Monitoring Damage Evolution of Concrete Prisms under Cyclic Incremental Loading by Acoustic Emission

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ABSTRACT

This study aims to monitor the damage growth of plain and fly ash concrete prisms with different curing periods under cyclic incremental loading using acoustic emission (AE) parameters. Higher flexural strength was observed for 28 days cured plain and fly ash concrete prisms as compared to 7 days cured. AE results for 7 days cured plain and fly ash concrete prisms have shown that, Kaiser effect exist in first two loading cycles and from third cycle onwards significant AE activity occurs prior to the previous cycle's maximum load. This is an indication of the start of damage almost at the same load in both the concretes. For 28 days cured fly ash concrete, AE activity during cyclic loading is observed only at 20 kN load as compared to plain concrete in which it occurs at 12 kN load. This shows that cyclic load flexural resistance of fly ash concrete for damage accumulation is higher than that of plain concrete. Load ratio of both types of concrete has been determined during each cycle. Decrease in trend of load ratio with loading cycle is an indication of damage growth. Higher load ratio in 28 days cured fly ash concrete shows addition of fly ash with extended curing which resists damage accumulation. An attempt has been made to classify damage levels during each cycles using NDIS 2421 standard and compared the types of damage in both plain and fly ash concretes.

Keywords: Damage, cyclic loading, concrete prism, fly ash, acoustic emission.

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1.   Introduction

Characterization of dynamic defects in different materials and components can be done using Acoustic emission technique (AET). AE is the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material [1]. Acoustic emission (AE) monitoring detect energy released from the test object and it is capable of detecting the dynamic processes which leads degradation of structural integrity. Elastic energy emitted in the form of elastic waves from an object undergoing dynamic changes detects by an AE sensor coupled to an object can gives information about the nature of changes taking place in the object. Some examples of AE sources relevant to structural integrity monitoring are deformation, crack growth and fracture, leaks and corrosion etc. [1].

AET has importance in on-line condition monitoring and maintenance of concrete structures because it has potential for characterization of damage in concrete materials and structures under load [2-6]. Many AE studies have been carried out to understand crack growth behavior of concrete under different conditions [7-9]. Nishibata et al. [7] studied the micro cracking in aggregate recycled concrete during monotonous compression and cyclic loading using AET. Recently researchers have used AE waveforms to analyze cracking modes in concrete under compression and bending loads [8-9].

During acoustic emission testing of cyclic incremental loading, AE events will occur again only if previous applied load level is exceeded and this phenomenon is named as Kaiser effect [10]. Concrete is a typically heterogeneous material and contains numerous pores and micro cracks along the aggregates. The failure process of concrete is the gradual accumulation of damage and hence during cyclic loading Kaiser effect is an indication of damage level in concrete material [11]. Because of heterogeneity of concrete, the load at the onset of AE is not exactly equal to the previous maximum load, and it is always a little less than the previous load level. This is called Felicity effect and its quantification is called load ratio or felicity ratio. A criteria for the assessment of damage in concrete has been proposed by NDIS-2421 standard by the Japanese Society for Non-destructive Inspection which is based on Kaiser effect [12]. This defines two parameters namely load ratio and calm ratio. The Load ratio is the ratio of load at the onset of AE activity to previous maximum load and Calm ratio is the ratio of cumulative AE activity during unloading process to total AE activity during the last loading cycle. To monitor damage level in each loading cycle, a scatter plot between load ratio and calm ratio proposed by NDIS-2421 standard has been used [11-12].

Usage of fly ash as partial replacement of cement in concrete has successful track record. Fly ash is a by-product of coal based power generating plants. The utilization of fly ash in concrete as partial replacement of cement is gaining importance as it has environmental, technical and economic benefits such as reduced amount of waste materials, reduced energy requirement, cleaner environment, durable service performance and cost effective structures. Using fly ash as a supplementary cementitious material greatly contributes to improve the mechanical properties of

hardened concrete and durability of concrete through pore refinement, control of high thermal gradients, resistance to chloride and sulphate penetration, and continued micro structural development through long term hydration, pozzolanic reaction and filler effect [13]. In fly ash concrete, the pozzolanic reaction between fly ash and calcium hydroxide (Ca(OH)$_2$) produced by hydration of cement results in additional calcium silicate hydrate (C-S-H) product and fills up the capillary pores, making the fly ash concrete more impermeable in microstructure as compared to normal concrete [14-15]. Haneef et al. [16] studied the influence of fly ash and curing on cracking behavior of concrete using acoustic emission during uniaxial compression loading. AE generated during compression loading were monitored and correlated with different stages of cracking and the effect of fly ash on the cracking mode was also discussed [16].

This paper presents the performance of plain and fly ash concrete prisms with different curing periods subjected to four point loading using AE activity. The aim of this study is to monitor the damage growth under cyclic incremental loading using AE parameters and compare the results of plain and fly ash concrete.

2.   Experimental

Plain and fly ash concrete prisms having dimensions 700mm x 150mm x 150mm were cast in accordance with IS 516-1959 as shown in Figure 1. The plain concrete specimens were the control specimens made of cement, natural aggregates, water and super plasticizer. In the fly ash concrete prisms, 30 % of cement was replaced with fly ash. Mix proportions of the concrete prisms are given in Table 1. Ordinary Portland cement (43 Grade) conforming to IS 8112 and siliceous type Fly ash conforming to IS 3812: Part: 2 were used. The specific gravity and fineness of fly ash were 2.13 and 426 m2/kg respectively. The concrete test specimens were cured for 7 and 28 days by submerging them in water at room temperature.

Figure 1. Concrete prisms used for study.

Table 1. MIX PROPORTIONS OF CONCRETE SPECIMENS

Concrete Type	W/B ratio	Total Binder kg/m^3	Cement kg/m^3	Fly Ash kg/m^3	Fine Agg. kg/m^3	Coarse Agg. (kg/m^3)	
						12.5mm	20mm
plain	0.44	380	380	-	809.4	550.5	550.5
Fly ash replaced	0.44	380	266	114	787.4	535.6	535.6

AE measurement was carried out during four-point bending tests of both plain and fly ash concrete. The schematic of the experimental set up used for AE monitoring is shown in Figure 2. The sensor was fixed firmly at the side face of the specimens with silicon grease and the photograph of the setup is shown in Figure 3. Two specimens were tested in each condition and variation of applied load and AE activity were recorded simultaneously. AE signals generated during the cyclic loading were recorded using a 150 kHz resonant sensor along with a 40 dB pre-amplification and a band pass filter (100-300 kHz). The AE signals were recorded by using AE DiSP data acquisition system supplied by M/s Physical Acoustics Corporation. To remove the background noise, a threshold of 35 dB was used. For SEM investigation, small pieces from fracture surface were used and examination was carried out using a Camscan scanning electron microscope.
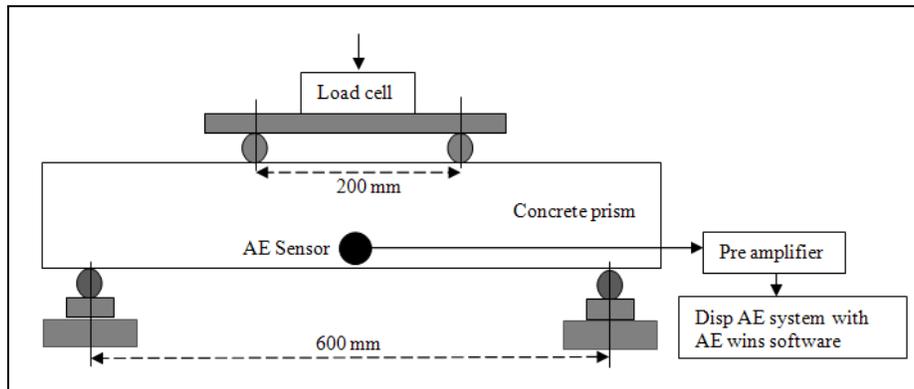

Figure 2. Schematic of the experimental set up used.

3.   Results and discussions

Flexural strength of the concrete prisms obtained from the respective ultimate loads from two tests in each condition is given in Table 2**.** Higher flexural strength was observed for 28 days cured plain and fly ash concrete prisms as compared to 7 days curing. In 7 days cured condition,

plain concrete prisms shows higher strength as compared to that of fly ash replaced prisms. After 28 days of curing, fly ash concrete shows higher flexural strength as compared to that of plain concrete. The difference in flexural strength between plain and fly ash concrete specimens at 28 days curing is more compared to that of 7 days curing. This is due to the pozzolonic reaction in fly ash concrete which progresses continuously with curing period thereby enhancing the strength of fly ash concrete.
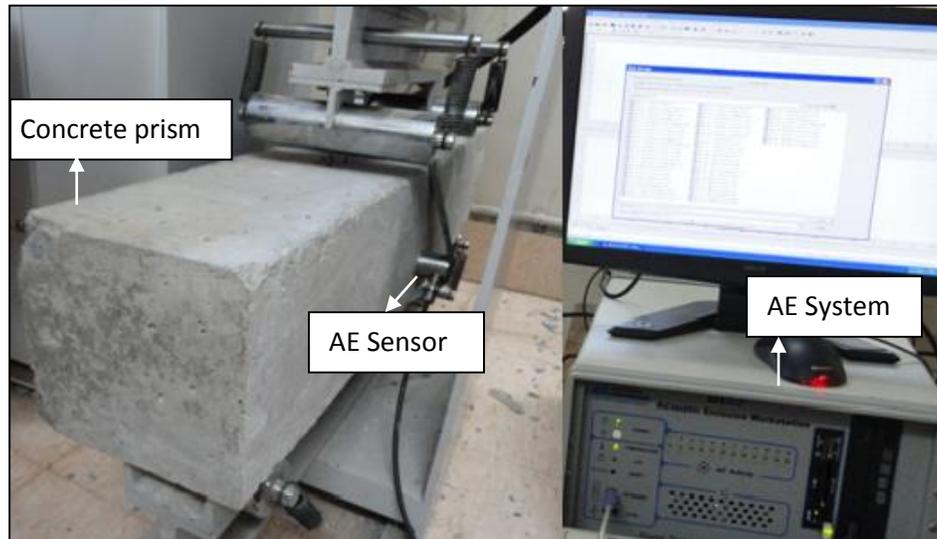

Figure 3. Photograph of the experimental set-up

Table 2. VALUES OF FLEXURAL STRENGTH OF PLAIN AND FLY ASH CONCRETE.

Curing periods	7 days		28 days	
Mix type	Plain	Fly ash	Plain	Fly ash
Flexural strength (N/mm^2)	3.25 3.48	2.72 2.99	3.89 4.1	5.08 4.55
Average	3.37	2.86	3.99	4.82

Figures 4 and 5 show the variation of applied load, AE energy and cumulative AE strength vs. time during the cyclic loading of 7 days cured plain (Figure 4) and fly ash (Figure 5) concrete prisms respectively. In 7 days cured concrete prisms, cyclic loading was carried out with steps of 4 kN. The results presented in Figures 4-5 show that for initial loading cycles, dominant AE activity can be observed up to maximum load in each cycle. During unloading of each cycle, less AE activity is generated. AE activity during cyclic or repeated loading of concrete structures could be due to different sources: closure of pre-existing cracks and formation of micro cracks through weak boundaries present in interfacial transition zone (ITZ).

To understand the Kaiser effect, AE generated in each cycle has been analyzed. The Kaiser effect represents the irreversibility of AE activity in a material and it states that no AE would be generated in the material until it is loaded beyond its prior maximum load level. Figures 4 and 5 clearly show that in the second loading cycle of both concretes cured for 7 days, AE activity is observed only after crossing previous maximum load (4 kN). This result shows that AE activity follows Kaiser effect in second loading cycle. From third cycle onwards significant AE activity can be seen before previous maximum load (8 kN, shown by arrow in Figures 4-5) in both concrete prisms and this is an indication of damage accumulation. Plain concrete specimens failed in 5th cycle at 18.3 kN load. But fly ash concrete prism failed in 4th cycle at 15.3 kN load.
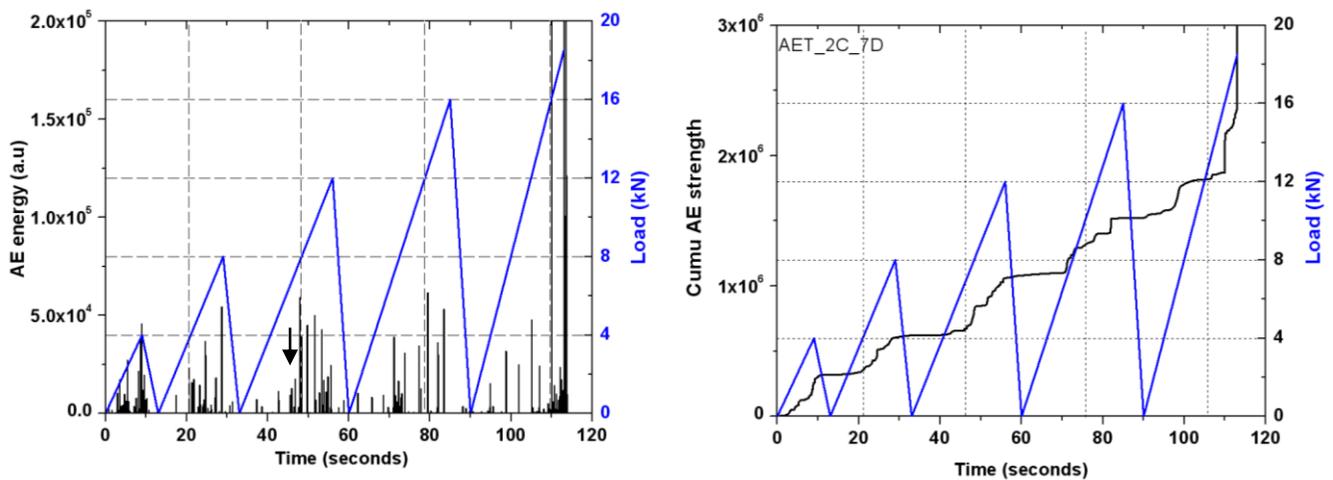
Figure 4. Variation of load and AE activity during cyclic loading of plain concrete prism cured for 7 days.
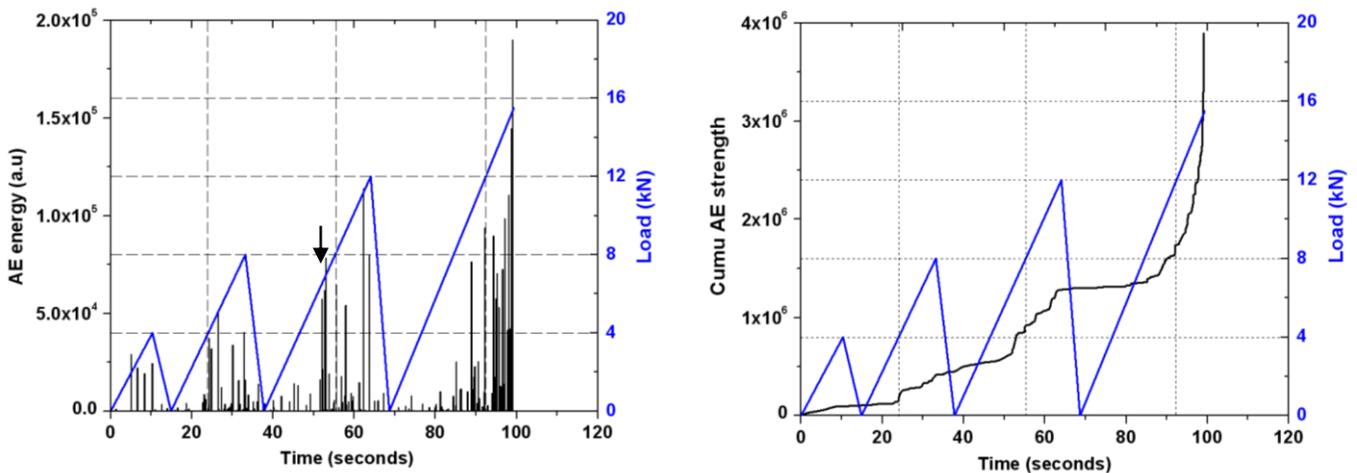
Figure 5. Variation of load and AE activity during cyclic loading of fly ash concrete prism cured for 7 days.

Variation of applied load, AE energy and cumulative AE strength vs. time for 28 days cured plain and fly ash concrete prisms are given in Figures 6 and 7 respectively. In plain concrete cyclic incremental loading was carried out with steps of 4 kN. The AE activity is generated only after crossing the previous cycle's maximum load up to third cycle. From 4th cycle onwards AE activity is generated before previous cycle's maximum load of 16 kN and this is an indication of damage growth. The concrete failed at 21.9 kN load at 5th cycle. In fly ash concrete cyclic incremental loading was carried out with steps of 5kN and AE activity generated during loading in each cycle is reduced when compared to that of plain concrete. During initial three loading cycles, there is no dominant AE activity before previous cycle maximum load. During 4th cycle of loading, AE activity is generated prior to the previous cycle maximum load of 20 kN. Fly ash concrete failed in 5th cycle at 28 kN load.

The results presented above show that the dominant AE activity during cyclic loading for 28 days cured fly ash concrete prisms is observed only after 20 kN load as compared to plain concrete in which it occurs at 16 kN load. This shows that in fly ash replaced concrete prisms, damage accumulation occurs at higher load as compared to plain concrete prisms. Delayed damage accumulation in 28 days cured fly ash concrete prisms compared to 7 days could be attributed to continued pozzolonic reaction of fly ash due to extended hydration which can fill the existing pores and voids in the concrete. This has been verified by examination under SEM.
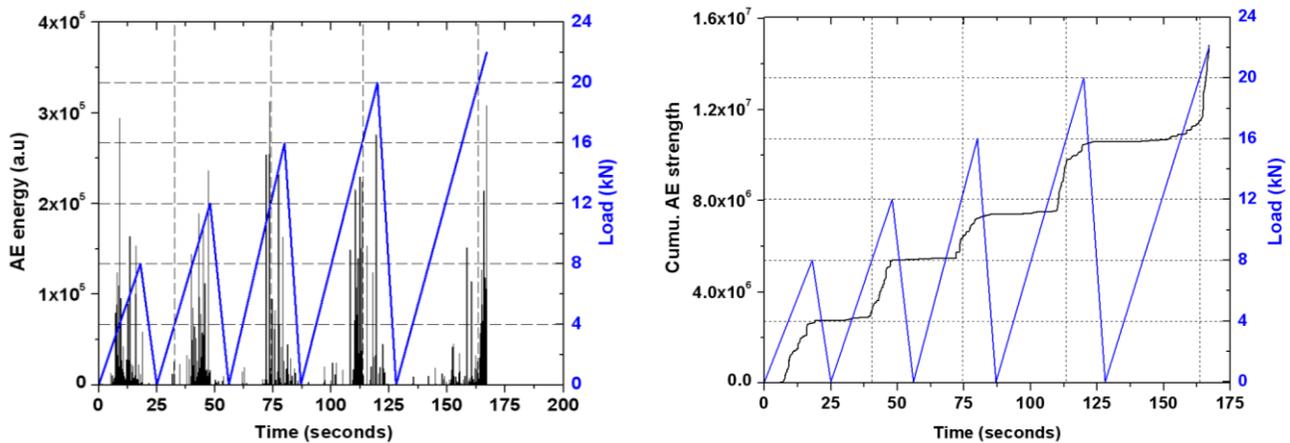

Figure 6. Variation of load and AE activity during cyclic loading of plain concrete prism cured for 28 days.
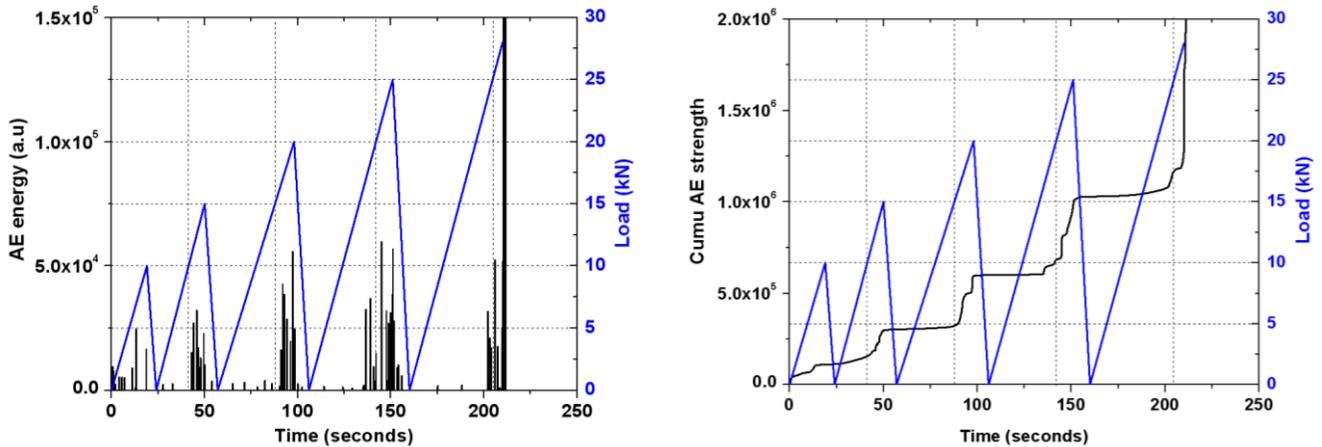
Figure 7. Variation of load and AE activity during cyclic loading of fly ash concrete prism cured for 28 days.

Figures 8 (a-b) show the variation of load ratio with loading cycle of plain and fly ash concrete prisms cured for 7 and 28 days respectively. The load ratio of both types of concrete decrease with loading cycle for both 7 and 28 days cured concrete prisms. Comparing both cured periods, 28 days cured prisms shows higher load ratio for any cycle when compared to 7 days cured specimens. It is also clear that 28 days cured fly ash concrete shows higher load ratio. Decrease in load ratio is an indication of damage growth hence this result shows that addition of fly ash with proper curing resists damage accumulation. This can be explained using Zhang's model [17].

According to this model, the unreacted fly ash particles act as fine aggregate and become obstacle to the damage propagation. Thus, fly ash concrete can withstand higher load without damage propagation as compared to plain concrete. For longer curing period, CSH paste and aggregates interfacial bond strength increases due to the hydration of di-calcium silicate and therefore, transition zone undergoes densification. This has beneficial effect on resisting damage propagation in both types of concretes and this explains higher load ratio in 28 days cured concrete prisms compared to 7 days cured concrete prisms.
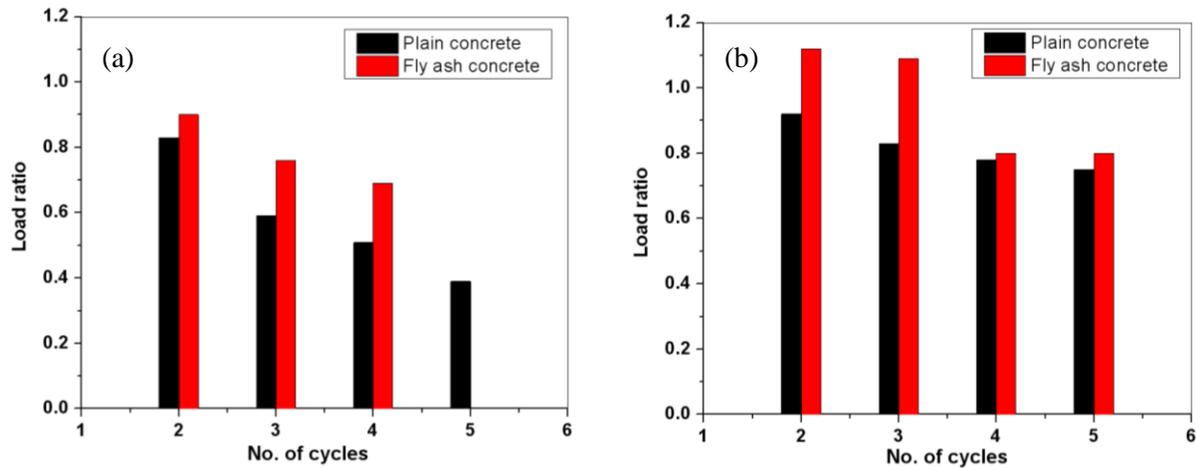
Figure 8. Variation of load ratio with loading cycle of plain and fly ash concrete prisms cured for a) 7 days and b) 28 days.

Figures 9 (a-b) show NDIS based damage classification plots of 7 days cured plain and fly ash concrete prisms respectively. Classification of damage is based on dividing scatter plot of load ratio and calm ratio into different zones. For classifying load ratio and calm ratio plane into different damage zones, reference data used by Ohtsu et al. [18] were adopted, i.e. a value of 0.9 for the x-axis (Load ratio) and 0.05 for y-axis (Calm ratio) was used. Using these plots damage accumulation during cyclic loading is classified in to minor, intermediate and heavy damage. In these plots first cycle data is not included since load ratio cannot be calculated due to non-availability of previous maximum load. During second loading cycle, 7 days cured plain concrete is loaded to about 40% of the ultimate load and fly ash concrete loaded about 52 % of the ultimate load. From Figures 9 (a-b) it is clear that for both plain and fly ash concrete prisms damage level during second loading cycle lies in the intermediate damage zone. All other points corresponding to successive loading cycles of 7 days cured plain and fly ash concrete prisms lie in the intermediate damage region up to failure cycle. Both concrete prisms fail catastrophically after maximum load is reached at final cycle.

NDIS based damage classification plots of 28 days cured plain and fly ash concrete is given in Figures 10 (a-b). Damage levels in both concretes during second loading cycle lie within the minor damage zone of the NDIS chart and this does not indicate any significant damage in the prisms caused by initial loading cycles. But during third and fourth loading cycles of plain concrete, damage level is shifted to intermediate level. In the fly ash concrete, damage level corresponding to third cycle still remains in the minor damage zone as compared to plain concrete and only for fourth cycle damage level shifts to intermediate zone. Delayed shift of damage to intermediate zone for 28 days cured fly ash concrete prisms indicates the reduced tendency of brittleness of the fly ash concrete, which is due to occurrence of additional pozzolonic reaction at

longer curing which can fill the remaining pores and voids in the concrete and this also can be confirmed by SEM examination.
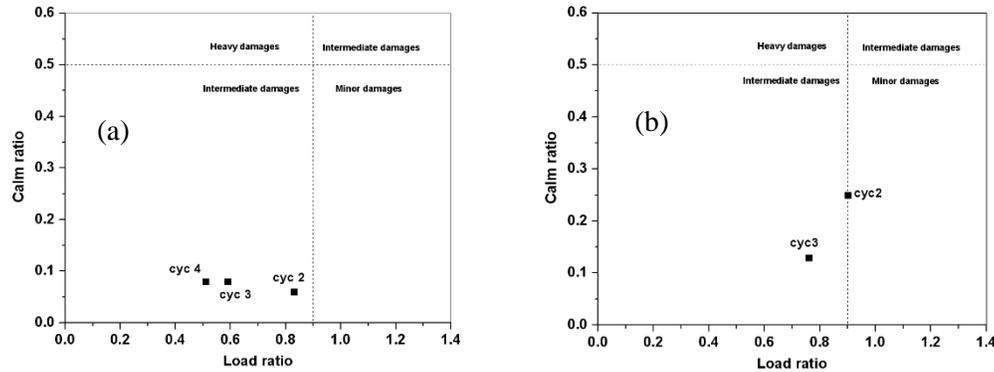

Figure 9. Classification of AE data based on NDIS standard for 7 days cured a) plain concrete b) fly ash concrete prisms.
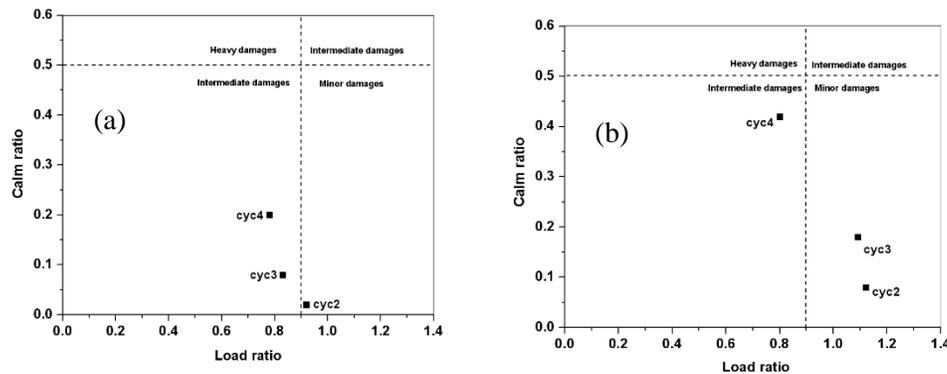

Figure 10. Classification of AE data based on NDIS standard for 28 days cured a) plain concrete b) fly ash concrete prisms.

SEM micrographs of the fracture surfaces of the plain and fly ash concrete specimens cured for 28 days are shown in Figures 11 (a-b) respectively. Microstructure of fracture surface of plain concrete appears less dense as compared to that fly ash concrete and pores of larger size are also seen in Figure 11(a). SEM image of fracture surface of plain concrete also shows diverged multiple cracking and more localized failure regions due to discontinuity in the mortar phase. These multiple cracks originate from pores and other week boundaries and propagate into many directions and shown by arrows in Figure 11(a). SEM image of fracture surface of fly ash concrete clearly shows a denser and interconnected network of needle like hydrates [Figure 11(b)] which is formed due to additional pozolonic reaction.
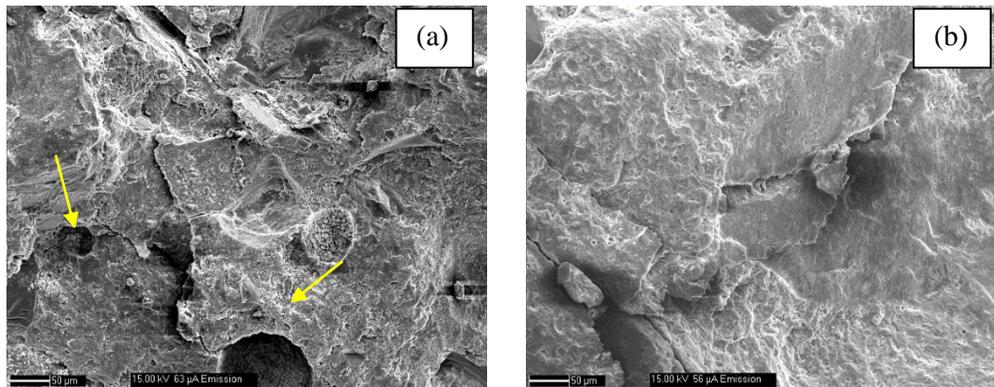
Figure 11. SEM images of fracture surface of a) plain and b) fly ash concrete cured for 28 days.

4.   Conclusions

Based on the above results following conclusions are drawn:

1. In seven days cured plain and fly ash concrete prisms, Kaiser effect exists in first two loading cycles and from third cycle onwards significant AE activity can be seen prior to the previous cycle's maximum load 8 kN. This is an indication of start of damage growth at similar load in both the concretes.
2. In 28 days cured fly ash concrete, AE activity during cyclic loading is observed only after 20 kN load as compared to plain concrete in which it occurs at 12 kN load. Hence cyclic load flexural resistance of fly ash concrete for damage accumulation is higher than that of plain concrete. This has been attributed to additional pozzolonic reaction developed in fly ash concrete as verified under SEM examination.
3. The load ratio of both types of concrete decrease with loading cycle and this indicates damage growth. Higher load ratio in 28 days cured fly ash concrete shows addition of fly ash with extended curing resists damage accumulation.
4. As per NDIS 2421 Standard for Japanese Society for Nondestructive inspection, damage accumulation classified prior to failure stage is confined to intermediate level for 28 days cured fly ash concrete subjected to cyclic loading. This is further substantiating that the damage accumulation in fly ash concrete due to cyclic flexural load is significantly less than that of plain concrete.

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