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Study of mechanisms of explosive spalling in high-strength concrete at high temperatures using acoustic emission

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HIGHLIGHTS

- ▶ This study used the AE method for detecting the explosive spalling process in HSC.
- ▶ It was found that AE events were indeed indicative of the state of the explosive failure process.
- ▶ *b*-Value analysis was successfully applied to clarify the fracture process.

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ABSTRACT

Mechanisms behind explosive spalling of high-strength concrete during a heating test were investigated on the basis of acoustic emission (AE) measurements of wet and air-dried specimens. The relation between the measured values of the internal temperature and vapour pressure and AE events produced by micro-cracking were investigated. It was found that AE events were indeed indicative of the state of the explosive failure process. Furthermore, *b*-value analysis was successfully applied to clarify the fracture process, regardless of the moisture content of the specimens.

1. Introduction

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.

One mechanism involves the thermo-mechanical process, which is directly associated with the temperature field. As the temperature of the concrete surface increases, the temperature gradients give rise to a distribution of compressive stress in a direction parallel to the concrete surface; the distribution leads to the development of tensile stresses in a perpendicular direction. When the tensile stress exceeds the tensile strength, explosive spalling of concrete occurs, as shown in Fig. 1 [1,2].

The second mechanism involves the mass transfer of liquid phases (liquid water, vapour, and dry air). When the temperature of the concrete surface increases, the moisture content of the concrete varies with depth from the concrete surface, as shown in Fig. 2. Consequently, the vapour pressure in the vapour zone and humid zone becomes larger than that in the dry zone and moist zone. In particular, the vapour pressure dramatically increases at the boundary between the vapour zone and humid zone. Around the peak of the vapour pressure, since high vapour pressure in concrete generates a large tensile stress, concrete spalling would occur [3,4].

Several studies have investigated the second mechanism by comparing vapour pressure with saturated vapour pressure (SVP) [5–7]. It has also been found that the spalling behaviour of concrete is strongly affected by its water content [8]. These studies have shown that explosive spalling could be minimised through the addition of synthetic fibres (especially polypropylene fibre) to high-strength concrete (HSC) [8–10,4,11–18].

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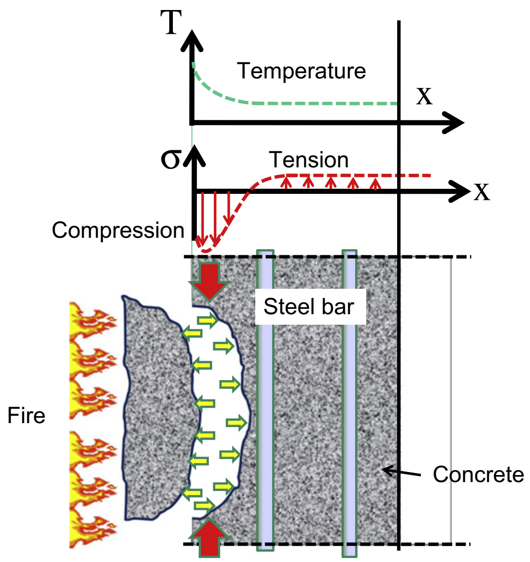

Fig. 1. Spalling mechanism: thermal dilation.

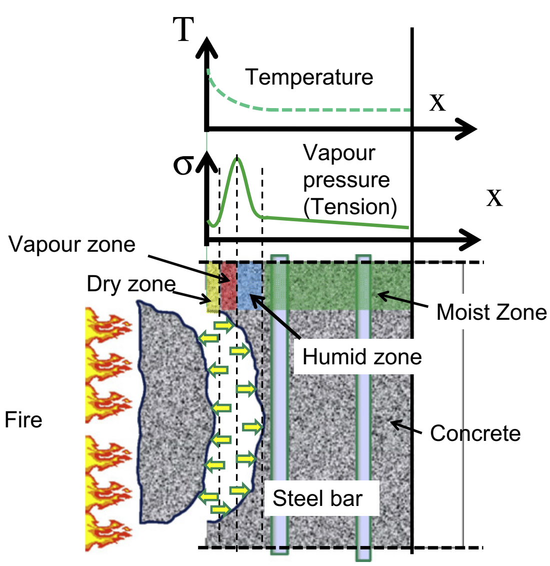

Fig. 2. Spalling mechanism: vapour pressure.

For studying the cracking of concrete, acoustic emission (AE) is known to be particularly useful [19–24]. The Gutenberg–Richter (GR) law is widely used to describe the amplitude distribution of AE signals [25].

$$m = \log a \quad (1)$$

$$\log N = a - bm \quad (2)$$

where m is the magnitude as defined in seismology; m is equivalent to the log scale of the amplitude 'a' of the AE signal. N is the number of signals with a magnitude greater than m, and the coefficient b is the negative slope of the $\log N$–m plot.

AE techniques have been used for damage assessment of materials [26–36]. Specifically, the coefficient exponent b (the so-called b-value) changes with the type of damage. In the initial stages of micro-cracking, a large number of low-amplitude AE signals are dominantly generated; in the later stages, fewer signals are generated, but with higher amplitudes. This implies a progressive decrease in the b-value as the specimen approaches impending failure. This is the core of the so-called 'b-value analysis' used for damage assessment.

AE has previously been used to monitor the explosive spalling behaviour of HSC during heating tests [37–39].

This paper describes the use of AE for monitoring the explosive spalling of HSC during a heating test. The monitoring of the explosive spalling process and comparison of the measured vapour pressure and temperature for different AE events can help elucidate the mechanisms of the explosive spalling process. Further, the applicability of b-value analysis to the estimation of the explosive spalling behaviour of concrete under high temperatures is studied.

2. Materials and methods

2.1. Materials

As listed in Table 1, early strength Portland cement with a specific surface area of 4550 cm^2/g and a density of 3.13 g/cm^3 (chemical composition is shown in Table 2) was used for preparing the concrete material; the water/cement ratio was 0.30. Crushed river stone with a maximum size of 25 mm was used as the coarse aggregate. The main component of the superplasticizer (SP) admixture was a polycarboxylic acid polymer. The fresh concrete properties and the mechanical properties of the hardened concrete at 28 days were measured, as shown in Table 3.

2.2. Specimens and curing conditions

Two types of curing conditions for specimens are mentioned in Table 4. Two specimens were considered for each of the conditions. The dimensions of each specimen were 400 × 400 × 100 mm. As shown in Fig. 3, specimens were tested directly after wet curing (wet) or after further air-drying. The concrete specimens were cast and left in the formwork for 1 day. The specimens were then wet cured at 20 ± 2 °C for 64 days. After wet curing, some specimens were air-dried in controlled conditions (20 °C, RH 40%, 118 days).

2.3. Estimation of water content [40]

Before the heating test, the distribution of the water content of the specimen was determined with six ceramic RH sensors placed at depths of 0, 4, 6, 8, 10, and 52 mm from the surface (Fig. 4).

The water content of concrete was estimated as humidity from the RH values determined by using non-heating-type ceramic humidity sensors. As shown in Fig. 5, this sensor consisted of a humidity-sensing element (ceramic) and a resis-

Table 1
Mixture proportion.

Water cement ratio	Unit weight (kg/m^3)				
	Water	Cement	Fine aggregate	Coarse aggregate	Admixture
0.3	132	440	840	1060	22

Material	Description	Density (g/cm^3)
Water	Tap water	1
Cement	Early strength Portland cement	3.13
Fine aggregate	River sand	2.61
Coarse aggregate	River stone	2.62
Admixture	Super plasticizer and air entraining agent (Poly-carboxylic acid cross-linked polymer)	1.01