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FIRE SPALLING BEHAVIOUR OF HEAT-RESISTANT REPAIR MATERIALS UNIDER RING RESTRAINED CONDITION

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Vapor pressure, Restrained stress

Abstract: When repaired RC structures are exposed to fire, there is a risk of fire spalling, as in the case of concrete. Our group previously investigated the fire spalling behavior of cement materials using ring-restrained heating tests and developed heat-resistant repair materials (HRM) that can be used within an application range of 300℃ or less. However, we have not yet examined whether the HRM materials can be applied at temperatures above 300 ℃. In this study, we evaluated the fire spalling behavior of HRM using a ring-restrained heating test, and a small cylindrical electric furnace was used. In addition, the effect of jute fibers on the fire spalling prevention of repair mortar was examined. In a results, the maximum fire spalling depth of the Control specimen was 12 mm, and the fire spalling suppression effect on HRM was confirmed by mixing more than 0.1 vol% of Jute fiber. We discussed the relationship between the restrained stress, vapor pressure, and internal temperature at 5 mm from each specimen. Vapor pressure increased to 8 MPa at 140℃ for the control specimen, and fire spalling occurred. The restrained stress was 4 MPa at 140 ℃. For the jute specimens, the maximum restrained stress ranged from 2 to 3 MPa, and the restrained stress of the jute specimen was lower than that of the control specimen. The maximum vapor pressure in the jute specimens was approximately 11 MPa. Although the maximum vapor pressure of the jute specimen was higher than that of the control specimen, no fire spalling occurred.

1 INTRODUCTION

As social infrastructure ages, the number of deteriorated reinforced concrete (RC) structures is increasing. Repair mortars are used to repair the cross sections of deteriorated RC structures. When repaired RC structures are exposed to fire, risk is happened of fire spalling. Thermal stress, vapor pressure, and a combination of these theories have been proposed as mechanisms of concrete fire spalling[1,2]. In previous studies, small cylindrical and prismatic specimens were heated in an electric furnace at a constant temperature to evaluate mortar for fire spalling[3]. In this method, the presence or absence of fire spalling in the unrestrained condition was evaluated. This method is not appropriate for fire spalling evaluation because actual structures are subjected to fire in a restrained condition. On the other hand, Japan Concrete Institute has standardized a fire spalling test method using small restrained specimens, and the ring-restrained heating test being studied by this research group has been incorporated as part of this method [4]. In previous studies, examples of ring-restrained specimen heating tests have been reported [5]. Currently, polymer cement mortar (PCM) is commonly used to repair deteriorated RC structures. PCM is a pre-mix mortar with 5-20% organic polymers [6]. However, it has been found that PCM has a risk of fire spalling and a decrease in tensile adhesion as temperature rises [7]. In a previous study, some studies reported that ring-restrained specimens of PCM with various polymers were heated using the RABT30 heating curve, and that fire spalling occurred [8]. In our research group, it has been developing heat-resistant repair materials (HRM) that can be used in the application range of 300°C or lower, and residual mechanical properties of HRM was evaluated[9]. However, HRM did not evaluate fire spallling behavior and preventive method at temperatures above 300°C. Recent study reported preventive effect fire spalling of high strength concrete with natural Jute fiber [10,11]. In this study, it examined a ring restraint test using a small cylindrical electric furnace in order to investigate a simple method to evaluate the fire spalling of HRM. It evaluated preventive method of fire spalling was addition with

Table 1 Mixture proportion of HRM

Specimen	Water and Binder ratio (%)	Unit weight (kg/m^3)					Jute fiber
		Water	Cement	Blast furnace slag	Fine aggregate	Chemical admixture	Vol %
Control	38.7	198	399	112	260	3.7	0
Jute0.1						3.7	0.1
Jute0.2						5	0.2

Table 2 Fresh properties and compressive strength, Moisture content

	Mortar flow	Temperature after mixing	Compressive strength	Moisture content
Type	mm	℃	MPa	mass%
Control	179.5	26.7	68.4	/
Jute0.1%	187.5	19.8	56.1	7.1
Jute0.2%	178.5	19.7	45.5	7.1

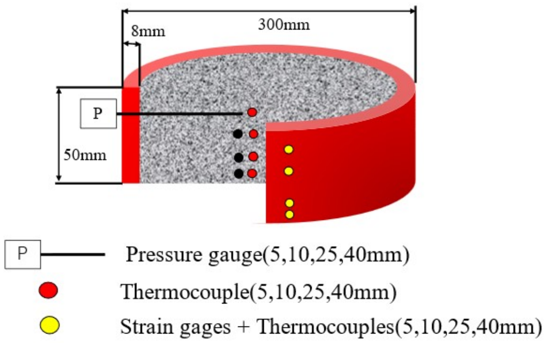


Figure 1 Ring specimen

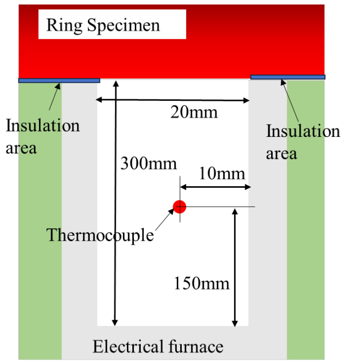


Figure 2 Cylindrical electric furnace

natural Jute fiber. Addition ratio were 0 , 0.1 and 0.2 vol% of Jute fiber. The internal temperature, vapor pressure, and restrained stress were measured. Grading evaluation of the fire spalling size was also conducted.

2 EXPERIMENT OUTLINE

2.1 Mixture proportion of HRM

Table.1 shows the mixture proportion of HRM used in this study. Water and binder ratio(W/B) was 38.7 %. Ordinary Portland cement and blast furnace slag fine powder was used. High performance AE water reduce agent was used. Jute fiber was used as the fire spalling suppression fiber. Jute fiber has a length of 12 mm and a diameter of 50 µm. Jute fiber has a straw (hollow) like structure because it is a plant fiber and is expected to reduce vapor pressure by forming a vapor pressure dissipation network when heated [10]. The amount of admixture was adjusted according to the fiber content. Fresh properties and compressive strength, moisture content are shown in Table 2. The mortar flow test was performed following Japan Industrial Standard(JIS) R5201, Physical Testing Methods for Cement[12]. The flow value decreased as the fiber content increased. The compressive strength tended to decrease as the fiber content increased. The moisture content of the Control specimens is omitted due to incomplete measurement.

2.2 Ring-restrained specimen

Figure1 shows an overview of the ring-restrained specimen used in this study. A steel ring with an outer diameter of 300 mm × height of 50 mm × thickness of 8 mm was used as the restraining ring. The measured items were internal temperature, water vapor pressure, and restrained stress. K-type thermocouples and stainless steel pipes for measuring water vapor pressure were set inside the specimens at 5, 10, 25, and 40 mm from the heating surface. The preparation of the specimens was as follows. The above mentioned rings were fixed to the formwork, mixed with the prescribed HRM, and cast. One day after casting, the formwork was removed and the specimens were sealed in plastic bags and cured for one month. Immediately before the heating test, thermocouples and strain gauges (temperature limit: 80°C) were set at 5, 10, 25, and 40 mm from the on the side of the ring. A stainless steel pipe and a pressure gauge were connected, and the pipe was filled with silicon oil as a pressure-transmitting medium to measure the water vapor pressure generated during heating.

2.3 Heating test

Figure 2 shows an overview of the heating test apparatus. A cylindrical electric furnace was used for the heating test. The opening of the furnace is 200 mm in diameter. The electric power is single-phase 200 V 1.8 KW, and the maximum temperature is 1150°C. The ring specimen is set in the opening of the electric furnace. Heating was performed by setting the ring specimen in the opening of the electric furnace. The heating test method is described below. Step1: Set the furnace temperature at a constant 850°C. Step2: Strain gages and thermocouples are affixed to the sides of the ring. Step3: Connect a pressure gauge to the stainless steel pipe of the ring specimen and make it ready to measure the vapor pressure. Step4: Then, lift the ring specimen by a crane and move it to the top of the electric furnace and stand by. Step5: Open the top cover of the electric furnace and set the ring specimen in the opening. The time when the specimen was placed in the electric furnace was defined as the heating start time. In the conventional method, the specimen is set in the gas furnace and the temperature in the furnace is raised according to a predetermined temperature curve to conduct the fire spalling test. The heating time was 15 minutes. During the heating test, the time of fire spalling was recorded by checking the sound generated by the detonation.

2.4 Restrained stress

The restrained stresses during heating were calculated from Equation (1) based on the thin-walled cylinder theory. The restrained stress was calculated from strain gage measurements taken in the height direction from the heating surface.

$$\sigma_{re} = \varepsilon_\theta \cdot E_s \cdot \frac{t}{R} \tag{1}$$

σ_{re}: Restraint stress in concrete
ε_θ: Circumferential strain of steel ring
E_s: Modulus of elasticity of steel ring
t: Thickness of ring
R: Inner radius of the ring

2.5 Evaluation for fire spalling grade

Table 3 shows the grading indexes of fire spalling evaluation of concrete. In this study, the grading evaluation of fire spalling size was conducted based on the standards of the Japan Concrete Institute[4]. The fire spalling evaluation Indexes were below. Index 1 is the maximum fire spalling depth. Index 2 is the fire spalling area ratio. Index 3 is the fire spalling volume ratio. The measurement interval points were set at the intersection of each mesh when the heating range was divided by a 10-mm mesh.

3 RESULTS AND DISCUSSION

3.1 Heating surface condition of each specimen

Figure 3 shows the fire damage condition of the heated surface of each specimen. In the case of control specimen, fire spalling on the entire heated surface with a maximum fire spalling depth of 12 mm. While fire spalling did not occur in Jute fiber-mixed specimens at 0.1 vol% and 0.2 vol%, respectively, and surface cracks on the heated surface were observed. Table 4 shows the results of the grading evaluation of the fire spalling scales.

In case of control specimen, index 1: maximum depth of fire spalling was D, and index 2: fire spalling area fraction was E. The

Table 3 Fire spalling grade

	Index 1: Maximum fire spalling depth	Index 2: Fire spalling area ratio	Index 3: Fire spalling volume ratio
A	No fire spalling, no cracks	No fire spalling, no cracks	No fire spalling, no cracks
B	No fire spalling, but there are cracks in the shape of a fissure	No fire spalling, but there are cracks in the shape of a fissure	No fire spalling, but there are cracks in the shape of a fissure
C	Less than 10mm	Less than 10% of total area	Less than 10% of total area
D	Less than 10~30mm	Less than 10~50% of total area	Less than 10~20% of total area
E	30mm or more	50% or more of total area	20% or more of total floor area

a) Control b) Jute0.1 c) Jute0.2

Figure 3 Fire damage condition

fire spalling area fraction was based on the area of the heated region φ200 mm. Index3: fire spalling volume fraction was C. In case of specimens with Jute fiber, all indexes were B, regardless of the fiber mixing ratio. This reason is due to surface cracks on the heated surface.

3.2 Temporal change of internal temperature

Figure 4 shows the temporal change of the internal temperature of each specimen and the temperature inside the furnace. In the control specimen (Figure 4 a)), the temperatures at 5 mm and 10 mm positions increased rapidly at about 8 min and 13 min, respectively. This is considered that fire spalling occurred, then the thermocouple exposed to the furnace directly, the temperature increased. Fire spalling started from 2min to 13min, furnace temperature repeated that decreasing and increasing, rapidly. This is due to the rapid evaporation of water and effect of latent heat in the mortar at the time of fire spalling. Maximum temperatures at 5 and 10mm were 450°C and 550°C, respectively. In the case of Jute 0.1% and 0.2%vol specimens, internal temperatures increased during heating. The maximum temperature at 5mm in Jute 0.1% and 0.2%vol specimens were 400°C and 350°C, respectively. Internal concrete temperatures were not seen decreasing and increasing rapidly due to fire spalling.

3.3 Restrained stress

Figure 5 shows the temporal change over time of the restrained stress for each specimen. The restrained stress was calculated in the range of temperatures below 80°C on the steel ring surface. The overall trend is that the restrained stress increases as the internal temperature of the specimen increases. In the case of control specimen, restrained stress increased or decreased due to fire spalling at the 5mm and 10mm positions. Maximum restrained stress was about 4.8 MPa at 5mm from the heating face. In the case of Jute specimens with 0.1%vol and 0.2%vol, the maximum of restrained stress at 5mm from the heating face were 2.0 and 2.5 MPa, respectively. The restrained stress of the Jute fiber-mixed specimen was lower than that of the Control specimen. This is because the

Table 4 Results of the grading evaluation of the fire spalling scales

	Fire spalling status			Grade		
	Maximum fire spalling depth (mm)	Fire spalling area ratio (%)	Fire spalling volume ratio (%)	Index 1	Index 2	Index 3
Control	12	78	9.1	D	E	C
Jute0.1%	0	0	0	B	B	B
Jute0.2%	0	0	0	B	B	B

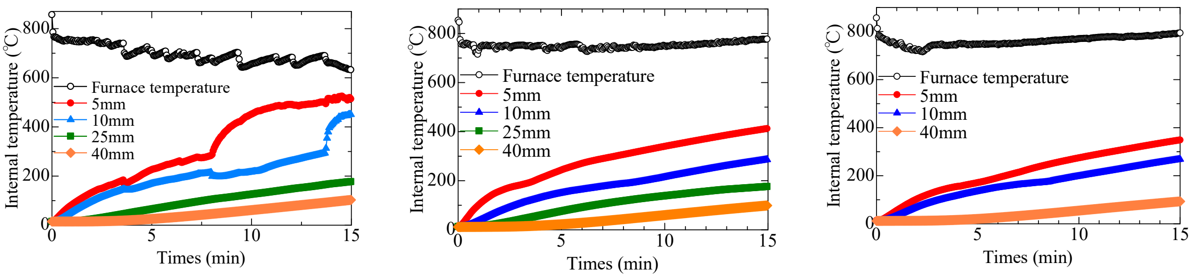


Figure 4 Internal temperature

compressive strength and elastic modulus of Jute specimens is lower than control specimens.

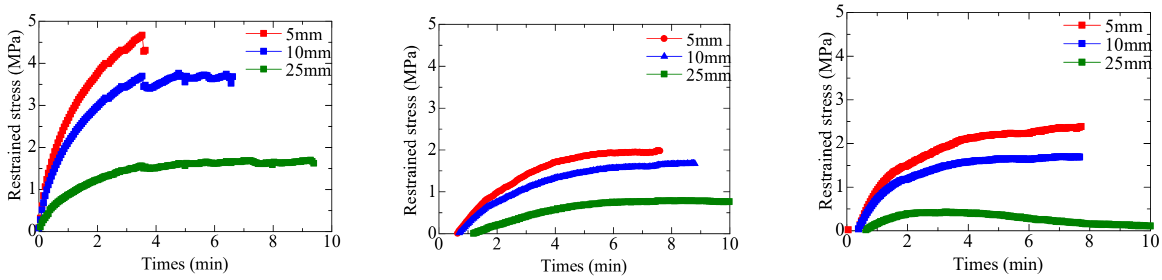
3.4 Vapor pressure

Figure 6 shows the temporal change of vapor pressure in each specimen. In case of control specimen, the vapor pressure at the 5mm position from the heating surface increased rapidly, then the maximum value was 8MPa at 2min, then, decreased rapidly. This is because fire spalling occurred at 2min from starting heating test. In the case of Jute specimens with 0.1% and 0.2%vol, Vapor pressure increased from the 5 mm position close to the heating surface. Maximum vapor pressure of Jute specimens with 0.1% and 0.2%vol were 12 MPa and 11 MPa, respectively. All Jute specimens did not occur fire spalling. Vapor pressure of Jute specimens was higher than control specimens. Previous studies [10] reported the vapor pressure of specimens with jute was higher than without jute fiber.

3.5 Relationship between restrained stress and vapor pressure and internal temperature

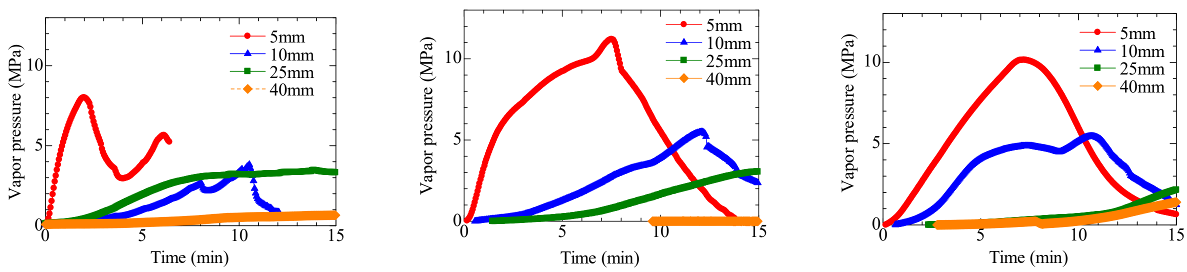
Figure 7 shows the relationship between the restrained stress and vapor pressure and internal temperature at the 5 mm position for each specimen. The saturated vapor pressure curve (SVP) is also shown. In case of Control specimen, vapor pressure increased and 8MPa at 140 °C , then fire spalling occurred. Restrained stress was 4MPa at 140 °C. In case of Jute specimens, the maximum restrained stress ranged from 2 to 3 MPa, and the restrained stress of Jute specimen was smaller than control specimen. The maximum Vapor pressure is about 11 MPa in jute specimens.

Although the maximum vapor pressure of jute specimen is higher than control specimen, fire spalling did not undergo. According to Ichikawa et al.[13], the left side of the SVP curve is the supersaturated region, and the right side is the unsaturated region. The vapor pressure at 5 mm of Jute specimen was in the supersaturated region. This is because water content was 7%mass (Table2).



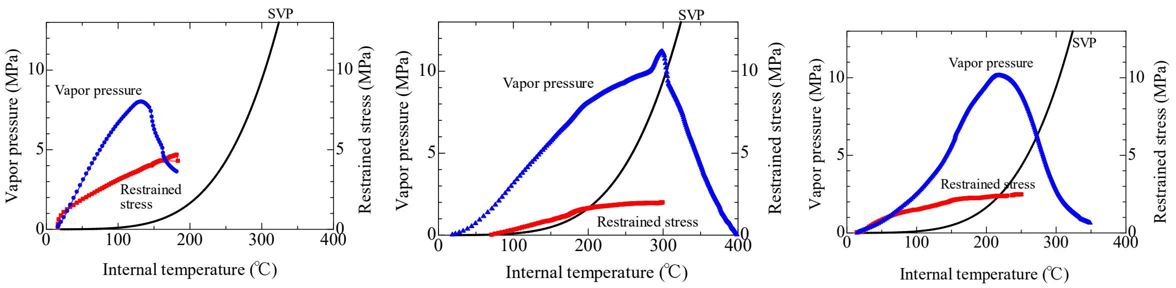
a) Control b) Jute0.1 c) Jute0.2

Figure 5 Restrained stress



a) Control b) Jute0.1 c) Jute0.2

Figure 6 Vapour pressure



a) Control b) Jute0.1 c) Jute0.2

Figure 7 Relationship between vapour pressure, Thermal stress and Internal temperatura (position :5mm fro heating face)

3.6 Preventive effect of fire spalling with Jute fiber

Our research group has proposed an fire spalling model that takes into account tensile strain fracture and vapor pressure [14]. In this model, it supposed tensile strain occurs in the height direction of the ring specimen due to the restrained stress caused by heating, resulting in the formation of layered cracks. The maximum restraint stress of the Jute fiber-mixed specimens was smaller than that of the control specimens. This is thought to be due to the relaxation of the restraint stress caused by the thermal degradation of the Jute fiber. According to previous studies, Jute fiber has straw-like structure, the difference in thermal expansion between the cement matrix and the Jute fibers during heating causes a breakdown of adhesion (PITS effect)[10]. As a result, it created a pressure release network in the specimen, fire spalling did not occur. On the other hand, Jute fibers are hydrophilic, and thus retain water in the straw structure during mixing and casting. The water retained in the straw structure evaporated upon heating and contributes to an increase in vapor pressure. Additionally, a previous study reported the results of thermal analysis of Jute fiber to indicate that a change in mass due to fiber dehydration also occurs at around 50°C. Moreover, another paper reported air bubble was entrained near Jute fibers during mixing [15]. It is considered these effects suppressed fire spalling with Jute fiber during heating.

4 CONCLUSIONS.

The findings of this study are as follows.

1) By considering a cylindrical electric furnace and heating method, a fire spalling evaluation method for cementitious materials by a simplified ring-restrained heating test was proposed.
2) It was found that the simplified ring-restrained heating test can be applied to cementitious materials to evaluate the fire spalling in case of fire.
3) The heating test of HRM at a constant temperature of 850°C occurred in fire spalling.
4) On the other hand, the specimens mixed with Jute fiber at 0.1 vol% and 0.2 vol% do not occur fire spalling, indicating that HRM with more than 0.1 vol% of Jute fiber can be used in high-temperature environments of 300°C or higher.
5) The vapor pressure of the specimens without Jute fiber was lower than that of the specimens with Jute fiber.

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