International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 33 العدد
Part 2 المجلد
January 2024 يناير

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

Acoustic Emission Analysis for Crack Classification and Localization in Prestressed Concrete Structures

Hisham A. Elfergani

Faculty of Engineering -University of Benghazi, Libya

Hisham.elfergani@uob.edu.ly

Abstract:

The deterioration caused by the corrosion of reinforcement steel in reinforced and prestressed concrete poses a significant threat and requires careful attention. Failure to address this issue could lead to loss of life and substantial financial consequences. One specific application of concern is in prestressed concrete cylinder pipes, extensively utilized for water and wastewater conveyance. The predominant challenge in these pipes is the corrosion of prestressed wires, which has the potential for catastrophic failure. In the case of the Man-made River in Libya, early detection of corrosion becomes crucial to prevent water disruptions in residential and industrial areas. This study explores the application of the Acoustic Emission (AE) technique for detecting and pinpointing the initial stages of corrosion, as well as categorizing various types of cracks. Preliminary findings suggest that AE effectively identifies corrosion in representative structures, offering the capability to pinpoint and classify crack locations and types.

Keywords: Acoustic emission, corrosion, prestressed concrete, reinforcedconcrete, crack classification

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

تحليل الانبعاث الصوتي لتصنيف وتحديد مواقع الشقوق في الهياكل الخرسانة سابقة الاجهاد

هشام عبد العزيز الفرجاني
قسم الهندسة الميكانيكية – كلية الهندسة – جامعة بنغازي
Hisham.elfergani@uob.edu.ly

الملخص:

التدهور في الخرسانة الذي يسببه تآكل أسلاك الحديد الصلب في الخرسانة المسلحة والسابقة الإجهاد يشكل تهديدًا كبيرًا ويتطلب اهتماماً دقيقًا. عدم التصدي لهذه المشكلة يمكن أن يؤدي الى انهيارات كبيرة ممكن تسبب فقدان في الأرواح وتكبد خسائر مالية كبيرة.

هذه المسألة حرجة بشكل خاص في الهياكل الخرسانية الكبيرة مثل أنابيب الخرسانة السابقة الإجهاد المستخدمة على نطاق واسع في نقل المياه ومياه الصرف الصحي. القلق الرئيسي في هذه الأنابيب يدور حول تآكل الأسلاك السابقة الإجهاد، الذي قد يؤدي إلى انهيارات كارثية. اكتشاف التآكل في مراحله المبكرة أمر بالغ الأهمية لمنع حدوث انهيار الأنابيب بتالي انقطاع المياه عن المنازل والصناعات مثال على ذلك أنابيب النهر الصناعي في ليبيا. يتناول هذا البحث تطبيق تقنية الانبعاثات الصوتية (AE) لاكتشاف التآكل في الأسلاك الحديدية في الأنابيب الخرسانة سابقة الإجهاد في مراحله المبكرة، وتحديد مواقع التآكل، وتحديد وتصنيف أنواع التشققات المختلفة التي تحدث بها. حيث أشارت نتائج الدراسة إلى أنه باستخدام تقنية الانبعاثات الصوتية يمكن اكتشاف التآكل في الهياكل الخراسانية سابقة الإجهاد، مع تحديد دقيق لمواقع التشققات تصنيفها.

الكلمات المفتاحية: الانبعاث الصوتي، التآكل، الخرسانة المسبقة الإجهاد، الخرسانة المسلحة، تصنيف التشققات

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

1. Introduction

Corrosion poses a significant challenge in various structures, incurring billions of dollars in annual costs. Special attention is warranted for the risk of corrosion in these structures, as failure can result in not only financial losses but, in extreme cases, a loss of life. Studies suggest that the primary cause of failures in bridges and concrete pipes is corrosion, typically occurring shortly after construction. Moreover, the lifespan of concrete structures is further compromised by steel corrosion induced by aggressive ion attacks from chloride or carbonation products [1, 2, 3]. Concrete pipes, responsible for water transport, represent a structure significantly impacted by corrosion. The Man-Made River project in Libya serves as a notable example, experiencing catastrophic corrosion-related failures since installation, with five pipe failures reported. Overcoming substantial challenges, engineers are not only focused on future corrosion protection but are also striving to identify optimal methods for corrosion detection and preventing the deterioration of pipes [1,4]. This project seeks to utilize the Acoustic Emission (AE) technique to identify early stages of corrosion, aiming to forestall the eventual degradation and failure of concrete structures.

AE is a phenomenon that arises from the rapid release of energy within 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” [5].The rapid release of elastic energy, the AE event, propagates the structure until it reaches the surface where a piezoelectric transducer is positioned. These transducers detect the displacement of the surface at different locations and convert it into a usable electric signal. 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. As shown in Figure 1.

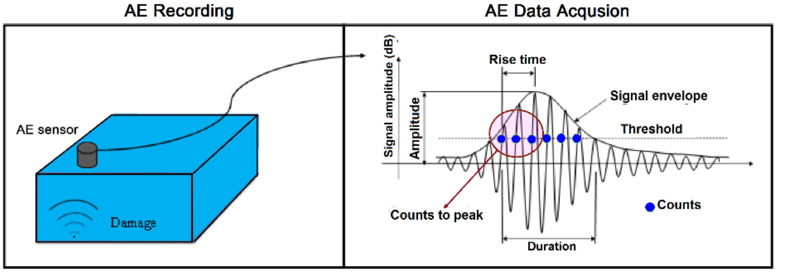


Figure 1. Acoustic Emission (AE) technique

According to many of researches [6, 7, 8, 9, 10, 11, 12] the relationship between RA values (rise time/ Amplitude) and average frequencies (counts/duration) can be used for classification of crack types. They reported that when an AE signal has low average frequency and high RA value it is classified as shear type crack. However, when it has a high average frequency and low RA value classified as tensile type crack as shown in figure 2 and 3.

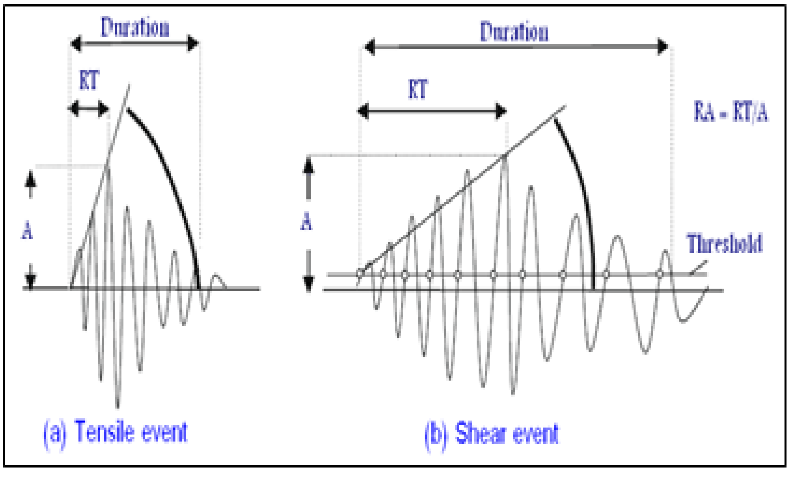


Figure 2. Typical waveforms [4]

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

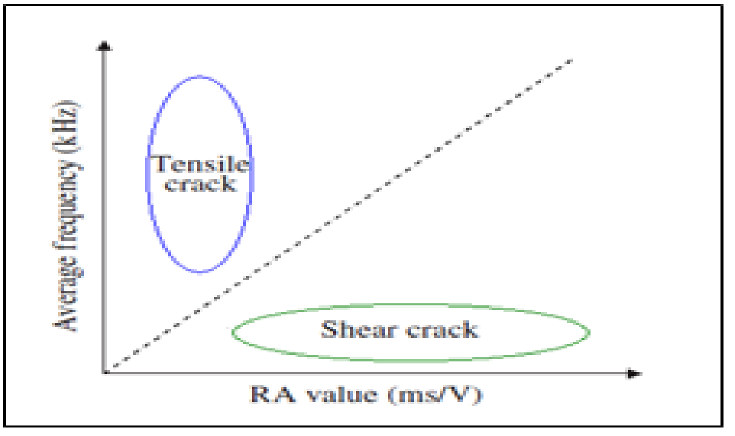


Figure 3. Crack classification [4]

The Man-Made River Project (MRP) stands as one of the prominent civil engineering achievements of the 20th century, situated in Libya. Its primary objective is the transportation of water from deep aquifers in the Sahara desert to the coastal region, where over 90% of the population resides. This extensive water conveyance spans nearly 4000 km through networks of prestressed concrete cylinder pipes (PCCP) [13].

Pre-stressed concrete cylinder pipes are strategically designed to capitalize on the compressive strength and corrosion-resistant properties of Portland cement concrete and mortar, along with the tensile strength of prestressing wire. The majority of these pipes have an inner diameter of 4.0 m, a length of 7.5 m, and a weight exceeding 70 tonnes. The concrete pipe comprises a 225 mm thick concrete core encased in a thin steel cylinder, with externally wrapped prestressed wires. To keep the concrete core under compressed, high tensile steel wire is applied through over-wrapping at a close pitch under uniform tension. These prestressed wires are safeguarded by a 19mm thick layer of cement mortar to shield against corrosion and mechanical damage. Figure 4 illustrates a typical cross-section of the PCCP. [14]

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

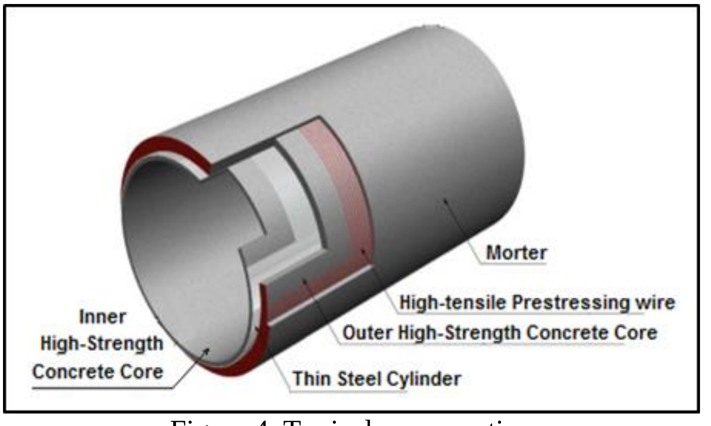


Figure 4. Typical cross-section

Between 1999 and 2001, five catastrophic failures occurred in four-meter diameter pipes, marking a critical period after a decade of operational use. The primary cause of these failures is attributed to the corrosion of prestressed wires within the pipes, resulting from the infiltration of chloride ions from the surrounding soil. The timely detection of corrosion at its initial stages is crucial to prevent further failures that could disrupt water flows. The most non-destructive methods employed in the project can identify wire breaks; they lack the capability to detect the presence of corrosion. Consequently, in areas where excavation has not been undertaken, significant damage may remain unnoticed. In this context, Acoustic Emission (AE) holds notable advantages over other Non-Destructive Testing (NDT) methods. The AE technique proves effective in reliably identifying the early stages of the corrosion process, before substantial damage to the concrete occurs. Additionally, it can provide insights into the extent of damage taking place within the concrete [6, 11, 15, 16, 17].

2 Experimental Procedure

2.1 Tension holding frame

Since it was intended in this work to simulate as close as possible the real physical conditions surrounding the high strength steel wires in concrete pipes, it was important to place and maintain all

وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م تم استلام الورقة بتاريخ: 6/ 1 /2024م

relevant wire samples under tension equal to 70% of their ultimate tensile strength in PCCP. To achieve this objective a tension frame was designed and fabricated. The frame consists of two blocks (190mm x 45mm x 45mm) and two threaded steel bars (studding) having a diameter of 20 mm and a length of 500 mm. Two holes (20 mm diameter) and two (6mm) are drilled in each block. Figure 5 shows a schematic drawing for the tension holding frame and the real one. The two blocks are assembled via two threaded bars tightened by means of eight nuts. [18]

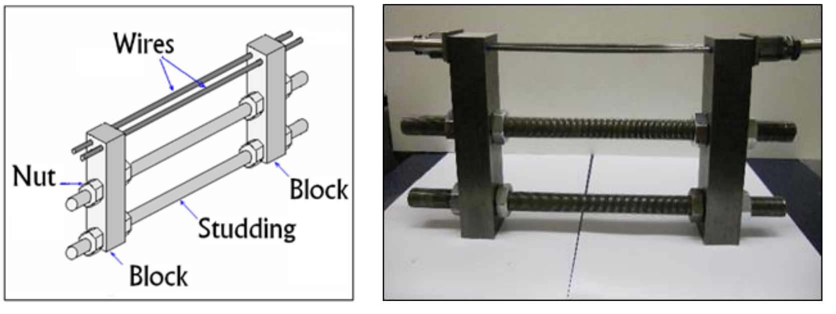


Figure 5. Tension holding frame

2.2 Wire preparation

The pair of operational high-strength steel wire specimens originated from the MRP manufacturing plant in Libya. The metallurgical composition and mechanical properties, verified by the wire manufacturers, are outlined as follows: Carbon steel (carbon 0.8-0.84%, 0.85-1.00%Mn, 0.030 %Max S, 0.035% Max P, 0.20-0.35% Si). The tensile strength of the wires is approximately 1738 MPa.

To conduct the experiments, both working wire samples were threaded through 6 mm diameter holes in steel blocks and then through two customized bolts and nuts designed for regulating the tension load of each wire. Subsequently, a steel cylinder was threaded onto the wire. The cylinder was compressed using a load machine, allowing the modified nut and bolt to expand between the clamped cylinder and the steel block, thereby introducing tension into the wire. Each wire underwent a tensile force of 20 kN by adjusting the bolts and nuts, and the resulting strain was monitored using strain gauges attached to the wires

2.3 Concrete and mortar preparation

The concrete specimen (200×200×50mm), representative of the inner pipe was prepared according to the technical specification for PCCP manufacturing used in GMRP, which is in accordance with AWWA C301-92 (Standard for Pre-stressed Concrete Pressure Pipe, Steel Cylinder Type, for Water and Other Liquids)[19]. Three days after casting, the wires, along with their holding frame, were positioned on the upper surface of the specimen. Subsequently, a 200×200mm mortar layer with a thickness of 20mm was applied to the concrete surface. This mortar composition entails one part cement to a maximum of three parts fine aggregate by weight. The final construction configuration is illustrated in figure 6. [18]

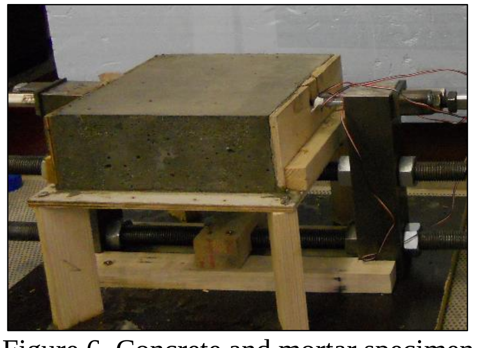


Figure 6. Concrete and mortar specimen

2.4 Accelerated corrosion technique

In order to examine corrosion effects within a realistic timeframe, it is sometimes necessary to expedite the initiation period and control the corrosion rate during the propagation stage. In the simulation of prestressing steel wire corrosion, a corrosion cell was created using an impressed current of 100μA/cm². This value is noted to correspond to the maximum corrosion rate for concrete in laboratory conditions, as discussed by Li and Zhang [19], and has been adopted by various researchers in their laboratory studies. In this particular experimental setup, wire corrosion was induced using an impressed current of 100µA/cm². The prestressed wires were incorporated into an electrical circuit with the positive pole of the power supply, while the negative pole was connected to a stainless steel plate (30*150 mm) placed on the upper mortar. A 4% NaCl solution was applied to the mortar surface, with a silicon sealant utilized to contain the solution on the upper surface, as outlined in [18].

2.5 Acoustic emission set-up

AE instrumentation generally includes transducers, filters, amplifiers, and analysis software. In this study, four AE sensors (R3I with a resonant frequency of 30 kHz) were affixed to the surface of the mortar. Silicon sealant was employed to mount the sensors, securing them onto the upper surface of the mortar using a U-shaped plate. The plate was fastened with screws to ensure a secure attachment and optimal coupling. Subsequently, the sensitivity of the sensors was assessed using the Hsu-Neilson source [8, 9, 20]. The experimental setup is illustrated in figures 7.

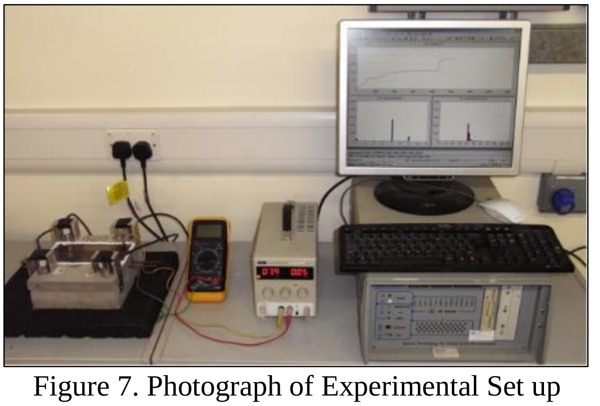
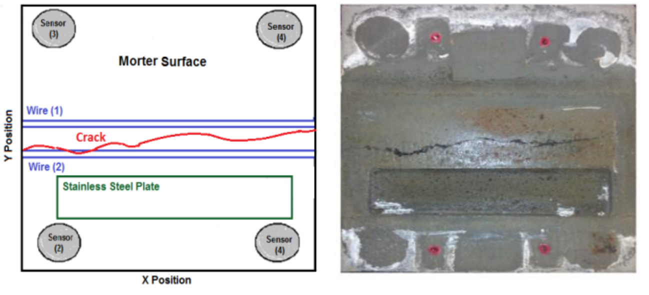


Figure 7. Photograph of Experimental Set up

3. Results and Discussion

Figure 8a illustrates a schematic representation of the specimen post-testing, displaying the placement of sensors on the mortar surface, wire positioning, the presence of the stainless steel plate, and the observed crack shape. In Figure 8b, a photograph captures the top surface of the mortar after the completion of the test, once more revealing the distinctive crack shape



(a) (b)

Figure 8. Schematic Diagram and photo of top mortar surface

Figure 9 illustrates the corroded wires and the corrosion product after the removal of the mortar. It is clear that substantial corrosion took place in the upper wire, and this is the location where the majority of AE signals were detected and pinpointed.

Figure 9. Photo of upper concrete surface and wires

Figure 10 illustrates the positions of hits with minimum amplitude of 45dB throughout the entire test duration. It is evident that the greatest concentration of impacts and the highest energy align with the areas of maximum wire corrosion and the visibly observed crack after the test.

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

Two specific zones have been selected as illustrative examples for distinguishing between cracked and non-cracked areas. The selection of these areas was based on visual observations, as depicted in figures 8b and 9. Zone 1 is representative of regions affected by corrosion and cracks, while zone 2 exhibits the absence of any cracks.

In figures 11a and 11b, the AF vs. RA values are presented for various regions with a concentration of events on the mortar surface. Figure 11a specifically displays the AF vs. RA for zones associated with corrosion and crack regions. The majority of data points in this zone exhibit diverse AF values and low RA values (less than 10 ms/v), forming a distinctive "vertical trend." Referring to figure 3, this trend suggests that the cracks in this area are of the tensile type. Contrastingly, figure 11b illustrates the relationship between RA values and AF in an area with a low concentration of AE locations and no observed cracks. Notably, in this region, the RA values have a broad distribution (ranging from 0 to 40 ms/v), and AF values span from 10 to 30. This distribution signifies the absence of a distinct crack type trend.

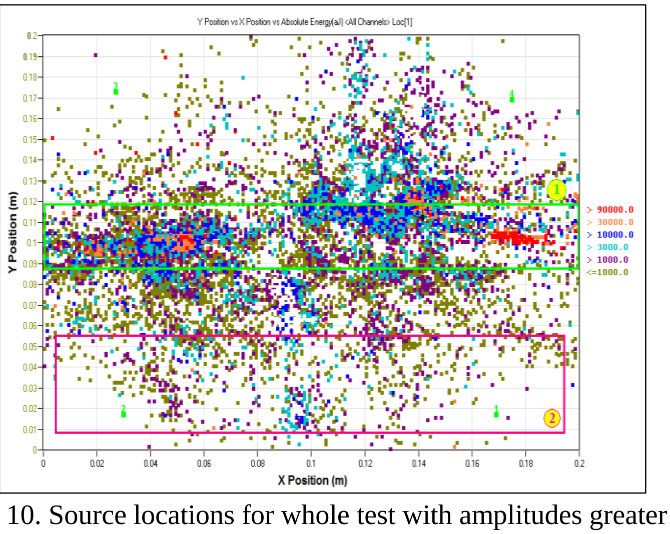
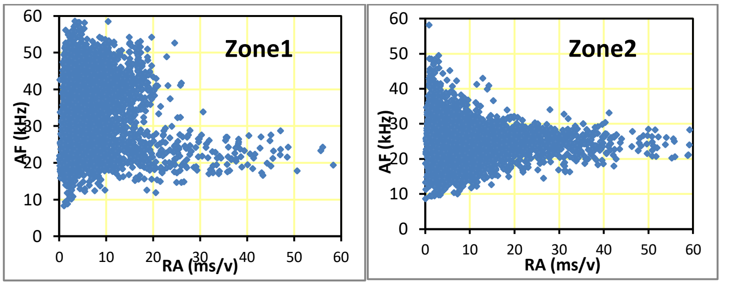


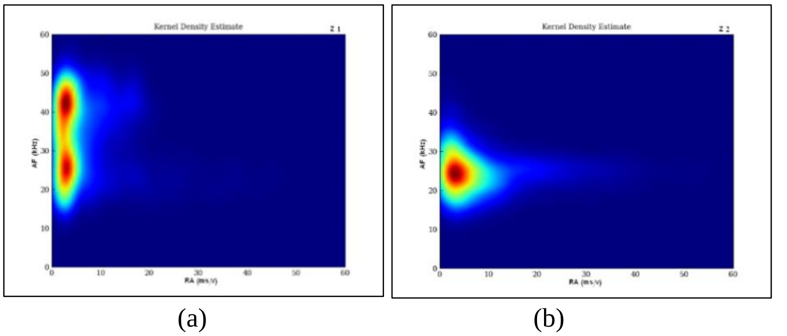
Figure 10. Source locations for whole test with amplitudes greater than 45dB



(a) (b)

Figure 11. Relation between the RA value and average frequency of (a)zone1 and (b) zone2

Furthermore, these areas can be visualized using Kernel Density Estimation Function (KDEF) as shown in figure 12 (a and b). This enables the easier identification of areas with high data concentration, with varying colors such as brown indicating the highest number of data points and blue representing the lowest.



(a) (b)

Figure 12.Kernel Density Estimation Function of (a) zone 1and (b) zone

The correlation between RA and AF values has been proven to enable the identification of crack areas, as illustrated in figures 11 and 12. This suggests the potential for providing corrosion alarms and pinpointing locations for pipe engineers before any wire breaks occur. Moreover, understanding the types of cracks could aid in identifying damaged areas before complete mortar failure. Further analysis indicates that the measured values remain unaffected by distance, making this approach highly suitable. Ongoing research is exploring the specific mechanisms within the structure that lead to

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

varying RA and RF values. The results imply that utilizing acoustic emission (AE) techniques for structural health monitoring in concrete pipes and other structures, such as bridges, is feasible. However, when applying AE techniques on actual pipe lines, certain limitations must be considered, including source attenuation, sensor number and placement, as well as noise from the surrounding environment and water flow.

4. Conclusion

The application of the AE method has been employed for detecting corrosion in small-scale pipe samples and a more advanced AE parameters data analysis approach to this application has been used to evaluate differing crack types. Using the relationship between RA value and AF value, the crack area and crack type can be identified and distinguish.

References

[1].K. Ann,J. Ahn,J. Ryou, The importance of chloride content at the concrete surface in assessing the time to corrosion of steel in concrete structures, Construction and Building Materials (2009) No. 23, pp239–245.

[2].E. Verstrynge, C. Van Steen, E. Vandecruys, Steel corrosion damage monitoring in reinforced concrete structures with the acoustic emission technique: A review,Construction & Building MaterialsJournal (2022),Vol. 349, 26 September, pp.128732.

[3].L. Zhe, J. Zuquan, W. Penggang , Z. Tiejun, Corrosion mechanism of reinforced bars inside concrete and relevant monitoring or detection apparatus: A review, Construction and Building MaterialsJournal (2021) Vol. 279, 12 April pp. 122432.

[4].T. Fujian, Z. Guoshuai,L. Hong-Nan, V. Els, A review on fiber optic sensors for rebar corrosion monitoring in RC structures, Construction and Building MaterialsJournal, (2021)Vol. 313, 27 December, pp. 125578 .

تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

[5].R. Miller, E. Hill, P.O. Moore, Non-destructive Testing Handbook, Acoustic Emission Testing (2005) Vol. 6, USA.

[6].V. Eline,V. Menno, R. Edwin,L. Geert, V. Els V, Experimental study on acoustic emission sensing and vibration monitoring of corroding reinforced concrete beams, Engineering StructuresJournal, (2023)Vol. 293, 15 October , 116553.

[7].D. Aggelis, Classification of cracking mode in concrete by acoustic emission parameters, Mechanics Research Communications (2011), No. 38, pp.153-157.

[8].H. Elfergani, R. Pullin, and K. Holford, Damage assessment of corrosion in prestressed concrete by acoustic emission, Construction & Building Materials Journal (2013), Vol.40, pp. 925–933.

[9].K. Ohno, M. Ohtsu, M, Crack classification in concrete based on acoustic emission, Construction and Building MaterialsJournal (2010), No. 4, pp. 2339-2346.

[10].C. Abarkane, A.M. Florez-Tapia, J. Odriozola, A. Artetxe, M. Lekka, E. García-Lecina, H. Grande, J. Vega,Acoustic emission as a reliable technique for filiform corrosion monitoring on coated AA7075-T6: Tailored data processing, Corrosion Science (2023)Vol.214, 15 April, pp.110964.

[11].S. Lian , k. Zheng , Y. Zhao, J. Bi , C. Wang, Y. Huang, Investigation the effect of freeze–thaw cycle on fracture mode classification in concrete based on acoustic emission parameter analysis, Construction and Building MaterialsJournal (2023) Vol. 362, 2 January, pp. 129789.

[12].N. Yong, Z. Xiao-Ping, B. Filippo, Evaluation of fracture mode classification in flawed red sandstone under uniaxial compression,Theoretical and Applied Fracture MechanicsJournal, (2020)Vol. 107, June pp. 102528.

[13].A. Kuwairi, Water mining: the Great Man-made River, Libya, Proceedings of ICE Civil Engineering 159 May (2006), paper 14382, pp. 39-43.

International Science and Technology Journal
المجلة الدولية للعلوم والتقنية
Volume 33 العدد
Part 2 المجلد
January 2024 يناير
المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ
تم استلام الورقة بتاريخ: 6/ 1 /2024م وتم نشرها على الموقع بتاريخ: 31/ 1 /2024م

[14].Singh, S. K.: Corrosion Studies on Prestressing Steel Wire, Ph.D. Thesis (2000) Imperial College, University of London.

[15].F. Liu , R. Guo , X. Lin , X. Zhang , S. Huang , F. Yang , X. Cheng, Monitoring the damage evolution of reinforced concrete during tunnel boring machine hoisting by acoustic emission, Construction and Building MaterialsJournal, (2022) Vol. 327, 11 April ,pp. 127000.

[16].A. Carpinteri, G. Lacidogna and N. Pugno, Structural damage diagnosis and life-time assessment by acoustic emission monitoring. Engineering Fracture Mechanics (2007) No.74, pp273–289.

[17].C. J. Hellier, Handbook of Non-destructive Evaluation (2001) McGraw-Hill, USA.

[18].H. Elfergani, Monitoring Stages of Damage in Concrete Structures by Using the Acoustic Emission Technique, African Journal of Advanced Pure and Applied (2024) vol. 3, Issue 1, January – Marc pp.127-133.

[19].X. Li, Y. Zhang, Analytical Study of piezoelectric Paint for Acoustic Emission-Based Fracture Monitoring, Fatigue and Fracture of Engineering Materials and Structures (2008) No.31, pp 684-694.

[20].N. N. Hsu, F.R. Breckenridge, Characterization and Calibration of Acoustic Emission Sensor. Materials Evaluation (1981) No. 39 (1) pp. 60-68.