DEVELOPMENT AND EVALUATION OF A MODEL FOR FIRE-RELATED HSC SPALLING FAILURE

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Abstract : This paper reports on an experimental study regarding the behavior of restrained high-strength concrete in response to the type of extreme heating associated with fire. The study was intended to support estimation of thermal stress from the strain in a restraining steel ring and vapor pressure in restrained concrete under the conditions of a RABT 30 rapid heating curve. Thermal stress calculation was based on the thin-walled cylinder model theory. A spalling failure model based on a strain failure model was also proposed. The results indicated that such modeling enables estimation of the point at which spalling starts during heating and the consequent spalling depth.

1. Introduction

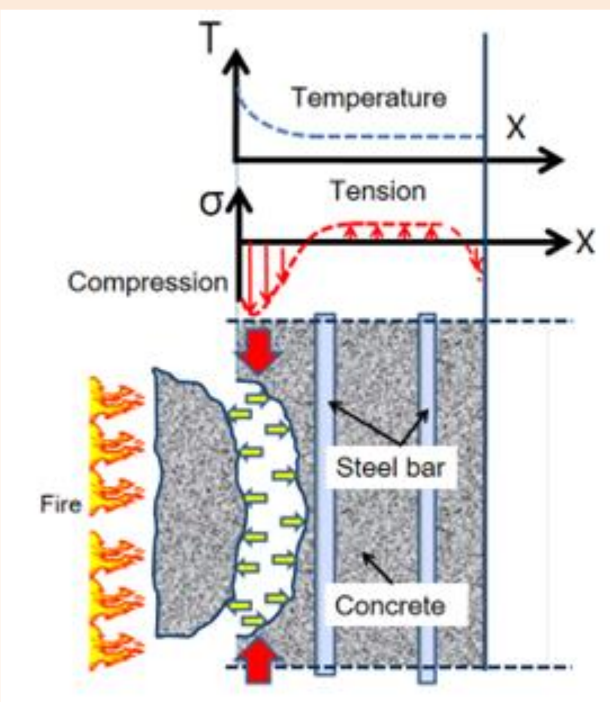

Fig.1 Thermal stress

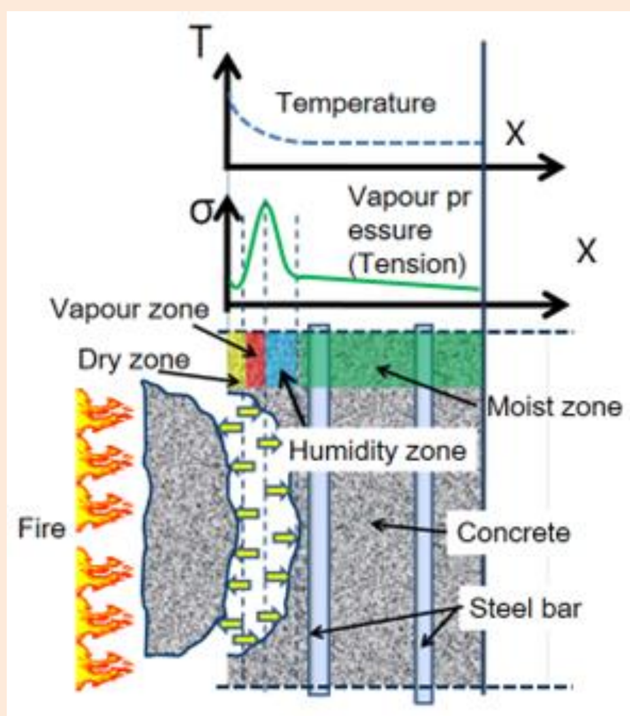

Fig.2 Vapor pressure

Fire poses one of the most serious risks to concrete buildings and structures because it often results in explosive spalling of concrete. There are two mechanisms by which concrete can be damaged by fire. The first is restrained thermal dilation resulting in biaxial compressive stress states parallel to the heated surface, which leads to tensile stress in the perpendicular direction (Fig.1).

The second is the build-up of concrete pore pressure due to vaporization of physically/chemically bound water resulting in tensile loading on the microstructure of the heated concrete (Fig.2).

However, few reports to date have outlined actual experimental studies on the exact influence of thermal stress. The authors previously reported that a method involving the restraint of concrete with steel rings in heat testing can be used to clarify characteristics of thermal stress and explosive spalling behavior.

2. Model for Estimation of Thermal Stress and Strain Failure

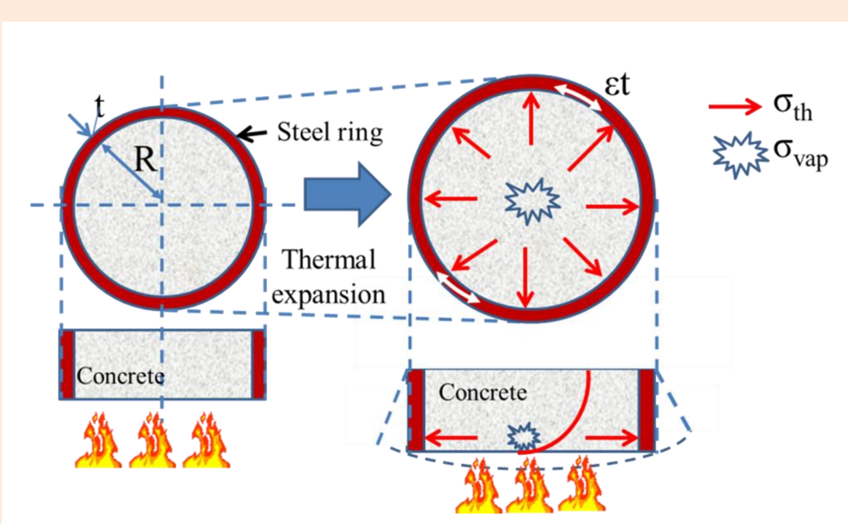

Fig.3 Estimation of thermal stress

Figure 3 shows the method used to estimate thermal stress. Thermal stress calculation was based on the thin-walled cylinder model theory as shown by Eqs. (1) and (2).

$$\sigma_{re} = \sigma_{th} + \sigma_{vap} \quad (1)$$

$$\sigma_{re} = \varepsilon_t \cdot E_s \cdot \frac{t}{R} \quad (2)$$

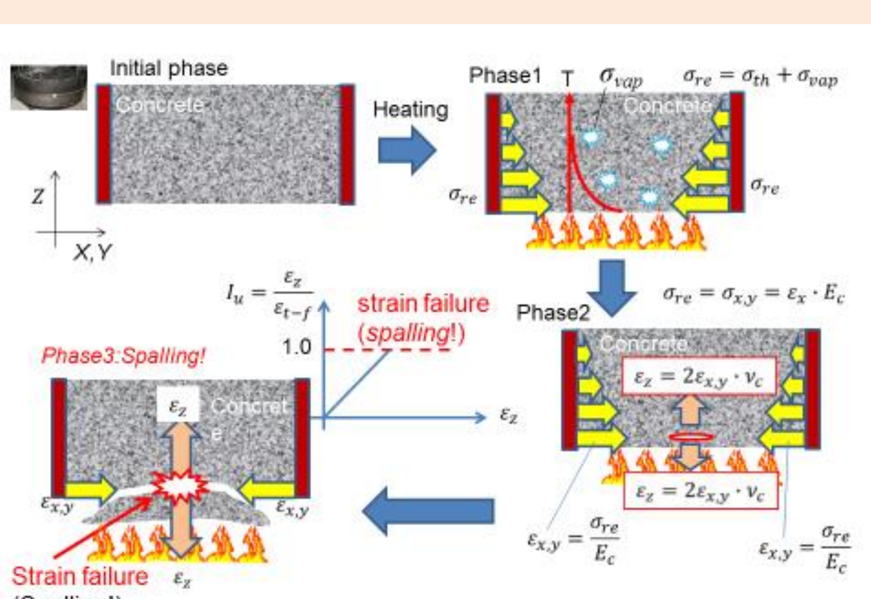

Fig.4 Strain failure model of explosive spalling

Figure 4 shows a strain failure model of explosive spalling under thermal stress. Strain at a certain depth from the heated surface was calculated using eqs. (3) and (4), and the index of the strain failure model was given by Eq. (5).

Tensile strain failure occurred when the index of the strain failure model exceeded 1.0 (I_u > 1.0).

$$\sigma_{re} = \sigma_{x,y} = \varepsilon_{x,y} \cdot E_c \quad (3)$$

$$\varepsilon_z = 2\varepsilon_{x,y} \cdot v_c \quad (4)$$

$$I_u = \varepsilon_z / \varepsilon_{t-f} \quad (5)$$

3. Outline of Experiment

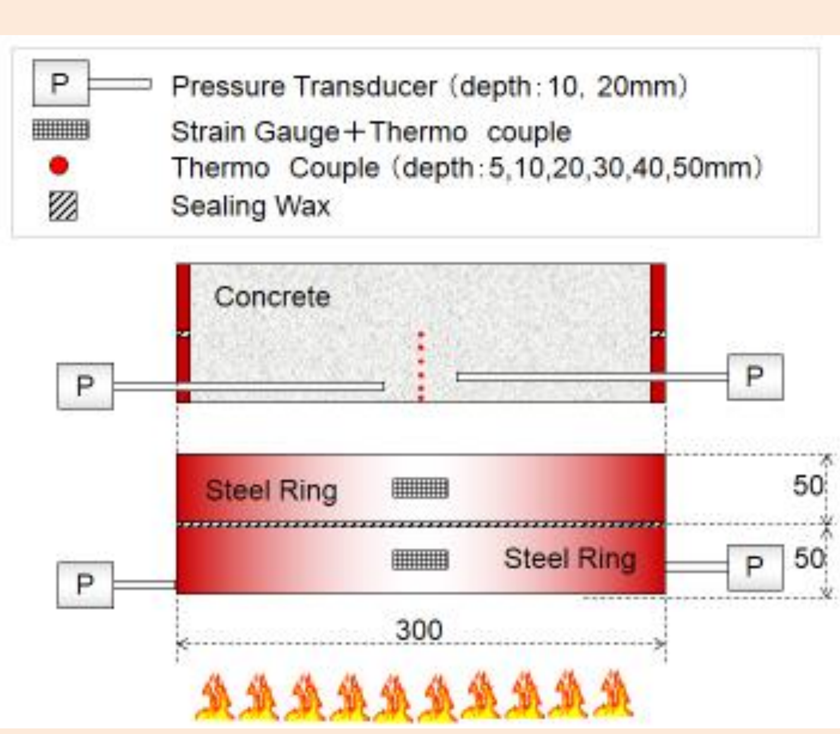

Fig. 5 Specimen

Figure 5 shows the configuration and dimensions of the two specimens used with two pairs of steel rings (diameter: 300 mm; thickness: 8 mm; length: 50 mm).

Two strain gauges and two thermocouples were attached at 25 and 75 mm from the heated surface and outer surface of the steel rings.

Stainless steel pipes (inner diameter: 2 mm; length: 200 mm) were placed in the concrete at distances of 10 and 20 mm from the heated surface and parallel to it.

Six type-K thermocouples were placed in the central zone of the specimens at 5, 10, 20, 30, 40 and 50 mm from the heated surface.

The heating tests were based on a RABT 30 heating curve.

4. Results and Discussion

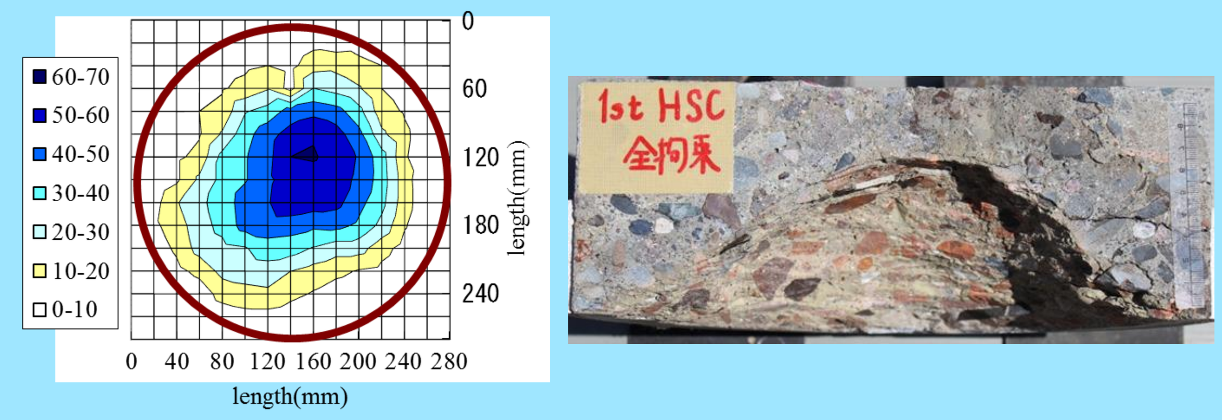

Fig.6 Spalling depth

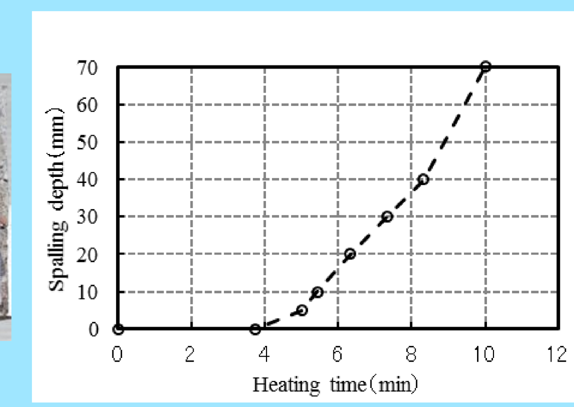

Fig.7 Spalling depth and time

Figure 6 shows results for the depth of spalling after the heating test. The maximum value was about 70 mm, and the depth at the center part was greater than that at the outer part. The specimens were severely damaged.

Figure 7 shows the relationship between spalling depth and time during the heating test. Spalling began approximately 4 minutes after heating was started, and the spalling rate was about 10 mm/min.

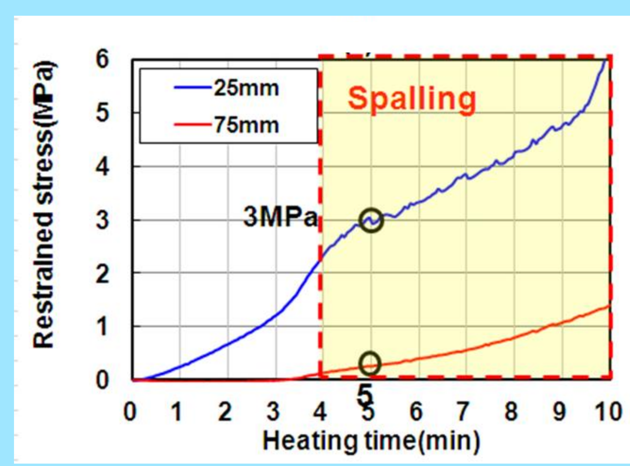

Fig.8 Restrained stress

Figure 8 shows the results of restrained stress calculation based on ring strain at a point 25 mm from the heated surface. After 5 minutes of heating, the value reached 3 MPa at this point.

$$\sigma_{x,y}(z) = \sigma_{x,y-25} \cdot \frac{\Delta T_c(z)}{\Delta T_{c-25}} \quad (6)$$

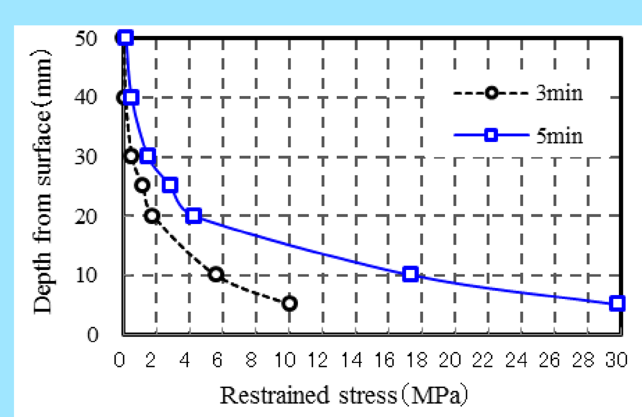

Fig.9 for distribution of restrained stress at three and five minutes

Distribution of restrained stress was estimated using Eq. (6). Restrained stress itself was calculated using an experimental value at a point 25 mm from the heated surface, and was assumed to be in proportion to the temperature increment.

Figure 9 shows the results for distribution of restrained stress at 5 and 5 minutes.

After 5 minutes of heating, restrained stress 5 mm from the heated surface was about 30 MPa.

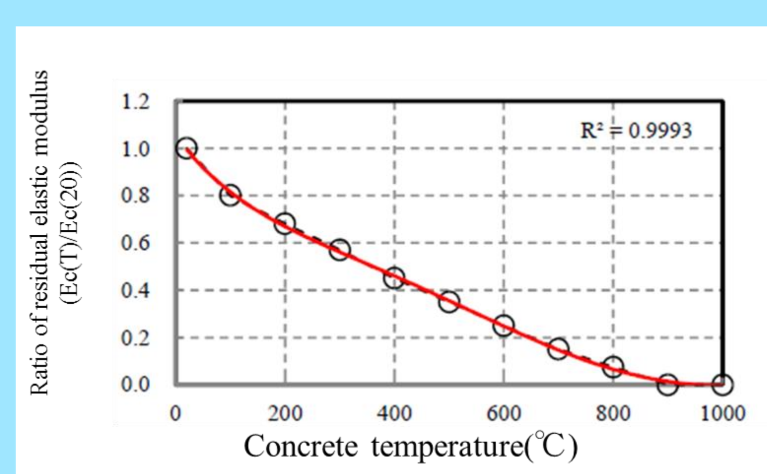

Fig.10 Ratio of residual elastic modulus and temperature

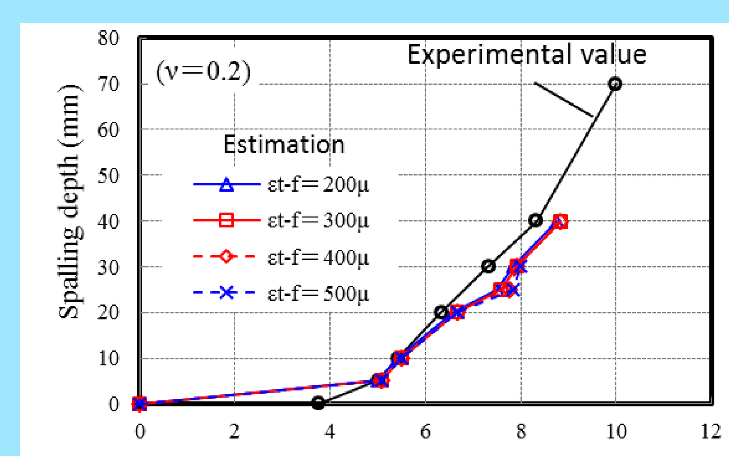

Fig.11 Spalling depth (Experiment. vs. Estimation)

In this work, a strain failure model of explosive spalling was verified. The relationship between the ratio of residual elastic modulus and temperature was used in the AIJ model as shown in Fig. 10. *The residual Poisson's ratio of concrete upon heating was 0.2 and the ultimate strain upon tensile failure ranged from 200 to 500 μ.* The spalling depth was estimated using eqs. (3) to (6).

It was assumed that spalling occurred if the index of the strain failure model in Eq. (6) exceeded 1.0. Figure 14 shows spalling depth comparison with experimental and estimation values.

It can be seen that the maximum spalling depth was estimated to be about 40 mm at nine minutes. These outcomes clearly indicate that the proposed model can be used to estimate spalling depth up to 9 minutes from the start of heating.

In this study, the range from 200 to 500 μ for the ultimate strain upon tensile failure had no influence on spalling depth estimation.

5. Conclusion

The results obtained from the study can be summarized as follows:

1. The proposed method involving the restraint of concrete with steel rings in heat testing can be used to clarify characteristics of thermal stress and explosive spalling behavior.
2. The proposed spalling failure model based on a strain failure model was found to support estimation of spalling depth up to nine minutes from the start of heating.

Acknowledgement

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References : Toru TANIBE, Mitsuo OZAWA, Ryota KAMATA, Yuichi UCHIDA, Keitetsu ROKUGO:THE STUDY OF EVALUATION METHODS AND SPALLING FAILURE MODEL OF HSC IN THE EVENT OF FIRE ,Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures) Vol. 70 (2014) No. 1 p. 104-117 ,(In Japanese)

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