THE HISTORY AND DEVELOPMENT OF ACOUSTIC EMISSION IN CONCRETE ENGINEERING

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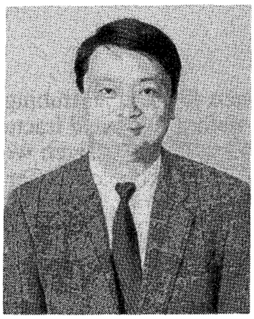

Masayasu OHTSU

Acoustic Emission (AE) is applied to a variety of fields related to concrete engineering. With increasing need for maintenance, the nondestructive evaluation of in-service structures is being actively investigated all over the world. In particular, there is a realization that a number of civil structures are approaching the limit of their service life in Japan. AE techniques look promising as means of inspecting such structures and evaluating their structural integrity. In addition to the demand for the maintenance, the application of AE to construction monitoring is drawing fresh attention. Research activities related to concrete technology are summarized with a brief review of historical developments.

Keywords : *acoustic emission, nondestructive evaluation, crack detection, construction monitoring, maintenance*

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1. INTRODUCTION

In the 1960s AE (acoustic emission) techniques drew a great deal of attention for the inspection of pressure vessels in the U. S.. The level of research activity became so high that International AE Symposia were held all over the world. Among these, the International Symposium organized by the Japanese Society for Nondestructive Inspection (JSNDI) has been held every other year since 1972 [1]. In the field of civil engineering, it is only in Japan that AE conferences have been held continuously, and the 5th Domestic Conference was held in 1993 [2]. In response to this high level of research activity, AE has been investigated increasingly as a diagnostic tool for existing concrete structures. Further, the application of AE to construction monitoring has also attracted a good deal of attention recently. Thus, an updated review of the application of AE to concrete engineering is given here. In addition, historical development of AE in concrete engineering are briefly summarized.

2. HISTORY OF AE RESEARCH

Earlier in AE history, major efforts were directed at probing the fundamentals of AE phenomena and studying AE behavior during the deformation and fracture of various materials. In the literature [3], it began in Germany in 1950 with the research work on metal carried out by J. Kaiser, although AE on rock was known in mining technology. Terminology-wise, the use of "AE" was initiated by B. H. Schofield in the U. S. in 1954. He published the pioneering report entitled "Acoustic Emission under Applied Stress". Quite recently, T. F. Drouillard found that the first report on a scientifically planned AE experiment was published in Japan [4]. In order to study fracture of earth's crust, F. Kishinouye of the Earthquake Research Institute at Tokyo Imperial University, conducted a series of experiments to record AE signals from fractures of wood [5]. To date, this is recognized as the oldest AE report anywhere.

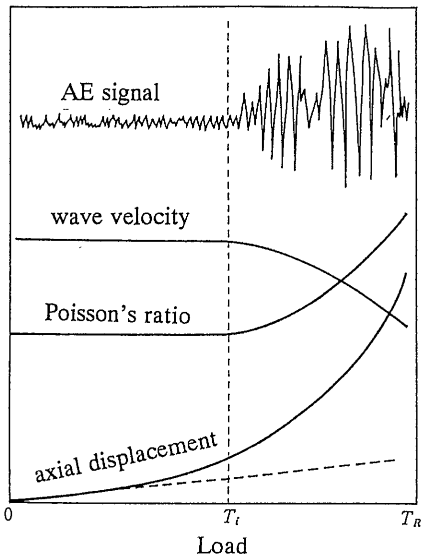


Fig. 1 Mechanical parameters of concrete under compression [7]

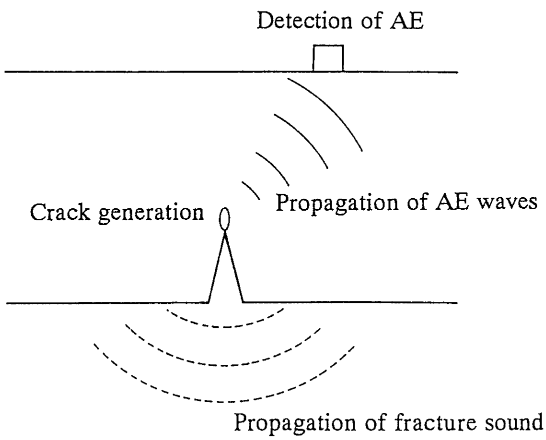


Fig. 2 Generation, propagation and detection of AE signals

With regard to AE research in concrete, three early papers were published [6,7,8]. These discussed the relation between the fracture process and volumetric change in the concrete under uniaxial compression. With the crude equipment of the day, it was reported that AE events were recorded above 75 % failure load, with occurrence increasing more and more as the final failure was approached. As can be seen in Fig. 1, this AE activity over 75% failure load is closely correlated with the decrease in wave velocity and volumetric change (increases in Poisson's ratio and axial displacement). This fact led to one well-known episode of misunderstanding in Japan. Based on the high AE activity at greater than 75% failure load, the concept of "genuine strength of concrete" was proposed by H. Yokomichi of Hokkaido University [9]. Although this was only a comment on the fact that the stress level at the onset of active AE generation was closely related to the fatigue limit and creep strength of concrete, a newswriter tragically misinterpreted this concept and erroneously reported that accidental failure of concrete structures might occur due to faulty design based on conventional non-genuine strength.

Recent application of AE to concrete engineering started in the late 1970s [10,11,12,13]. Originally, technology developed for use with metals was modified to suit concrete. Later, research interest grew stronger. In 1986, T. F. Drouillard listed 76 papers in the bibliography: AE literature-concrete [14]. A committee report on nondestructive testing by the Japan Concrete Institute (JCI) collected 116 papers published in Japan and 8 overseas during the period 1980 to 1991 [15]. These outcomes are updated in the following sections.

3. BASICS OF AE MEASUREMENT

3. 1 AE phenomena

Cracking takes place with the release of stored strain energy at the time of fracture. As a result of microcracking, some of the stored energy is released as elastic waves, which are called acoustic emission (and abbreviated as AE). As shown in Fig. 2, AE waves propagates through concrete and can be detected on the surface by an AE sensor, which turns the vibrations into electrical signals. The propagation of fracture sound was originally referred to as AE, since it is acoustic and audible.

On the basis of elastodymanics, it has been clarified that AE waves could be synthesized as elastic waves due to dislocation motion [16]. Physically, AE waves consist of P waves (longitudinal waves) and S waves (shear waves), and further might include surface waves (Rayleigh waves), reflected waves, diffracted waves, and other components. In particular, the latter portion of AE waveform normally results from resonance vibration of AE sensor. A detected AE waveform should theoretically start with the P wave portion. If the noise level is high and the P wave is interfered with, the first motion may not be discriminated and either the S wave or Rayleigh wave may be observed. It should be noted that the first motions detected are thus not necessarily P waves at the source (flaw) location.

In metals, two types of AE waveform are conventionally known. One is of a burst type and the other is continuous. It is, however, understood that they are basically identical; their durations become different depending on attenuation. In a material with high attenuation, AE wave amplitude decreases immediately, while the amplitude is maintained in low-attenuation materials. The former leads to AE waves of burst type, and the latter gives rise to continuous AE waves.

3. 2 Measuring system

AE signals are usually amplified first by a pre-amplifier and then by a main amplifier, as shown in Fig. 3. They are filtered using a bandpass filter. A typical AE sensor transforms elastic vibrations of 10^{-9} mm amplitude into electrical signals of 10^{-6} V amplitude. Sensors need to have high signal-to-noise (S/N) ratio and a flat frequency response over a broad range. The

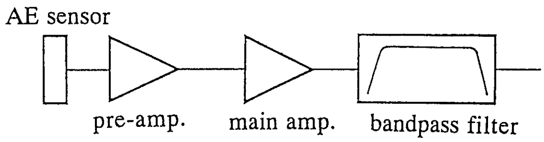


Fig. 3 AE measuring system

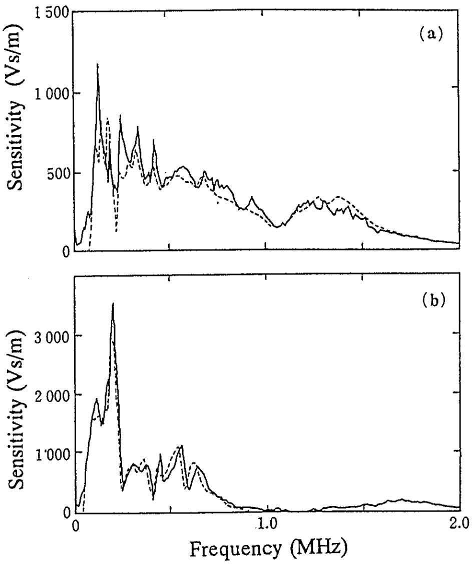


Fig. 4 Frequency response of AE sensors

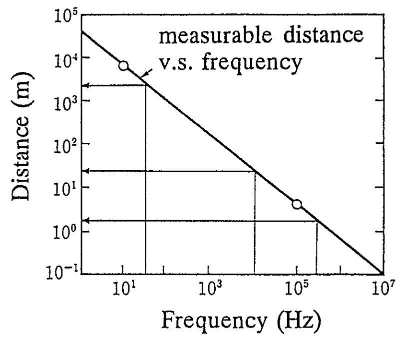


Fig. 5 Relation between distance and frequency range

frequency response of commercially available AE sensors are given in Fig. 4; the top figure is for a broad–band transducer and the bottom for a resonant type. When AE waves are generated in concrete, the detected signals are masked by these responses. As can be seen, both transducers respond so irregularly that the frequency content of an AE signal would be smeared by the sensor response. It should be noted that the use of waveguide introduces further complexity to frequency content of AE waves.

The gain of the amplifier is given in dB (decibels), which represents the ratio between input voltage Ei and output voltage Eo, as follows;

$$dB = 20 \log_{10}(Eo/Ei). \quad (1)$$

In concrete, it is found that AE events can be detected using amplifier with 60 to 100 dB of gain.

The optimal frequency range in concrete is known to be from several kHz to a few hundred kHz. The range analyzed has been increases as equipment has improved. In the past, any frequencies below a few kHz could be utilized. Attenuation properties depend on the frequency range: higher frequency components propagate in concrete with greater attenuation. The attenuation is quantitatively represented by Q value. When AE waves with an energy level E are attenuated by ΔE over a one–wavelength propagation distance, Q is defined as,

$$Q = 2\pi E/\Delta E \quad (2)$$

In the case of a genuine elastic material, $\Delta E = 0$ and thus Q is infinite. In typical metals, Q is greater than 1,000, whereas it is known that Q values are lower than 100 in rock and concrete. When AE waves propagate for a distance D, the amplitude U(f) decreases as,

$$U(f) = \exp(-\pi f D/vQ), \quad (3)$$

where v is the wave velocity. In concrete, typical values are Q = 10, v = 4000 m/s, and D = 1 m. Substituting these values into Eq. 3 for a frequency component f = 100 kHz gives exp(−0.65) = 0.522. This implies that the amplitude of a 100 kHz components attenuates to approximately half after propagating 1m. Based on this result, the empirical relation indicated in Fig. 5 [17] is proposed. This gives base–line information for the determination of sensor array. For a measuring area at 10 m distance, AE waves with frequency components lower than 100 kHz only are detectable. The fundamental requirements for AE measuring equipment are prescribed in the JSNDI standards [18].

3. 3 AE signals and analysis

AE signals are analyzed using both analog and digital methods. Analog processing allows several AE parameters to be extracted, while quantitative waveform analysis is possible by digital processing.

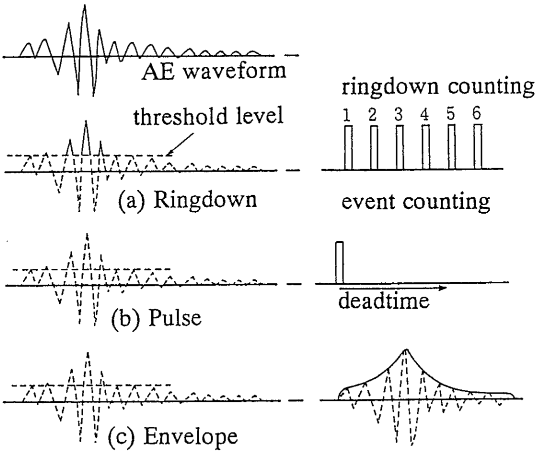


Fig. 6 Counting methods for AE events

(a) Analog parameters

1) AE counts: the occurrence of AE events in the fracture process is counted. The counting methods commercially available are summarized in Fig. 6. All cycles above a threshold level are counted by ringdown counting. This method is useful in metal, because continuous AE signals are often observed. In concrete, event counting is carried out by either setting a deadtime or rectifying the waveform into an envelope. The number of event counts should then correspond closely to AE occurrence. However, this is not the case in typical observations. AE events of small amplitude may not be discriminated from the noise, and AE waves may attenuate quickly en route to the sensor from a distance. Accordingly, the number of AE events is considered to be correlated with AE generating behavior in the fracture process.

2) Amplitude distribution: the maximum amplitude marked in Fig. 7 correlates with the relative size of AE events, although it is usually smeared by propagation effects between the sensor and the source (microcrack). In seismology, the Gutenberg–Richter relation between maximum amplitudes of seismic waves and the frequency of occurrence is known. It has been modified for AE events, and a statistical relationship between the number of AE events N and the maximum amplitude a is obtained as follows:

$$\log_{10}N = \alpha - b \log_{10}a. \tag{4}$$

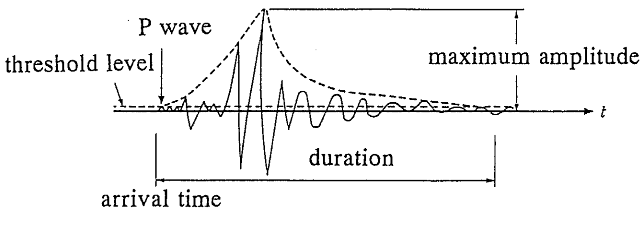
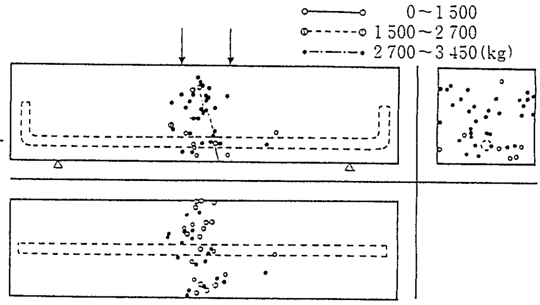


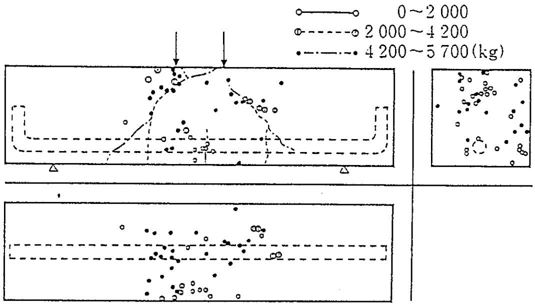
Fig. 7 AE waveform parameters

In this logarithmic equation, the gradient b is negative, implying that AE events of large amplitude are observed less often than those of small amplitude. It has also been reported that the value b decreases as the material approaches impending failure [12].
3) RMS voltage: the root mean square (RMS) voltage of the waveform in Fig. 7 is readily obtained using analog circuitry. It approximately corresponds to the area below the envelope of the waveform in Fig. 7, and is occasionally referred to as equivalent to AE energy.

(b) Digital processing
1) Source (flaw) location: the arrival time of the AE waveform at a sensor is dependent on the distance between the AE source and the sensor. Therefore, differences in arrival times at various sensors leads to a system of algebraic equations giving source location [19,20]. As an example, AE source locations determined in bending tests of reinforced concrete beams are shown in Fig. 8. Two failure modes, bending failure and diagonal shear failure, are clearly identified from the 3-D maps of source location [3].
2) Spectral analysis: the frequency components of AE waves are readily analyzed by a FFT (fast Fourier transform) procedure. The frequency components of detected AE waves in concrete depend considerably on the geometrical relationship between crack location and observation point because of inhomogeneity in the concrete material [21]. In addition, frequency components are influenced greatly by the sensor characteristics, as indicated in Fig. 4.
3) Moment tensor analysis: the source location procedure has been further investigated and coupled with the outcome from a theoretical treatment of AE waves based on elastodynamics [22]. As a result, a moment tensor analysis was proposed as the source inversion procedure [23]. In order to classify crack modes into tensile and shear types and to determine



(a) AE locations subjected to bending failure



(b) AE locations subjected to diagonal shear failure

Fig. 8 Source locations in RC beams

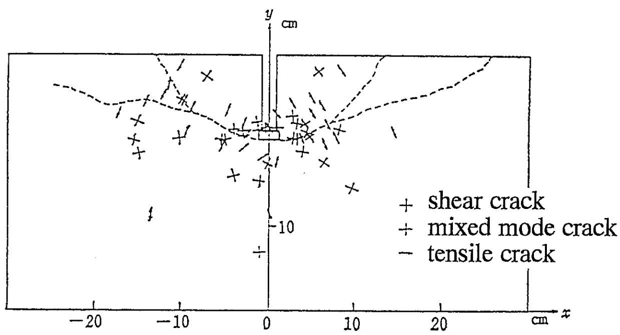


Fig. 9 Moment tensor analysis in a pull-out test.

crack orientation, this procedure has been developed into the SiGMA code (simplified Green's function for moment tensor analysis) [24]. Successful application to a pull–out test of an anchor–bolt is shown in Fig. 9 [25]. In SiGMA analysis, a 6–channel system of digital waveform memory is necessary for a 3–D problem, and a 4–channel system is good enough for a 2–D problem [26].

4. APPLICATION TO CONCRETE ENGINEERING

AE measurements are used in a variety of fields in concrete engineering. With the demand for nondestructive evaluations of in–service structures, AE techniques offer great promise as means to estimate structural integrity. Construction monitoring, in addition, has received a great deal of attention. These new applications of AE in concrete engineering are summarized here, since the state of the art has been published previously [15].

4. 1 Thermal cracking under mass concrete construction

In the placement of ready–mixed concrete, thermal cracking often occurs due to the uneven temperature distribution when the structure is of large mass. To detect cracks promptly and implement proper treatment, AE monitoring is being considered [27]. A major concern is noise elimination, since a variety of construction noise is always present. Typical AE signals observed on site are given in Fig. 10. AE waveforms and their frequency spectra are recorded during concrete casting. AE sensors are attached to reinforcing bars in formwork. In the figure,

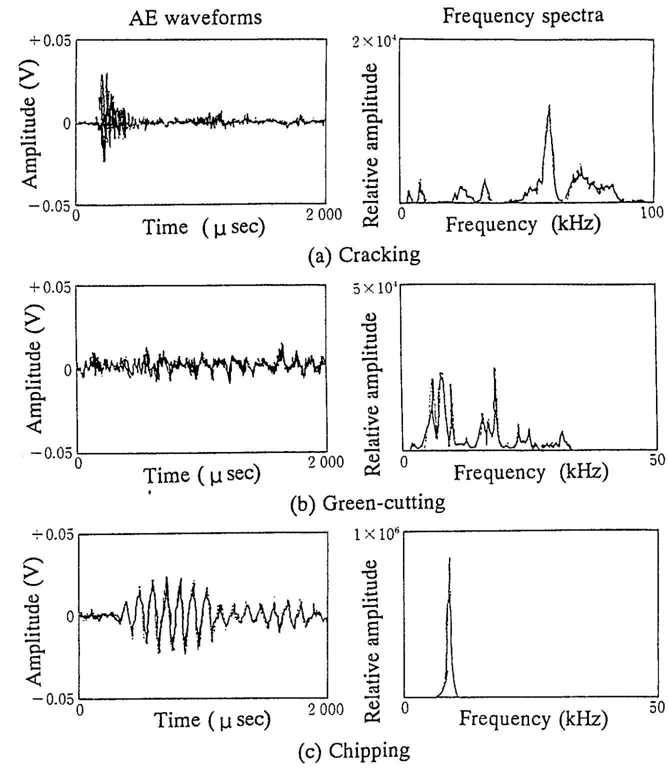


Fig. 10 AE signals during mass concrete construction

green–cutting means the removal of dirt from the concrete surface using water. The AE wave–forms of thermal cracks are different from those of such AE sources as green–cutting and chip–ping. So, thermal cracking should be easily identified by measuring AE events with a properly filtered system.

4. 2 Development of cemented materials

In developing cement–based materials such as alumina cement [28] and asbestos cement [29], AE monitoring has been applied. An application to the concrete hardening process has also been reported in the development of autoclave aerated concrete [30].

4. 3 Freezing and thawing effects

One significant deterioration of concrete in a severe environment is caused by freeze and thaw. Because concrete usually contains moisture, freezing results in microcracking around water voids due to the volumetric increase. After thawing, the volumetric change is repeated due to refreezing. The resulting microcracks are accumulated in the concrete. AE measurements during freezing and thawing [31] are shown in Fig. 11. The ratio of released energy to elastic energy in the process starts to increase at the 30th freeze–thaw cycle, when high AE activity is observed. This implies that continuous AE monitoring of the freezing and thawing process could give warning of degradation. Another application of AE source location during cyclic freezing and thawing process has also been reported [32].

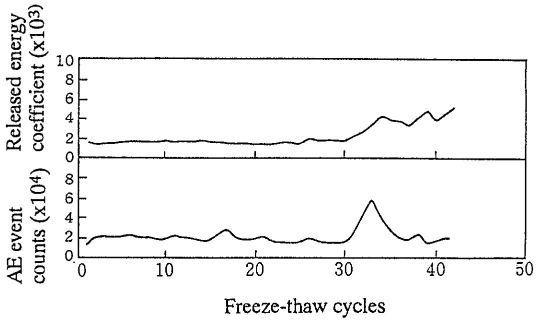


Fig. 11 AE generation during freeze–thaw action

4. 4 Application to hardened concrete

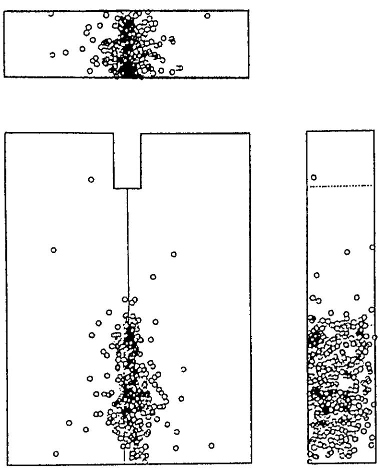


Fig. 12 Identification of the fracture process zone by AE source location

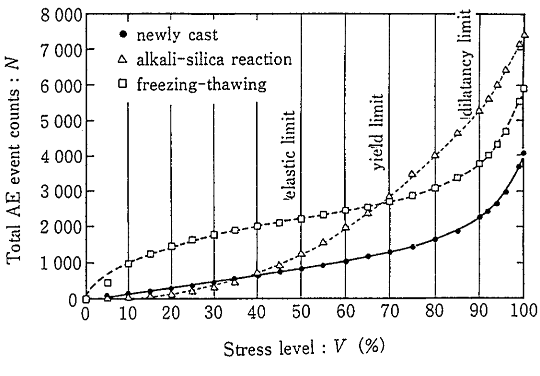


Fig. 13 Total AE event count versus stress level in concrete sample

AE behavior during the fracture process has been investigated in relation to the Kaiser effect [33]. Under cyclic loading, AE activity is quite low as sequential loading takes place up to the preload level. Based on this knowledge, the estimation of previous stress level is under investigation [34,35], although results are still marginal. In other areas, AE behavior at failure of jointed concrete [36] and during fatigue in water [37] is being investigated.

An application to fracture mechanics was recently reported [38,39]. To determine the parameters of fracture mechanics and determine the fracture process zone, AE generation was monitored. The source location procedure can be successfully applied to identify the fracture process zone, as shown in Fig. 12 [40]. Nucleation in the process zone might be correlated with the intense zone of AE cluster. It is found that AE clusters spread out as the gravel size increases.

As a diagnostic method for evaluating structural integrity, the application of AE to core tests is being studied. One procedure has been proposed for uniaxial compression tests of core samples [41, 42]. The different type of AE activity under compression are compared in Fig. 13 for a sound concrete sample and deteriorated samples affected by alkali–aggregate reaction and the freezing–thawing effect [41]. It is clear that AE activity is high even at low stress levels when concrete contains many microcracks due to deterioration. A quantitative method of evaluating deterioration from the AE activity measured under compression is proposed [42].

4. 5 Reinforced concrete

AE studies of actual concrete structures have generated a lot of interest, because diagnostic techniques are of great concern to concrete engineers [25]. With respect to the inspection of in–service concrete structures, a relationship between crack width in reinforced concrete (RC) members and the occurrence of the Kaiser effect was been reported [43]. As summarized in Table 1, the disappearance of the Kaiser effect coincides with the crack width expanding beyond the critical limit in the design code or with the initiation of diagonal shear failure. Thus, if the Kaiser effect is present, minor deterioration of an in–service RC structures is suggested. On the disappearance of Kaiser effect, the moment tensor analysis was applied to cyclic bending tests of RC beams. One of the results is shown in Table 2 [44]. It is observed that the number of shear cracks increases with the more loading cycles. The result of Table 1 is confirmed from the fact that the Kaiser effect was not observed from the first cycle in this experiment.

Table 1 Relation between crack width and Kaiser effect

crack nucleation	Kaiser effect
tensile cracks of width less than 0.15–0.2 mm	observed
tensile cracks of width more than 0.15–0.20 mm	not observed
shear cracks	not observed

Table 2 Number of cracks and the loading process

Loading cycles	tensile cracks	mixed cracks	shear cracks	total
1st loading	3	5	7	15
unloading	8	5	10	23
2nd loading–1	15	8	14	37
holding	3	4	4	11
loading–2	13	6	23	42

Another important aspect of the maintenance of RC structures is reinforcement corrosion. AE activity related to the corrosion process has also been studied [45].

4. 6 Concrete structures

So far, the measurement of AE in existing structures has rarely been attempted. Photos 1 and 2 show a mobile AE measuring facility and in–situ AE observations conducted in Australia. A

Photo 1 A mobile facility for AE measurement

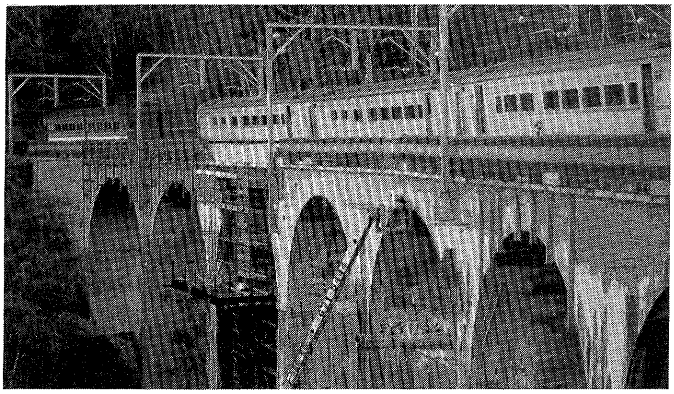


Photo 2 In-situ AE measurement

result of an in-situ observation attempted in Japan is given in Fig. 14 [46]. These are AE waveforms detected in a composite bridge of steel and prestressed concrete (PC) bridge. Measurement were conducted with traffic load, although AE events were seldom recorded.

In existing structures, detailed observation might be required for the prediction of service life. For this purpose, practical application of moment tensor analysis is under investigation. Results of a tensile test on a reinforced concrete (RC) frame model are shown in Fig. 15 [47]. Moment tensor analysis was performed. The observed AE sources are located close to the final surface cracks. Tensile cracks open up vertical to the surface cracks, while shear cracks are almost parallel to the surface cracks. These results confirm the applicability of moment tensor (SiGMA) analysis to the elucidation of cracking mechanisms in concrete structures.

To identify the crack distribution in an existing concrete structure, a useful technique is source location. In-situ AE observations have been performed in a cracked retaining wall [48]. As the temperature and ground water level changed, AE events were observed. Two-dimensional AE source locations are shown at the top of Fig. 16. Because AE sources were distributed away from the existing surface cracks, calibration was carried out by a pencil-lead break test. Based on the location errors observed in the calibration test, the locations were corrected. Results are given in the bottom figure. AE sources are located close to the surface cracks. This suggests that most AE events are nucleated by rubbing motion of the cracked surfaces due to temperature changes.

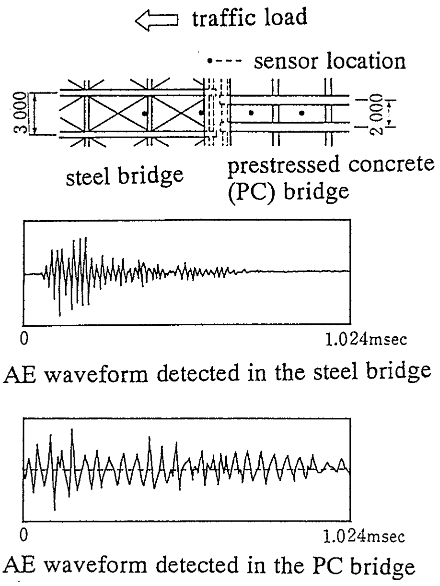


Fig. 14 AE waveforms detected in a composite bridge

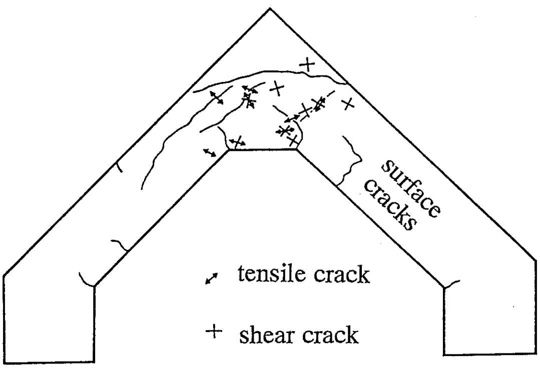


Fig. 15 Moment tensor analysis in a tensile test of an RC frame

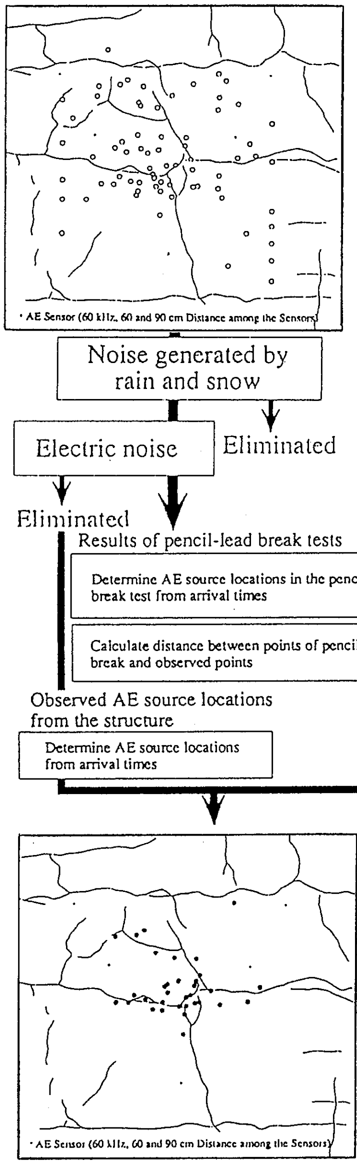


Fig. 16 Two-dimensional source location in a concrete retaining wall

4. 7 Grouting

Other field applications of AE have been developed in a variety constructions. An application to the grouting process is under investigation [49]. By employing an AE monitoring system as shown in Fig. 17, a procedure for consistent grouting is being studied.

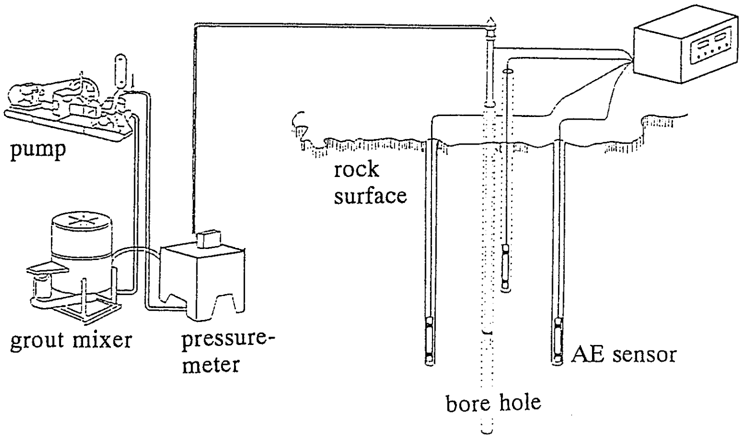


Fig. 17 AE monitoring system for grouting

5. CONCLUDING REMARKS

AE research activity is increasing in the field of concrete technology because of the urgent demand for repair, restoration, and rehabilitation of concrete structures. In addition, the application of AE to construction monitoring is in progress. This activity demonstrates that AE research in civil engineering has shifted from the development stage to the application stage. The latest results in relation to concrete technology have been summarized. Because civil engineering covers a variety of fields and consists of many on-site practices, AE has not always been successful when applied to practical problems. Further studies are, therefore, still needed to meet the demands of particular targets.

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