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Spalling and Water Vapour Pressure of Concrete with Heating Velocity†

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In this study, concrete specimens of 30, 50, 70 and 90 MPa were heated at the heating rate of 1 °C/min and the ISO-834 standard heating curve to evaluate spalling and vapour pressure. It was found that the higher the strength that the concrete develops, the more section is lost. In addition, the increasing rate of water vapour pressure on the surface of concrete at an early phase were found to have a significant impact on the concrete spalling.

Keywords: Heating velocity, High strength concrete, Water vapour pressure, Spalling.

INTRODUCTION

Concrete, when exposed to high temperature including a fire, is vulnerable in several regards compared with concrete at room temperature. Of the various vulnerabilities, concrete spalling, the process of surface failure in which concrete has broken up, flaked or become pitted, causes the section loss of the structural members and consequently can threaten the stability of the entire building's structure.

In the concrete spalling mechanism, vapour pressure, thermal strain on the surface caused by the difference in internal and external temperatures and the combination of the two aforementioned factors have been revealed as the causes of spalling. The factors that affect spalling can be divided into internal factors and external factors in relation to the mechanical properties of the concrete itself[1-5]. Therefore, for a thorough understanding of spalling these two factors should be sufficiently considered. If heating rate, one of the external factors, differs, the behaviours of condensation and vapour pressure in concrete may vary as a result. However, most of the previous studies on the spalling phenomenon evaluated the internal factors related with the mechanical properties of concrete[1].

For this reason, heating velocity and compressive strength were set as experimental variables in this study for external and internal factors, respectively. To evaluate the spalling and vapour pressure according to the two factors, concrete specimens with different compressive strength were tested. Spalling properties, the relation between spalling and internal vapour pressure were also evaluated.

EXPERIMENTAL

The physical properties of materials used in this study are given in Table-1.

TABLE-1
PHYSICAL PROPERTIES OF MATERIAL

Physical properties	C	BFS	SF	G	S
Specific surface (cm^2/g)	3,160	6,000	200,000	–	–
Specific gravity	3.1	2.9	2.2	2.67	2.65
Size (mm)	–	–	–	20	5
Absorption (%)	–	–	–	1.0	100

C: Ordinary portland cement, BFS: Blast furnace slag powder, SF: Silica fume, G: Coarse aggregate, S: Fine aggregate

Concrete: As shown the Table-2, to evaluate the effect of compressive strength, one of the internal factors, on spalling with the passage of heating, the concrete strength was set at five different levels: W/B 0.55, 0.40, 0.33 and 0.23. In the high strength concrete with less than W/B 0.33, silica fume was added to improve the strength by 5 and 16 % of the weight of the concrete.

Preparation of specimen: To evaluate the vapour pressure inside of the concrete according heating velocity, the specimens were made with dimensions of 100 mm (width) × 100 mm (depth) × 200 mm (height). The specimens were cured under

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TABLE-2
PROPORTION OF THE CONCRETE MIXTURES AND PROPERTIES OF CONCRETE

Properties	30 M	50 M	70 M	90 M
Water/cement	0.55	0.40	0.35	0.31
Water/cementitious	0.55	0.40	0.33	0.23
Water (kg/m^3)	185	175	165	160
Cement (kg/m^3)	336	437	475	508
Blast furnace slag powder (kg/m^3)	0	0	0	104
Silica fume (kg/m^3)	0	0	25	83
Fine aggregate (kg/m^3)	797	770	792	708
Coarse aggregate (kg/m^3)	956	924	950	849
Fresh concrete				
Slump (mm)	175	-	-	-
Slump flow (mm)	-	420	435	620
Air contents (%)	5.7	5.1	4.5	2.5
Hardened concrete				
28 day-Compressive strength (MPa)	31	45	66	95

water for 7 days, then air dry curing was conducted up to 180 days at a steady temperature and humidity chamber set as 20 ± 2 °C, R.H. 50 ± 5 %.

Test methods

Heating method: The heating method of this study is shown in Fig. 1. The heater used in this study uses a heating coil heated by electric resistance. The highest temperature and the temperature rise rate can be controlled using a temperature controller. The heating method was set as heating velocity of 1 °C/min. for the slow heating condition and as ISO-834 standard fire curve for the rapid heating condition to evaluate the spalling and water vapour pressure of the concrete. The highest temperature was set at 900 °C.

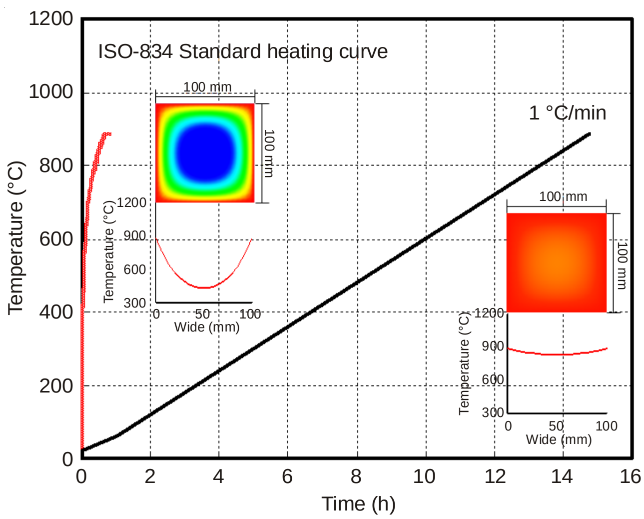


Fig. 1. Heating method

Water vapour pressure measurement: A metal tube was embedded through which the vapour to be measured could pass from inside to outside as Fig. 2. The metal tube (with an internal diameter of 1mm and an external diameter of 2 mm) was made of SUS304 material, which has good thermal resistance.

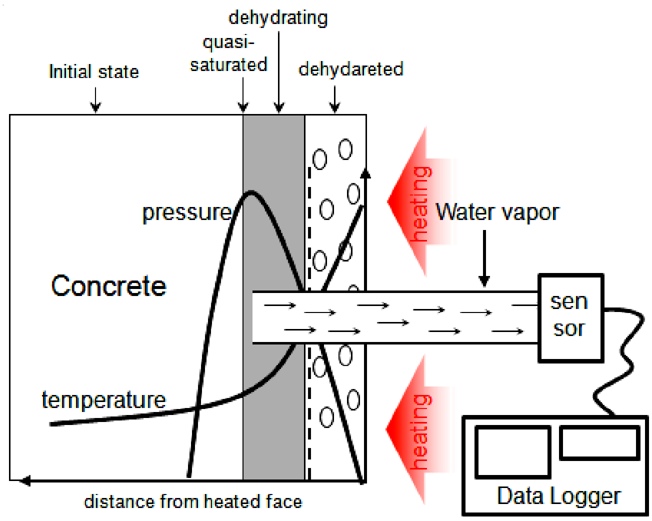
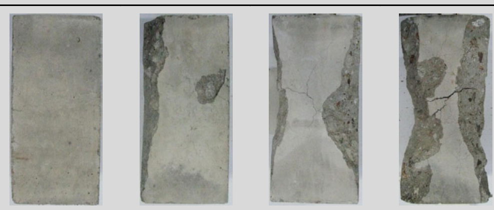
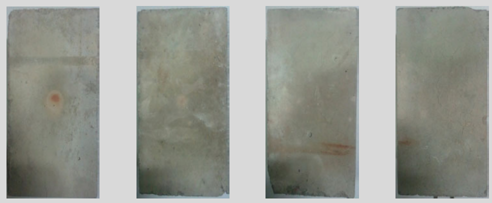


Fig. 2. Water vapor pressure measurement

TABLE-3
SPALLING WITH HEATING VELOCITY

Heating velocity	Specimen ID			
	30 M	50 M	70 M	90 M
ISO-834				
1 °C/min				

RESULTS AND DISCUSSION

Spalling: Table-3 shows the spalling of concrete according to heating velocity and compressive strength of the concrete. For the specimens heated in ISO-843 Standard heating curve, spalling was found in all specimens except that with 30 M. In terms of the specimens with 50 and 70 M, spalling was found at the corners and on the surface at which relatively higher stress was concentrated. On the other hand, for the specimen with 90 M, spalling was found on the entire surface. Under the slow heating condition, when heated at 1 °C/min, no spalling was found in any specimens. Based on the results, the rapid heating velocity was considered to be the cause of spalling within an identical range of compressive strength.

Fig. 3 shows weight loss ratio of concrete specimen, which was calculated by comparing the weight after the concrete was heated with the weight before heating. In the concrete specimens where no spalling was found – the 30 M specimen under the rapid heating condition and those with four different levels of strength - about 7~9 % of weight was lost, which is believed to be because of the various forms of moisture vapourized by heating. In the specimens where slight spalling was found – those with 50 and 70 M - about 10-11 % of weight was lost, which is considered as a relatively smaller loss of section. However, in the specimens where severe spalling was found, 25 % of weight was lost in the specimen with 90 MPa which is considered significant.

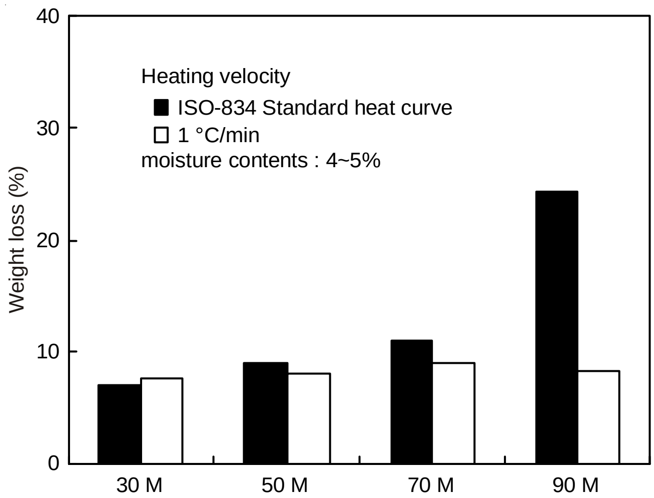


Fig. 3. Weight loss ratio of concrete specimen

Water vapour pressure: Fig. 4 shows the water vapour pressure according to heating velocity and compressive strength. The water vapour pressure was measured at a depth of 30 mm from the surface that was known to affect spalling. Under the rapid heating condition, water vapour pressure was occurred almost simultaneously upon heating, increased rapidly after specimen reached 100 °C and was shown to be highest at about 200 °C. However, under the slow heating condition, vapour pressure occurred at around 200 °C and was shown to be highest at around 400 °C.

Under the rapid heating condition, the water vapour pressure generated on the surface was transferred to the depth of 30 mm at around 100 °C lower than that under the slow heating condition and the highest pressure was measured at about 200 °C lower than that under the slow heating condition. Therefore, the higher the heating velocity is raised, the earlier the vapour pressure is found and the higher the risk of spalling become as a result. This can be verified with the spalling shape evaluation.

Fig. 5 shows the initial increase velocity of water vapour pressure between 9 and 12 min, during which the initial spalling was found at the depth of 30 mm from the surface of the concrete under the rapid heating condition. In the 30 M where no spalling was found, vapour pressure increased at the velocity of 12.6 kPa/min, while in the 50M and 70M where slight spalling was found, vapour pressure increased at the velocity of 45 kPa/min and 61.2 kPa/min, respectively. In the 90 M where severe spalling was found, water vapour pressure increased rapidly at the velocity of 88.2 kPa/min at the initial phase. Overall, the more weight was lost due to spalling, the higher the surface vapour pressure increase in the initial phase.

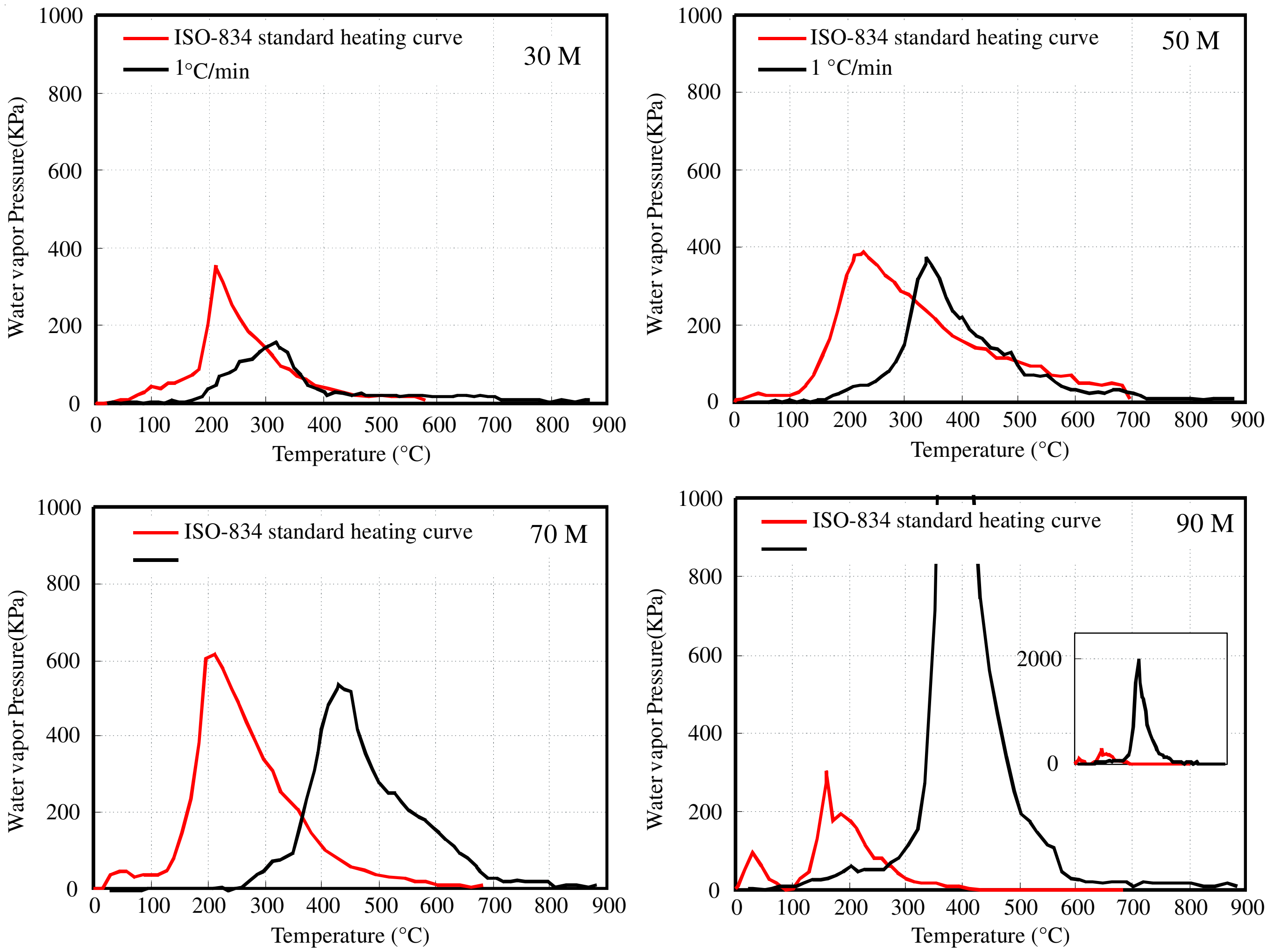


Fig. 4. Water vapour pressure at 30 mm from surface with heating velocity

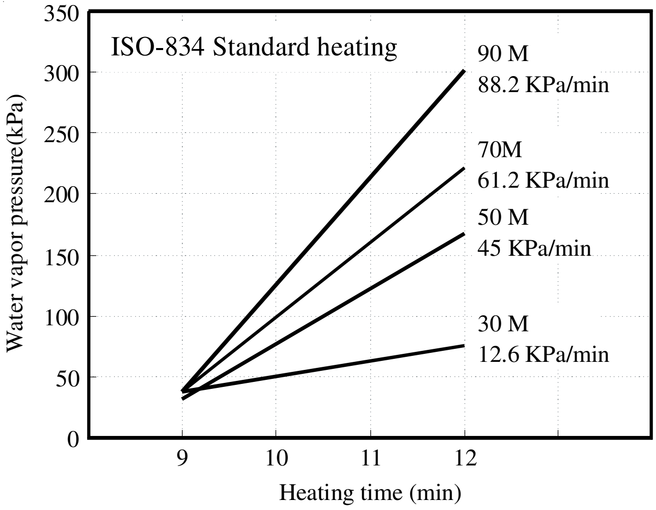


Fig. 5. Increase of water vapor pressure at 30 mm from surface with ISO-834 heating

Conclusions

• The spalling of concrete was found to take place due to rapid heating and in the concrete specimens with compressive strength of 90 MPa or higher, more than 25 % of weight was found to have been lost.

• In the specimens to which slow heating was applied, no spalling was found even though the water vapour pressure was high compared with the water vapour pressure under rapid heating.

• In the concrete specimens to which rapid heating was applied, the surface water vapour pressure increased in the early phase and when the increase velocity of water vapour pressure was measured at 45 kPa/min or higher, spalling was found.

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