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Monitoring Stages of Damage in Concrete Structures by Using the Acoustic Emission Technique

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Abstract:
The significant degradation caused by the corrosion of steel wire in prestressed concrete is a matter of great concern. It requires special attention in certain applications, as failure could result in not only a financial burden but also a potential loss of life. It is crucial to recognize that corrosion is not just a long-term issue; numerous studies have documented instances of bridges and concrete pipes failing shortly after construction due to corrosion.

Structures such as prestressed concrete cylinder pipes (PCCP), responsible for transporting water, exemplify the impact of corrosion. The Man-Made River Project in Libya has experienced five instances of pipe failures attributable to corrosion since its installation. The primary cause of this damage is the corrosion of prestressed wires within the pipes, initiated by the infiltration of chloride ions from the surrounding soil.

In the context of the Man-Made River in Libya, the early detection of corrosion is vital to prevent disruptions to water supply for homes and industries. This paper presents the application of the Acoustic Emission (AE) technique to identify and locate the initial stages of corrosion and categorize different types of cracks. The results from laboratory studies suggest that AE is effective in detecting corrosion in representative structures. Furthermore, it can distinguish and classify the location and type of cracks by analyzing AE signal parameters.

Keywords: Acoustic emission, corrosion, prestressed concrete, reinforced concrete, micro crack, macro crack.

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مراقبة المراحل المختلفة لتضرر المنشأت الخراسانية بستخدام تقنية الانبعاثات الصوتية

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الملخص
الأضرار الذي يسببه تآكل ألاسلاك الحديدية في الخرسانة بشكل عام والخرسانة سابقة الاجهاد بشكل خاص مصدر قلق كبيرللمهندسين ويتطلب اهتمامًا خاصًا لبعض المنشأت الخراسانية المسلحة، حيث يمكن أن يؤدي انهيارفي بعض المنشأت الخراسانية في بعض الاحيان الى خسائر بشرية علوة على الخسائر الاقتصادية.

حيث سجلت العديد من الدراسات حالات انهيار في الجسور وأنابيب الخرسانة بعد وقت قصيرمن استخدامها نتيجة تأثير التأكل. المثال على ذلك خمس انهيارات كبيرة حدثت في أنابيب الخرسانة سابقة الاجهاد بمشروع النهر الصناعي في ليبيا المستخدم عن نقل وتوفير المياه بعد عشر سنوات من تشغيله وكان السبب الرئيسي لهذه الانهيارات هو تآكل أسلاك سابقة

الاجهاد في الانابيب نتيجة لتسرب أيونات الكلوريد من التربة المحيطة مما تسبب في انقطاع المياه على معظم الاماكن السكنية نتيجة لتسرب أيونات الكلوريد من التربة المحيطة. لهذا السبب يعتبر الكشف المبكر عن التآكل أمرًا مهما حيويًا لتجنب حدوث انهيارات اخرى و انقطاع إمدادات المياه. في هذا البحث تم دراسة مدى امكانية تطبيق تقنية الانبعاث الصوتي (AE) للكشف المبكر للمراحل الأولية للتآكل وتحديدها وكذلك تصنيف ألانواع مختلفة من التشققات. حيث بينت نتائج الدراسات المعملية أن تقنية الانبعاثات الصوتية فعالة في اكتشاف التآكل في مراحله المختلفة في الهياكل الخراسانية علاوة على ذلك قدرتها على التمييز وتصنيف موقع ونوع التشققات من خلال تحليل متقدم لاشارت وموجات الانبعاثات الصوتية.

الكلمات المفتاحية: الانبعاث الصوتي، التآكل، الخرسانة سابقة الاجهاد، الخرسانة المسلحة، التشقق الدقيق، التشقق الكبير.

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1. Introduction

Various structures, including bridges, buildings, concrete pipes, robust tanks, dams, protective shells for nuclear reactors, railway sleepers, piles, and pressure vessels, are constructed using prestressed concrete. In this construction method, prestressing steel wires are permanently placed under tension to compensate for the concrete's insufficient tensile strength. By ensuring that the concrete remains in compression under normal loads through prestressing the steel reinforcement, the occurrence of tensile cracking in the concrete is minimized. Typically, prestressed steel exhibits a strength four to five times greater than mild steel. The primary benefits of prestressed concrete structural materials lie in their increased strength, reduced weight, and resistance to cracking, resulting in cost advantages over alternative materials [1].

Corrosion poses a significant challenge in numerous structures, leading to estimated annual costs in the billions of dollars. The UK Department of Transport has assessed the yearly expense for rehabilitating concrete structures affected by corrosion issues to be £755 million [2]. Given that corrosion can lead to severe consequences, including loss of life and financial losses, special attention must be given to addressing this issue in prestressed concrete structures. Studies consistently highlight corrosion as a primary cause of failure in bridges and concrete pipes, occurring shortly after construction. While concrete generally provides an ideal protective environment for embedded steel wires, the lifespan of concrete structures is shortened due to steel corrosion induced by aggressive ion attacks from chloride or carbonation products [2].

Concrete pipes, essential for water transport, are particularly susceptible to corrosion. The pipes of the Great Man-Made River Project in Libya have experienced five instances of catastrophic failure due to corrosion since their installation. Beyond safeguarding against future corrosion, engineers face the critical challenge of identifying the most effective methods to detect corrosion and prevent the deterioration of these pipes [1]. This project aims to utilize the Acoustic Emission (AE) technique to detect the early stages of corrosion, mitigating the risk of deterioration and eventual failure in concrete structures

AE refers to the elastic energy liberated by materials experiencing deformation. Also, it can be defined as “the transient elastic waves which are generated by the rapid release of energy from localised sources within a material” [3, 4]. The rapid release of elastic energy, the AE event, propagates through the structure to arrive at the structure surface where a piezoelectric transducer is mounted. These transducers detect the displacement of the surface at different locations and convert it into a usable electric signal. [5, 6, 7] By analysis of the resultant waveform in terms of feature data such as amplitude, energy and time of arrival, the severity and location of the AE source can be assessed. Figure 1 shows a summary of the AE detection process. [5, 6, 7].

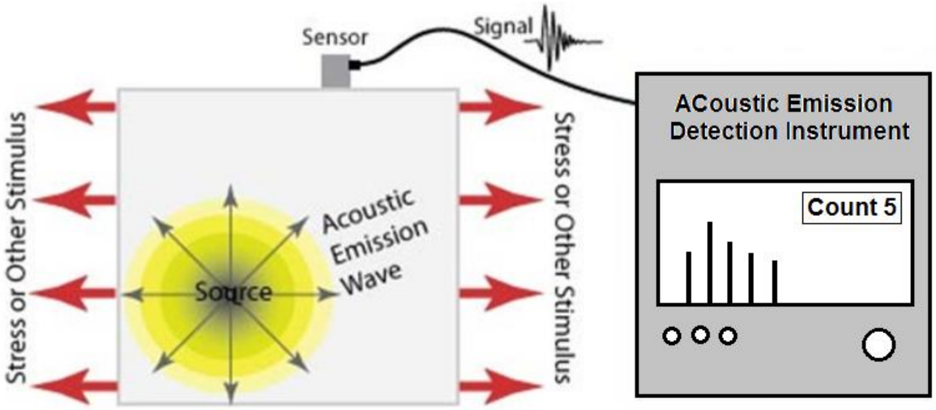

Figure 1: AE diagram of the acoustic emission sequence

The Man-Made River Project (MRP) is one of the major civil engineering projects of the 20th century located in Libya. The project is concerned with water transportation from the aquifers deep in the Sahara Desert to the coastal region where over 90% of the population lives. The water is conveyed throughout almost 4000 km of prestressed concrete cylinder pipe (PCCP) networks. [2, 8, 9]

Pre-stressed concrete cylinder pipes are designed to take the best advantage of the compressive strength and corrosion-inhibiting property of Portland cement concrete and mortar and the tensile strength of prestressing wire. The majority of pre-stressed concrete cylinder pipes are 4.0 m in inner diameter; with a length of 7.5 m, and over 70 tonnes in weight. The concrete pipe consists of a 225 mm thick concrete core within an embedded thin steel cylinder and externally wrapping prestressed wires. The cured concrete core is prestressed by applying over-wrapping with high tensile steel wire at a close pitch under uniform tension. The prestressed wires are coved by a 19mm thick layer of cement mortar to protect the wires against corrosion and mechanical harm. A typical cross-section of the PCCP is shown in Figure 2.

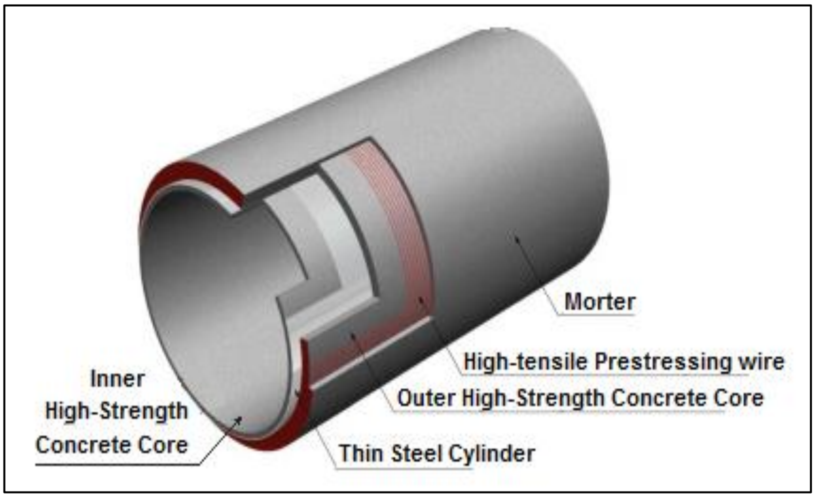

Figure 2: Typical cross-section

Five disastrous failures in pipes with a diameter of four meters occurred a decade into their operation. The primary cause of the damage was the corrosion of prestressed wires within the pipes, resulting from the infiltration of chloride ions from the adjacent soil. Detecting corrosion at its initial stages has been crucial to prevent additional failures that could disrupt the flow of water. While most non-destructive methods employed in the project can identify wire breaks, they fall short in detecting the presence of corrosion. Consequently, areas with substantial damage may remain unnoticed in locations where excavation hasn't been conducted. In this regard, Acoustic Emission (AE) holds significant advantages over other Non-Destructive Testing (NDT) methods because AE can reliably identify the early stages of the corrosion process before notable harm to the concrete occurs. Additionally, AE can provide insights into the extent of damage occurring in the concrete [4, 10, 11, 12, 14].

2. Experimental Procedure

2.1 Concrete and mortar preparation

The concrete specimen (600×600×50mm) was prepared according to the technical specification for prestressed concrete cylinder pipe manufacturing used in MRP, which is in accordance with AWWA C301-92 (Standard for Pre-stressed Concrete Pressure Pipe, Steel Cylinder Type, for water and other Liquids.) [2]. The water to cement ratio used was 0.4 and the material proportions were 1:2:2.5:0.4 by weight of cement, sand, aggregate and water respectively and the concrete design strength was about 58.5MPa strength at 28 days.

Three days later, after the concrete specimen was completely cured, the steel wires were placed on the upper surface of this specimen. Mortar of 600×600mm and 20 mm thickness was coated on the upper surface of the concrete. The water to cement ratio used was 0.4 and the material proportions were 1:2:0.4 by weight of cement, sand and water respectively and the concrete design strength was 56.5MPa strength at 28 days. The mortar should consist of one part cement to not more than three parts fine aggregate by weight. The final construction is shown in Figure 3.

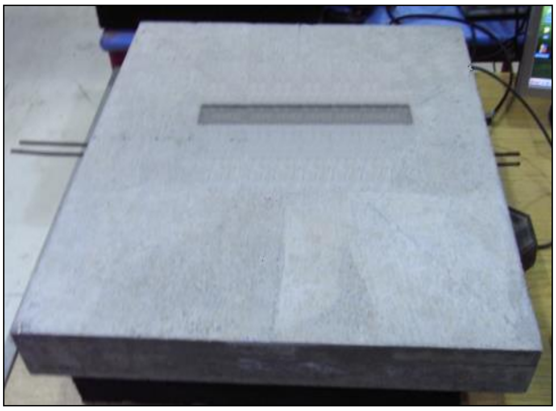

Figure 3: Concrete / mortar specimen

2.2 Accelerated corrosion Technique

To study the effects of corrosion within a realistic time-scale, it is sometimes necessary to accelerate the initiation period and occasionally control the rate of corrosion during the propagation stage. To simulate the corrosion of prestressing steel wires, the corrosion cell was induced by an impressed current (500µA/cm²). This is reported as corresponding to the maximum corrosion rate for concrete in laboratory conditions and has been used by several researchers in the laboratory as discussed by Li and Zhang [13]. In this experimental work, the wire corrosion was induced by impressed current (500µA/cm²). The prestressed wires were contacted in an electrical circuit with positive pole of power supplier and the negative pole connected with a stainless steel plate (30*300 mm) resting on the upper mortar. A 4% NaCl solution was poured on the surface of the mortar. Silicon sealant was used to pool the solution on the upper surface. [14]

2.3 Acoustic Emission Set-up

AE instrumentation typically consists of transducers, filters, amplifiers and analysis software. Four AE sensors (R3I – resonant frequency 30 kHz) were mounted to surface of mortar. The four AE sensors were mounted using silicon sealant and were fixed on the upper surface of mortar with a U shaped plate. The plate was screwed to hold the sensors down and to ensure a good coupling. Then the sensitivity of the sensors was checked by using the Hsu-Neilson source [14]. The experimental test set up is shown in Figures 4.

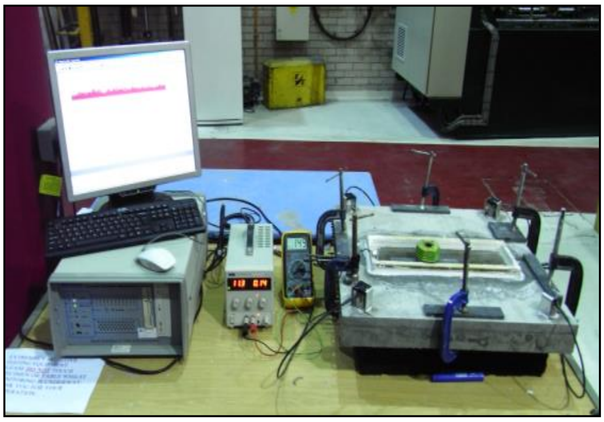

Figure 4: Photograph of experimental set up

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3. Results and discussion

AE monitoring was conducted for approximately seven days. In order to eliminate background noise and provide a better distinction of location regions a threshold of 40dB was used for data analysis. Figure 5 displays the locations of signals with a minimum amplitude of 40dB throughout the entire test duration. Notably, the concentration of the highest hits and the region with the highest energy corresponds to the positions of maximum wire corrosion and the crack, which were visually monitored at regular intervals during the test and captured in Figure 6.

In Figure 6, a photograph of the top mortar surface post-test is presented, with sensor positions marked, showcasing the crack formation. A comparison of this image with the earlier location plot reinforces the conclusion that AE accurately detected concrete cracking resulting from wire corrosion within the specimen.

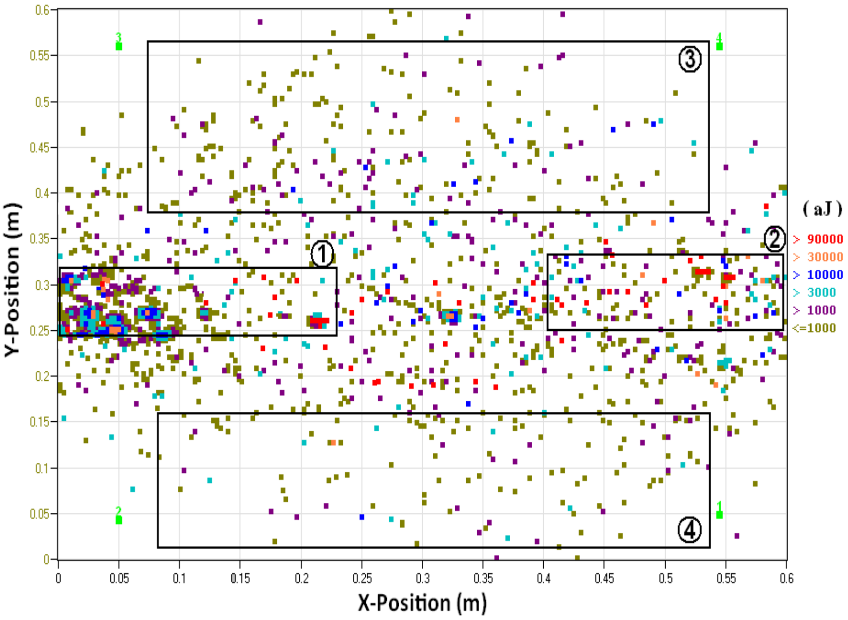

Figure 5: Source locations for whole test with amplitudes greater than 45dB

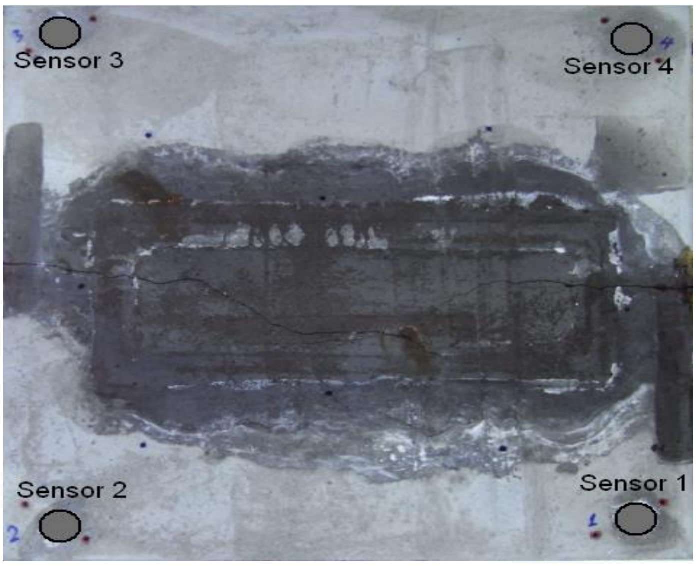

Figure 6: Photo of top mortar surface

Four zones have been chosen as examples to distinguish between the crack area and noise and also to classify mode types. Areas were chosen based on visual observation (Figure 5 and Figure 6). Zones 1 and 2 in Figure 5 have a high concentration of hits and energy and are referred to the cracking areas and zone 3 and 4 are no cracking areas. All the detected and located signals with a minimum amplitude of 40 dB detected by all sensors for almost seven days of continuous monitoring are shown in Figure 7 as signal amplitude against time and Figure 8 displays the cumulative hits against time. Figure 9 displays the same data set but this time as energy against time. The detected energy is attributed to a number of sources; active corrosion, micro cracking, macro cracking, propagation of mortar cracking, separation of the mortar from the concrete and noise, as observed by visual inspection.

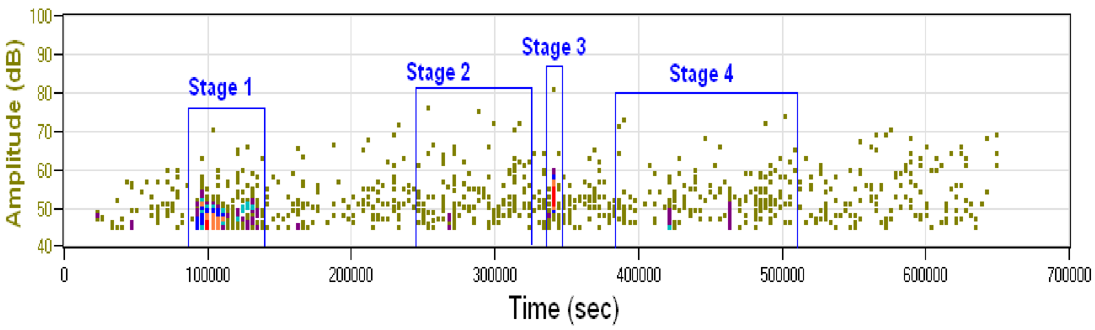

Figure 7: Amplitude of detected signals for duration of investigation

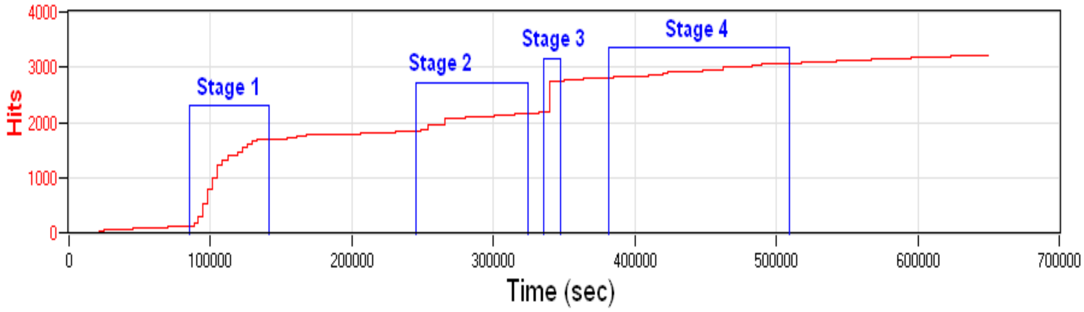

Figure 8: Cumulative Hits Vs Time

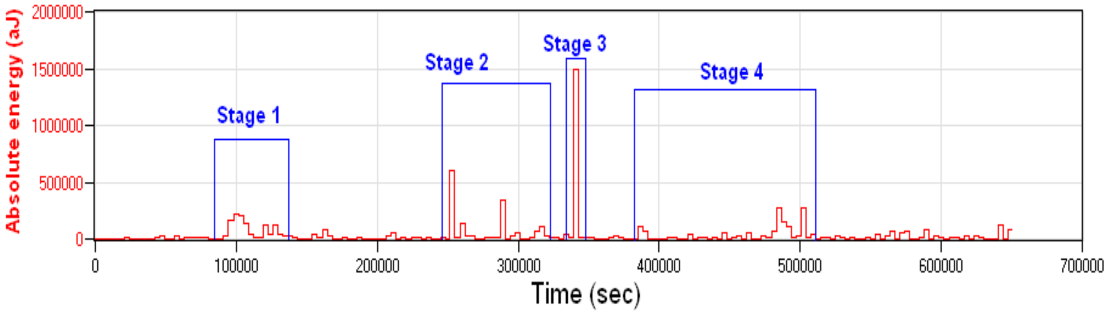

Figure 9: Absolute energy of detected signals for duration of investigation

It can be seen that in Figure 7, 8 and 9 there are four significant stages which contain signals with a combination of high amplitude, large energy and an increased rate of hits. The increased hit rate, low amplitude and low energy in stage 1 is associated with the energy release from the corrosion activity (corrosion products accumulation at the interface of reinforced wire/ mortar and concrete and the friction of corrosion products at the inner sides of the pores). Stage 2 exhibits increase in the number of hits with a slightly higher energy and amplitude and is attributed to micro crack formation. In Stage 3, the sources emitted high energy and high amplitude over a short interval of time which is attributed to the energy release from the formation of the macro crack due to the products of corrosion from wire 1 and 2 as observed in visual inspection. The following increase in the number of hits with smaller energy and smaller amplitude than Stage 3 and longer interval of time than Stage 2 is attributed to macro crack propagation as shown in Stage 4. These results are corroborated by visual observations throughout the test.

By comparing these results with visual observations during the test, the increase in the hits rate low amplitude and small energy is attributed to the energy release from the corrosion activity (corrosion products accumulation at the interface reinforced wire / mortar and concrete and the friction of corrosion products at the inner sides of the pores). This result shows a good agreement with results demonstrated by Ohno and Ohtsu [6]. A large number of signals with smaller amplitudes is associated with micro cracks events. Macro crack events emit fewer signals in a small period but with larger amplitude and high energy. This result shows a good agreement with results demonstrated by Colombo et al [17]. By comparing between macro crack and micro crack events, the results and visual observation shown that the amplitude and absolute energy released from macro crack formation are higher than micro crack formation. This result shows good agreement with results demonstrated by Aggelis [18].

Furthermore, the gradual increase of the number of hits emitted with higher energy than those due to micro crack formation and lower than those due to macro crack formation correspond to macro crack propagation. This result shows good agreement with the result demonstrated by Aggelis and Muralidhara. [18, 19]

4. Conclusion

This paper investigated the use of AE to monitor, detect and locate damage in reinforced mortar/concrete specimen. The results show that the AE techniques can be successfully used to detect, locate and characterise the different stages of damage in reinforced concrete/mortar specimens.

- The results confirm that AE could be used effectively to detect and locate damage areas at a very early stage due to corrosion.
- The AE parameters analysis of correlation amplitude, hits and energy versus time plots were shown to be useful indicators of corrosion onset, micro crack, macro crack and crack propagation.

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