EXPERIMENTAL STUDY OF INFLUENCE OF FLY ASH AND SILICA FUME ON ACOUSTIC EMISSION CHARACTERISTICS OF SCC BEAMS

T.Hemalatha[1], J.M.Chandra Kishen[2], Ananth Ramaswamy[3]
[1, 2, 3] Department of Civil Engineering, Indian Institute of Science, Bangalore, INDIA-560 012.
E-mail of corresponding author: hemabalan@civil.iisc.ernet.in

ABSTRACT

In this work, the acoustic emission (AE) characteristics of three-point-bending concrete beams are investigated to study the influence of addition of fly ash and silica fume. The mineral additions added to enhance the workability of self compacting concrete (SCC) also alter its mechanical and fracture properties. The transformation in the microstrucrure of SCC due to the mineral additions is reflected by means of AE characteristics. The results of load, AE events, AE-energy and amplitudes of signals from microcracking are analyzed. The width of the fracture process zone and damage zone are computed using AE-data. It is observed that the occurrence of AE events increases in the beams with mineral additions and at the same time the width of fracture process zone (FPZ) measured is found to decrease indicating the brittleness of SCC with mineral additions.

INTRODUCTION

Acoustic emission (AE) is a kind of microseismic wave generated from dislocations, microcracking and other irreversible changes in a stressed material. The monitoring of these stress waves provides the details of the nature of failure within the specimen. Hence AE is looked upon as a non destructive tool to study the fracture characteristics of metallic and other engineering structures [1,2]. Several works have focused on relating acoustic emission characteristics to the properties of the fracture process zone. The mechanisms which are responsible for the quasi brittle nature of plain concrete are crack deflection, micro cracking, aggregate bridging, crack face friction, crack tip blunting by voids and crack branching [4]. All these mechanisms influence the size of the fracture process zone (FPZ) which characterizes the fracture of concrete. This fracture process zone depends upon the material's micro structure, grain size, rate of loading, dimensions of specimen and other parameters [3]. The micro structure of SCC is greatly influenced by the addition of mineral admixtures which in turn affects the size and nature of the fracture process zone (FPZ).

SCC is generally made with mineral additions (fly ash and silica fume) to improve the self compacting properties such as flowability, passing ability and segregation resistance. These mineral additions alter the microstructural build up which in turn affects the fracture properties. Not much work has been reported in the literature for studying the influence of mineral additions on fracture characteristics of SCC. Hence in this study, AE characteristics are measured and discussed in order to explain the difference in FPZ of three point bending SCC beams with and without mineral additions.

EXPERIMENTAL DETAILS

Materials

Ordinary Portland Cement (OPC) conforming to Indian Standards is used for this work. Natural sand (0-3mm) and gravel (3-12.5mm) are used for SCC mixtures. A "class F" fly ash that complies with the requirements of ASTM C 618 and micro silica 920-D grade (ELKEM) that conforms to ASTM C1240 are used. A polycarboxylate based super plasticizer incorporating viscosity modifying agent is used for enhancing the workability.

Three types of SCC are prepared and analyzed. The mixes are designated as SCC1, SCC2 and SCC3. Mix proportion details are tabulated in Table 1. SCC1 is made without any mineral admixture and SCC2 with fly ash at 20% by weight of cement without cement replacement and SCC3 with fly ash and micro silica at 20% and 10% by weight of cement, respectively, over and above the cement as designated.

Table 1: Mix proportion details of three SCC mixes

Material	SCC1	SCC2	SCC3
	kg/m^3		
Cement	490	480	490
Fly ash	-	96	98
Silica fume	-	-	49
Fine aggregate	865	819	838
Coarse aggregate	758	699	683
Water	221	220	186
Superplasticizer	4.9	10.1	11.6

Casting and curing

The fresh properties of self compacting concrete are as important as their hardened properties. Firstly, SCC mixes with requisite self compactability as well as the target strength are arrived at through trials and the test results for qualifying the SCC are tabulated in Table 2.

Table 2: Properties of SCC at fresh state

Test	SCC1	SCC2	SCC3	EFNARC STANDARD
Slump-flow (mm)	700	680	655	650-800
L-Box(secs)(h2/h1)	1	0.9	0.82	0.8-1.0
V-Funnel(secs)	6	7	10	6-12

After testing for fresh properties, the three mixes are poured into their respective moulds. The moulds for three point bend test are fabricated for the dimensions as shown in Table 3. After 24 hours the prisms are de-moulded and cured under water for 28 days.

Table 3: Dimensions of beam used for testing

Depth	Span	Length	Thickness	Notch Size
mm				
152	380	430	50	30.4

Testing of Specimens

Compression test is performed on cubes of 150 mm size. Split tensile strength and modulus of elasticity are determined by performing test on 300 mm long cylinders with 150 mm diameter. The results are presented in Table 4.

Table 4: Properties of SCC at hardened state

	Compressive strength	Splitting tensile strength	Young's Modulus
	MPa	MPa	GPa
SCC1	35	3.24	30
SCC2	55	4.67	31
SCC3	75	6.5	33

All the prism specimens are tested in a closed loop servo-controlled testing machine of 500 kN capacity under three point bending. The testing machine and the instrumentation used for testing are shown in Fig. 1. A specially calibrated 50 kN load cell is used for measuring the load. The load-point displacement is measured using a linear variable displacement transformer (LVDT). The crack mouth opening displacement (CMOD) is measured with a clip gauge. All the tests are performed in CMOD control with a rate of opening of 0.0007 mm/sec. The results of load, displacement, CMOD and time are simultaneously acquired through a data acquisition system. The signals from AE sensors are captured and recorded by the AE acquisition system for further analysis.

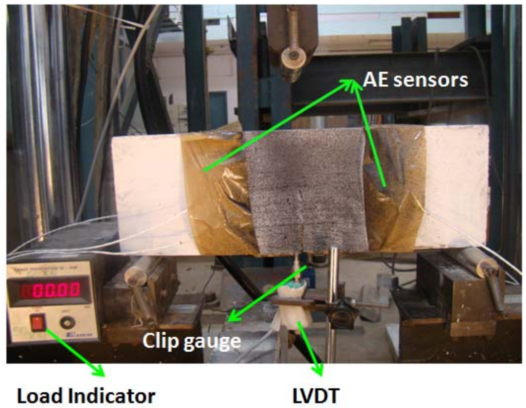

Fig. 1: Experimental setup of three point bend beam test

AE System

The AE system used in this experiment consists of R6D resonant type differential sensors, having the diameter and height of 19 mm and 22 mm respectively. The AE system can be used in the temperature range of 65 to 177 degrees Celsius, with the operating frequency of 35100 kHz. The vacuum grease LR (high vacuum silicon grease) is used as the couplant material. The AE signals are amplified with a gain of 40 dB in a pre-amplifier. A six-channel AE win for SAMOS E2.0 (Sensor based Acoustic Multichannel Operating System) developed by Physical Acoustics Corporation (PAC)-USA is used for AE data acquisition. A threshold of 45 dB, which is normally used for concrete, is adopted.

RESULTS AND DISCUSSION

Brittleness from Width of FPZ

Fig. 2 shows the occurrence of AE events along the length, width and thickness of the specimen. It is observed that the maximum number of AE-events occur in SCC with fly ash and silica fume. The number of AE-events in the SCC2 (with only fly ash) and SCC1 (without any mineral additions) is relatively smaller and is maximum in SCC2 followed by SCC1. In SCC3 specimen, the number of AE-events is 6144 whereas in SCC2, it is 5202 and in SCC1 it is as low as 4494. Since an AE-event is related to the occurrence of micro cracking the large number in case of an SCC3 specimen indicates the formation of large process zone. But this is not true in SCC because the width of the fracture process zone is found to be least in SCC3.

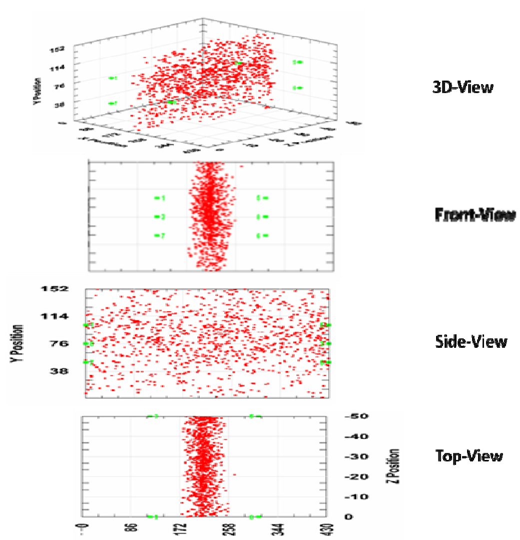

Fig. 2: Occurrence of AE events along front, side and top views

The cumulative number of AE events during the entire experiment is plotted against horizontal position x (along the span of the specimen). The width of the fracture process zone (W_{FPZ}) from AE data is computed using the method proposed by Haidar [6]. The width of the FPZ (W_{FPZ}) is determined by drawing a line at 20% of N_{max} where N_{max} is the maximum number of events shown on Y-axis. Furthermore, the width of the damage zone (W_D) using AE data is computed using the method proposed by Rossi [5] in which the width of damage zone (W_D) is determined by drawing a line at 50% of N_{max} as shown in Fig. 3a. It is seen that the width over which the AE events occur is related to the size of the fracture process zone which is highest for SCC1 beam and this width decreases for SCC2 and SCC3 specimen as shown in Fig. 3b. The width of the fracture process zone and damage zone is computed for all the three SCC mixes and tabulated in Table 5.

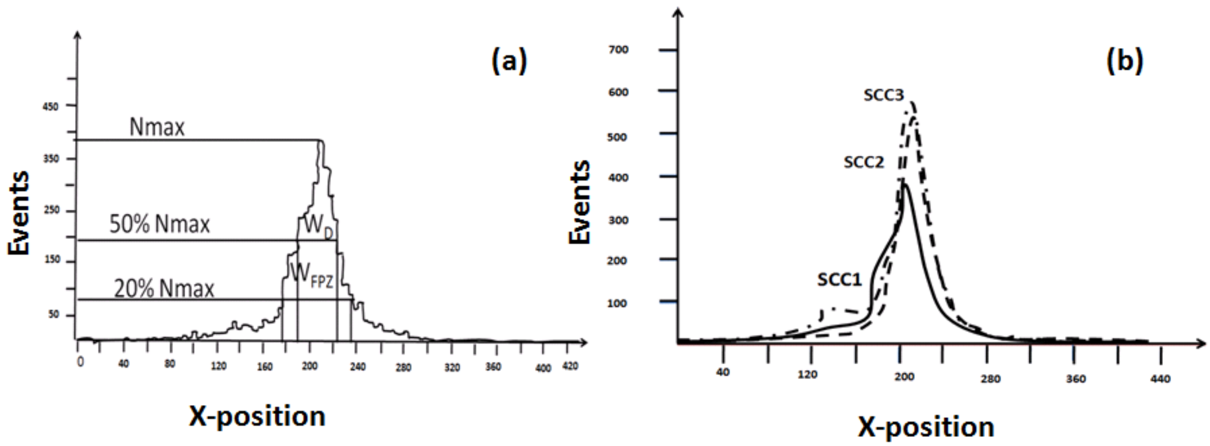

Fig. 3 (a): Measurement of width of FPZ and width of damage zone from AE events versus X position (along the length of the specimen) 3(b) Events versus X position for three SCC mixes

Table 5: Width of FPZ and width of damage zone for three SCC mixes

Mix	W_{FPZ} mm	W_D mm
SCC1	60	36
SCC2	53	24
SCC3	47	20

It is seen that the width of the FPZ and damage zone decrease from SCC1 to SCC2 and SCC3 in that order. Furthermore, the source of emissions is the indication of microcrack formation and it is postulated that the total acoustic emission count N is directly proportional to the size of the fracture process zone [7].

$$N=k*W_{FPZ} \tag{1}$$

From the AE count results of all the three SCC, it is found that N is more in SCC3 when compared to SCC2 and SCC1. Whereas the size of the process zone considerably reduces from SCC1 to SCC3. Equation (1) indicates that the number of events is directly proportional to the size of the fracture process zone. But from the results obtained it is observed that the size of the fracture process zone reduces even though the number of events increases. Hence, the influencing factor here is the constant k and this constant of proportionality depends on microstructure, grain size, rate of loading, type of specimen and other parameters. As the experiment is conducted on the same size of specimen with same rate of loading, the only variable is its microstructure. The change in micro structure which results in a difference in the size of the FPZ is due to the inclusion of fly ash and silica fume and also the variation in the amount of coarse aggregate in three SCC mixes. The more of the powder content and less coarse aggregate content in SCC3 and SCC2 results in an absence or reduction in the toughening mechanisms.

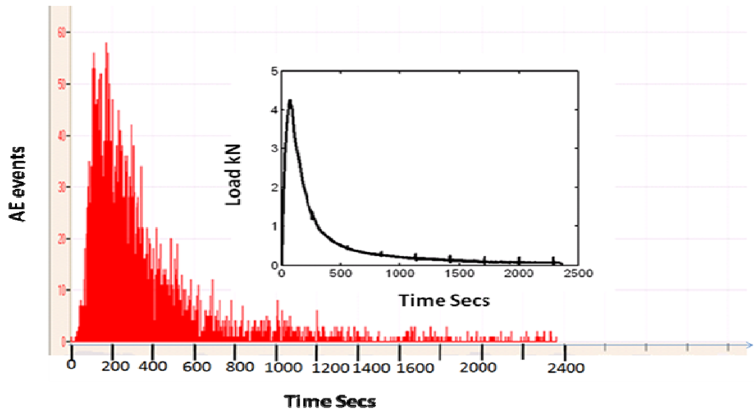

Fig. 4: Correlation of AE events and Load with time

Fig. 4 is the typical plot of SCC1 showing occurrence of AE events with time. The load versus time plot inside the figure is useful in correlating the micro and macro fractures with respect to load. At the beginning of the test, many AE events are detected within a short period. The material experiences micro fracturing as soon as it is loaded and it is reflected in terms of AE events. It is observed from the plot that the AE events increase till it reaches the peak load and start decreasing in the softening portion of load time curve. The micro fracturing results in more number of AE events initially and once it coalesces to form a macro crack, the number of micro events decreases. It is observed from the plots of SCC2 and SCC3, the time at which micro cracks coalesce to form macro crack is lesser which leads to the brittle failure in these two SCC than SCC1.

Brittleness from Weibull Function

According to the statistical theory of damage of quasi-brittle materials, concrete can be considered to be composed of many microelements. Under the external load, the rupture probability of each microelement is different but normally complies with a Weibull distribution [8]. It is reasonable to consider that each AE event is the result of the rupture of a microelement. Therefore, the rupture probability density of the microelements in SCC at a time can be presented by the ratio of the AE hit ratio (dN/dT) to the total number of AE hits (N_{tot})

$$f(T) = \frac{dN_T}{dT} \Big/ N_{tot} \tag{2}$$

While the rupture probability of the microelement at that time is:

$$F(T) = N_T \big/ N_{tot} \tag{3}$$

Therefore, the rupture probability density and the rupture probability ratio of the microelement for three point bending concrete beams can be described by the Weibull function[8], namely ,

$$f(T) = \frac{dN_T}{dT} \Big/ N_{tot} = \theta m \left(T - T_0\right)^{m-1} \exp\left[-\theta \left(T - T_0\right)^m\right] \tag{4}$$

$$F(T) = N_T \big/ N_{tot} = 1 - \exp\left[-\theta \left(T - T_0\right)^m\right] \tag{5}$$

Where θ and m are parameters related to the size and deformation properties of the specimen, respectively. The values of m and θ in Weibull function depend on the geometry and brittleness of the concrete. Therefore, the brittleness of SCC beams can be determined quantitatively by AE techniques during the entire loading process.

Fig. 5 shows the experimental results from AE testing and the bilogarithmic fitting of AE cumulation. As same size of beam is used for this study, the θ value (0.001) does not change much and m value is as reported in the Table 6.

Table 6: Slope for three SCC mixes from Weibull Function

	m
SCC1	1.2652
SCC2	1.1146
SCC3	0.998

From the slope of the fit, it is observed that the value of m (brittleness parameter) decreases from SCC1 to SCC3 which indicates the brittle behavior of SCC3 with respect to SCC2 and SCC1.

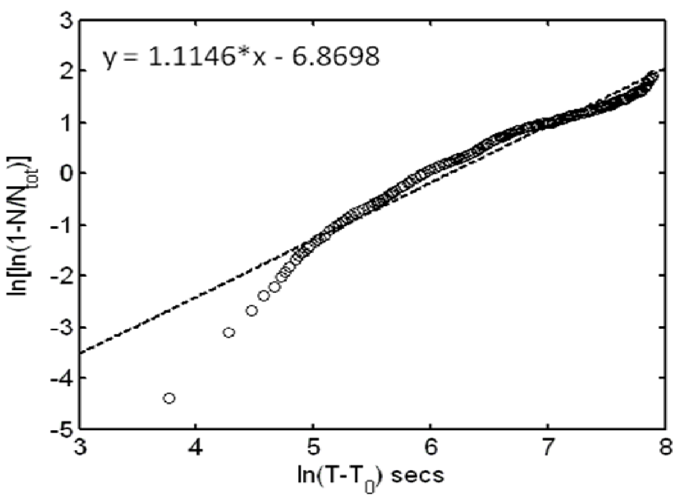

Fig. 5: Typical plot of the fitting curve of AE rate for a SCC2 beam

Brittleness from b-value

The analysis of the b-value provides information between the microcrack beginning and the stage where macrofracture occurs by localization i.e., where the number of microcracks is high which join to create a localized macrocrack. Fig. 6 shows the typical plot of AE events and b-value versus time for SCC1. It is observed that the b-value increases initially, reaches a maximum and then decreases and remains constant.

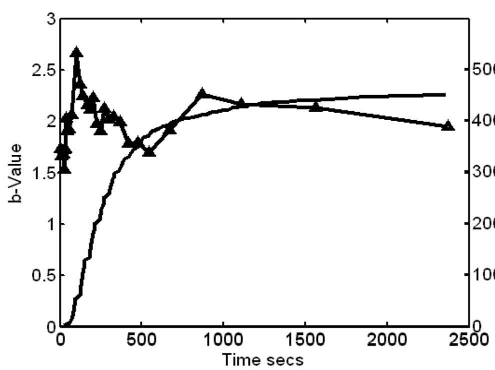

Fig. 6: Typical plot of AE events , b-value vs time for SCC1

The microcracking formation and macrocracking initiation is observed in all the three SCC and the difference among the three arises on the basis of how soon the transition from micro cracking to macrocracking takes place. The time of transition from microcracking to macro cracking is measured for all the three SCC. The total time taken by three SCC for failure are different and in order to compare these transition times for micro and macrocrack growth, a time ratio called as 'transtion time' in percentage is introduced. This is the ratio of time at which b-value is minimum to the total time. The transition time at minimum b-value which is the representation of macrocrack initiation is obtained for all the three SCC mixes. The minimum and maximum b-values obtained and the transition time at which the lowest b-value is reached for three SCC, which is the indication of brittleness are given in Table 7.

Table 7: Maximum and minimum b-value and transition time in percentage

	b-value $_{min}$	b-value $_{max}$	Time %
SCC1	1.659	2.665	23
SCC2	1.752	1.982	20
SCC3	1.759	2.344	20

It is observed that the macrocrack is initiated soon in SCC2 and SCC3 in comparison with SCC1. This is due to the presence of higher powder content in SCC2 and SCC3. The lower b-value indicates the macrocrack growth initiation and the transition time shows how fast the micro crack coalasces to form macrocrack. As discussed earlier the b-value also indicates the earlier coalascence of macrocracking in SCC3 and SCC2 than in SCC1.

CONCLUSION

The failure processes of three-point-bending SCC beams with and without mineral additions have been studied and different characteristics have been observed. With the addition of mineral admixture the AE events increases but the width of the spread of these micro fracturing is less because of the less amount of coarse aggregate presence and absence or less toughening mechanisms. The two parameter Weibull distribution returns the statistical distribution of AE characteristics, which represents the brittleness of the material. The SCC3 is observed to be brittle than the other two from the Weibull distribution results.

The b-value obtained from three SCC mixes is also in agreement with the results obtained from width of FPZ and Weibull parameters suggesting that the SCC with mineral addition behaves in a brittle manner while SCC without such addition is less brittle.

REFERENCES

[1] A.K.Maji, R. Sahu, “Acoustic emission from reinforced concrete”, Experimental Mechanics, Vol 34 1996, pp.379-387.
[2] K.Wu, B.Chen, W.Yao, “Study of the influence of aggregate size distribution of mechanical properties of concrete by acoustic emission technique”, Cement and concrete Research, Vol. 31, 2001, pp 919-923.
[3] N. K. Opara, “Fracture process zone presence and behavior in mortar specimens”, American concrete Institute materials Journal, Vol.90, 1993,pp 618-626.
[4] S. Shah, S. Swartz, C.Ouyang, in: Fracture Mechanics of Concrete: Applications of Fracture Mechanics to Concrete, Rock and Other Quasi-brittle Materials, John Wiley & Sons Inc., New York N.Y., 1995.
[5] Rossi.P, R. J.L.Gervais J.P.and Bruhat D, “The use of acoustic emission in fracture mechanics applied to concrete”1990, Engineering Fracture Mechanics, Vol. 35, 751-763.
[6] K. Haidar, G. Pijaudier-Cabot, J. Dube, A. Loukili,” Correlation between the internal length, the fracture process zone and size effect in model materials”, Materials and Structures, Vol. 38, 2005, 201-210.
[7] I. G. Palmer, P. T. Heald, “The application of acoustic emission measurements to fracture mechanics”, Materials Science and Engineering, Vol. 11, 1973, 181-184.
[8] Bing Chen, Juanyu Liu, “Experimental study on AE characteristics of three point bending concrete beams”, Cement and Concrete Research, Vol. 34, 2004, 391-397.