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INSIGHTS INTO THE FRACTURE MECHANISM OF CONCRETE WITH POLYPROPYLENE FIBER THROUGH ACOUSTIC EMISSION TECHNIQUE

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Abstract. Concrete is a quasi-brittle material characterized by limited tensile strength and toughness, making it prone to cracking under different loading conditions. Its fracture behavior is heavily influenced by factors such as aggregate size and type, water-cement ratio, curing practices, and the incorporation of fibers. This research investigates the impact of polypropylene fibers on concrete's fracture performance using Acoustic Emission (AE) monitoring. The study aims to correlate AE parameters—such as event counts, amplitude, and energy—with various fracture stages, providing insights into the initiation, growth, and merging of microcracks leading to large-scale failure. The distribution of AE events is used to quantify the relative brittleness of the specimen. The nature of cracks, i.e. tensile or frictional can also be determined through the average frequency of AE. The b-value analysis of AE events can give further details on the crack growth rate in a specimen. Geometrically similar concrete specimens with varying amounts of polypropylene fibers were subjected to controlled static loading, while AE sensors continuously tracked crack development. The study captures key characteristics of the Fracture Process Zone (FPZ), such as its size, development rate, and the transition from stable to unstable crack growth. The results demonstrate that polypropylene fibers effectively enhance concrete's fracture toughness, as confirmed by AE analysis. The findings provide crucial insights into the behavior of the FPZ, which can aid in optimizing concrete designs and improving the durability and performance of concrete structures, especially in applications where crack control and damage monitoring are essential.

1 INTRODUCTION

Concrete's exceptional compressive strength, durability, and flexibility make it a popular choice for construction. However, under tensile or flexural pressures, it is susceptible to cracking and fracture because of its inherent brittleness and low tensile strength. These drawbacks often limit its long-term dependability and structural efficiency, especially in environments where dynamic or impact stresses are present. Fiber integration into the concrete matrix has become a successful strategy to overcome these constraints. Because of its many benefits, such as their affordability, ease of dispersion, chemical inertness, and resilience to environmental deterioration, polypropylene (PP) fibers have become a popular option for fiber reinforcement in concrete [1, 2]. These artificial fibers, which are made from thermoplastic polymers, are strong and lightweight, which makes them useful for filling up fractures and enhancing concrete's resistance to breaking. By boosting its toughness, flexural and tensile strength, impact resistance, and failure behavior, fiber inclusion into concrete has increased its application in construction [3–5].

The fracture mechanism in concrete involves crack initiation, propagation, and eventual failure, influenced by material heterogeneity and internal flaws. The acoustic emission (AE) technique proves to be a highly effective and reliable method for analyzing the fracture behavior of concrete. Its ability to detect, monitor, and classify crack growth in real-time provides critical insights into the material's damage evolution and failure mechanisms. By correlating AE event characteristics with fracture stages, this technique significantly enhances the understanding of the fracture process zone and the overall behavior of concrete under various loading conditions. Consequently, AE serves as a valuable tool in advancing the design and durability of concrete structures. As cracks evolve and grow, they release energy in the form of elastic waves, which AE captures and analyzes through parameters like amplitude, frequency, and cumulative hits [6, 23]. These signals reveal critical information about fracture modes, such as tensile cracking (Mode I), shear cracking (Mode II), and mixed-mode fracturing [23]. AE enables early detection of damage, localization of crack sources, and real-time monitoring of fracture progression, offering a deeper understanding of the material's fracture toughness and crack resistance [8]. AE signals generated by elastic waves originate from microcracks within concrete. Different types of cracks, such as tensile and shear cracks, produce AE signals with unique characteristics. As a result, AE signal features are commonly used to identify and differentiate various failure mechanisms in concrete [9]. Widely used to study fiber-reinforced concrete and the effects of environmental and loading conditions, AE provides invaluable insights into improving the durability and reliability of concrete materials.

Wu et al. [10] studied the acoustic emission (AE) characteristics during the fracture processes of mortar, concrete, and steel fiber-reinforced concrete (SFRC) beams, clarifying the failure mechanisms for each material. Prem and Murthy [11] analyzed the damage mechanisms in reinforced concrete (RC) beams under four-point bending, categorizing the damage into four zones: micro-crack formation, visible cracks, steel yielding, and concrete crushing. Farnam et al. [12] examined the waveform properties of individual concrete components, such as aggregate, paste, and interfacial transition zones (ITZs), identifying distinct failure mechanisms like aggregate and matrix cracking. Gostautas et al. [13] demonstrated that AE parameters can differentiate damage types in fiber-reinforced concrete (FRC), such as fiber breakage, matrix cracking, and debonding. For FRC, AE signals arise not only from matrix cracking and aggregate-matrix debonding, as in plain concrete, but also from fiber pullout, sliding, and fracture [14]. AE provide an effective and non-invasive method for determining the fracture process zone (FPZ) in concrete. By capturing and analyzing AE event characteristics, such as energy, frequency, and spatial distribution, AE enables precise identification of FPZ size, shape, and growth dynamics. High-energy AE events typically correspond to the formation of macrocracks, while lower-energy events are associated with microcracking activity [21]. Advanced analyses, including b-value assessment and event clustering, further enhance the understanding of damage progression within the FPZ. Soulioti et al. [15] found that AE activity increases with wavy steel fiber content in steel fiber reinforced concrete, a trend also observed by Li [16]. Furthermore, Aggelis et al. [17] noted that total AE hits decrease as the fiber aspect ratio increases from 30 to 80 under uniaxial compression. It was reported that fracture occurs in three stages: pre-peak, main fracture, and failure, with tensile cracking producing higher frequency and shorter waveforms compared to shear events. They observed that AE signals vary significantly with fiber parameters in concrete. Their studies on three steel fiber types—straight, hooked, and undulated—showed that hooked and wavy fibers create extensive matrix cracking due to mechanical interlocking, while straight fibers exhibit shear characteristics dominated by friction during pullout.

Singh et al. [25] demonstrates the effectiveness of wedge splitting tests, combined with acoustic emission and digital image correlation techniques, in analyzing the fracture behavior of plain concrete. The identification of microcracking and macrocracking phases, along with the progression through four distinct failure stages, provides a comprehensive understanding of the fracture process. The integration of AE event analysis with the generalized logistic b-value model highlights its utility in tracking damage evolution and predicting failure. Furthermore, the strong correlation of AE event distributions with microcrack behavior underscores the critical role of the fracture process zone in quasi-brittle materials.

The fracture behaviour of fiber-reinforced concrete has received a lot of attention in recent years. For the purpose of forecasting the long-term performance of concrete structures, fracture mechanics offers important insights into the initiation, propagation, and failure processes of cracks. By bridging fractures and lowering the stress concentration near crack tips, the addition of PP fibers changes the microstructure of the concrete and its fracture characteristics. The continuous monitoring of fatigue fracture formation in plain concrete specimens under varying amplitude loading is made possible by the efficient use of acoustic emission (AE) methods [24]. There are few open problems need to be addressed while studying the fracture mechanisms in polypropylene fiber-enforced concrete using acoustic emission. These include lack of precise correlation between AE parameters and fracture process zone, and the influence of fiber content and its orientation on AE response. This study uses AE monitoring to investigate the incorporation of PP fibers into concrete and how they affect fracture behavior. In order to provide a thorough knowledge of how PP fibres contribute to improving concrete's resistance to cracking and failure, the research intends to connect AE parameters with fracture characteristics. In this study, the influence of PP fiber on FPZ size and AE parameter has been explored to understand the fracture mechanism of fiber-enforced concrete.

2 EXPERIMENTAL DETAILS

2.1 Materials

This study have M30 grade concrete which was designed in accordance with IS 10262:2019 guidelines. The mix included ordinary Portland cement (OPC 43 grade) as the binder, fine aggregates conforming to Zone II grading, and coarse aggregates with a maximum size of 12.5 mm. The specific gravities of fine aggregates and coarse aggregates, are measured as 2.71, 2.67 respectively. Water-to-cement (w/c) ratio was maintained at 0.4 for all mixes. Polypropylene (PP) fibers are incorporated at varying dosages (e.g., 0.2%, 0.4%) by volume of concrete) to enhance the mechanical properties. Beam specimens were prepared based on RILEM recommendations, with dimensions of 900 mm × 75 mm × 225 mm, with pre-notch of 45 mm. Pre-notching was done during casting to ensure crack initiation points for fracture analysis.

The polypropylene micro-fibers used in the research are monofilament fibers specifically designed for concrete reinforcement. These fibers have a diameter of approximately 22 microns and a length of 18 mm, ensuring proper dispersion and bonding within the concrete matrix. The fibers exhibit a tensile strength of around 400 MPa, a modulus of elasticity of 3.5 GPa, and a specific gravity of 0.91. They are chemically inert, resistant to alkalis, acids, and salts, and have a melting point above 160°C, ensuring durability and performance in concrete. The primary purpose of incorporating PP micro-fibers is to enhance the tensile strength, ductility, and crack resistance of the concrete.

After mixing, the fresh concrete was promptly poured into pre-prepared plastic molds. The specimens were subjected to vibration for 3–5 minutes on a vibrating table to ensure proper compaction. They were then left under laboratory conditions for 24 hours before being carefully demolded. Following this, the specimens were transferred to a standard curing room, maintained at a constant temperature of 25°C and 95% humidity, where they remained until achieving 28-day strength. After 28 days of curing, the cube strength of the concrete is determined to be 34.5 MPa. The modulus of elasticity and tensile strength of the concrete are found to be 25,000 MPa and 3.4 MPa, respectively.

2.2 Experimental setup

The three-point bending test was conducted on expermental setup comprising of a 500 kN universal electro-hydraulic servo actuator with data acquisition system. The clear span length was set to 750 mm, and the beams were rotated 90° from the casting surface to reduce eccentric effects caused by surface roughness. At the start of each test, a pre-loading equivalent to approximately 10% of the ultimate flexural load was applied to stabilize the testing system. Following this, a uniaxial load was applied to the beams at a constant crack mouth opening displacement control rate of 0.01 mm/min. During the test, the axial loads and beam's mid span deflections were automatically measured and recorded by a computer.

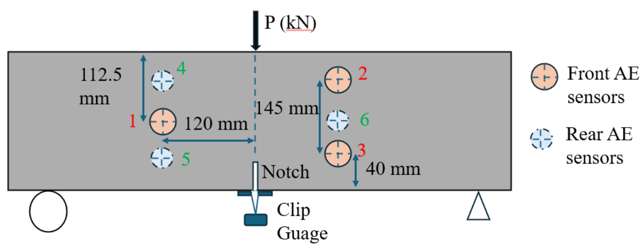


Figure 1: Schematic diagram of three point bending specimen with position of AE sensors.

To monitor the cracking process in concrete and capture the emitted signals, six AE sensors were installed on the beam's surface. Three sensors are distributed in frontage and remaining three in rear side of specimen as shown in Fig. 1. The process of mounting the AE sensors involved three steps: 1) coating the AE sensor surface with Vaseline as a coupling agent; 2) securing the sensors to the specimen surface using plastic tape; 3) conducting a pencil break test to evaluate the coupling effect between the sensors and the specimen along with to measure wave propagation speed and verify the three-dimensional positioning accuracy of the sensors.

3 RESULT AND DISCUSSIONS

The acoustic emission (AE) technique is a comprehensive non-destructive testing technology that has improved significantly in recent years. This technique passively detects elastic wave signals produced by material damage using AE sensors. An AE system gathers these signals, which are then examined to determine the degree of material damage. Widely used in industries including metals, semi-rigid materials, bases, grouting sleeves, masonry structures, and concrete structures, AE is prized for its long-term real-time monitoring capabilities and great sensitivity to even the smallest damage.

When assessing structural damage, AE metrics such as ringing counts, energy, rising time, peak frequency, amplitude, and average frequency are crucial. Through variations in AE counts, energy, and other factors, researchers have used AE methods to track fracture qualities in concrete, identifying different fracture parameters and crack propagation behaviours. Increased beam damage has been linked to a drop in peak frequency content. The location of AE occurrences in concrete specimens is shown in Fig. 2. These figures show the number of AE events that occurred while testings. As the amount of PP fibre grows, the number of AE events increases which shows the reduction of brittleness of concrete. It is observed that a specimen with a PP fibre capacity of 0.4% has the greatest frequency of AE occurrences. This significant increase in AE eventsgives the production of a large process zone since an AE event signifies the occurrence of microcracks. These figures show that the density of AE occurrences is quite high for the PP fibre concrete mix. The number of AE events for reference concrete mix (PP0) is observed as 1681 where as for PP fiber mix PP0.2 and PP0.4 it is higher as 2485 and 2852 respectively. This suggest that specimen PP0.4 have relative ductile behavior than the reference concrete specimen (PP0). Additionally, it has been shown that the frequency of AE occurrences is almost constant for specimens of small, medium, and large sizes.

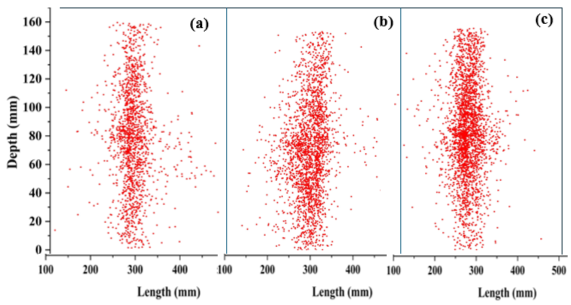
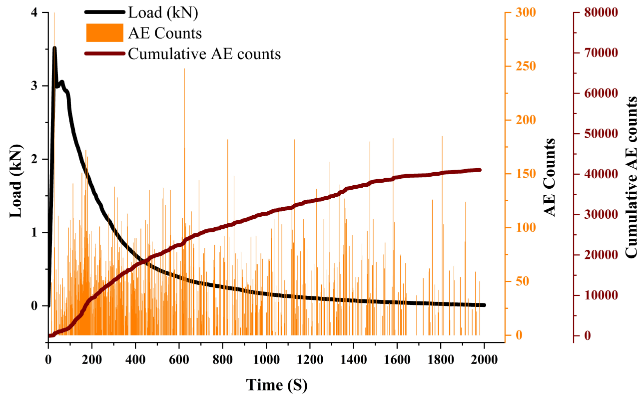
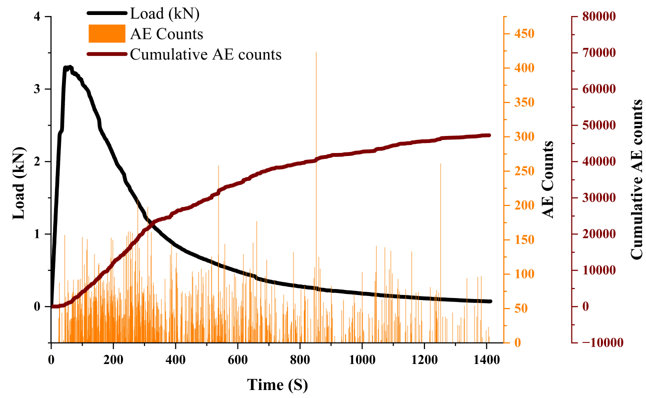


Figure 2: AE events positions of (a) conventional concrete and (b) 0.2% PP fiber concrete (c) 0.4% PP fiber concrete.

To comprehend fracture processes and physical phenomena, AE signal characteristics including hits, counts, amplitude, duration, rising time, and energy have been thoroughly studied. A signal that crosses the threshold and causes the system to capture data is referred to as a hit. The count indicates how many times a signal waveform above the threshold in a certain amount of time. The signal's peak voltage, expressed on a decibel scale, is represented by the amplitude. Rise time is the amount of time between the signal's triggering and peak amplitude, while duration is the amount of time between the signal's triggering and disappearance. Both amplitude and time affect energy, which is the area under the rectified signal envelope. The rising angle, reverberation frequency, average frequency, and beginning frequency are further AE characteristics.



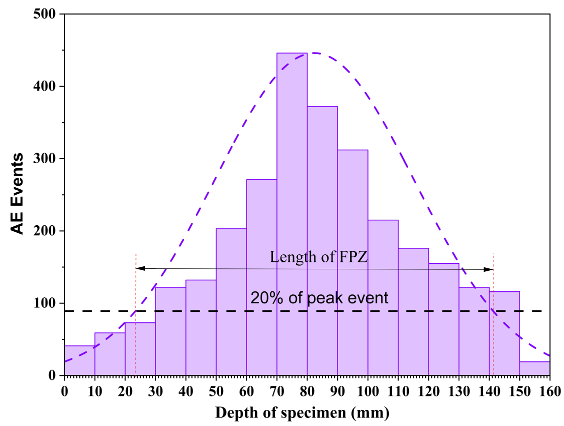
(a)



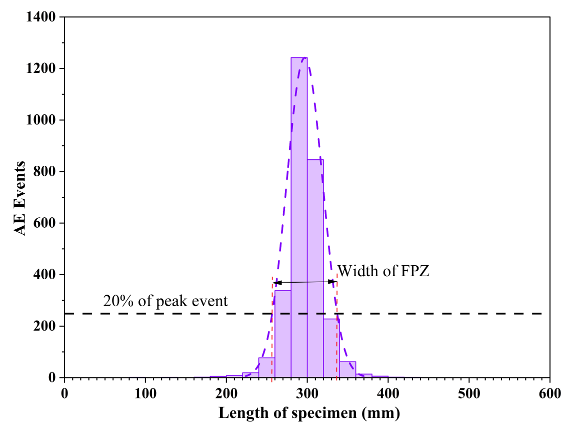
(c)

Figure 3: Variations in cumulative AE count, AE count, load with time for (a) conventional concrete and (b) PP fiber concrete mix.

The AE evolution features of PP fiber concrete specimens with varying loading times are thoroughly examined based on the AE ringing count and the cumulative AE energy in order to fully assess the intensity of AE activities and to represent the general trend of the energy released from the specimens. This is because the closure and inoculation of internal microcracks during the loading process are linked to the occurrence of AE activity and energy release. Fig. 3 presents the variation of load (kN), acoustic emission counts, and cumulative AE counts with respect to time (s) for conventional concrete and 0.4% volume of PP fiber concrete specimen under static loading. The load-time curve demonstrates the peak load capacity, followed by a significant drop indicating crack formation and failure. The AE count-time curve reflects the intensity of micro-cracking, peaks near the ultimate load and persists post-peak due to ongoing damage. The cumulative AE count provides a comprehensive view of the total cracking events, showing a sharp rise around the peak load and stabilizing as the damage saturates. The slope of the cumulative AE energy curve, the variation law of the load–time curve, and the variation characteristics of the AE ringing count all show that the AE development exhibits clear stage features and has a strong relationship with the loading process. Conventional concrete's AE count is high around the peak load and just after, indicating quick crack development and propagation. In contrast, PP fibre concrete's AE counts are more evenly distributed over time, suggesting a gradual and delayed cracking process. While polypropylene fibers help to slow crack propagation, leading to more prolonged AE activity over time, concrete without fibers experiences a gradual reduction in AE events over time. This decline reflects the lack of mechanisms to resist fracture widening and the progression of damage. The PP fiber concrete, which exhibits a more progressive rise in the cumulative AE count that persists even in the post-peak area, the cumulative AE count increases abruptly around the peak load, suggesting a fast beginning of widespread cracking. In post-peak region, the curve continues to increase at a slower rate for conventional concrete, stabilizing toward the end, suggesting that most damage occurs in the early stages of failure. Whereas the presence of PP fibers leads to more distributed and sustained damage processes, preventing abrupt failure. The cumulative AE energy curve climbs gradually and almost linearly, whereas the AE ringing counts marginally increase. Addition of PP fiber enhances the concrete's ability to absorb energy even after initial cracking, leading to an increase in fracture energy. The specimens undergo linear elastic deformation at this stage when they are loaded, and the majority of the deformation may be recovered once the load is released. Crack growth and penetration cause the specimen to become unstable when the stored energy inside it surpasses the energy capacity. PP fiber concrete specimen shows enhanced ductility and crack resistance, attributed to the fiber bridging effect. The gradual rise in cumulative AE counts reflects sustained energy dissipation and delayed failure.



(a)



(b)

Figure 4: Determination of FPZ size through histogram between AE events number and Size of specimen.

A histogram of acoustic emission events in relation to the specimen's depth and span is used to determine the length and breadth of the fracture process zone (FPZ) [24]. They defined the FPZ length as the region where the local energy exceeds 15% of the total energy in the specimens or where the peak amplitude distribution or AE energy surpasses 30%, using this AE criterion to identify the failure zone. The FPZ Size in this investigation were calculated using histograms of cumulative AE events up to failure. The FPZ length is computed at 20% of the peak event along the specimen's depth, as shown in Fig. 4 (a), and the FPZ width is measured at 20% of the peak event along the specimen's length, as shown in Fig. 4 (b). However, the length of FPZ depends on the moving location of the crack tip, so depending on the loading. The average results from three specimens in each category were taken into account for the study. The FPZ length observed for reference concrete, 0.2% PP fiber concrete and 0.4% PP fiber concrete are 102.68, 109.11 and 118.78 mm respectively and width of FPZ for the same are 84.26, 99.71 and 110.40 mm respectively. An increment of 15.69% and 31.42% was observed in FPZ length and width respectively for PP0.4 concrete specimen. The improvement in FPZ size (both length and width) is observed with increase in PP fiber content. Hence, a larger FPZ significantly enhances the fracture performance and durability of concrete. It improves toughness, delays crack propagation, redistributes stresses, and provides better resistance to environmental degradation. These advantages lead to increased structural integrity, extended service life, and safer failure mechanisms, making a larger FPZ highly desirable for critical applications, especially in high-performance concretes.

4 CONCLUSIONS

This study demonstrates the utility of AE analysis in monitoring the fracture and crack propagation in concrete, correlating acoustic signals to development of fracture process zone. The PP fiber concrete mix significantly outperforms conventional concrete in fracture behavior and durability. Conventional concrete shows rapid crack propagation and micro-crack concentration around the peak load, leading to abrupt failure. In contrast, PP fiber concrete exhibits gradual and sustained cracking, delayed failure, and enhanced ductility due to the fiber bridging effect. The progressive rise in cumulative AE counts and energy in PP fiber concrete highlights its superior energy dissipation and resistance to crack, making it a more reliable and durable material for structural applications. Furthermore, addition of PP fibers enhance the FPZ size which delay the crack propagation, enabling gradual failure and sustained damage control, making it more durable and reliable than conventional concrete. The future aspect of this work can include integration of AE technique with AI based data driven techniques. A thorough understanding of fracture mechanisms can lead to standardized damage assessment frameworks in the design of sustainable concrete mixes.

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