Acoustic Emission Analysis of Prestressed Concrete Structures

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Abstract. Corrosion is a substantial problem in numerous structures and in particular corrosion is very serious in reinforced and prestressed concrete and must, in certain applications, be given special consideration because failure may result in loss of life and high financial cost. Furthermore corrosion cannot only be considered a long term problem with many studies reporting failure of bridges and concrete pipes due to corrosion within a short period after they were constructed. The concrete pipes which transport water are examples of structures that have suffered from corrosion; for example, the pipes of The Great Man-Made River Project of Libya. Five pipe failures due to corrosion have occurred since their installation. The main reason for the damage is corrosion of prestressed wires in the pipes due to the attack of chloride ions from the surrounding soil. Detection of the corrosion in initial stages has been very important to avoid other failures and the interruption of water flow. Even though most non-destructive methods which are used in the project are able to detect wire breaks, they cannot detect the presence of corrosion. Hence in areas where no excavation has been completed, areas of serious damage can go undetected. Therefore, the major problem which faces engineers is to find the best way to detect the corrosion and prevent the pipes from deteriorating. This paper reports on the use of the Acoustic Emission (AE) technique to detect the early stages of corrosion prior to deterioration of concrete structures.

1. Introduction
Several structures e.g. bridges, buildings, concrete pipes, strong tanks, dams, nuclear reactor protective shells, railway sleepers, piles and pressure vessels are made of prestressed concrete in which prestressing steel wires are put into a permanent state of tension to compensate for the inadequate tensile strength of the concrete. Tensile cracking in the concrete is minimised by ensuring that the concrete is in compression under normal working loads by prestressing the steel reinforcement. Generally prestressed steel is between four to five times stronger than mild steel. The main advantages of prestressed concrete structural materials are that they are stronger, lighter and “crack free” [1] and hence these materials offer cost benefits over other materials.

Corrosion is a big problem in numerous structures. The cost due to corrosion is estimated in billions of dollars every year. Department of Transport in the UK evaluated that, the cost of recondition of concrete structures damaged by corrosion problems is £755 million a year [2]. The problem of corrosion in this type of structure must be given special consideration because failure may result in the worst scenario a loss of life but at a minimum a loss in finance. Most studies indicate the main reason of failure of bridges and concrete pipes is due to corrosion during the short period after they were constructed. The concrete provides the ideal environment to protect the steel wires which are
embedded in it possibly for over 50 years [3]. However, the life of a concrete structure becomes shorter due to steel corrosion which may occur by aggressive ion attack from products of chloride or carbonation [2].

The concrete pipes which transport water are one such structure that has suffered from corrosion. For example, the pipes of Great man-made river project of Libya have suffered catastrophically from this affect. Five pipe failures due to corrosion have occurred since their installation. However, the big problem which faces the engineers, apart from future corrosion protection, is to find the best way to detect the corrosion and prevent the pipes from deteriorating [1]. This project aims to use the AE technique to detect the early stages of corrosion prior to deterioration and eventual failure of the concrete structures.

Acoustic emission (AE) is defined as the elastic energy released from materials which are undergoing deformation. Also it can be defined as “the transient elastic waves which are generated by the rapid release of energy from localized sources within a material” [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. By analysis 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.

The Great Man-Made River Project (GMRP) is the 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 and the main regions of agriculture and industry are located. The high quality ground water is conveyed throughout almost 4000 km of prestressed concrete cylinder pipe (PCCP) networks as shown in Figure 1. The PCCP networks consist mainly of four metre diameter pipes and 6.6 million cubic metres water is transported every day. The purpose of the project is to transform thousands of hectares of semi-desert into rich fertile agricultural land. [1, 5, 6]

Pre-stressed concrete cylinder pipes are designed to take best advantage of the compressive strength and corrosion-inhibiting property of Portland cement concrete and mortar and the tensile strength of prestressing wire. Each transportation line pre-stressed concrete cylinder pipe is mainly 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 19 mm 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.
The pipe is designed in accordance to AWWA standard C301 [7]. The pressure evaluation is based on the maximum steady state operating pressure plus a safety factor of about 5m head of water, and accommodates transients up to 140% of rated pressure. Classifications of the primary transportation system range from 6 bar to 28 bar in 2 bar increases, the different classifications are controlled by changes in prestressing wire diameter, pitch and number of layers during pipe manufacture. In order to protect the pipelines from risks including temperature variations and other environmental conditions they are laid in seven metre deep trenches.

Due to prestressed wire corrosion in the concrete pipes induced by chloride ions absorbed from the aggressive soil, five catastrophic failures in four metre diameter white pipes occurred between 1999 and 2001 after ten years of operation. The main reason for the damage is corrosion of prestressed wires in the pipes due to attack the chloride ions from soil. Detection of the corrosion in initial stages has been very important to avoid other failures which will interrupt water flows. Initially traditional techniques such as potential mapping, tapping and close-interval potential surveys were used to make a vast survey of the current pipelines. Then, experts used electromagnetic inspection and acoustic monitoring was used to inspect and monitor the rate of deterioration of pipes [6]. The time and location of wire break events can be determined by this method, however the detection of corrosion was not considered. Even though most of non-destructive methods, which are used in the project, are able to detect wire break, they cannot detect the presence of corrosion. Hence in areas where no excavation has been completed, areas of serious damage can go undetected. In this respect AE has significant advantages compared with other NDT methods because the AE technique is the only one able to reliably detect the very early stages of the corrosion process, before significant damage to the concrete has occurred and furthermore it can indicate the level of damage occurring to the concrete. [8, 9, 10]

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 prudent to place and maintain all relevant wire samples under tension equal to 60% of their U.T.S in PCCP. To achieve this objective a tension frame was especially designed and fabricated.

The frame consists mainly 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 3 shows a schematic drawing for the tension holding frame. The two blocks are assembled via two threaded bars tightened by means of eight nuts.
2.2 Wire preparation
The two working high strength steel wires samples were supplied from GMRA PCCP manufacturing plant in Libya. The metallurgical composition and mechanical properties as certified by the wire manufactures is summarized 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 almost 1738 MPa. The two working wire samples were passed through 6 mm diameter holes in the steel blocks and then two modified bolts and nuts (designed to control the tension load of each wire). Finally a steel cylinder was then threaded over the wire. The cylinder was then compressed in a load machine. In this way the modified nut and bolt could be expanded between the clamped cylinder and the steel block and as a result tension could be introduced into the wire. Each wire was subjected to a tensile force of 20 kN by adjusting the bolts and nuts and monitored via strain gauges mounted on 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 PCC Pipe Manufacturing used in Great Man-Made River Project, which is in accordance with AWWA C301-92 (Standard for Pre-stressed Concrete Pressure Pipe, Steel Cylinder Type, for Water and Other Liquids.) [11] Three days after casting the concrete specimen, the wires combined with their holding frame were placed on the upper surface of this specimen. Finally the mortar 200*200mm and 20 mm thickness was coated on the upper surface of the concrete. The mortar should consist of one part cement to not more than three parts fine aggregate by weight. The construction is shown in Figure 4.

![Figure 4 Concrete and mortar specimen](image)

2.4 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 impressed current (100µA/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 [12].

In this experimental work, the wire corrosion was induced by impressed current (100µA/cm²). The prestressed wires were contacted in an electrical circuit with positive pole of power supplier and the negative pole connected with stainless steel plate attached the upper mortar. Then a 5% NaCl solution was poured on the surface of the mortar.
2.5 Acoustic emission set-up
Four Physical Acoustic Limited (PAL) AE sensors (R3I – resonance 30 kHz, R6D – resonance 60 kHz) were mounted to the surface of mortar as shown in Figure 5. A PAL DiSP system was used to acquire and capture all AE data. The sensitivity of the AE system was checked using the Hsu-Neilson source [13].

Figure 5 Schematic Diagram and Photo of Experimental set up

3. Results and Discussion

Figure 6 shows the cumulative acoustic energy as detected by all sensors for almost nine days of continuous monitoring. The detected energy is attributed to active corrosion and mortar cracking. The graph demonstrates the behaviour of the energy emission in three regions of time. Each period of time marked represent three days of monitoring.

Figure 6 Energy vs. time

Figure 7 shows the variation strains of two wires (strains 1, 2 for wire 1 and strains 3, 4 for wire 2) with time. In addition, the current supply (corrosion rate) is added as a function of time.
Figure 7 Strain and current vs. Time

Figure 8 shows source location of sample before supplying current (no corrosion) for about 20 hours. It can be seen that there is a low level of events prior to the onset of corrosion. A colour key that indicates the number of signals detected at a position is also provided.

The period of test is divided to three different stages as shown in Figures 6 and 7. The first stage, which is first three days, is named period 1. The energy emitted is attributed to constant corrosion
activity, a small visible crack and the separation of mortar from the concrete. It can be noted that in this stage, considerable decrease in strains is evident (Figure 7) due to initial crack in this location. Furthermore, Figure 9 shows the source location of signals within this period 1. It can be seen that the highest hits concentration appears in the region of corrosion reaction, where the stainless steel plate (cathodic reaction) and wire (anodic reaction) are placed.

The second stage is between the fourth day and sixth day which is named period 2. In this stage, it can be seen that the current and strains are constant while the emission energy increases significantly as shown in Figure 6 and 7. Furthermore, it can be seen that in Figure 10 the locations considerably increase due to the growth of the crack and split of mortar from concrete. Also, a high concentration of hits in the area of corrosion reactions can be observed.

Figure 9 Source location for first three days (Period 1)

Figure 10 Source location for middle three days (Period 2)
During the final three days (period 3 in Figure 6 and Figure 7) it can be noted that the energy decreases due to decrease of current (corrosion rate). In addition, Figure 11 shows source location on the mortar surface. It can be seen that the number of hits is decreased from period two.

Figure 11 Source location for last three days (Period 3)

Figure 12 shows the distribution of hits with minimum amplitude 40dB for whole test (three periods) while Figure 13 shows hits distribution with amplitude greater than 47dB for whole period of the test. It can be noted that the highest hits concentration and highest energy in region coincide with maximum wire corrosion which was visibly observed post test.

Figure 12 Source locations for 9 days
Figure 13 Source locations for whole test with amplitudes greater than 47dB

Figure 14(a) is a schematic diagram of the specimen after testing. The figure shows the sensors mounted on mortar surface, wires, stain steel plate and crack shape. Figure 14b is a photograph of the top mortar surface after finish the test, again showing the crack shape. Comparing the two figures with previous locations reinforces that the AE was detecting the concrete cracking as a result of wire corrosion within the specimen.

The corrosion wires and corrosion product once the mortar had been removed is shown in Figure 15. It is evident that significant corrosion occurred in the upper wire and it was in this location that a large majority of AE signals were detected and located. The results offer encouragement to the use of the AE technique to detect early corrosion in pipe structures, however for full validation considerable larger specimens will have to be considered. A further series of investigations are planned that will utilise environmental chambers to assess temperature effects and geometric effects with the ultimate aim of producing a guide to detecting early corrosion in pipe structures using AE.
4. Conclusion
This paper reveals that use of the AE technique as a non-destructive technique can detect the onset of corrosion activity in wire in the interface between prestressed concrete and mortar as found in prestressed concrete pipes. Furthermore, this technique is able to locate approximately the corrosion activity on small prestressed concrete samples.

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