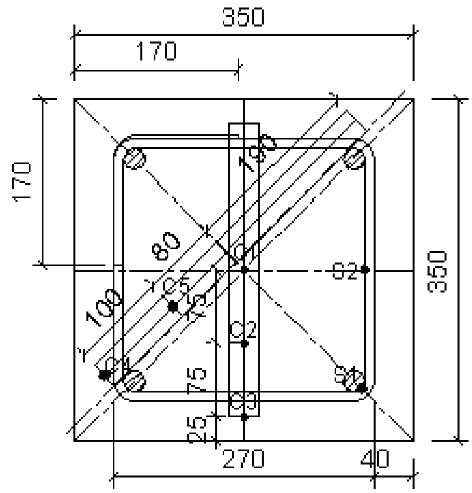


Figure 2: Location of thermocouples

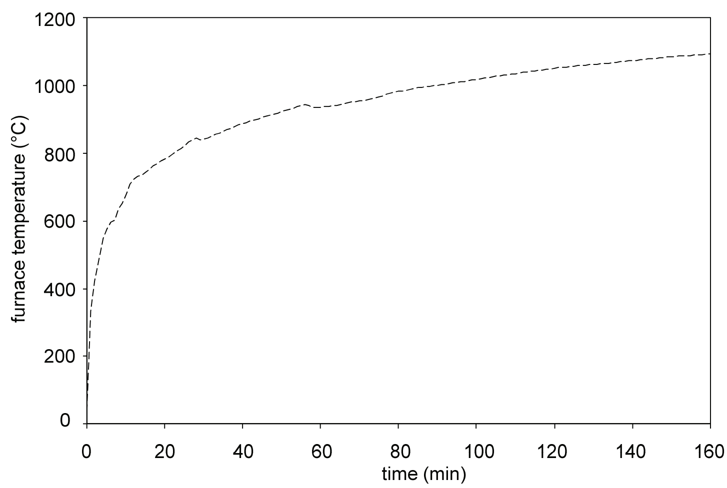


Figure 3: ISO 834 standard fire curve

3. Results

3.1. Temperature distributions of the HSC columns

Temperature distributions of the C11 column during the fire tests measured at five different locations are illustrated in Figure 4. As shown, the temperature inside the concrete column varies from 250˚C to 790˚C, while temperature of heating chamber reaches about 1100˚C after three hours of heating. During fire tests, delay of temperature increase is shown at around 20min due to moisture evaporation occurred when temperature of concrete reaches 100˚C. Spalling of the concrete occurs along with moisture evaporation, which leads to rapid increase of the temperature inside the concrete columns.

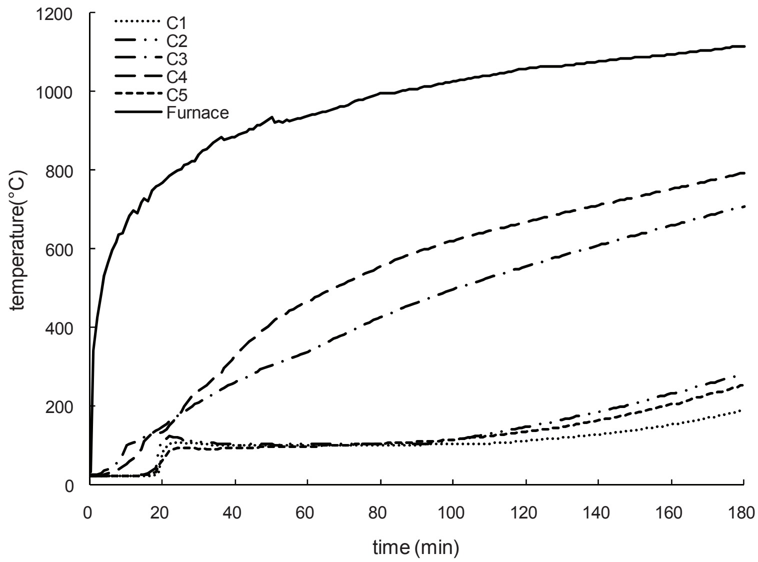


Figure 4: Temperature distributions of the C11 column

The effect of different cross sectional area on the temperature distributions can be found from Figure 5(a). According to the experimental results, the higher temperature distribution is observed as the cross sectional area increases. This may be because the temperature distribution is related to the area of surfaces subjected to heating. However, the temperatures measured at a distance of 175mm from the surface of the columns are not sensitive to the cross sectional area which may be due to thermal conductivity of the concrete. Figure 5(b) illustrates temperature distributions of the columns with the cover thickness of 40mm and 60mm. The column with 60mm of cover thickness shows about 20-30% lower temperature distributions compared with the column with 40mm of cover thickness.

The temperature distributions of the columns with same reinforcement ratio but with different arrangements of the reinforcing bars are illustrated in Figure 5(c). Because the thermal conductivity of steel is larger than that of concrete, the columns with the more distributed reinforcement arrangement result the higher temperature distributions.

3.2. Spalling

The spalling of the fire damaged HSC column is quantified by measuring the spalling depth of each face of the specimen exposed to the fire. The area loss of each specimens are then calculated as illustrated in Figures 6(a) to (c). In Figure 6(a), the column with the largest cross sectional area shows the largest area loss among other columns; however, the differences of area loss between the columns C11, C21, and C41 are not significant. The column with cover thickness of 60mm shows about 74% less area loss compared with the column with cover thickness of 40mm. Last, as reinforcing bars are arranged in more distributed manner, more spalling occurs in the HSC columns.

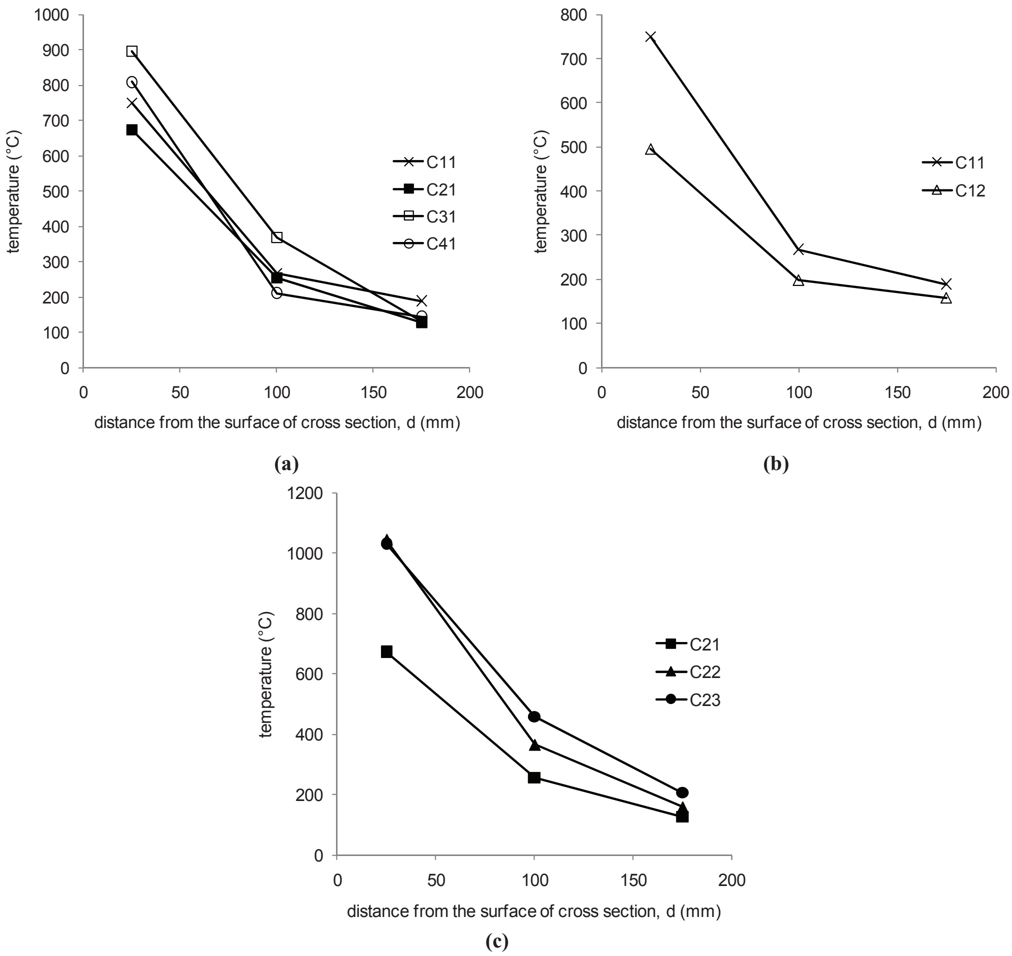
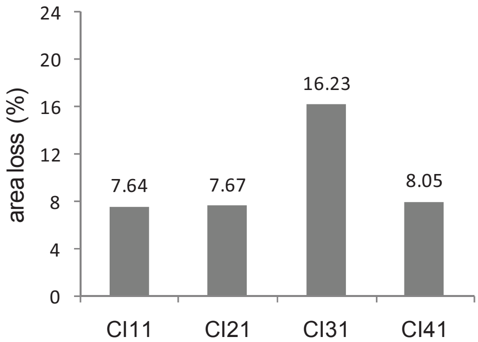
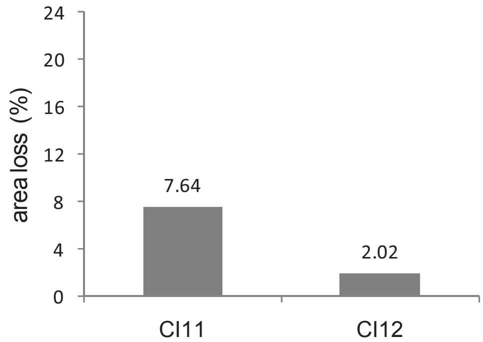


Figure 5: The effect of (a) cross sectional area, (b) cover thickness, and (c) arrangement of reinforcements on temperature distributions of the tested column. The temperatures are measured at the end of the fire tests.

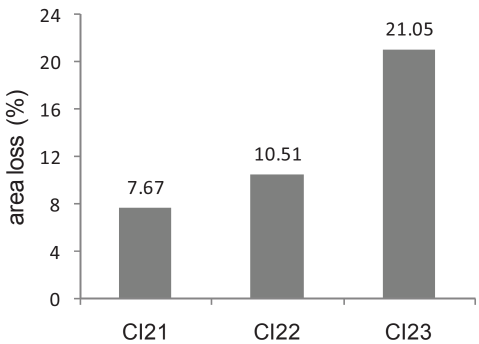
4. Conclusions

In this study, the effect of different cross sectional areas, cover thicknesses, and reinforcement arrangements on temperature distributions and spalling of HSC columns is investigated. The experimental results indicate that temperature distributions and spalling are affected by these parameters. The column with the larger cross sectional area and thinner concrete cover shows the higher temperature distributions. Even with a same reinforcement ratio, the more distributed arrangement of reinforcing bars results in the higher temperature distributions of the HSC column. Spalling of the HSC column is highly related to the temperature distribution; that is the HSC column showing the higher temperature distributions results in the larger spalling. However, the effect of cross sectional area of the column on area loss is not significant.





(a) **(b)**



(c)

Figure 6: The effect of (a) cross sectional area, (b) cover thickness, and (c) arrangement of reinforcements on area loss of the tested column.

5. Acknowledgments

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