Cracking behaviour of restrained cementitious materials with expansive agent by comprehensive analysis of residual stress and acoustic emission signals

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Expansive agent was added in concrete to compensate shrinkage and improve resistance against shrinkage induced cracking. This study investigates cracking evolution of restrained cementitious materials with and without expansive agent based on a comprehensive analysis of residual stress and acoustic emission (AE) signals. Residual stress was calculated according to the measured strains in a dual-ring test. AE parameters such as AE counts, energy, frequency, amplitude and the AE based b -value were studied. The obtained results indicated that the addition of expansive agent led to expansion at early ages, in which case the cement pastes were in a state of compression and the residual tensile stress was delayed. As the material neared the age of visible cracking, an abrupt residual stress release, as well as an obvious AE characteristic (e.g. AE counts and energy) change, would be observed. The most AE hits had an average frequency around 50 kHz. AE hits with larger amplitude occurred less often than the AE hits with smaller amplitude, but the corresponding energy released was much higher. A remarkable decreasing trend in b -value was observed before the sudden residual stress release for the plain cement paste, whereas for the paste with expansive agent the b -value varied relatively smoothly.

Notation

$\langle A \rangle$	arithmetic mean amplitude
$A_{\min}$	minimum amplitude (or threshold limit) of acoustic events
A_T	peak amplitude of acoustic emission hits
a	empirical constant
b	acoustic emission based b -value
E_S	elastic modulus of invar steel, 141 GPa
N_C	number of acoustic emission hits with amplitude greater than A_T
R_{IC}	inner surface radius of ring specimen
R_{ISI}	inner surface radius of inner steel ring
R_{OC}	outer surface radius of ring specimen
R_{OSO}	outer surface radius of outer steel ring

ε_{in}	measured strains at inner face of inner steel ring
ε_{out}	measured strains at outer face of outer steel ring
$\sigma_\theta(R_{IC})$	maximum residual stress that develops at R_{IC}

Introduction

Cement-based materials have been widely used in all kinds of structures while early-age cracking due to shrinkage (e.g. autogenous and drying shrinkage) can be a significant problem. Aggressive agents such as chloride ions can penetrate into concrete along the cracks and lead to corrosion of reinforcing steel bars (Lura *et al.*, 2003; Schlitter *et al.*, 2013; Weiss *et al.*, 1998). In hardened cement composites, volume changes caused by hydration and thermal or drying shrinkage are

restrained by the surrounding structure (e.g. reinforcing bars and aggregates), which leads to development of residual tensile stress and a high risk of cracking (Han *et al.*, 2015; Zou and Weiss, 2014). The problem of early-age cracking has been a greater concern owing to the increasing application of high-strength concrete or high-performance concrete (HPC), which has a lower water to binder ratio and a higher susceptibility to cracking (Hossain and Weiss, 2004; Jensen and Hansen, 2002). Addition of expansive agent could be an effective method for improving resistance against shrinkage-induced cracking (Corinaldesi *et al.*, 2015; Momose and Kanda, 2011). When added into concrete, expansive agent would generate expansion in the mixture, which could reduce or even eliminate shrinkage and lead to compressive stress in a certain restraint condition (Hyeonggil *et al.*, 2015).

Since the 1990s, various studies have been performed to assess cracking behaviour when submitted to restrained shrinkage (Altoubat and Lange, 2001; Briffaut *et al.*, 2011; Grysbowksi and Shah, 1990; Hossain and Weiss, 2006; Moon and Weiss, 2006). Owing to its versatility and simplicity, the ring test has been applied widely to assess residual stress development, remaining stress capacity, cracking potential and cracking age (Hossain and Weiss, 2004; Schlitter *et al.*, 2013; Zou and Weiss, 2014). In the restrained ring test, restraint is imposed immediately after the concrete is cast and the residual stress that develops can be calculated by measured strains at the surface of the steel rings (Schlitter *et al.*, 2013). A sudden change of measured strains on the steel rings could be an indication of cracking and cracking risk can be evaluated by residual stress. Schlitter *et al.* (2010, 2013) developed the dual-ring test to study both expansion and shrinkage of cement-based materials in which invar steel rings were employed, in the case of thermal expansion of the steel rings themselves that cannot be ignored.

In addition, many attempts (Byounggeon and Weiss, 2003; Farnam *et al.*, 2015; Ohtsu, 1996; Sagar and Prasad, 2012a; Sagar *et al.*, 2012b) have been made to identify the crack evolution, that is, the initiation and propagation of micro-cracks. Among the techniques applied to detect cracking, acoustic emission (AE) is a real-time, non-destructive test method to monitor crack growth and the damage process, not only on the surface but also inside the materials (Ohtsu, 2005; Saliba *et al.*, 2014). When a crack develops in cement-based materials, energy is released simultaneously by the formation of elastic waves which can be captured by an AE station. Several researchers have used AE as a quantitative means to monitor crack development and the damage process in concrete by analysing the characteristics of the AE waves (e.g. AE hits, energy, amplitude, duration and frequency, and so on) (Ohtsu, 1996; Sagar and Prasad, 2012a; Sagar *et al.*, 2012b). As AE can offer a continuous measurement of cracking formation, it may serve as a useful tool in understanding the fundamental mechanisms by analysis of AE

signals in cracking (Carpinteri *et al.*, 2013; Landis and Ballion, 2002).

The ring test has an advantage of assessing residual stress and cracking time while more information about cracking evolution is still needed. Although Byounggeon and Weiss (2003), Sagar and Prasad (2012a), Sagar *et al.* (2012b) used AE techniques in concrete engineering and applied the technique to assess the formation of micro-cracks, crack healing and damage in concrete under various types of load, there has been very little research in quantifying AE parameters in the shrinkage-induced cracking process of restrained specimens. In this study, the dual-ring tests were carried out to assess quantitatively the residual stress in the restrained specimens and the AE signals were recorded simultaneously. The objective of the current research was to identify the initiation and growth of micro-cracks by a comprehensive investigation of residual stress and AE parameters. In addition, the AE based *b*-value analysis correlating with the residual stress development was performed as a tool to characterise the cracking evolution. Previous researchers have used the variation of AE based *b*-values to predict the fracture process in rock or concrete samples (Prem *et al.*, 2015; Rao and Lakshmi, 2005; Shiotani *et al.*, 2001). It logically follows that a more accurate characterisation of the cracking condition in the restrained ring specimens could be possible by analysis of the variation of the AE based *b*-value.

Experimental programme

To describe fully the residual stress and the corresponding AE characteristics, a dual-ring test was employed, in which AE sensors were fixed on the surface of the restrained ring specimens to detect elastic waves. The details are described in the following sections.

Materials and mixture proportioning

In this experiment, ordinary Portland cement (OPC) was used with a calculated Bogue phase composition of 54.1% tricalcium silicate (C_3S), 18.6% dicalcium silicate (C_2S), 6.3% tricalcium aluminate (C_3A) and 9.4% tetracalcium aluminoferrite (C_4AF). The expansive agent used was a compound expansion additive. The chemical compositions of cement and expansive agent are listed in Table 1. Water to cementitious materials ratio was chosen as 0.3. To quantify different cracking performance of the cement pastes, three types of specimens were prepared in which the mass content of expansive agent was 0, 4% and 6% (weight percentage of cementitious materials).

The dual-ring test

Based on previous studies (Briffaut *et al.*, 2011; Hossain and Weiss, 2006), a dual-ring restraint test was performed to evaluate quantitatively the residual stress in the specimens. Figure 1 shows an overview of the dual concentric rings made of invar steel used in the test. R_{IC} and R_{OC} are the inner surface radius and outer surface radius of the ring specimen, respectively; R_{ISI} is the inner surface radius of the inner steel ring; R_{OSO} is

Material	w: %								
	Aluminium oxide (Al_2O_3)	Calcium oxide (CaO)	Iron (III) oxide (Fe_2O_3)	Potassium oxide (K_2O)	Magnesium oxide (MgO)	Sodium oxide (Na_2O)	Sulfur trioxide(SO_3)	Silica (SiO_2)	Loss
Cement	4.34	62.16	3.08	0.72	1.71	0.12	2.68	20.74	4.45
Expansive agent	6.45	68.30	0.51	—	1.39	—	20.80	2.22	0.33

Table 1. Chemical compositions of raw materials

Figure 1. Geometry of restrained steel rings

the outer surface radius of the outer steel ring. The dimensions are as follows: $R_{ISI} = 60$ mm, $R_{IC} = 90$ mm, $R_{OC} = 150$ mm, $R_{OSO} = 165$ mm. The height of the inner steel ring, outer steel ring and the specimen was chosen as 75 mm.

Three strain gauges (with accuracy to $\pm 1 \mu\epsilon$) were fixed to the outer surface of the outer ring and the inner surface of the inner ring at 120° with respect to each other at mid-height, respectively, to measure the strain of the steel rings in the test. Strains of the steel rings were recorded by a data acquisition system every 1 min after the cement paste had been cast. The averages of the measured strains on the outer and inner ring were taken as the strains of the outer and inner ring, respectively.

The ring specimens were sealed with plastic sheets immediately after the cement paste had been cast between the inner and outer steel rings to prevent fast drying by moisture evaporation. The plastic sheets were removed after 24 h, permitting drying from the top and bottom surfaces of the ring specimen, and cured in drying conditions. The specimens were all stored in a $20 \pm 2^\circ\text{C}$, $60 \pm 5\%$ relative humidity (RH) environment. Figure 2 gives an illustration of water evaporation and residual

Figure 2. Illustration of water evaporation in drying curing condition

stress distribution along the radial direction for the restrained ring specimen in drying curing conditions (Hossain and Weiss, 2004, 2006).

Acoustic emission test

Set-up and sensors

The AE system used in this experiment was from Physical Acoustics Corporation (PAC). The AE set-up consists of piezo-electric-based acoustic sensors, pre-amplifiers, a high-speed data acquisition system (allowing sampling rates of up to 1 mega samples per second for each channel) and a monitoring system (Figure 3(a)). The acoustic sensor was an R6a resonant type sensor and the signals were amplified using a preamplifier (Figure 3(b), 40 dB) and fed directly to a six-channel AE station with a bandwidth of 400 kHz. Then the AE signals were filtered and post-processed with the help of the software packages AEWIn from PAC.

To record the specific AE signals generated in the restrained ring test, AE sensors were placed on the top surface of the specimens (Figure 3(c)). The sensing surfaces of the AE sensors were brushed with silicon grease as a coupling agent (Sagar *et al.*, 2012b) and fastened properly to ensure a better contact at the AE sensor–cement paste interface. Before recording the AE signals, all of the sensors had been calibrated with the pencil lead breaking procedure on a metal plate (Prem *et al.*, 2015) and had behaved well. Noise tests were performed and the amplitude threshold was chosen as 30 dB after a series of careful adjustments.

Figure 3. Experimental set-up for AE measurement: (a) schematic diagram of AE measurement system; (b) pre-amplifier gain, 20 dB, 40 dB, 60 dB, selectable; (c) restrained ring specimen with AE sensors on the surface

AE data processing

Acoustic emission parameters such as AE hits, AE counts, energy, amplitude, duration time and frequency were used to relate the AE activity to the cracking behaviour (Byounggeon and Weiss, 2003; Ohtsu, 1996). Any structural change process or failure that occurs inside the material may yield AE signals, which are termed as AE hits (Prem *et al.*, 2015). The AE counts are the number of times that the measured signal level is higher than the threshold signal level (i.e. 30 dB in this experiment) in a specific AE hit, which serves as the first level of quantified AE information and an important hint at the magnitude of AE activities. The AE energy is the true energy of any hit (Sagar *et al.*, 2012b), which could be related to the energy released in the damage process. The AE amplitude depends on the magnitude of any micro-fracture event occurring in the materials and a relationship between amplitude A and energy E can be established, which should follow $E \propto A^2$, as the energy is the area under the curve of the AE waveform (Prem *et al.*, 2015). So AE energy is also related to the duration time, which is a materials- and source-dependent parameter. The average frequency is obtained by the frequency component having the average power spectral density (psd) in an AE power spectrum, generated using the fast Fourier transform (FFT). In the measurements of the present study, the frequency spectrum was also used to quantify micro-crack evolution.

Furthermore, the AE amplitude distribution was analysed according to what is known as b -value analysis (Prem *et al.*, 2015; Rao and Lakshmi, 2005; Shiotani *et al.*, 2001). A close

analogy may exist between the AE activity caused during the cracking process of specimens in the restraint condition and the natural seismic activity occurring within the Earth's crust (Rao and Lakshmi, 2005); therefore, the dynamics of cracking evolution may also follow a power law distribution for rupture events. In the AE technique, the Gutenberg–Richter relationship could be expressed as Equation 1 (Gutenberg and Richter, 1954).

$$1. \quad \log N_C = a - b \log(A_T)$$

where A_T is the peak amplitude of AE hits in decibels, N_C is the number of AE hits with amplitude greater than A_T , a is an empirical constant and b is the AE based b -value. To use the Gutenberg–Richter equation (GBR method) for the AE data analysis, it is necessary to revise the measured AE amplitude divided by a factor 20 (Sagar *et al.*, 2012b). It was reported that the b -value could be used as a representation for the relative proportion of large to small fracture events evolved during the damage process (Sagar and Prasad, 2012a; Sagar *et al.*, 2012b).

In 1965, Aki (1965) also proposed a statistical method related to the b -value estimate based on a maximum likelihood estimate. The b -value based on Aki's method is given by Equation 2.

$$2. \quad b = \frac{\log(e)}{\langle A \rangle - A_{\min}}$$

where $\langle A \rangle$ is the arithmetic mean amplitude and $A_{\min}$ is the minimum amplitude (or threshold limit) of the acoustic events.

Results and discussion

Determination of residual stress

Figures 4 and 5 show the measured strains of the inner and outer steel rings respectively. In the case of plain cement paste (without expansive agent), the shrinkage strain was recorded on the inner steel rings with an abrupt change of strain at about 98 h, indicating cracking occurrence, and the expansion strain was hardly recorded on the outer steel rings. However, in the case of cement pastes with 4% and 6% expansive agent, it could be observed that shrinkage strain on the inner steel rings and expansion strain on the outer steel rings were recorded, which confirmed expansion in the mixture at an early age. It could also be noted that greater expansion led to a larger expansion strain on the outer steel rings when a higher content of expansive agent was added to the mixture.

Figure 4. Measured strains of inner steel rings

Figure 5. Measured strains of outer steel rings

Using the measured strain of the steel rings, the maximum residual stress in the specimens can be calculated using Equation 3 (Schlitter *et al.*, 2010).

$$\sigma_{\theta}(R_{IC}) = -\varepsilon_{in} E_S \left(\frac{R_{IC}^2 - R_{ISI}^2}{2R_{IC}^2} \right) \times \left(\frac{R_{OC}^2 + R_{IC}^2}{R_{OC}^2 - R_{IC}^2} \right) - \varepsilon_{out} E_S \left(\frac{R_{OSO}^2 - R_{OC}^2}{2R_{OC}^2} \right) \times \left(\frac{2R_{OC}^2}{R_{OC}^2 - R_{IC}^2} \right) \quad (3)$$

In this equation $\sigma_{\theta}(R_{IC})$ is the maximum residual stress that develops at R_{IC} ; ε_{in} and ε_{out} are measured strains at the inner face of the inner steel ring and the outer face of the outer steel ring; and E_S is the elastic modulus of invar steel, which is taken to be 141 GPa.

Figure 6 illustrates the residual stress development for the restrained ring specimens which were exposed to the drying condition after 24 h. It could be observed that, for the plain paste, residual tensile stress increased gradually until a sudden stress release at about 98 h. At the same time a localised, visible crack was found on the surface of the corresponding ring specimen (Figure 7). However, the pastes with expansive agent (4%, 6%) were in a state of compression (a compressive stress about 1.8–2.2 MPa) in the first 60 h because of shrinkage reduction. The tensile stress was delayed to 75 h for 4% paste and 102 h for 6% paste. The residual tensile stress was relatively lower for cement paste with 6% expansive agent than for that with 4% expansive agent, and no visible cracks were found for either of the pastes with 4% or 6% expansive agent in the experiment.

Analysis of AE hits

AE counts and energy released

Figure 8 shows AE counts and cumulative AE counts plotted against time in the experiment. From Figure 8 it was observed

Figure 6. Residual stress of specimens

Figure 7. A visible crack observed on the plain paste specimen

Figure 8. AE counts and cumulative AE counts

that there was a rapid increase by 3857 around 98 h in the cumulative AE counts for the plain cement paste, which was consistent with the occurrence of the sudden residual stress release around 98 h and could be attributed to a large number of AE hits released by formation of macro visible cracks. In the case of paste with 4% expansive agent, the number of AE counts was relatively fewer and the cumulative AE counts increased along a gradient with a smaller increase range, for example, 453, 590, 1231, which could be due to initiation and propagation of micro-cracks inside.

It is known that AE energy is related to energy release in a material during fracture and could offer a quantitative measure of cracking propagation (Sagar and Prasad, 2009, 2011). Figure 9 shows AE energy and cumulative AE energy plotted against time. Similarly, a rapid increase was observed around 98 h in the cumulative AE energy for the plain cement paste. The paste with 4% expansive agent

Figure 9. AE energy and cumulative AE energy

Figure 10. AE frequency spectrum for specimens

released less energy and the increase range was relatively lower, for example, 228, 418, 658.

AE frequency spectrum

The frequency spectrum of the AE signals was analysed as shown in Figure 10. Farnam *et al.* (2015) reported that AE events with a high frequency range (e.g. 300~400 kHz) indicated aggregate cracking, and low-frequency AE events (e.g. 100~300 kHz) indicated matrix cracking (paste and interfacial transition zone, ITZ). From Figure 10 it can be observed that the AE signals had a wide frequency range from 0 to 1000 kHz, whereas most AE hits had a relatively lower frequency, around 50 kHz for all of the specimens whether with expansive agent or not. This could be an indication that

micro-cracking induced by restrained volume change had an even lower average frequency than that obtained in the wedge splitting test.

AE amplitude

Figures 11 and 12 show AE amplitude and AE hit duration time, respectively. The AE amplitude threshold was set at 30 dB in the experiment and the specimens had largest amplitudes of 76 dB, 75 dB and 61 dB for the plain, 4% and 6% pastes, respectively. It could also be observed that AE signals with the largest amplitude and duration time were recorded around 98 h, which coincided with sudden stress release, rapid increases in cumulative AE counts and cumulative AE energy. It should be noted that the occurrence of penetrating tensile cracking had greater AE amplitude and duration time than cracking initiation and propagation.

Figure 13 shows the number of AE hits on the vertical scale and amplitude in dB on the horizontal scale. It was observed

that AE hits with larger amplitude (e.g. $A \geq 50$ dB) occurred less frequently than the AE hits with smaller amplitude, which occurred at a relatively higher number. AE energy released was taken into account and the percentage in terms of the total AE energy was calculated and is shown in Figure 14. It could be observed that AE hits with amplitude less than 50 dB were much more numerous, while the AE energy associated with these AE hits was relatively lower (Table 2). It could be said that the damage that occurred owing to these AE hits was much less. The AE hits with amplitude above 50 dB were fewer, but the corresponding AE energy released was much higher. They made a significant contribution to the fracture process zone (FPZ) owing to their high contribution of AE energy (Sagar *et al.*, 2012b).

The *b*-value estimate

The mechanical performance of cement-based materials is greatly influenced by the initiation and propagation of micro-cracks inside. The initiation and propagation of micro-cracks

Figure 11. AE amplitude measured in experiment

Figure 13. Variation of AE hits with amplitude

Figure 12. AE hit duration measured in experiment

Figure 14. Distribution of AE energy

AE amplitude: dB	AE hits		AE energy released (relative units)	
	Number	%	Total energy	%
For plain cement paste				
Total	333	100	1897	100
30~50	313	94.0	299	15.76
Above 50	20	6.0	1598	84.24
For cement paste with 4% expansive agent				
Total	271	100	987	100
30~50	260	95.9	222	22.5
Above 50	11	4.1	765	77.5
For cement paste with 6% expansive agent				
Total	563	100	535	100
30~50	552	98.0	275	51.4
Above 50	11	2.0	260	48.6

Table 2. Distribution of AE amplitude and AE energy

were studied based on the variations of AE based b -value. In previous studies the b -value analysis was mainly performed on cement-based materials under external load (Carpinteri *et al.*, 2013; Sagar *et al.*, 2012b). In the case of restrained cement paste specimens, volume change prevented by steel rings resulted in the development of residual stress. Obviously there would be micro-cracks when the residual stress developed close to tensile strength, which could yield different AE signals with different amplitudes and energy. Then the b -value would show a change during the damage process and could be used to estimate the cracking development.

The AE based b -values of both GBR method and Aki's method were computed as described in the section entitled 'AE data processing' and are shown as a function of time in Figure 15. It could be observed that the temporal variation of the b -value obtained from both the methods followed similar trends. Useful information could be obtained when residual stress development was taken into account. From Figure 15(a), for the plain cement paste it was observed that AE based b -value initially increased, which could be due to an increase in the number of AE hits and the initiation of internal cracks. A decrease in the b -value was reported during the failure of quasi-brittle materials such as rock samples under compressive load (Lockner, 1993; Main *et al.*, 1989). In this experiment, the present authors also observed a remarkable decreasing trend in b -value between 58 h and 93 h with the development of tensile stress, earlier than the sudden residual stress release at 98 h. It could be said that AE signals were more sensitive to crack propagation and had an advantage in the accurate identification of damage developed in cement-based materials. After visible cracking had been detected, the AE based b -value varied, which might be analogous to the after-shocks in an earthquake.

Figure 15. Variations of AE based b -value and residual stress with time in: (a) plain specimen; (b) specimen with 4% expansive agent; (c) specimen with 6% expansive agent

From Figure 15(b), for the cement paste with 4% expansive agent it was observed that the AE based b -value varied between 0.95 and 1.5. An increase in the b -value was recorded when residual stress turned to tensile stress around 75 h. The b -value of the cement paste with 6% expansive agent is shown

in Figure 15(c) and it can be observed the b -value varied smoothly with a change in the later stage. The magnitude of the b -value of the cement paste with 6% expansive agent was higher than the other two specimens, indicating less cracking for the paste with 6% expansive agent (Zitto *et al.*, 2015). The b -values of restrained specimens with expansive agent were mostly dominated by the AE events having lower magnitudes or energy corresponding to a relatively lower risk for cracking.

Conclusions

Based on the results obtained in the study, the major conclusions can be drawn as follows.

- (a) Comprehensive analysis of residual stress and the AE parameters can give a more accurate description of the cracking evolution of cement-based materials due to volume change in restraint tests.
- (b) Addition of expansive agent led to expansion at early ages in the cement paste which delayed the generation of tensile stress and reduced the residual stress. Sudden residual stress release would be an indication of macro visible cracking.
- (c) For the plain cement paste a rapid increase in the cumulative AE counts or cumulative AE energy was observed which could be due to a large number of AE hits released by formation of macro visible cracks. A lower gradient with smaller increase range in cumulative AE counts or cumulative AE energy was observed for the cement paste with expansive agent, which could be due to the initiation and propagation of micro-cracks. The most AE hits had the average frequency around 50 kHz for all of the specimens in the restrained ring test. AE hits with larger amplitude occurred less than the AE hits with smaller amplitude, which occurred in relatively higher number. The AE hits with larger amplitude were fewer, but the corresponding energy released was much higher.
- (d) The initiation and the propagation of micro-cracks could be related to the variations of AE based b -value. For all of the specimens in the restrained test, the temporal variations of the b -value obtained from GBR and Aki's method followed similar trends. For the plain cement paste a remarkable decreasing trend in b -value was observed earlier than the sudden residual stress release, which showed AE signals had more sensitivity to crack propagation. For the paste with expansive agent the b -value varied relatively smoothly.

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REFERENCES

- Aki K (1965) *Maximum Likelihood Estimates of b in the Formula $\log N = a - bm$ and Its Confidence Limits*. Bull Earthquake Research Institution 43, Tokyo University, Tokyo, Japan.
- Altoubat S and Lange DA (2001) Creep, shrinkage, and cracking of early age concrete. *ACI Materials Journal* **98**(4): 323–331.
- Briffaut M, Benboudjema F, Torrenti JM and Nahas G (2011) A thermal active restrained shrinkage ring test to study the early age concrete behavior of massive structures. *Cement and Concrete Research* **41**(1): 56–63.
- Byounggeon K and Weiss WJ (2003) Using acoustic emission to quantify damage in restrained fiber-reinforced cement mortars. *Cement and Concrete Research* **33**(2): 207–214.
- Carpinteri A, Lacidogna G, Accornero F *et al.* (2013) Influence of damage in the acoustic emission parameters. *Cement and Concrete Composites* **44**: 9–16.
- Corinaldesi V, Nardinocchi A and Donnini J (2015) The influence of expansive agent on the performance of fibre reinforced cement-based composites. *Construction and Building Materials* **91**: 171–179.
- Farnam Y, Geiker MR, Bentz D and Weiss J (2015) Acoustic emission waveform characterization of crack origin and mode in fractured and ASR damaged concrete. *Cement and Concrete Composites* **60**: 135–145.
- Grysbowski M and Shah SP (1990) Shrinkage cracking of fiber reinforced concrete. *ACI Materials Journal* **87**(2): 138–148.
- Gutenberg B and Richter CF (1954) *Seismicity of the Earth and Associated Phenomena*, 2nd edn. Princeton University Press, Princeton, NJ, USA.
- Han Z, Haora L and Xuechao Z (2015) On concrete restrained eccentric ring and squared eccentric ring shrinkage test methods. *Construction and Building Materials* **84**: 239–244.
- Hossain AB and Weiss WJ (2004) Assessing residual stress development and stress relaxation in restrained concrete ring specimens. *Cement and Concrete Composites* **26**(5): 531–540.
- Hossain AB and Weiss WJ (2006) The role of specimen geometry and boundary conditions on stress development and cracking in the restrained ring test. *Cement and Concrete Research* **36**(1): 189–199.
- Hyeonggil C, Myungkwan L, Ryoma K, Takafumi N and Gyuyong K (2015) Restrained shrinkage behavior of expansive mortar at early ages. *Construction and Building Materials* **84**: 468–476.
- Jensen OM and Hansen PF (2002) Water-entrained cement-based materials: II. Experimental observations. *Cement and Concrete Research* **32**(6): 973–978.
- Landis E and Ballion L (2002) Experiments to relate acoustic energy to fracture energy of concrete. *Journal of Engineering Mechanics* **128**(6): 698–702.
- Lockner D (1993) The role of acoustic emission in the study of rock fracture. *International Journal of Rock Mechanics and Mining Sciences* **30**(7): 883–899.

- Lura P, Jensen OM and Breugel KV (2003) Autogenous shrinkage in high-performance cement paste: an evaluation of basic mechanisms. *Cement and Concrete Research* **33**(2): 223–232.
- Main IG, Meredith G and Jones C (1989) A reinterpretation of the precursory seismic b-value anomaly from mechanics. *Geophysical Journal International* **96**(1): 131–138.
- Momose H and Kanda T (2011) Quantitative estimation of drying shrinkage reduction effects due to an expansive additive. *Journal of Structural and Construction Engineering* **76**(666): 1367–1373.
- Moon JH and Weiss WJ (2006) Estimating residual stress in the restrained ring test under the circumferential drying. *Cement and Concrete Composites* **28**(5): 486–496.
- Ohtsu M (1996) The history and development of acoustic emission in concrete engineering. *Magazine of Concrete Research* **48**(177): 321–330.
- Ohtsu M (2005) Nondestructive evaluation of damaged concrete due to freezing and thawing by elastic-wave method. *Journal of Advanced Concrete Technology* **3**(3): 333–341.
- Prem D, Kapil JC and Ashavani K (2015) Acoustic emission characteristic and b-value estimate in relation to waveform analysis for damage response of snow. *Cold Regions Science and Technology* **119**: 170–182.
- Rao MVMS and Lakshmi KJP (2005) Analysis of b-value and improved b-value of acoustic emissions and accompanying rock fracture. *Current Science* **89**(9): 1577–1582.
- Sagar RV and Prasad BKR (2009) AE energy release during the fracture of HSC beams. *Magazine of Concrete Research* **61**(6): 419–435.
- Sagar RV and Prasad BKR (2011) An experimental study on acoustic emission energy as a quantitative measure of size-independent specific fracture energy of concrete beams. *Construction and Building Materials* **25**(5): 2349–2357.
- Sagar RV and Prasad BKR (2012a) A review of recent development in parametric base acoustic emission techniques applied to concrete structures. *Nondestructive Testing and Evaluation* **27**(1): 47–68.
- Sagar RV, Prasad BKR and Kumar SS (2012b) An experimental study on cracking evolution in concrete and cement mortar by the b-value analysis of acoustic emission technique. *Cement and Concrete Research* **42**(8): 1094–1104.
- Saliba J, Loukili A, Grondin F and Regoin JP (2014) Identification of damage mechanisms in concrete under high level creep by the acoustic emission technique. *Materials and Structures* **47**(6): 1041–1053.
- Schlitter JL, Senter AH, Bentz DP, Nantung T and Weiss WJ (2010) Development of a dual ring test for evaluating residual stress development of restrained volume change. *Journal of ASTM International* **7**(9): 1–13.
- Schlitter JL, Bentz DP and Weiss WJ (2013) Quantifying stress development and remaining stress capacity in restrained, internally cured mortars. *ACI Materials Journal* **110**(1): 3–11.
- Shiotani T, Yuyama S, Li ZW and Ohtsu M (2001) Application of AE improved b-value to quantitative evaluation of fracture process in concrete materials. *Journal of Acoustic Emission* **19**: 118–133.
- Weiss WJ, Yang W and Shah SP (1998) Shrinkage cracking of restrained concrete slabs. *Journal of Engineering Mechanics* **124**(7): 765–774.
- Zitto ME, Pietrkowski R, Gallego A, Sagasta F and Benavent-Climent A (2015) Damage assessed by wavelet scale bands and b-value in dynamical tests of a reinforced concrete slab monitored with acoustic emission. *Mechanical Systems and Signal Processing* **60–61**: 75–89.
- Zou DH and Weiss WJ (2014) Early age cracking behavior of internally cured mortar restrained by dual rings with different thickness. *Construction and Building Materials* **66**(15): 146–153.

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