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FATIGUE DAMAGE PREDICTION OF CONCRETE USING ACOUSTIC EMISSION APPROACH WITH ACCOUNT OF CONCRETE HETEROGENEITY

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Abstract. Concrete, a ubiquitous construction material for structures like bridges, roads, and marine installations, is prone to fatigue damage caused by factors such as traffic loads, wind, and wave forces. Despite its wide usage, the intricate process of concrete fatigue failure remains relatively unexplored. Heterogeneity, a common attribute of materials, significantly influences how concrete behaves when subjected to fractures. This study aimed to address this knowledge gap by investigating how concrete's heterogeneity, particularly in terms of varying aggregate sizes, impacts its susceptibility to fatigue-induced fractures. The research employed beam specimens subjected to central loading under controlled loads. To continuously monitor the loading process, the study employed acoustic emission (AE) monitoring, a technique that captures acoustic events. The insights gleaned from the investigation revealed noteworthy aspects of concrete behavior. The initial stiffness of concrete beams was found to be higher when larger aggregate sizes were incorporated. However, as the number of fatigue cycles increased, these beams experienced a gradual decline in stiffness. Notably, the rate of stiffness degradation escalated with higher cycle counts, and a pronounced drop in stiffness was observed right before beam failure, indicating a pivotal phase in concrete's fatigue life. The AE technique emerged as a valuable tool for analyzing fatigue-induced damage in concrete. By monitoring AE events continuously, the study unveiled three distinct fatigue damage zones: crack initiation, gradual crack progression, and eventual beam failure. AE parameters effectively showcased the influence of concrete heterogeneity, as represented by varying aggregate sizes, on its fatigue response. Notably, the AE event analysis consistently demonstrated a recognizable pattern of concrete failure under fatigue loading, affirming the reliability of the AE technique in tracing the fracture process. In summary, this research contributes insights into the intricate fatigue behavior of concrete, particularly regarding how material heterogeneity, notably aggregate size variations, shapes this behavior. The findings underscore the significance of AE monitoring for comprehending fatigue and fracture characteristics, emphasizing the pivotal role of aggregate size in shaping these attributes. By enhancing our understanding of concrete performance, this study aids in designing more durable and robust structures.

1 INTRODUCTION

Concrete is a complex material composed of three phases: the cement matrix, aggregates, and the interface transition zone (ITZ) between them. The presence of aggregates in the cement paste significantly impacts the fracture properties of concrete and influences the overall failure modes of the material. Various studies in the existing literature have highlighted the influence of material heterogeneity, particularly the variation in aggregate size, on different fracture properties, thus shaping the overall fracture behavior of concrete. Mihashi et al. [1] observed an increase in the fracture energy (G_f) with increasing aggregate size. On the other hand, Siregar et al. [2] reported a decrease in fracture energy with increasing aggregate size distribution in high-performance concrete. Tasdemir et al. [3] found that both fracture energy (G_f) and characteristic length (L_{ch}) increase with the maximum size of aggregate. Chen et al. [4] also observed that both G_f and the fracture toughness (K_{IC}) increase with larger aggregate sizes. However, Zhao et al. [5] reported that there is no significant influence of aggregate gradation on the fracture toughness of concrete. These findings highlight the complex relationship between aggregate size and fracture properties in concrete, indicating that the influence of aggregate heterogeneity on concrete fracture behavior depends on various factors and requires further investigation. While there have been numerous studies on the effect of heterogeneity on concrete behavior under monotonic loading conditions [6], the influence of heterogeneity under fatigue loading is relatively scarce and not yet fully understood.

Fatigue failure is a common cause of structural damage in engineering structures [7–9]. It is a progressive process of internal structural changes in a material under repeated loading. In concrete, these changes are primarily related to the development of internal microcracks over time, leading to an increase in irrecoverable strain and modifications in the material's mechanical properties [10–12]. Concrete is inherently heterogeneous and contains various defects such as pores, air voids, and shrinkage cracks. The fatigue failure process in concrete can be divided into three main stages [13]. The first phase, known as fault initiation, concerns the weak areas of the concrete or mortar. The second stage, sometimes referred to as microcracking, is characterized by the gradual and progressive expansion of the inherent faults to a critical size. An unstable crack growth present in the last stage, a continuous or macrocrack will form and eventually fail. The fatigue behavior of concrete can be significantly different from its behavior under monotonic loading. Heterogeneous materials often exhibit non-uniform crack propagation paths and varying crack growth rates during cyclic loading. The presence of heterogeneity, such as different aggregate sizes, can introduce additional complexities to the fatigue process, affecting crack initiation, propagation, and eventual failure. To address this research gap, further investigations are needed to study the effect of heterogeneity on concrete under fatigue loading. Advanced experimental techniques, such as acoustic emission technique with fatigue tests under controlled loading conditions, can be utilized to capture the fatigue behavior of concrete with different aggregate sizes and distributions.

The use of the Acoustic Emission (AE) technique has proven to be valuable in characterizing the fracture behavior of concrete [14]. By measuring the intensity of AE activity and analyzing AE parameters extracted from AE signals, researchers can gain insights into the fracture mechanisms and damage progression in concrete. AE parameters such as amplitude, energy, and duration are conventionally used to categorize crack modes and assess crack growth in concrete. The AE technique has been applied to evaluate the concrete damage degree and to study the propagation, attenuation, and distortion of AE signals in concrete specimens of different sizes and distances between sensors. The paper in question offers a qualitative account of concrete fatigue damage using the AE technique. Notably, the fatigue damage of plain concrete has received limited research attention, and the influence of concrete heterogeneity on its fatigue behavior remains unexplored in the existing literature.

In this proposed research, laboratory investigations are conducted using center point bending tests of beams in conjunction with AE techniques to evaluate fracture characteristics. The experimental results and correlations are used to analyze the influence of concrete heterogeneity, particularly the variation in aggregate size, on fracture parameters.

2 AE TECHNIQUE FOR FRACTURE CHARACTERIZATION

Acoustic emission (AE) is the emission and transmission of stress waves that occur as a result of damage in concrete. When a concrete structure is subjected to mechanical loading, it accumulates strain energy within its material. When dislocation, crack formation, or crack propagation occurs, there is a rapid release of this stored strain energy, leading to the generation of an AE event. This AE event produces a mechanical wave within the structure, which can be detected at the surface using piezoelectric transducers. These transducers convert the stress wave into an electric signal, enabling the monitoring and analysis of concrete's internal damage and behavior.

In this study, AE signals have been recorded using six R6I-AST sensors, which are mounted close to the cracking zone of the concrete specimens. The event definition values have been set at 170, 215, and 290 for small, medium, and large specimens, respectively. To ensure effective transmission of acoustic waves and proper mounting of the sensors on the specimen, a thin layer of high vacuum grease is applied to fill the gaps caused by surface roughness. The sensors are then securely mounted on the specimen using high-strength in-extensible masking tape. Before each test, a pencil break test is conducted to calibrate the sensors and calculate the wave velocity of the acoustic waves for the specific specimen. In this study, the measured acoustic wave velocity for the concrete specimen is 3000 m/s. This calibration ensures accurate and reliable measurement of the AE signals during the subsequent tests.

3 SPECIMEN PREPARATION AND TESTING ARRANGEMENTS

3.1 Specimen preparation

Geometrically similar beams of three different sizes of grade M30 have been cast. The specific gravities of the fine and coarse aggregates used were found to be 2.72 and 2.60, respectively. To investigate the influence of heterogeneity on fatigue fracture behavior, three different sizes of coarse aggregates, namely 6 *mm*, 12 *mm*, and 20 *mm*, were considered. The cube strength values after 28 days of curing were measured to be 40.45 MPa, 35.92 MPa, and 33.64 MPa for aggregate sizes of 20 *mm*, 12 *mm*, and 6 *mm*, respectively. A total of 54 beams with a span-to-depth ratio of 2.5 and varying maximum aggregate sizes were cast for the flexural fatigue testing. All specimens had a constant notch depth-to-depth ratio of 0.2. The dimensions of the specimens are detailed in Table 1.

3.2 Experimental procedure

Table 1: Dimensions of specimens

Specimen	Span (mm)	Width (mm)	Depth (mm)	Notch depth (mm)
Large (SL)	750	75	300	60
Medium (SM)	375	75	150	30
Small (SS)	187.5	75	75	15

Center point loading tests on plain concrete beams were conducted using a 500 kN fatigue testing machine equipped with a servo-hydraulic actuator and a data acquisition system, as shown in Figure 1. For the AE measurements, six AE-sensors were installed on the test specimen as depicted in Figure 1. These sensors were used to map the location of AE events in three dimensions. High vacuum silicon grease was applied to improve the acoustic coupling between the sensors and the concrete surface. During the tests, AE data, including hits, events, counts, energy, spatial locations, amplitude, and time, were simultaneously collected using a data capture device. A threshold of 40 dB was chosen to ensure a high signal-to-noise ratio in the collected AE data.

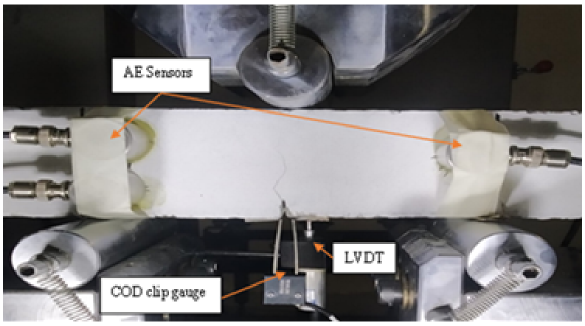

Figure 1: Test set up for center point loading

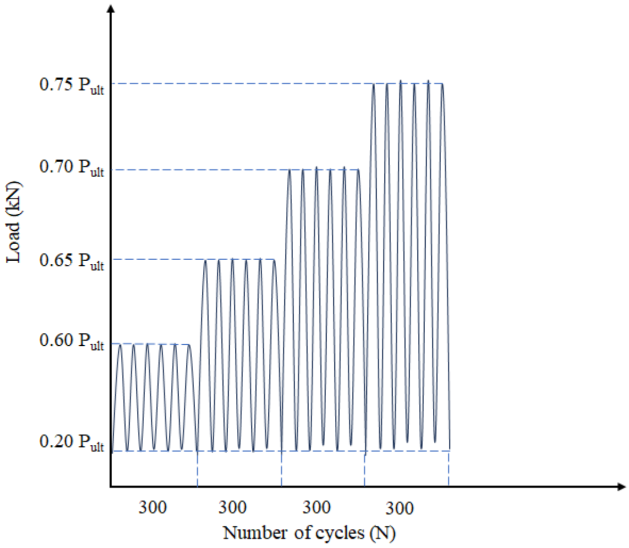

Figure 2: Schematic cyclic loading pattern

Three specimens of each type of beam have been examined under monotonic loading with crack mouth opening displacement control at a rate of 0.0005 *mm/s* to estimate the ultimate load. The mid-span displacement has been measured using an LVDT placed at the center on the underside of the beam. All fatigue testings were carried out under load control using sinusoidal waves with a frequency of 2 Hz. To assess the unloading compliance and to ensure some contact between the loading device and the specimen in order to prevent any impact loading when applying the fatigue load, the minimum load of 20% of the ultimate load was maintained for all cycles. The initial maximum load has been taken 60% of the ultimate load and after every 300 cycles, the maximum load is increased by 5% of the ultimate load as shown in Figure 2. Through a data acquisition system, the results of the load, displacement, CMOD, and the number of cycles with time were simultaneously acquired.

4 RESULTS AND DISCUSSION

4.1 Fracture parameters

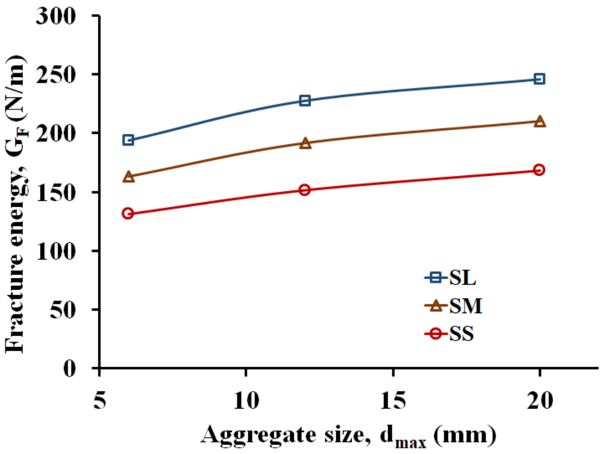

Figure 3: Variation of fracture energy with aggregate size

The fracture energy (G_F) values obtained through the work of fracture method from monotonic loading, are presented in Figure 3. It is noteworthy that the average fracture energy of three beams of the same size is considered in this analysis. Consistent with prior research reported in the literature [1, 15], it is evident that fracture energy increases as the specimen size and aggregate size increase.

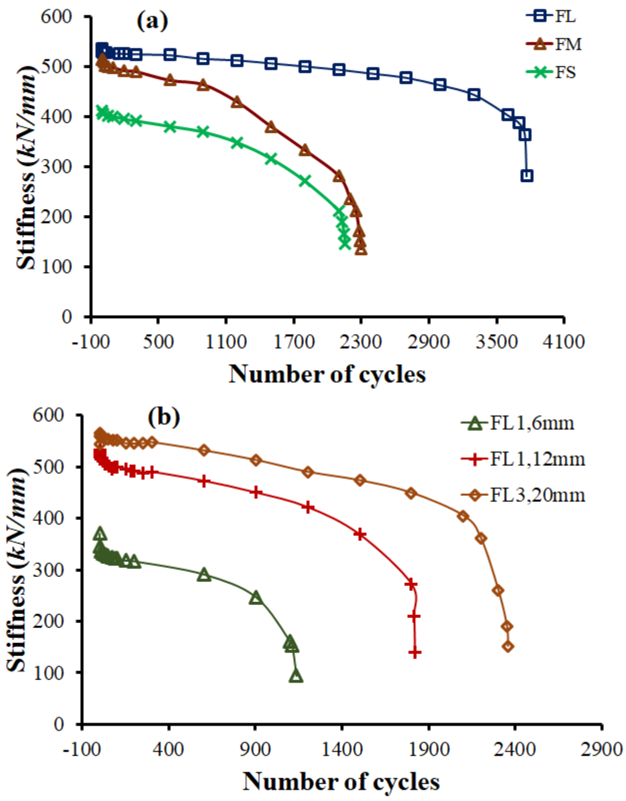

Figure 4: Variation of stiffness with loading cycles for (a) 20 mm aggregate size (b) large specimen size

This observation can be attributed to the larger size of the fracture process zone (FPZ) in beams with higher heterogeneity, which allows for a greater dissipation of energy, resulting in higher values of fracture energy. A more detailed examination of the computed results reveals that the rate at which fracture energy increases becomes lower as the specimen size and aggregate size increase. For concrete with a 20 mm aggregate size, the average fracture energy increases by approximately 20% when transitioning from small to medium-sized specimens, while the increase is around 14% when transitioning from medium to large-sized specimens. Additionally, the fracture energy increases by approximately 14% for large beams when the aggregate size changes from 6 mm to 12 mm, and by around 7% when transitioning from 12 mm to 20 mm aggregate size. These findings provide valuable insights into the correlation between fracture energy and various specimen characteristics.

4.2 Stiffness degradation with material heterogeneity

Figure 4 presents the variation of flexural stiffness with the number of cycles. The secant stiffness is computed between the minimum and maximum load levels for each cycle. The plot illustrates a gradual decrease in stiffness throughout most of the fatigue load duration, followed by a sharp decline just before failure. An interesting observation is that smaller specimens exhibit a higher rate of stiffness decrease compared to larger specimens, irrespective of the aggregate size. This behavior can be attributed to the presence of larger flaws or defects inherent to smaller specimens. These flaws can act as local stress concentrators, leading to more rapid crack propagation and contributing to a higher reduction rate in stiffness. Furthermore, in Figure 4b, it is evident that the rate of change of stiffness with the number of cycles increases as the aggregate size decreases. Smaller aggregates have a larger surface area per unit volume, resulting in a higher interfacial area between aggregates and cement paste. Weaker bonding at the interface between the cement paste and aggregates can contribute to more significant fatigue damage, leading to a higher reduction in secant stiffness.

4.3 Fracture characterization through Acoustic Emission

The application of acoustic emission (AE) for studying crack localization and fracture process in concrete has been extensively researched under monotonic loading [16–21]. These studies have significantly contributed to the understanding of crack behavior and fracture mechanics in concrete structures using AE techniques. Indeed, the application of the acoustic emission (AE) technique for studying fatigue crack growth in plain concrete is limited in the literature. Although some research has been conducted to evaluate fatigue damage in reinforced concrete slabs and asphalt concrete using AE, there is a noticeable lack of studies focusing on the use of AE for monitoring fatigue crack growth in plain concrete, particularly considering its heterogeneity effects. Consequently, one of the primary objectives of the current study is to fill this research gap and explore the potential and efficiency of AE in monitoring fatigue fracture characterization in plain concrete. By doing so, this research aims to contribute to a better understanding of the fatigue behavior of plain concrete and the influence of its heterogeneity on crack propagation and growth.

4.3.1 Cumulative absolute energy variation with normalized cycles

The cumulative absolute energy is a significant acoustic emission (AE) parameter used to analyze fatigue behavior in concrete. Figure 5 presents the variation of cumulative absolute energy with the normalized number of cycles for Specimen FL1 with 6mm aggregate size.
Zone I, which constitutes about 4.5% of the total life of the specimen, exhibits high absolute energy values, indicating early crack initiation during the initial stages of fatigue loading.
Once cracking in Zone I ceases, the specimen enters Zone II, which occurs at approximately 90.66% of the specimen's fatigue life. Zone II shows stable crack growth with relatively low scattered absolute energy, as depicted in Figure 8. The cumulative absolute energy exhibits a linear plot during this phase, indicating steady crack propagation. Upon completion of Zone II, the specimen transitions into Zone III, characterized by very high absolute energy. This rapid increase in absolute energy leads to the failure of the specimen.
Figure 6 displays the cumulative absolute energy for different aggregate sizes. It reveals that the initial absolute energy in Zone I increases as the aggregate size increases. Larger aggregate sizes require more energy for crack initiation. After crack initiation, stable crack growth occurs in Zone II, comprising approximately 90 to 95% of the specimen's fatigue life. In Zone III, there is a sudden surge in absolute energy, leading to rapid failure in a small number of cycles. The high absolute energy in Zone I suggests significant damage to the specimen at the beginning of its life.

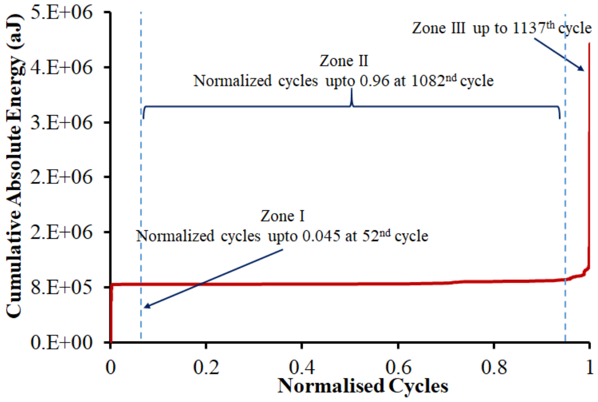

Figure 5: Three zones of damage under fatigue loading

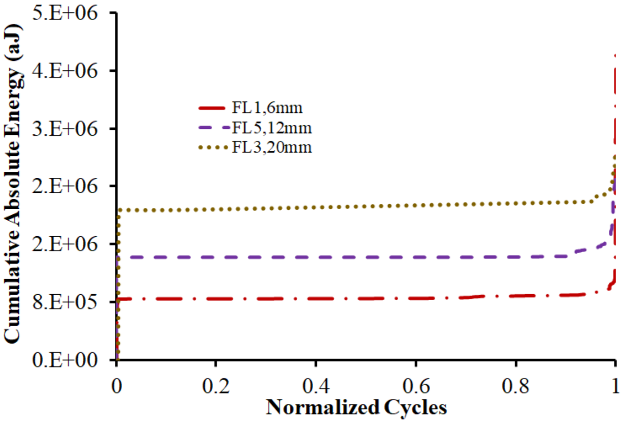

Figure 6: Variation of cumulative absolute energy with normalized cycles for different aggregate size

4.3.2 Absolute energy characteristics

The absolute energy distribution is depicted in Figure 7. The initiation of cracking is clearly related to Zone I of the fatigue damage process, according to absolute energy distribution. In the first cycle of fatigue loading, a high absolute energy of $5.86X10^5$ aJ occurs, which corresponds to the formation of early crack growth in the beam. According to Wang et al. [22] acoustic emission analysis reveals that the first region generally corresponds to the initiation of cracking immediately after the load is applied to the sample.

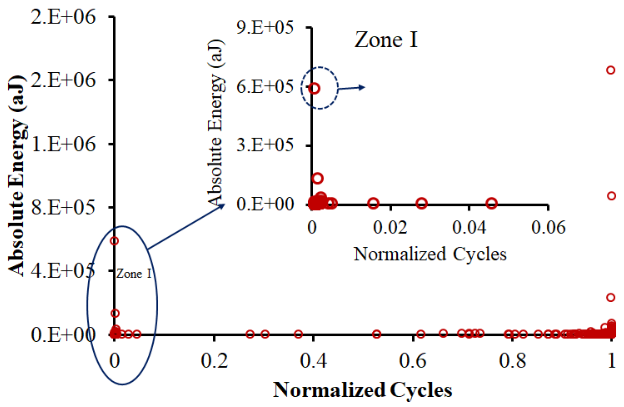

Figure 7: Absolute energy with normalized cycle in zone I

Up to 90.66% of the fatigue damage to the concrete beam occurs in Zone II, where the stable crack formation is observed. It happened in a linear manner that obeyed the Paris law. Because the crack growth in this zone was stable, it delivered low absolute energy compared to Zone I, resulting in low fracture energy emitted. This can be seen in Figure 8, which depicts the relationship between absolute energy and normalized cycles in Zone II. This implies that little crack growth, and consequently little acoustic emission activity, took place in this zone. Despite producing little absolute energy, this zone is critical in determining the beam's normal life. It can be used to forecast system behavior and determine how to sustain the load applied in this zone.

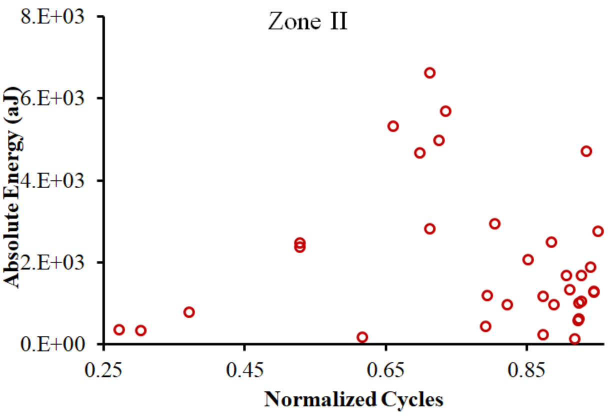

Figure 8: Absolute energy with normalized cycle in zone II

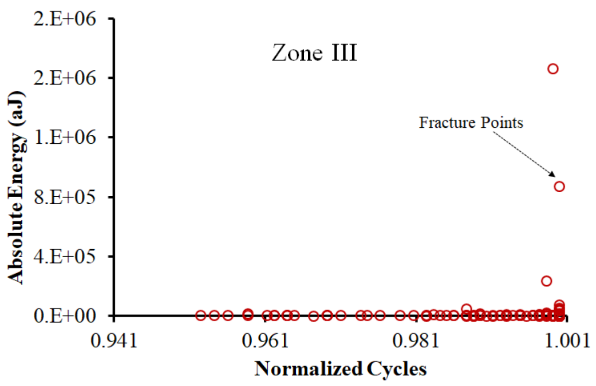

Figure 9: Absolute energy with normalized cycle in zone III

Figure 9 depicts the absolute energy distribution in Zone III during the fatigue damage process. The rupture that led to failure was located here. According to Wang et al. [22], this zone is closely related to the coalescence of microcracks into macrocracks. This is because the acoustic emission activity in this region increased rapidly, indicating structural instability. This was also due to an increase in crack density preceding failure, while acoustic emission activity rapidly increased just before the final failure. The high absolute energy of $1.66X10^6$ aJ in this zone corresponding to this crack progression was caused by the opening and closing of existing cracks in the concrete beam during fatigue loading and unloading, which resulted in a large number of acoustic emissions.

4.3.3 The relationship between the AE characteristic parameters and crack growth

Acoustic Emission (AE) is produced by the rapid release of local energy when microcracks form in concrete, resulting in the generation of transient elastic waves. While not all AE signals originate from the crack tip, the crack tip is the main source of damage. Therefore, it is reasonable to assume that AE data collected is primarily a result of the failure of the crack tip of the specimen.

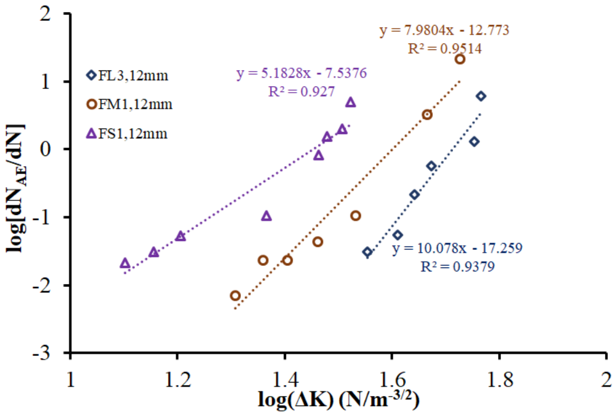

Figure 10: AE events increment with SIF range for different aggregate size

In an experimental investigation, the effects of loading variables on AE were identified by Morton et al [23]. The AE parameters have a correlation with fatigue life, crack propagation, and stiffness attenuation of concrete. A mathematical relationship is established between the AE events and stress intensity factor range (ΔK).

$$\frac{dN_{AE}}{dN} = A(\Delta K)^n \tag{1}$$

where N_{AE} is the cumulative AE events, A and n are the experimental parameters. By using Equation 1, cumulative AE events are well-fitted and subsequently used to study fatigue crack growth. Figure 10 displays the relationship between the rate of change of cumulative AE events and stress intensity factor range (ΔK) for different aggregate sizes of fixed specimen size.

5 CONCLUSIONS

In this study influence of the heterogeneity of concrete structures on the fatigue fracture characterization is investigated using the acoustic emission technique. The following conclusions can be drawn from the present study.

- Heterogeneity size considerably influences the fracture characterization of concrete. The fracture energy is highly dependent on the size of specimens and the aggregate. Fracture energy increase with the maximum aggregate size.

- The flexural stiffness of the concrete specimens decreases as the number of cycles increases, which demonstrates a loss of stiffness over time due to fatigue loading. This reduction in stiffness is more significant in smaller-size specimens and concrete mixtures with smaller aggregate sizes.

- Similar to the stiffness degradation AE parameters can be used to identify and characterize the concrete fracture. AE parameters, such as absolute energy and cumulative absolute energy, can provide insights into the damage evolution and fracture process in concrete under cyclic loading and it can also be utilized to study the effect of heterogeneity.

- Establishing a correlation between AE events and stress intensity factor range is a significant step in utilizing AE as a non-destructive fracture analysis tool. By fitting the AE events data with stress intensity factors, researchers can potentially replace the traditional crack length parameter in the Paris law with AE-based measurements. This allows for a non-destructive and real-time assessment of crack growth and damage progression in the material during fatigue loading.

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