Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division I

FRACTURE CHARACTERISTICS OF CONCRETE FOR DIFFERENT AGGREGATE SIZES USING ACOUSTIC EMISSION

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ABSTRACT

The three-point bending tests of plain concrete beams have been done to study the fracture and AE characteristics of concrete. It was found that the relative aggregate size significantly influenced AE characteristics. The micro-mechanism of the fracture process in concrete is investigated by the b-value. The development of fracture process in concrete is observed by computing b-value using cumulative frequency distribution of AE released. Fracture process in concrete is well simulated with the four zones in amplitude distribution. As size of coarse aggregate increases, the brittleness of the beam is also increased. Rupture probabilities of microelements in concrete comply with Weibull distribution. To describe influences of the different aggregate sizes on AE characteristics, fracture characteristics, and brittleness of concrete Weibull distribution function is used. The two parameters, *m* and *n* of the Weibull function depended on the brittleness and geometry of concrete, respectively. Weibull parameters show that specimen with smaller size aggregates are more reliable than the larger aggregate sizes.

Keywords: Acoustic emission (AE), Weibull parameters, Brittleness

INTRODUCTION

Concrete is a composite material, which exhibits heterogeneity in its properties. Due to this heterogeneity, a large number of micro-cracks develop in concrete, when it is stressed. These micro-cracks are important causes of failure of concrete. The component of concrete has the highest amount of aggregate, so they play an important role in its fracture properties. There have been many studies on the importance of aggregate size on fracture properties but they conflicts with each other. Mihashi et al. [8] find significant influence of aggregate size on the fracture energy, while Kleinschrodt et al. [7] argues there is no effect on the fracture energy with aggregate size. So there is no clarity on the damage assessment of concrete structures with their aggregate sizes. Various techniques have been used to study the fracture behaviour of concrete. Despite there being more technique, Acoustic emission (AE) technique is the most preferred because of its ability to detect internal micro-cracks. The localized internal energy released by micro cracks in stressed concrete generates elastic waves. Acoustic emission is the propagation of these elastic waves. AE technique is used to detect and record the generation and development of the micro-cracks. Various aspects of the fracture process can be better understood using the AE parameters like AE amplitude, frequency, events, energy etc.

Cumulative events with time of its occurrence illustrate the fracture process as shown in the Figure 3. Fracture process can be understood by the variation of cumulative events with time but b-value gives the deep analysis of the fracture process. Figure 4 illustrates the fracture process of concrete with the b-value analysis. After understanding the evolution of the damage state of concrete, it is also necessary to understand the reliability of concrete. Material strengths are related with its flaw sizes [5]. A normal distribution is used to describe material strength because the largest flaws are not symmetrical. For this purpose, the Weibull distribution is usually considered the best choice to characterize the concrete. Weibull parameters are related to the type and size of flaws.

EXPERIMENTAL DETAILS

Sample preparation:

The plain concrete beams of grade M30 were prepared to perform three-point bend (TPB) tests. Details of concrete mix proportion is listed in Table 1. The specimens were demolded one day after casting and then cured in a curing chamber at 25^{0}C up to 28 days. Nine centrally notched TPB specimens of different maximum aggregate sizes (6 *mm*, 12 *mm* and 20 *mm*) with span to depth ratio 2.5 and notch depth to depth ratio 0.2. Three beams were tested for each maximum aggregate size. Dimension of each beam was 515 *mm* x 150 *mm* x 75 *mm*. The 28 days compressive strength of the concrete mix specimens were tested in compression testing machine. Three-point bend test were conducted in structure laboratory Department of Civil Engineering, IIT Roorkee, India.

Table 1. Mix proportion

Material	Water, kg/m^3	Cement, kg/m^3	Coarse aggregate, kg/m^3	Fine aggregate, kg/m^3
Quantity	202.50	450.00	992.00	782.00

Testing arrangements:

For the central loading on simply supported beams of span S, the experimental setup consisted a BISS 500 kN Fatigue Testing Machine with servo hydraulic actuator and a data acquisition system is used as shown in the Figure 1. AE monitoring system AE win is used for the analysis of fracture process in concrete. The AE monitoring system has 6 channels one for each sensor. High vacuum silicon grease was used to improve the acoustic coupling between the sensors and concrete. The AE signals were amplified with a gain of 40 dB in the system. A threshold of 40 dB was selected to ensure a high signal to noise ratio. All specimens were tested under crack mouth opening displacement control at a rate of 0.0005 mm/s. The mid span displacement was measured using a LVDT, placed at the center on the underside of the beam.

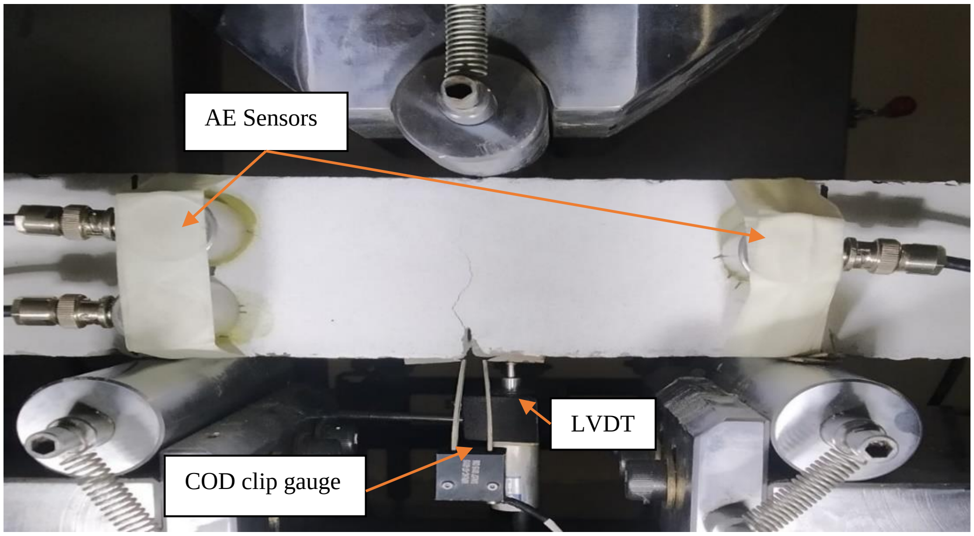

Figure 1.TPB test setup.

METHODOLOGY

An analysis of the b-value identifies and measures the extent of damage to concrete. The decreasing b-value trend suggests macro-cracks have formed, while the increasing b-value trend implies micro-cracks growth [4]. The reliability of the concrete with their different aggregate sizes have to check with the Weibull parameters. Both the above concepts are based on the AE parameters.

The b-value analysis:

The magnitude and frequency of the failures was related by Gutenberg and Richter. GR equation is mainly used to measure seismic activities. AE phenomena is somehow similar to seismic activities, so we can use b-value analysis based on AE parameters. Numerous studies have been conducted to correlate the b-value with strain in concrete at various stages of failure. By replacing the magnitude into the 1/20 of the AE amplitude GR b-value equation can be used as AE b-value equation as shown in the equation 1 [7].

$$log_{10}(N) = a - b\left[\frac{A_{db}}{20}\right] \tag{1}$$

In which N is the number of AE hits of amplitude $\geq A_{db}$, a is constant, b is AE-based b-value. In this logarithmic equation, the gradient b is negative, which means that large-amplitude AE events are observed less frequently than small amplitude events. Colombo et al. [7] observed that stage of micro-crack occurrence and vice versa. During the fracture process in concrete evolution b-value can be related to the types and stages of the crack. In the process of formation and localization of macro-cracks b-value decreases.

Weibull damage function:

During the analysis of real data, no solid motivation for the use of the third parameter was realised. Therefore, we focused on the two parameter Weibull distribution [2]. The rupture probability density function of the micro-cracks could be described as follows [3].

$$f(\varepsilon) = nm(\varepsilon - \varepsilon_0)^{m-1}\exp\left[-n(\varepsilon - \varepsilon_0)^m\right] \tag{2}$$

In which n and m are parameters related to the dimensions and elastic properties of the specimens, ε_0 is determined by experiments. The rupture probability can be found out by integrating the density function.

$$F(\varepsilon) = \int f(\varepsilon) = 1 - \exp\left[-n(\varepsilon - \varepsilon_0)^m\right] \tag{3}$$

In terms of AE event Weibull damage function is defined as following.

$$F(\delta) = \frac{N_\delta}{N_{tot}} \tag{4}$$

Where N_δ is the number of AE hits for a particular displacement (δ). In this study TPB test have been done by CMOD control. So the displacement here is taken as horizontal displacement that is CMOD. N_{tot} is the total AE hits acquire by the AE system. For TPB test in rupture probability ε can be replaced by displacement (δ). By equating Weibull damage function to the rupture probability and applying bi-logarithmic regression analysis following equation is determined.

$$\frac{N_\delta}{N_{tot}} = 1 - \exp\left[-n(\varepsilon - \varepsilon_0)^m\right]$$

$$\ln\left[-\ln\left(1-\frac{N_\delta}{N_{tot}}\right)\right] = m\ ln(\delta-\delta_0) + \ln n \tag{5}$$

The Weibull parameters *m* and *n* can be calculated by above equation by linear regression. δ_0 is the displacement at the time of first AE hit, which can be found with the experiment.

RESULTS AND DISCUSSION

Aggregate size effect on mechanical properties of concrete

The Load-CMOD curve of the concrete fracture under different sizes of aggregate has been shown in Figure 2. As shown, it has found that increase in aggregate size, the peak load increases. This is indicative of aggregate size having an obvious effect on fracture properties. There may be an increase in load due to a tortuous fracture path or increased roughness of the crack surface [3,6]. The peak load of 12 *mm* aggregate size is 17.65% more than that of 6 *mm* whereas, it is 64.71% more for 20 *mm* aggregate size. It is observed from the Load-CMOD curve in the loading process load attains its peak at about the same value of the CMOD.

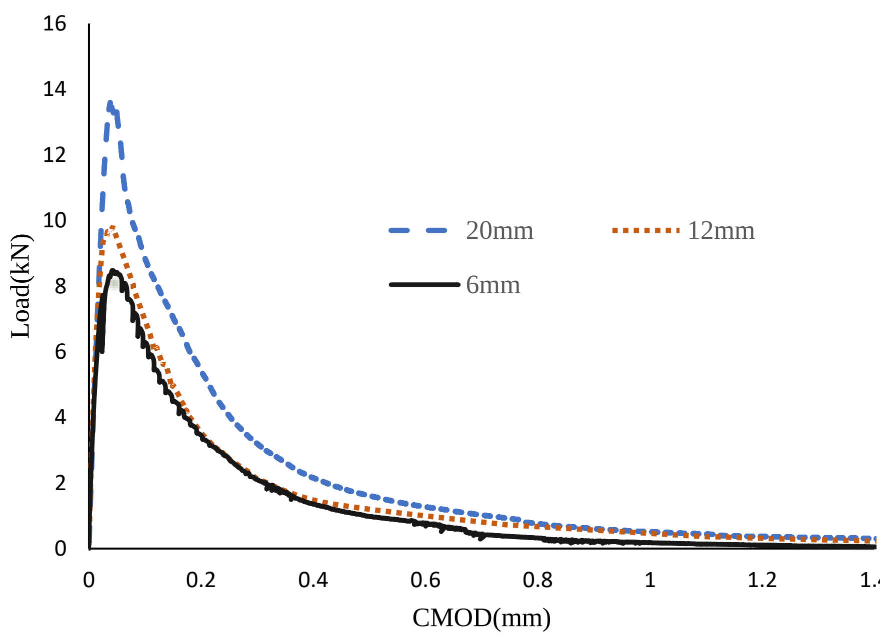

Figure 2. Load-CMOD curve for different aggregate size.

Cumulative events with time

The variation of Load/Cumulative events against time has been presented in Figure 3 for a typical specimen SM-1 having 6 *mm* aggregate size. The entire plot has been divided into three distinct zones, zone 1, zone 2 and zone 3. Negligible no of events have been found in zone 1. Most of the events have been observed to occur in zone 2 following the peak load. The above observation makes it evident that initially before peak negligible no of micro-cracks have been generated following which strong occurrence of events takes place. Further small number of new events has occurred in zone 3. Major macro-crack was developed in zone 2 and further loading unstable fracture without energy release. For all other specimens the similar pattern of the cumulative event variation with the time is observed.

The b-Value analysis

The rupture processes in plain concrete were investigated on the basis of the b-value. Figure 4 shows the variation of b-value with time and load. In the diagram, change of the AE based b-value over time was divided into four zones based on the growth pattern of cracking. It was observed that initially AE based b-value increased, perhaps this is because there has been an increase in AE hits and the beginning of internal cracks. During the initial stage of loading the AE released due to the cohesiveness of the crack in concrete began to show an increasing b-value. In stage II the internal crack initiation and propagation started at about the peak load. In this stage different inelastic toughening mechanism appears around the cracks which are isolated and randomly distributed in the specimen. During fracture in stage II a part of energy consumes by air voids acquired during curing for the high stress state near the crack tip. Hence in this stage AE hits and b-value decreases. In stage III AE based b-value recovers immediately as shown in Figure 4 due to the localization of the internal cracks into a major crack that propagate with increasing load. This stage shows the propagation of a stable macro-crack. In stage IV major crack propagate continuously that is unstable cracking starts. In this stage b-value decreased initially and later remains constant with the decrease of load.

The main fracture process phenomenon occurs in stage 1, 2 and 3 in b-value analysis. In Figure 3, it is clear that zone 2 is the most important zone of the fracture process. Most of the events takes place in zone 2. It can be concluded that the stage 1, 2 and 3 in b-value analysis and zone 2 in cumulative events curve are same. In cumulative events-time curve occurrence of events are high in zone 2 which indicates most of the fracture takes place in this zone, while in b-value curve beginning of micro-cracks, its initiation and propagation, toughening mechanism and localization of micro-crack to macro-crack can observed. The fracture process of concrete can be illustrated with more details, using b-value analysis.

Weibull parameters

Based on the stress level during TPB test, Weibull function is correlated to AE concrete hit generation behaviour. With the help of Weibull parameter, we can observe the fracture reliability of the concrete [8]. In this study two parameters *m* and *n* finds with the AE hits observation. Parameter *m* is slope of the regression line, represents the intrinsic properties of the material, parameter *n* is intersected of regression line which is scale parameter for the material. Figure 5 describe AE Weibull analysis for SM1, 6 *mm* specimens. Parameter *m* is 1.0464 and *n* is 0.1628 observed for this specimen. δo for this specimen is 0.000412 *mm* observed from the test. Similar trends are found for all other specimens. The Weibull parameters *m* and *n* for all specimens are shown in Table 2. Average of both parameters for three specimens have calculated and compared the average parameters with three aggregate sizes.

Average *n* values for all the three types of specimens are almost same. This is because of the same dimensions of the specimen as *n* parameter reflects the scale parameter in Weibull damage function. In the result *m* decreases as aggregate size increases but peak load increases with aggregate size. So, for higher flexural strength of the beam *m* value decreases. As shown in Figure 6, for initial value of $ln(\delta-\delta o)$ on the x-axis the $ln(-ln(1-N/Ntot))$ value on the y-axis increases with increase of aggregate size. As the stress level increases that means at higher values of displacement, the number of hits comes closer for different aggregate sizes. It is concluded from these results that the number of hit occurrence in 20 *mm* aggregate size is more compared to 12 *mm* and 6 *mm* in early stage of stress. Although the peak load of the larger sizes aggregate is more but its reliability is less. The damage state comes earlier to the larger aggregate size than the smaller ones as the *m* value is lowest for it. So, in this study 6 *mm* aggregate size specimens are more reliable than the larger sizes of aggregate.

The Weibull parameters can use as the material brittleness parameter also. Parameter *m* represents the intrinsic brittleness and *n* represents specimen geometrical brittleness [3]. As the geometry of all the specimens are same, the variation of *n* is negligible. The greater the value of *m*, the less brittle the material. So, the intrinsic brittleness of the material increases with the increase of aggregate sizes.

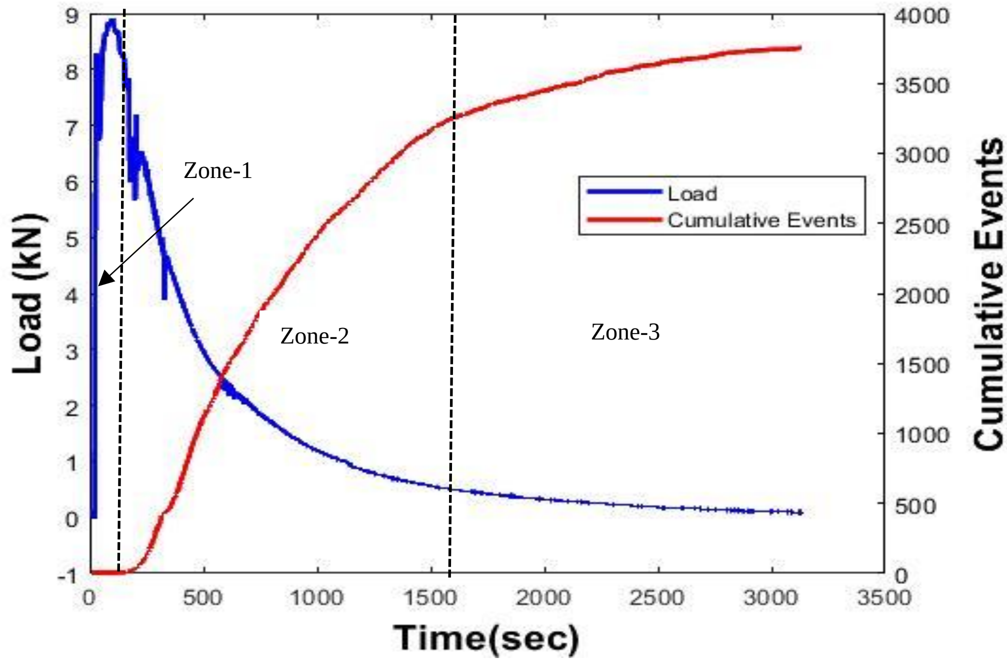

Figure 3. Load/Cumulative Events Vs Time curve for SM1, 6 *mm* aggregate size.

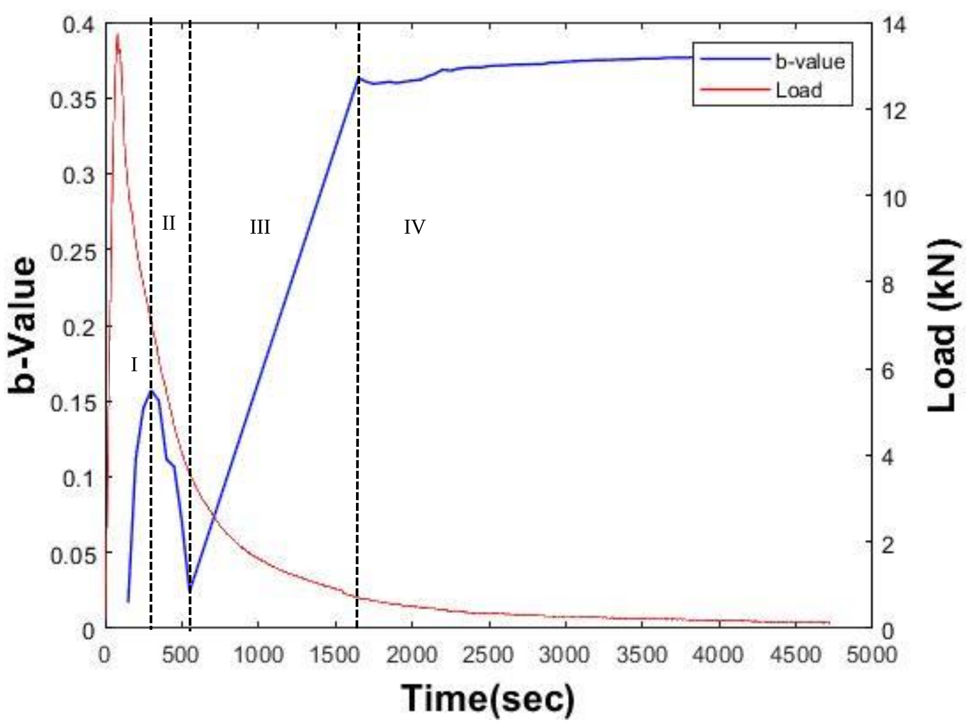

Figure 4. Variation of b-value with time for SM1, 6 *mm* aggregate size.

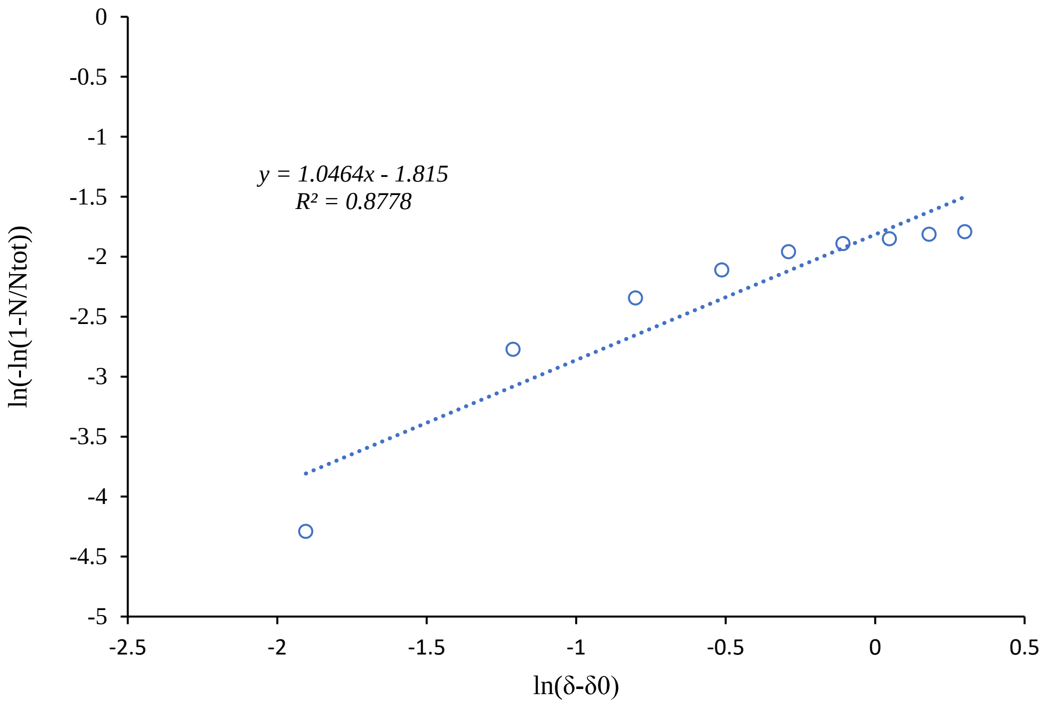

Figure 5. Linear regression analysis for Weibull damage parameter in SM1, 6 *mm* specimen.

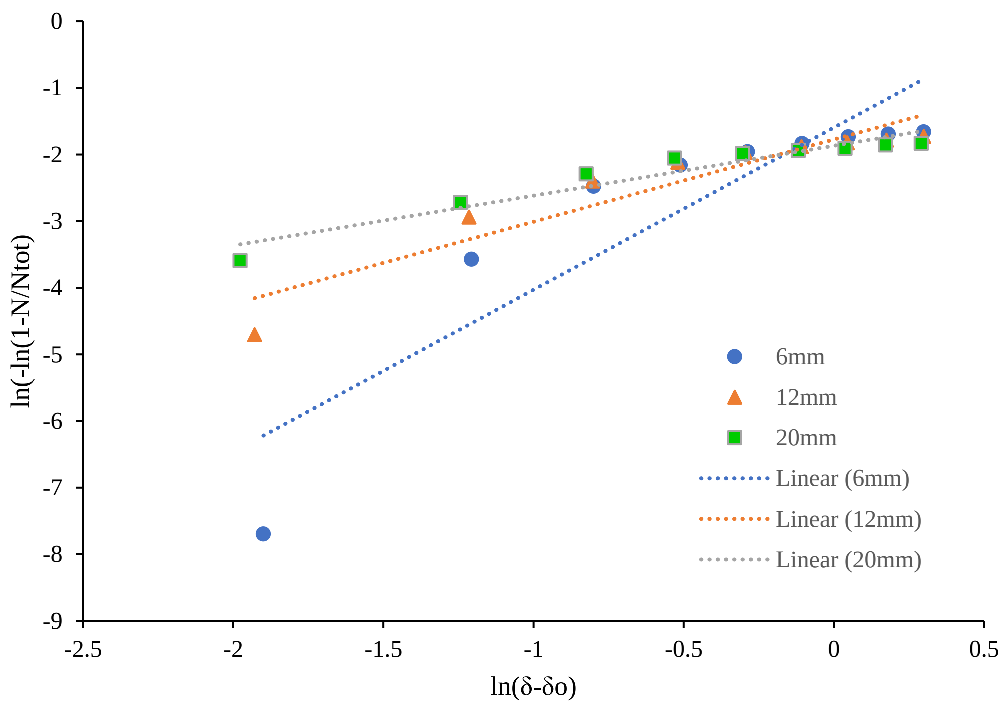

Figure 6. AE Weibull analysis of concrete having different aggregate size.

Table 2: Weibull parameters for all the specimens.

Aggregate size	Sample Name	*m*	Average (*m*)	*n*	Average (*n*)
6 *mm*	SM1	1.0464	1.6052	0.1628	0.179
	SM2	2.4334		0.2026	
	SM3	1.3359		0.1716	
12 *mm*	SM1	0.9292	0.9317	0.1682	0.1619
	SM2	1.2353		0.1697	
	SM3	0.6306		0.1479	
20 *mm*	SM1	0.7487	0.7407	0.1543	0.1529
	SM2	0.7437		0.1521	
	SM3	0.7297		0.1523	

CONCLUSION

1. The mechanical behaviour of the three-point bending concrete beams with different aggregate sizes are different. The peak strength increases with the aggregate sizes as its crack path is more tortuous and the skeleton effect of the aggregate also acts.
2. Fracture process of the concrete can be elaborated with the AE events. Most of the AE events occurs in zone 2 as shown in Figure 3. Coalescence of micro flaws, growth of micro-cracks and growth of main crack takes place in zone 2. In zone 3 there is unstable macro crack propagation without effective increase of events.
3. The b-value analysis of AE amplitude distribution explains much deeper failure process analysis of the concrete. In Figure 4 zone 1, 2 and 3 explains clearly the fracture process of the concrete.
4. Weibull parameter can relate the geometric and intrinsic properties of the material. Parameter *m* represents the intrinsic properties as it changes with aggregate size. Specimens of aggregate size 6 *mm* is more reliable than its larger aggregate size specimens.
5. Intrinsic brittleness of the concrete increases with their aggregate sizes. Concrete with aggregate size 20 *mm* is more brittle than smaller aggregate size specimens.

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