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Effect of coarse aggregate type and loading level on the high temperature properties of concrete

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HIGHLIGHTS

- The properties of concrete at high temperature were evaluated by aggregate types.
- The thermal properties of concrete are mainly affected by that of aggregate.
- LWC indicates better thermal properties than NWC.

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ABSTRACT

When concrete is exposed to temperature changes, its durability is reduced because of the decomposition of cement metrics generation of cracks within its structure as its component materials undergo different volumetric changes. Coarse aggregates play an important role in such behavior of concrete. We thus evaluated the influence of coarse aggregates on the fire resistance performance of a concrete structure by conducting a fire experiment under loading on two types of concrete, one with a granite-based coarse aggregate (NWC: normal weight concrete) and the other consisting of a clay-ash lightweight aggregate (LWC: lightweight concrete). LWC displayed a higher residual compressive strength than NWC under thermal load condition. NWC suffered from a large number of cracks at its interior at high temperatures, while the interior of the LWC demonstrated fewer cracks because of the voids in its interior to the mitigation of thermal expansion stress. When a load equivalent to 20% of its room temperature compressive strength was applied, both NWC and LWC demonstrated quasi-equilibrium between the thermal expansion strain and the loading-induced shrinkage strain. Whereas the 40% loading condition, the specimen exhibited shrinkage strain and its compressive strength was observed to undergo a sharp decrease from 500 °C.

1. Introduction

Concrete is a mixture of different kinds of materials such as cement pastes and aggregates that have different thermal expansion coefficients. Hence, when the temperature of concrete is elevated, not only cement hydration products are decomposed but crack occurs inside of concrete due to different volume change of component materials consist of concrete, Thus reducing concrete durability [1–5]. This thermal expansion of concrete is greatly affected by coarse aggregates, which account for most of the volume (see Fig. 1). Studies on the high-temperature properties of concrete with various kinds of coarse aggregates have been conducted by many researchers, especially on those employing artificial light-weight aggregates that have a small thermal expansion coefficient.

To examine the relationship between the concrete microstructure and its strength after exposure to fire, Turker et al. [6] analyzed different concrete microstructures employing three kinds of coarse aggregates, i.e., granite, limestone and pumice stone, after heating the concrete for four hours at the temperatures of 100, 250, 500, 700, and 850 °C. He reported that the concrete using pumice stone, which showed cracks in the aggregates at high temperatures rather than at the interfaces between the aggregates and pastes, had better interfacial conditions as compared to the concretes using either of the other two kinds of aggregates. Furthermore, Neville [7] reported that the strength of the concrete using normal-weight granite aggregates, unlike the light-weight aggregate concrete, begins abruptly decreasing at a temperature higher than the approximate value of 430 °C. It decreases by about 50% at

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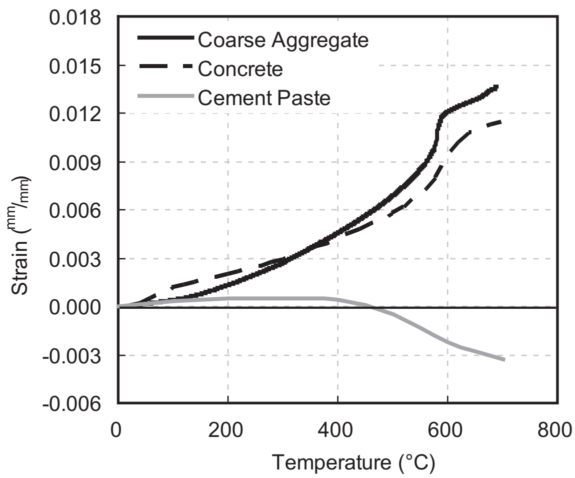

Fig. 1. Thermal expansion of concrete constituent material.

600 °C from the compressive strength at room temperature, and by about 80% above 800 °C, a temperature at which the structure of the concrete can collapse. Kong et al. [8] and Abeles and Bardhan-Roy [9] reported that the strength of the light-weight aggregate concrete was maintained up to about 500 °C, and then decreased by about 60% as the temperature increased from 500 °C to 800 °C. Uygunoğlu et al. [10] evaluated coefficient of thermal expansion of concrete with limestone and pumice stone heating up to 1000 °C. Also he reported that since concrete with porous pumice stone has low coefficient of thermal expansion, when it comes to applying to a structural member subjected to elevated temperature, spalling and risk of collapse of structure can be reduced. Among others, Al-Sibahy [11], Tanyildizi [12,13], Abdulkareem [14,15] and Sancak [16] examined high temperature properties of concrete with LWC.

However, existing studies on the high-temperature properties of this light-weight aggregate concrete have mostly focused on the basic mechanical properties such as the high-temperature compressive strength. However, few studies considering design load applied to structural member have been examined. Meanwhile, many situations have been reported where vertical members such as pillars suffered shear failure under a large load, due to the thermal expansion of horizontal members such as beams or slabs, as shown in Fig. 2 [17]. Also, creep strain can occur in concrete members, exposed to a fire for about 120–180 min, of comparable magnitude to the creep strain of concrete kept at room temperature for about 20–30 years. As shown in these cases, for evaluation of the fire resistance performance of the concrete structures, the strain properties that are introduced in the event of a fire as well as the basic mechanical properties should be considered with design load applied to structural member.

Accordingly, in this study, the effects of the different kinds of coarse aggregates on the fire resistance performance of concrete structures were evaluated by fire resistance tests under load by appraising the strain characteristics as well as the basic mechanical properties of concrete with either granite or clay-ash artificial light-weight coarse aggregates.

2. Experiment

2.1. Experimental plan and concrete mixing

The experimental plan is described in Table 1, while Table 2 shows the concrete mixing proportion. The water-binder ratio (W/B) was set at 35% for the normal-weight aggregate concrete and 33% for the light-weight aggregate concrete, and the standard design compressive strength was 60 MPa. The compressive strength at room temperature of NWC and LWC was 68, 69 MPa, respectively.

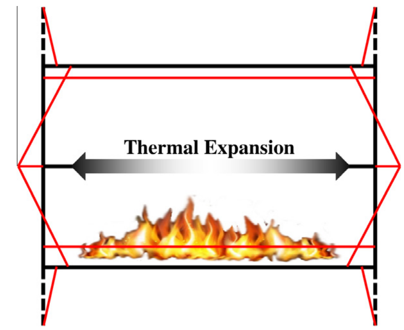

Fig. 2. Schematic diagram of the moment on structure during a fire.

Table 1
Experimental plan.

ID	Aggregate type	Pre-loading level ($\times f_{cu}$)	Target temp. (°C)	Evaluation items
NWC LWC	Granite Clay-ash	0.0 0.2 0.4	20, 100, 200, 300, 500, 700	• Stress–strain relation • High temperature • Compressive strength • Thermal expansion • Total strain • High temperature creep

Table 2
Concrete mixing proportion.

ID	W/B (%)	f_{ck} (MPa)	Air (%)	S/a (%)	Unit weight (kg/m^3)				
					W[a]	C[a]	SF[a]	S[a]	G[a]
NWC	35	63	4 ± 2	40	165	470	–	692	1071
LWC	33	59	4 ± 2	40	155	432	38	687	676

[a] W: water; C: cement; SF: silica fume; S: sand; G: gravel.

Loading conditions were set at 20% and 40% of the compressive strength at room temperature, as well as considering the non-loading condition. The target heating temperatures were the room temperature (20 °C), 100, 200, 300, 500, and 700 °C. At the respective target temperatures, the stress–strain relationship and high-temperature compressive strength were measured. The thermal expansion strain, which occurs during heating to the target temperature, and the steady-state creep strain at high temperatures, which occurs when the temperature is maintained at a fixed value, were also measured.

2.2. Materials

The physical properties of the materials and chemical composition of coarse aggregates used in this study are described in Tables 3 and 4, respectively. For the normal-weight aggregates, crushed granite gravel was used of up to 20 mm in size, 2.65 g/cm^3 in density, and water absorption ratio of 0.8%. On the other hand, artificial clay-ash type light-weight aggregates, which were added to the coal-ash to improve features such as the water absorption ratio, were used, up to 13 mm in size, 1.68 g/cm^3 in density, and water absorption ratio of 15.3% [18,19].

The thermal expansion coefficient, which has a great influence on the thermal properties of concrete, of the materials used in this study are described in Table 5. The thermal expansion coefficient of cement paste started to decrease at around 300 °C. However, the thermal expansion coefficient of coarse aggregates have been increased with increasing temperature, and especially thermal expansion coefficient of granite aggregate was greater than that of artificial light-weight aggregate.

The cross-sectional shape of the coarse aggregates is shown in Table 6. It was verified that the artificial light-weight aggregates had many pores inside, formed during the manufacturing process. Furthermore, it was confirmed by observing the interface between the aggregates and cement matrices that the cement paste permeated the pores on the surface of the artificial light-weight aggregates.