

ACOUSTIC EMISSION FOR CHARACTERIZING BEHAVIOR OF COMPOSITE CONCRETE ELEMENTS UNDER FLEXURE

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Abstract

Acoustic emission (AE) measurement was used to assess the behavior of concrete beams subjected to flexural loading. Plain concrete specimens and those with vinyl fiber-reinforced mortar layer as composite were prepared. Discussions are based on utilizing various AE parameters for investigating the fracture behavior of composite specimens from those of plain concrete specimens, as well as assessing locations of cracking and occurrence of debonding at interface between concrete and fiber-reinforced mortar layer. Part of the assessment was justified by visual inspection carried out during the loading tests. Results in general indicated that in terms of fracture development, the composite specimens behaved similarly to the plain concrete specimen, with higher flexural strength and possibly higher shear resistance as suggested by AE parameters. Besides, there was no significant interfacial debonding observed throughout the flexural tests, inferring that the bond stayed intact during the test, such that the specimens were able to sustain stress sufficiently as a composite element. The AE parameters were found useful in distinguishing between the flexure and shear fracture modes and thus can be utilized as indicators to predict fracture behavior of concrete structures in health monitoring process.

Keywords: Concrete, Fiber-reinforced mortar, Flexural test, Fracture behavior

Introduction

Acoustic emissions (AE) are stress waves produced by mechanical activities, such as dislocations, cracking and other irreversible changes in a stressed material. Typical AE sources are deformation processes caused by crack development, in which elastic energy is released and propagates through the structure in the form of stress waves that can be recorded as transient AE signals by piezoelectric sensors attached to the structure. The source of the signal, which is related to the cracking, is known as an AE event. The fracture behavior and its location in the measured structure can be evaluated when the relevant group of AE events and other characteristics of the recorded signals are properly interpreted. In AE techniques, the detected energy is released from the interior of measured structure rather than from external sources. Furthermore, AE technique has the capability of detecting dynamic processes associated with the integrity loss of the measure structure [1]. In other words, the major advantage of AE measurement is its feature that enables monitoring of fracturing process of the measured structure during an entire loading history, so that the initiation or changes in the mode of fracture can be determined.

Due to its importance as a widely used construction material, extensive research activities have been carried out to study the fracture and failure behaviors of concrete material. To achieve this purpose, one of the approaches is the application of AE technique in small-scaled laboratory

loading tests of concrete elements [2 - 5]. For failure assessment and maintenance of full-scaled, actual reinforced concrete and prestressed-concrete structures, successful applications of AE technique to account for various cases have also been reported [6 - 8].

In this paper, AE technique was applied to monitor the behavior of fiber-reinforced composite concrete elements subjected to four-point bending. Specimens to be investigated are composed of plain concrete and vinyl-fiber reinforced mortar layers with rebars at the tension side. As for the control specimen, plain concrete only with rebars was also prepared. Four-point bending tests were carried out to assess not only the strength but also the fracture behavior of the specimen, by interpretation of AE signals acquired from the testing. Besides, visual inspections were also conducted at specific intervals to investigate the surface condition and interfacial debonding to validate the results of AE measurement.

Experimental

Two sets of beam specimens were prepared for the study: (1) plain normal concrete beams; and (2) composite specimens composed of normal concrete layer and vinyl-fiber-reinforced mortar layer as the top and bottom half of specimen, respectively. Each specimen has a dimension of 150 mm x 150 mm x 530 mm, with two D13 SD295 (JIS G 3112) rebars embedded as tensile reinforcements. Concrete was designed to achieve a 28-day compressive strength of 40 MPa. Moist curing was adopted after concrete casting. The vinyl-fiber-reinforced mortar layer was overlaid by the shotcrete method, at 14 days of concrete age. The surface concrete was roughened by means of water blasting before the shotcrete. Curing of specimens was continued up to 28 days of age, before four-point bending tests in compliance with JSCE-G 552 were carried out. At the time of bending test, the average compressive strengths for concrete and vinyl-fiber-reinforced mortar were 47.4 MPa and 57.2 MPa, respectively.

For AE measurements, twelve PAC R6 AE sensors with resonant frequency of 60 kHz were attached, as illustrated in Fig. 1. The signals were pre-amplified 40 dB and recorded by a PAC DiSP 16-channel data acquisition system. A threshold of 40 dB_{AE} was selected to ensure high signal-to-noise ratio. Figure 2 shows a snapshot of the test.

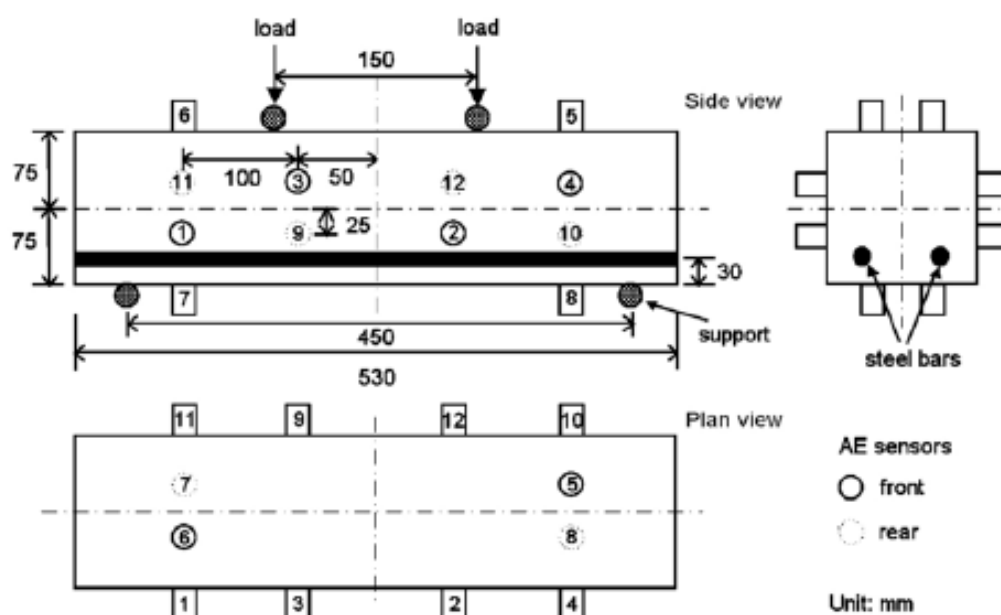


Fig. 1: Loading configuration and sensor arrangement.



Fig. 2: Test set-up.

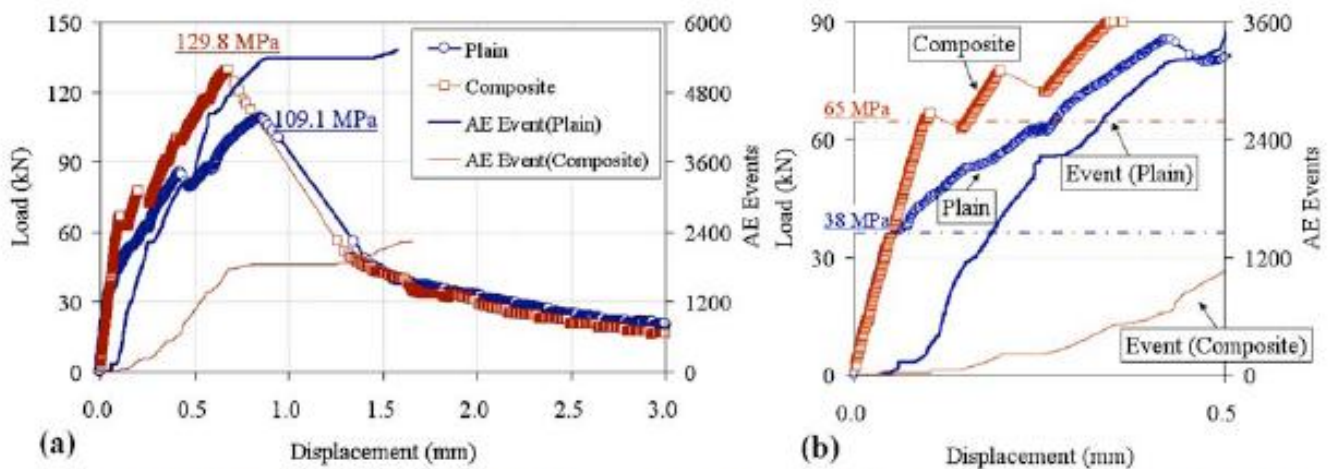


Fig. 3: Examples of load-displacement curves and AE cumulative events. a) Overall. b) Initial.

Results

Mechanical behavior

In Fig. 3, typical results of load vs. mid-span vertical displacement for both types of specimens are shown. The composite specimen exhibited a higher maximum load than that of the plain concrete specimen (129.8 MPa compared to 109.1 MPa). It is found from the area under the curve that the flexural toughness of the composite specimen is higher than that of the plain concrete specimen. Cumulative AE events of the specimens are given in the same figure. In the case of the plain concrete specimen, the number of AE events started to increase rapidly from the early stage (after approximately 38 MPa, or 35% of the maximum load), while in the composite specimen, major event outburst was recognized at a later stage of loading (after approximately 65 MPa, or 50% of the maximum load). Additionally, the total number of AE events was substantially smaller in this case (2255 compared to 5539 events of the plain concrete specimen). These strongly suggest that the incorporation of fiber-reinforced mortar layer has effectively enhanced the mechanical performance of concrete beam in such a way that early cracking was restrained by vinyl fibers, subsequently leading to the reduction in energy released due to intensive fracture.

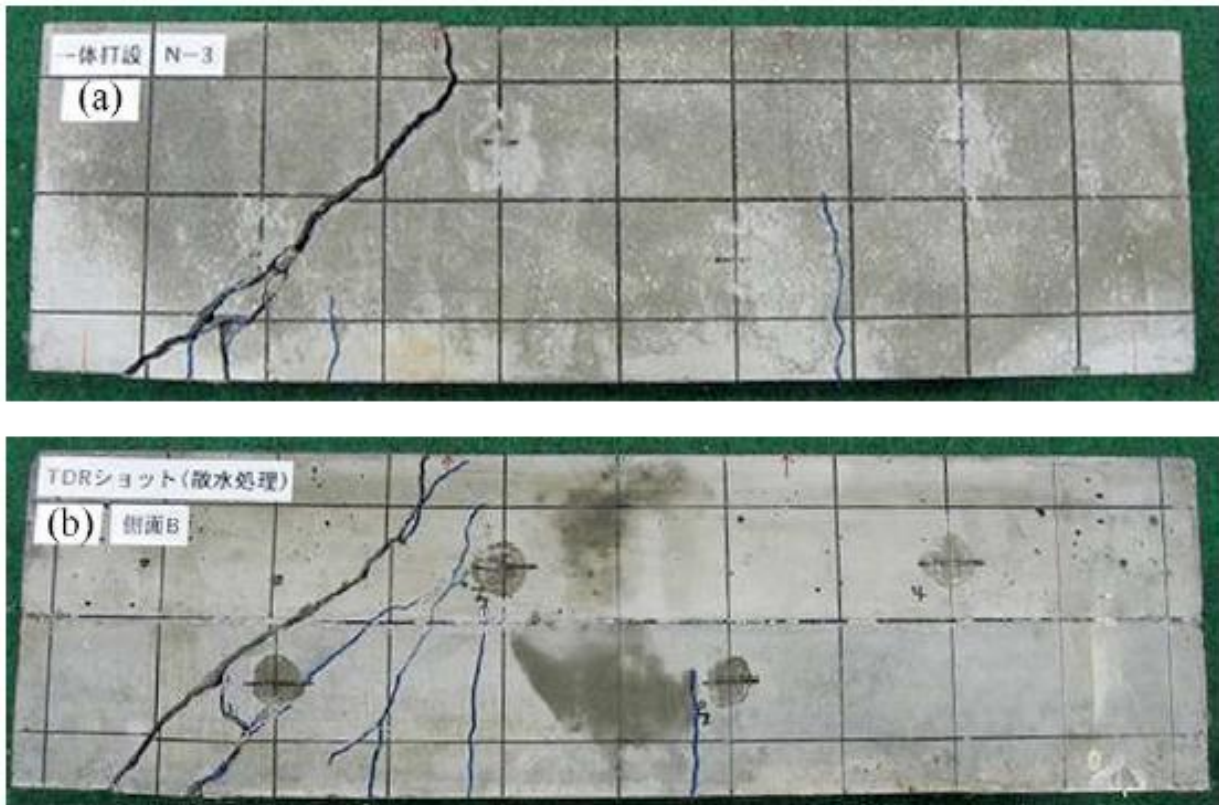


Fig. 4: Typical cracking of specimen under flexure. (a) Plain concrete. (b) Composite.

Typical fracture conditions of the specimens as observed through tests are shown in Fig. 4. Both type of specimens exhibited a similar way of cracking: propagation of vertical cracks near the mid-span due to flexure before diagonal cracks started to develop in the shear span. The shear cracks became dominant at later stages of loading. Both types of specimens were ruptured as a result of development of critical shear cracks at one side that extended from the loading point at the top to the support at the bottom of specimen before joining each other to form discontinuity. It is also worth mentioning that in all the composite specimens, no significant fracture along the interface between concrete and fiber-reinforced mortar layers was observed. This infers that the bond between concrete and fiber-reinforced mortar layers remained intact throughout the loading tests and premature interfacial debonding was not a concern that affects strength performance of the composite specimens.

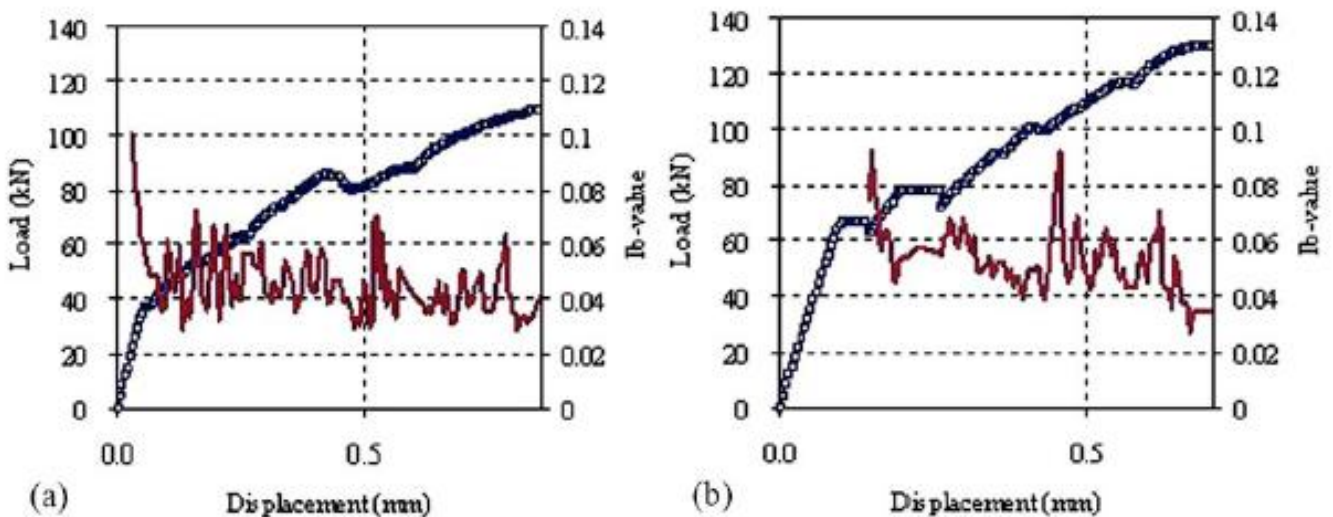


Fig. 5: I_b -value vs. displacement. (a) Plain concrete. (b) Composite.

AE parameters

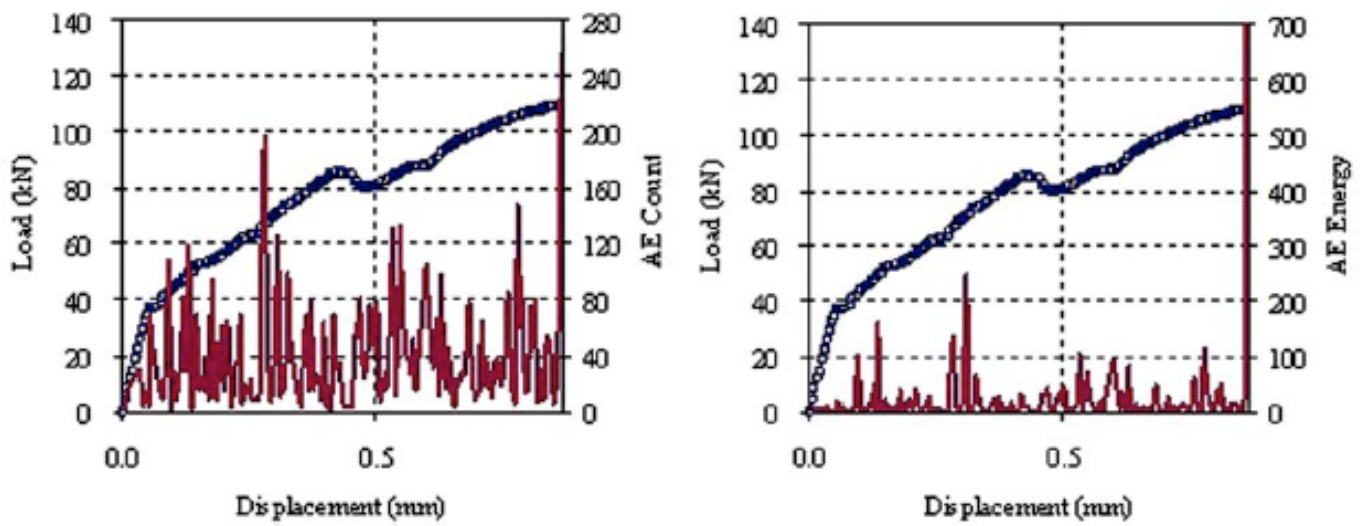
In general, it is reasonable that the fracture scale becomes larger with approaching the maximum load. The occurrence of large-scale fracture always gives rise to AE events of larger amplitude. However, at the same time, the accumulated damage also increases, leading to higher attenuation rate of the material and delaying the propagation of AE waves. These make the study of the amplitude by itself misleading. Thus, the amplitudes are studied by their cumulative distributions, using the improved b -value (Ib -value) analysis. This index takes the number of the latest events and their amplitude range into calculation. According to the cumulative amplitude distribution, the Ib -value changed following the progress of fracture. From the results, it is confirmed that as fracture becomes more intense, the percentage of the strong events increases relative to the weak ones in the total population of AE events. Therefore, the absolute gradient of this distribution or Ib -value will exhibit a small magnitude, together with an abrupt drop.

Examples of Ib -values calculated during the whole loading process until the yield stage for both types of specimens are depicted in Fig. 5. At the initiations of flexure cracking and critical shear fracture that lead to ultimate failure, significant drops in Ib -value can be identified. During the former, Ib -value dropped to less than 0.06 at 35% of the load, while in the latter, it dropped to less than 0.04 at the maximum load. These values can become the thresholds that are utilized to predict the fracture behavior of concrete elements. Also, Ib -value ranging from 0.04 to 0.06 can be considered as a range where an intermediate, mixed fracture mode of flexure and shear emerged. As shown in Fig. 5(a), Ib -value for the plain concrete specimens fluctuated around 0.05 between the initiation of flexure and the ultimate shear fracture. Furthermore, the value became less than 0.04 occasionally during the loading process. In contrast, in the composite specimen (Fig. 5(b)), the Ib -value was higher than 0.05 most of the time throughout the loading. The results suggests that the plain concrete specimen experienced a mixed mode of fracture from the early loading stage to failure, while it was highly possible that the composite specimen experienced flexure mode for a considerably longer period. By using Ib -value analysis, it becomes clear that the fiber-reinforced mortar has effectively enhanced the strength performance of concrete beam by restraining extensive damage with reinforcing fibers from the early stage of loading.

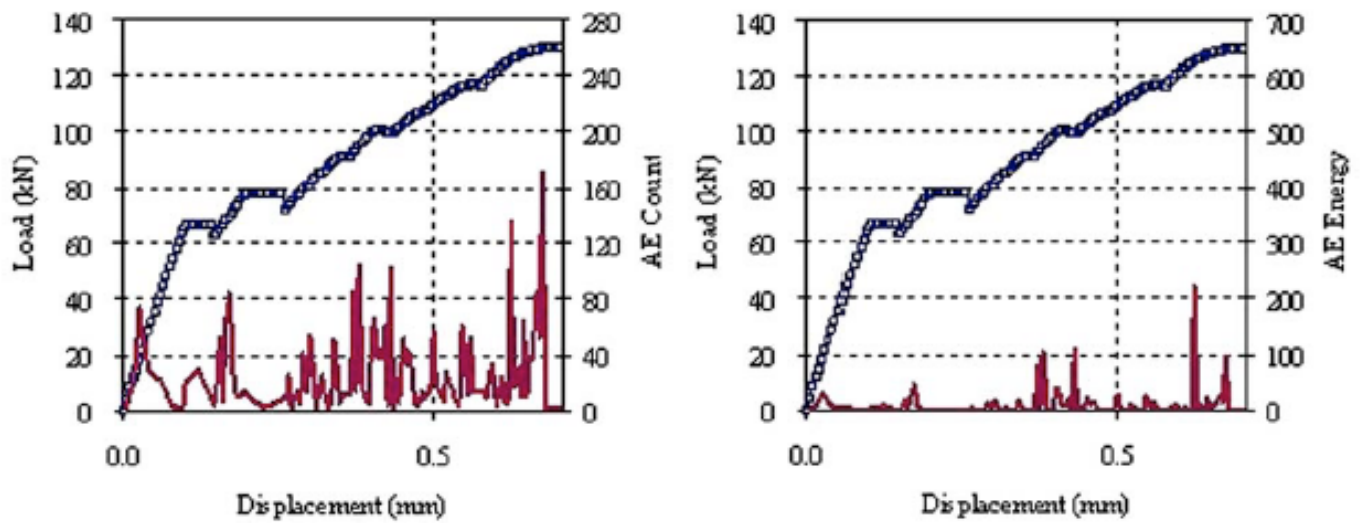
Another noteworthy detail is that elastic waves originating from the shear events exhibited generally higher amplitude than the flexure. This is supported by AE parameters known as AE counts and energy [9]. In Fig. 6, the results of AE counts and energy are presented. Similar to the finding of Ib -value analysis, both AE counts and energy can also be used to distinguish between shear and flexure fracture mode because both changes significantly. To be specific, AE counts rose to more than 80 at 35% of the load during flexure cracking. Subsequently, AE counts rose to more than 160 at the maximum load, when critical shear occurred. On the other hand, AE energy rose to more than 100 at 35% (flexure) and 200 at the maximum load (shear), respectively. Additionally, both parameters have lower values for the composite specimens, suggesting higher shear resistance. Table 1 summarizes the relevant AE parameters and their corresponding values to the

Table 1: Useful indicators for predicting fracture behavior.

	Flexure	Mix mode	Shear
Ib -value	Less than 0.06	0.06 - 0.04	Less than 0.04
AE count	More than 80	80 - 160	More than 160
AE energy	More than 100	100 - 200	More than 200



(a) Plain concrete.



(b) Composite.

Fig. 6: AE count and energy vs. displacement.

various fracture modes. The AE parameters can serve as useful indicators to predict fracture behavior of large-scaled concrete structures in health monitoring, when proper modifications or configurations are made to account for different cases. In fact, similar types of indicators, which are derived from various AE parameters, have already been used for the monitoring the deformation of rock slopes [9].

Locations of AE events

Examples of the 2D-AE event location for the following specific load stages are depicted in Fig. 7. In the same figure, the observed cracks after ultimate failure is also illustrated. The events are represented by circles, with the center and area of each circle representing the exact location of source and amplitude of energy released in a proportional manner, respectively. Figure 7(a) concerns the plain concrete specimen during loading from 35% to 57% of the maximum load. A great number of events are evident in the vicinity of the shear cracks on one side of the specimen. The smaller crack was also found on the other side, accompanying numerous AE events. It is noted that the development of cracks could hinder the acquisition of all AE signals. Severe scattering imposes wave attenuation and resulted in delay of the acquisition of individual signals,

and therefore for severely damaged material the accuracy of source location is expected to decrease.

In the composite specimen, as given in Fig. 7(b), during loading from 70% to 90% of the maximum load, the accumulation of events were noticed around the edges of the shear cracks at the top, as well as near the tips of smaller cracks (flexural cracks) that propagated vertically toward the top surface. There was no significant event suggesting debonding occurred at the interface between concrete and the fiber-reinforced mortar layer. This is consistent with the visual observations in confirming that the bond between concrete and fiber-reinforced mortar layers was adequate up to the ultimate failure.

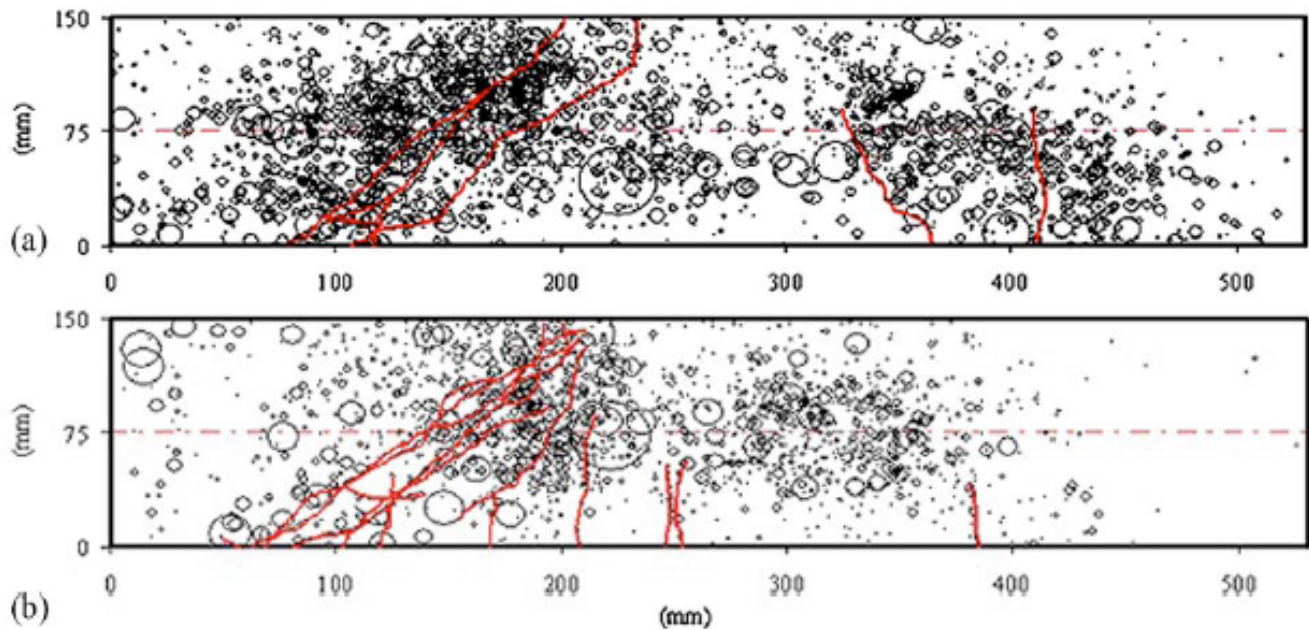


Fig. 7: Location of AE events and actual pattern of cracks. (a) Plain concrete. (b) Composite.

Conclusions

Acoustic emission technique was used to assess the fracture behavior of composite concrete specimens. It is found that the composite specimens with vinyl-fiber-reinforced mortar layer exhibited higher strength than that of the plain concrete specimens. Study of various AE parameters enabled us to distinguish between flexure and shear fracture modes that occurred during the loading. In both specimen types, the maximum failure was accompanied by macroscopic diagonal shear cracks.

Incorporation of vinyl fibers has effectively restrained the shear mode of fracture from its occurrence even from the early loading stage, delaying the initiation of critical fracture. AE event locations coincided well to a great extent with the observed crack locations. Throughout the tests, no debonding was observed in the composite specimens.

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