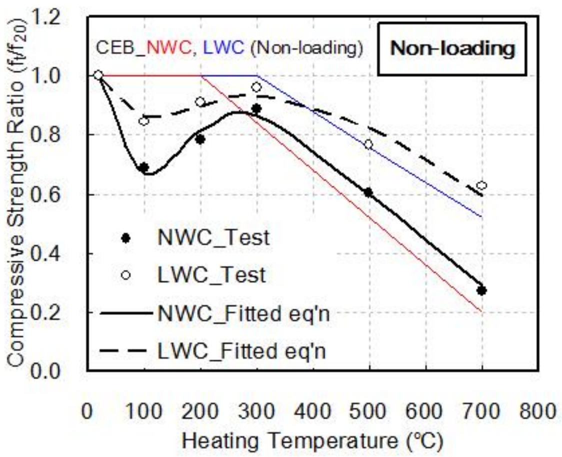
capacity of 2000 kN. To increase the temperature inside and outside of the test specimens to the same level, the heating rate was set at 1 °C/min as shown in Fig. 3, and in particular, in the temperature range up to 50 °C at the beginning of heating and before reaching the target temperature, the heating rate was set at 0.77 °C/min.

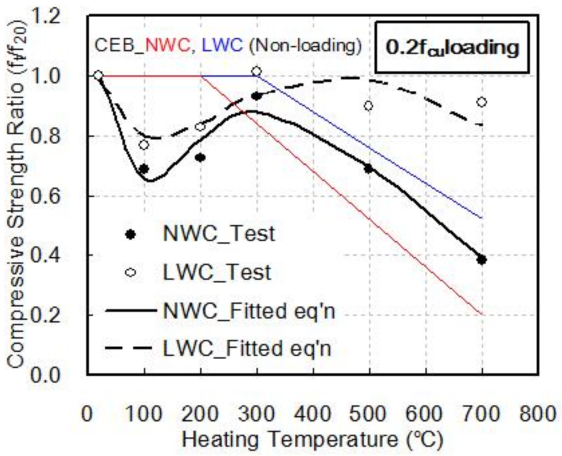
3. RESULTS AND DISCUSSION

3.1 Compressive Strength at Elevated Temperature

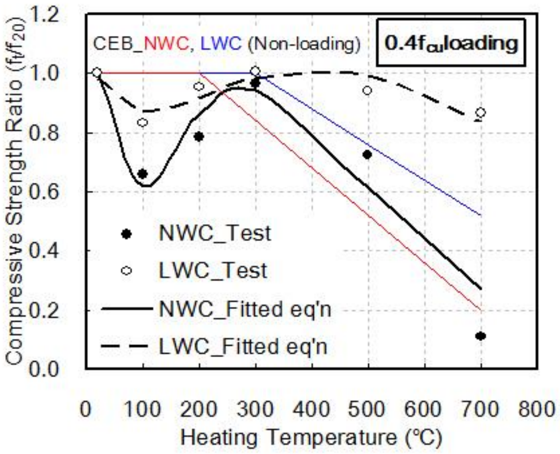
Fig. 4 shows the effects of the loading conditions and the type of coarse aggregate on the compressive strength at elevated temperature. Regardless of loading conditions, LWC showed higher residual compressive strength ratio than NWC. It is considered that crack occurrence at Interfacial Transition Zone (ITZ) by expansion of aggregates known as a cause of strength decrease at elevated temperature occurred little in LWC with lightweight aggregate in which has a number of pores. In addition, compressive strength at elevated temperature was increased by $0.2f_{cu}$ and $0.4f_{cu}$ loading. It is considered that thermal expansion stress is offset by the shrinkage stress by loading.



a) Non-loading condition



b) $0.2f_{cu}$ loading condition



c) 0.4f_{cu} loading condition

Fig. 4 Residual compressive strength by coarse aggregate type and loading conditions

Table 5 Constants of model equation of residual compressive strength

ID.	Loading level	a	b	c	d
NWC	Non	1.00	-0.44	0.84	-0.71
	0.2f_{cu}	1.01	-0.45	0.71	-0.64
	0.4f_{cu}	1.01	-0.78	1.18	-0.77
LWC	Non	0.99	0.12	0.27	-0.47
	0.2f_{cu}	0.99	-0.07	0.27	-0.40
	0.4f_{cu}	0.99	0.09	0.21	-0.38

Based on the experimental results, relationship between compressive strength and the heating temperature was formulated by the Eq. (1). Experimental constants in each test condition were shown in Table 5.

$$y = (a + b \times \theta + c \times \theta^2) \times \exp(d \times \theta)$$
$$\theta = (T - 20)/100 \tag{1}$$

Where y is the residual compressive strength ratio at temperature T °C, T is the temperature (°C), while a, b, c and d are experimental constants.

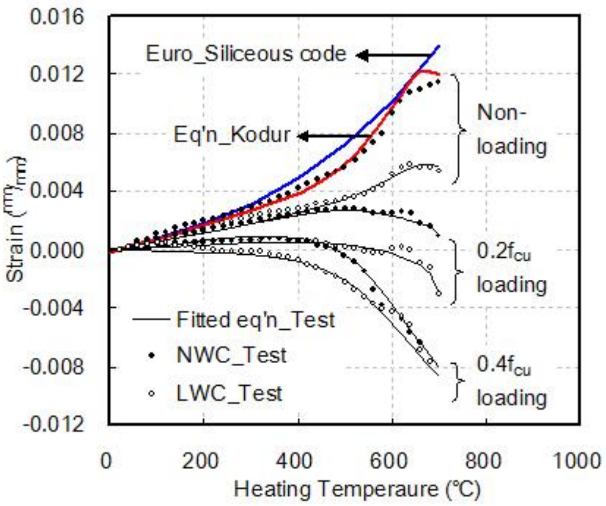


Fig. 5 Thermal expansion strain and total strain by coarse aggregate

Table 6 Model equation of thermal strain

ID.	Loading levels		
	Non	$0.2f_{cu}$	$0.4f_{cu}$
NWC	◆ Kodur Model Eq. • $0 \le T \le 450$℃ $\varepsilon = -0.0002+0.000011T$ • $450 < T \le 650$℃ $\varepsilon = -0.0115+0.000036T$ • $650 < T \le 700$℃ $\varepsilon = 0.0119$	• $0 \le T \le 450$℃ $\varepsilon = -0.0001+0.000006T$ • $450 < T \le 650$℃ $\varepsilon = 0.0039-0.000003T$ • $650 < T \le 700$℃ $\varepsilon = 0.0164-0.000022T$	• $0 \le T \le 450$℃ $\varepsilon = -0.00001+0.000001T$ • $450 < T \le 700$℃ $\varepsilon = 0.0144-0.000032T$
LWC	• $0 \le T \le 450$℃ $\varepsilon = -0.00014+0.000007T$ • $450 < T \le 650$℃ $\varepsilon = -0.0033+0.000014T$ • $650 < T \le 700$℃ $\varepsilon = 0.0058$	• $0 \le T \le 450$℃ $\varepsilon = -0.00002+0.000001T$ • $450 < T \le 650$℃ $\varepsilon = 0.0024-0.000005T$ • $650 < T \le 700$℃ $\varepsilon = 0.0326-0.000051T$	• $0 \le T \le 450$℃ $\varepsilon = 0.0001-0.000003T$ • $450 < T \le 700$℃ $\varepsilon = -0.0207-0.000042T$

3.2 Thermal Expansion Strain and Total Strain

Fig. 5 shows the thermal expansion strain and total strain by the coarse aggregate types. In the case of non-loading condition, as the temperature increases, NWC shows a great increase in the thermal expansion strain. LWC, in which the density of coarse aggregates is low, demonstrated a smaller thermal expansion strain than NWC.

Furthermore, in the case of $0.2f_{cu}$ loading condition, the both specimens showed the smallest strain as the thermal expansion strain is restrained by the shrinkage stress due to loading, whereas in the case of $0.4f_{cu}$ loading condition, they showed an abrupt shrinkage strain at temperatures higher than 500 °C because the stress due to loading becomes greater than that caused by the thermal expansion strain.

In previous studies, the model equations of thermal expansion strain that to be used for fire resistance design of concrete are proposed by coarse aggregate types, but it does not consider the influence of loading conditions. Therefore, thermal strain was formulated by type of coarse aggregate and the amount of loading with Kodur's model which corresponds with result of this study. Formulation is presented in Table 6.

4. CONCLUSIONS

1) Rate of diminution of compressive strength at elevated temperature and thermal expansion strain of LWC was smaller than NWC. In addition, regardless of coarse aggregate types, It was observed that the more loading increases, the higher compressive strength at elevated temperature becomes the smaller thermal expansion strain becomes.

2) Under $0.4f_{cu}$ loading condition, drastic shrinkage strain was observed above 500 °C. Especially It was observed that rate of diminution of compressive strength at elevated temperature of NWC was high.

3) Unlike existing model for fire resistance design of concrete, model for compressive strength at elevated temperature of concrete and thermal strain considering types of coarse aggregate and loading condition of structure was proposed in this study.

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