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The structural behavior and simplified thermal analysis of normal-strength and high-strength concrete beams under fire

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ABSTRACT

The objective of this study is to investigate the effects of concrete compressive strength and cover thickness on the structural behavior of reinforced concrete (RC) beams under fire. For this purpose, four normal-strength and high-strength concrete test beams were fabricated and tested under the ISO 834 standard fire curve to point of the failure. The test set-up was designed to evaluate the heat distribution and displacement changes of simply supported beams subjected to sustained loads under fire. Test results for normal-strength and high-strength concrete beams were compared for each of the test variables. The test results show that the relationships between time and temperature distributions in the beam sections are very similar and are unrelated to the strength of the concrete, with the exception of the upper part of the beam section. They also showed that the rates of deflection increase for both normal-strength and high-strength concrete beams is very similar before spalling but becomes remarkably high for high-strength concrete beams after spalling. A simplified model was proposed to determine the effect of spalling on the temperature gradient of a high-strength concrete beam. The results of finite difference method (FDM) analysis using this proposed model showed a section temperature gradient that was similar to that of the test results.

1. Introduction

Structures have to be able to maintain their stability and strength for a certain time to ensure life safety and property protection under fire. Concrete has been a leading structural material for a long time. Generally, concrete has been known to have good fire resistance. High temperatures induce severe microstructural changes and internal stresses that alter the mechanical properties of Portland cement concrete and result in a decrease in load capacity and an increase in the deformation of concrete members. However, from previous research, high-strength concrete (HSC) is known to have less fire resistance than normal-strength concrete (NSC), and HSC, especially, has been found to be prone to spalling under high temperature. HSC is defined as a concrete whose strength is over 40 MPa (in Korea) or over 42 MPa (in ACI committee 363). Spalling of concrete subjected to fire is related to pore pressure in consequence of the vaporization of water in the concrete and thermal stress induced from restrained thermal dilatation. Many researches have been done on the effect of spalling of HSC by many researchers, including Kalifa et al. [1–4]. Some studies on the mechanical properties and fire performance of HSC have also been conducted by Phan, Chan, and others [5–9]. Recent research on HSC under fire has focused on the changes in mechanical properties and spalling only for the material level, and on HSC columns for the structural level [10–15] and slabs [16,17]. Little research has been done on the structural behavior of HSC beams subjected to high temperature in comparison with NSC beams under the same conditions [18–21]. To ensure that HSC can be used safely in high-rise buildings, where HSC is commonly used in structural members, it is also important to examine whether HSC members suffer from fire damage to a greater degree than NSC members.

The different types of fire damage to HSC would be generated in structural members based on the type of cement, aggregate property, concrete mixture, percentage of moisture content, age, etc. [1–9]. These different types of fire damage to HSC include mechanical strength reduction, spalling, cracking, and deforming.

An experimental comparison of the influences of high temperature on HSC and NSC flexural members is very important in order to ensure appropriate fire protection and to investigate different aspects of the fire damage to HSC and NSC beams. This study was intended to investigate the effects of compressive strength, cover thickness, and fire exposure time on the structural behavior of HSC and NSC beams under fire. Test results were investigated by the temperature distribution in the beam section layer and the deflection caused by elevated temperature. A simplified analysis model was proposed to determine the effect of spalling on the temperature gradients of the HSC beams.

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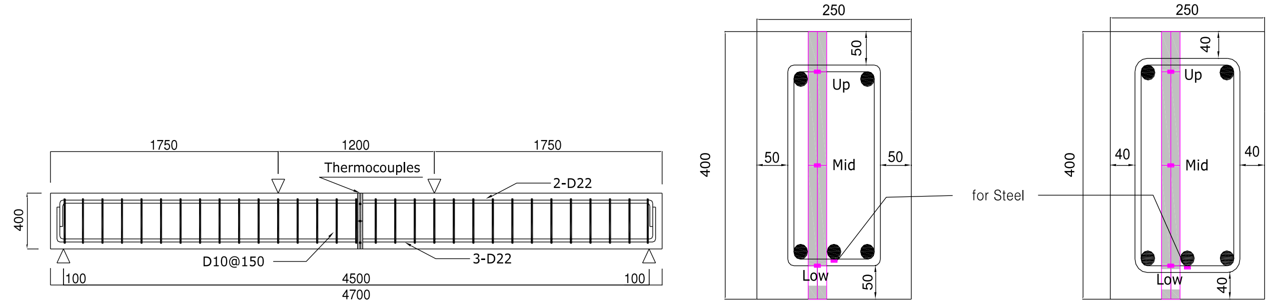
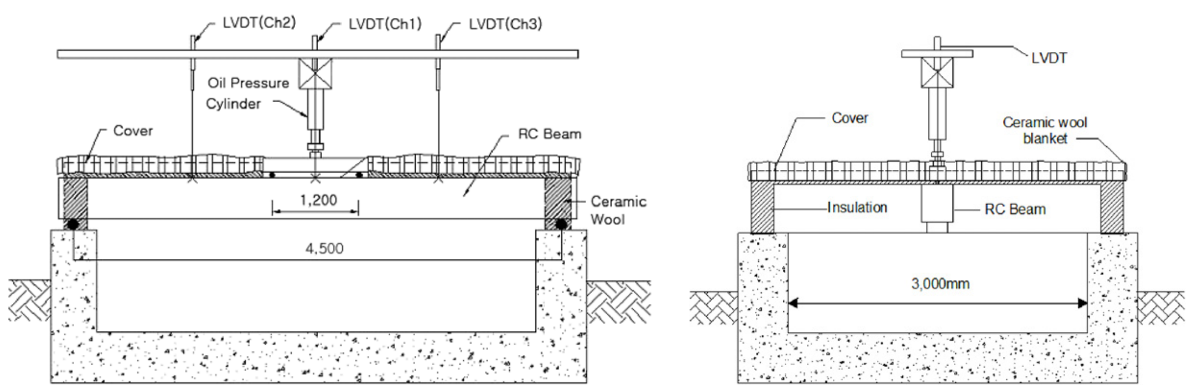


(a) Dimensions of test specimen.

(b) Details of member sections.

Fig. 1. Configuration of fire test beam and location of thermocouples in the sections (unit: mm).



(a) Lengthwise sectional view.

(b) Cross-sectional view.

Fig. 2. Test set-up of a beam in the fire chamber (unit: mm).

Table 1
Summary of test specimens.

Specimen	Exposure time to fire (min)	Initial total loading on beams (kN)	Strength of concrete (MPa)	Cover (mm)
N[a]4[c]	To failure	87.1	21	40
N5[d]	To failure	87.1	21	50
H[b]4	To failure	96.3	55	40
H5	To failure	96.3	55	50

Specimen designation:
[a] N: Normal-strength concrete.
[b] H: High-strength concrete.
[c] 4: 40 mm cover.
[d] 5: 50 mm cover.

2. Experimental program

2.1. Test specimens and parameters

Four beams were fabricated to investigate the effects of the test parameters on the structural behavior of NSC and HSC beams under fire. These test parameters were concrete compressive strength and cover thickness. The test beam size was 250 mm (width) $\times$ 400 mm (depth) $\times$ 4700 mm (length), and the test beams were designed in accordance with the American Concrete Institute (ACI) recommendations. For tension bars, 3-D22 bars were used, where "3" means the number of reinforcing bars, "D" means a deformed bar, and "22" means the nominal diameter in mm. For compression bars, 2-D22 bars were used. For stirrups, D10 bars were used at intervals of 150 mm. The thermocouples were packed in the center section of the span to measure the temperature during the fire test. Details of the test specimens and the location of the thermocouple are presented in Fig. 1(a) and (b). The test specimens and applied test parameters are listed in Table 1.

Table 2
Mix proportion of NSC.

W/C (%)	S/A (%)	W (kg/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)	Ad (%)
51.2	49.8	162	315	893	913	1.71

W/C: Water-cement ratio, S: Sands, C: Cement, A: Aggregates, Ad: Admixture, G: Gravels.

Table 3
Mix proportion of HSC.

W/C (%)	S/A (%)	W (kg/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)	Ad (%)
31	41	168	542	666	974	1.6

W/C: Water-cement ratio, S: Sands, C: Cement, A: Aggregates, Ad: Admixture, G: Gravels.

2.2. Materials

Ordinary Portland cement and pulverized fuel ash were used to make the concrete. The fine aggregate was a medium zone quartz sand whose maximum size was 5 mm, and the fineness modulus was 2.66. It is popularly used in Korea, and the coarse aggregate was also selected from those used in Korea. It was siliceous gravel whose maximum size was 25 mm, and the fineness modulus was 6.87. The mix proportions for NSC and HSC by weight are listed in Tables 2 and 3, respectively. The strengths and elastic modulus of reinforcement used in the test were 439 MPa and 156 GPa for D22 and 390 MPa and 172 GPa for D10, respectively.

2.3. Test set-up and data measurement

The simply supported beams were initially loaded under four-point loading with constant loads, as shown in Table 1, before high temperature was applied. The constant loads were calculated as dead load + 0.4 live load for NSC beams [9] and the loads