EXPERIMENTAL STUDIES AND THEORETICAL ANALYSIS ON CONCRETE STRUCTURES TO EVALUATE STRUCTURAL INTEGRITY OF HIGHWAY BRIDGE CONCRETE COLUMNS

by
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ABSTRACT

Inspection of bridge structures are conducted periodically, to ensure the integrity of the bridges. Presence and propagation of corrosion and fatigue cracks in reinforced concrete structures were investigated using Acoustic Emission (AE) technique and resistivity studies. When more than one type of defects is involved in damaging the structure, it becomes more difficult to identify the damaging activities and apply the most appropriate corrective measures.

Experimental studies were conducted on concrete structures, to evaluate the integrity of concrete columns using eddy current methods. In these efforts experiments, were carried out both on bridge structures and on laboratory test samples to arrive at a reliable methodology in recognizing the type of active defects. Acoustic emission method is very useful in monitoring active crack propagations and active corrosion processes. Acoustic emission is a transient signal, in that the emission of signal occurs during the event of either crack growth or during the corrosion process. Also, ambient disturbances, such as road noise, movement of heavy vehicles generate similar acoustic signals and it is essential that the technique employed in nondestructive testing method excludes the disturbing noises, wisely.

During corrosion processes corrosion products develop high levels of stresses within the concrete columns and induce the development of cracks. Acoustic emission arises owing to the corrosion activities as well as due to fatigue and similar mechanical failures in concrete. It becomes important to identify the nature of defects that causes the acoustic emission. In this work, methods of characterizing the AE signals to identify the source of the signal, as to whether the emission arose from the corrosion process or from other sources. The spectral content of AE signals provides some information on the sources of signals. Mechanical disturbances and road noises generate low frequency ranges of acoustic emission while emission due to the corrosion processes carry much higher ranges of frequencies, as well, with characteristic waveforms. High frequency components, however get absorbed in the structure easily and when the sensor is away from the source the signal may be lost among background noises.

In this study, it is attempted to characterize the AE signals based on the frequency spectral analyses and some of the measured AE parameters. Laboratory test samples were used to generate accelerated corrosion. Different parameters have been evaluated in its effectiveness to identify the type of activity that generated the emission. A Nondestructive Testing methodology to reduce the ambiguity in evaluating the integrity of bridge structures has been suggested, thus enabling corrective maintenance procedures to be applied at early stages of defects initiation and propagation, thus arresting the propagation of defects in timely manner.

Keywords: Concrete structures, Corrosion, Crack Detection, Structural Integrity, Highway Bridges, Acoustic Emission, Fatigue Cracks, Non-Destructive Testing.

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INTRODUCTION

Highway Bridges are a vital part of transportation system. Steel and concrete are used as important structural materials in the construction of bridges. There are about 600 thousand bridges in the United States, many of them built several decades ago with the life expectancy of about 50 years. Those days, the standards for corrosion prevention did not adopt standards used nowadays. The annual cost of corrosion damages in Transportation Industry amounts to \$29.7 billion out of which the damage in highway bridges amount to \$ 8.3 billions, in 2002 (5). Virginia Department of Transportation (VDOT) carries out periodical evaluation of the damages and deterioration in highway bridges and carries out maintenance, rehabilitation and repair (MR&R) to ensure safety and to prolong their useful life. Visual inspection is the most commonly used method of detecting corrosion. Electrochemical measurements and resistivity method are sometimes used to determine the vulnerability of concrete structures to corrosion. The process of identifying the deterioration is time consuming and in most cases the process is of subjective in nature. There are possibilities of human error in assessing the status of such damages. Better methods of testing the bridges are needed to perform these operations efficiently and effectively. In-service diagnosis methods for corrosion damage evaluation of steel-reinforced concrete structures in bridges are useful to reduce the maintenance costs and to ensure safety and reliability.

The process of corrosion in concrete structures involves several stages. Acoustic Emission (AE) monitoring is one of the most promising methods of monitoring the deterioration of the structure at different stages of deterioration. AE technique can be adopted to forewarn the maintenance team and to carryout repair work in a timely manner, thus saving the cost of repair and in prolonging the life of structures. Figure 1 shows the different stages of corrosion damages and indicates the importance of attending the maintenance at early stages (1).

The most appropriate NDT technique suitable for testing vary among bridges, since not all bridges are designed and constructed in the same way. In most cases, it may be essential to optimize the NDT technique to meet the requirements of each bridge structure. R&D efforts that continually evaluate the effectiveness of different NDT techniques, in collaboration with the maintenance group is very useful in developing and implementing the optimum methods of ensuring the integrity of bridge structures.

Virginia Department of Transportation (VDOT) carries out periodical evaluation of the damages and deterioration in aging highway bridges and performs maintenance, rehabilitation and repair (MR&R) to prolong their useful life. The process of identifying the deterioration, locating the defects and identifying the means of preventing further damages is time consuming and in most cases the process is of subjective in nature. There are possibilities of human error in assessing the status of such damages. Better methods of testing the bridges are needed to perform these operations efficiently and effectively. In-service diagnostic methods for the evaluation of corrosion steel-reinforced concrete structures are useful to reduce the maintenance costs and to ensure safety. Acoustic Emission (AE) monitoring is one of the most promising methods to monitor the deterioration of the structure. There are several NDT methods to complement AE monitoring. It is essential to support the results of AE tests, using other techniques too, to improve the reliability of test results. Resistivity measurement on the surface of concrete is identified as one of the useful methods to improve the reliability of testing for corrosion.

This research effort focuses on developing a reliable NDT technique to assess the integrity of concrete structures. It is intended to collect Acoustic emission signals from the test block and develop techniques of interpreting tests results to identify the signals from corrosion activities. In order to get sufficient signals due to corrosion the steel rod in the test block was subjected to accelerated corrosion, periodically as the AE signals were collected.

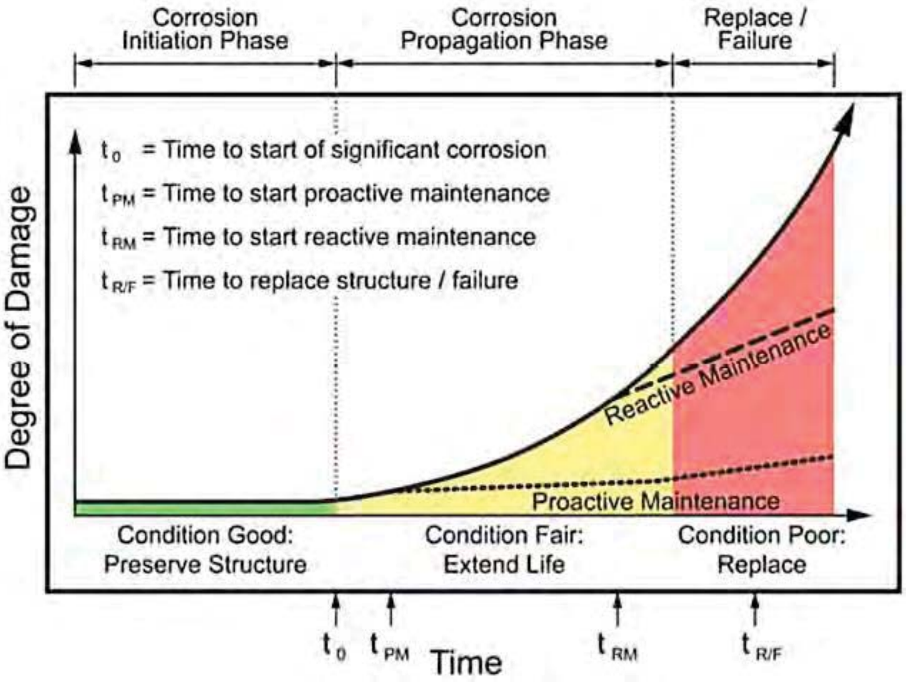


Figure 1. Typical bridge condition as a function of time (1)

OBJECTIVE

The purpose of this project is to develop reliable nondestructive testing (NDT) techniques to assess the integrity of the reinforced concrete structures used in bridges. When more than one type of defects is involved in damaging the structure, it becomes more difficult to identify the kind of damage and to carry out appropriate maintenance work, in timely manner. Presence and propagation of corrosion and fatigue cracks in reinforced concrete structures will be evaluated using Acoustic Emission (AE) technique and electrical resistivity measurements.

The Highway Bridge in the Denbigh Boulevard, crossing I-64, was used in the studies of corrosion related damages in the concrete columns. Figure 2 shows the picture of concrete columns affected by corrosion in the reinforced steels. AE signals arise from various sources, such as ambient noise and vibrations, vehicle and train movements, propagation of crack and corrosion activities. It becomes difficult to eliminate the unwanted parts of the signals and to identify the signals that arise from corrosion activities. The corrosion damages in the columns are clearly visible. Also, fine hairline cracks on the concrete surface are seen in many parts of the concrete structure. AE method of detecting the onset of corrosion and propagation of damage is useful, since it is possible to reveal the onset of corrosion activities at very early stages that provide enough time to carry out remedial measures.

In the current research work, essentially laboratory test samples were used to develop a reliable AE technology in identifying the corrosion activities at the midst of several disturbing unrelated emissions of acoustic signals. In addition to the AE method, usefulness of resistivity measurements, to predict the possibilities of the occurrence of corrosion in reinforced concrete structures, exposed to severe environments were studied. Experiments were carried out on laboratory test samples and also a few measurements on bridge structures to study the AE signals and resistivity values.

Corrosion process is a slow process in real situation. AE measurements were carried out on the test samples, as the corrosion was accelerated. The waveform of the AE signal and the parameters of AE measurements were studied to arrive at better methods of deducing the test results, to attain a reliable assessment of the damage in the concrete.

SCOPE

Virginia Department of Transportation (VDOT) carries out periodical evaluation of the damages and deterioration in aging highway bridges and performs maintenance, rehabilitation and repair (MR&R) to prolong their useful life. The process of identifying the deterioration, locating the defects and identifying the means of preventing further damages is time consuming and in most cases the process is of subjective in nature.

This project aims at developing a reliable nondestructive testing (NDT) technique to assess the integrity of bridge structures at Hampton roads, VA, to ensure their safety.
Acoustic emission monitoring is very useful in collecting data from the concrete structures, without the need for the operator at the bridge site. Large volumes of data are collected during the course of monitoring the structure. Identifying the useful part of the measured data and interpreting the test results are time consuming and also, ambiguous in many circumstances.

This research work is expected to provide a better methodology in assessing test results acquired from the NDT instrumentation.

METHODOLOGY

Detection of Corrosion in Concrete Structures

Technologies considered to detect corrosion

Corrosion in metallic materials is of several types, such as uniform attack, pitting corrosion, galvanic corrosion, crevice corrosion, stress corrosion, intergranular corrosion and erosion corrosion. Process of corrosion is associated with phase change, intergranular and transgranular stress corrosion cracking, evolution of micro bubbles, microfractures, etc. (12). All these phenomena give rise to acoustic emission.

In the case of reinforced concrete structures, AE hits are caused by friction sources between cracked surfaces and by the friction sources between concrete and reinforcement. Significant differences of AE event patterns are observed during corrosion damage by AE hit rates generated during loading and unloading situations (13). The acoustic emission technique has been shown to be an indirect measure of the corrosion rate, measuring the damage induced in the concrete by the production of expansive oxides, as seen in figure 3 (14,30). Corrosion process in a structure can be divided into four stages, namely, conducive environment, onset of corrosion, acceleration of corrosion and deterioration process. Each stage generates its own pattern of AE signals.

Corrosion in concrete structures in Highway bridges are caused by several factors, such as, CO_2 gas emitted by automobiles, NaCl used in roads during the winter, retained rain water in porous concrete structure and lower oxygen concentration around steel rods. In most cases corrosion undergoes an electrochemical reaction, in that there involve an anode and a cathode in an electrochemical medium. With the movement of electrons aided between the anode and cathode, corrosion takes place.

At the anodic sites, the metal ions turn into ferrous ions (Fe^{2+}), liberating electrons that travel through the steel to the cathodic sites (32). At the cathode, oxygen (O_2) and water (H_2O) are reduced and combine with the electrons released from the steel bars to form hydroxyl ions (OH). As a result, ferrous hydroxide $Fe(OH)_2$ forms. With further reactions with water and oxygen, hydrous ferric oxide $Fe_2O_3.3H_2O$ forms giving rise to reddish brown rust. This reaction is significant to the durability of the concrete due to the change in the volume ratio of corrosion product to steel. Ferrous hydroxide has a volume of expands up to ten times. The increase in volume at the steel / concrete interface generates large tensile stresses in the concrete, inducing microcracking in the concrete layer. With time this results in debonding of concrete with steel and spalling of concrete takes place.

Figure 2: Concrete columns of Denbigh Boulevard Bridge affected by corrosion. Pieces of concrete fallen off from the column are shown in figure 3.

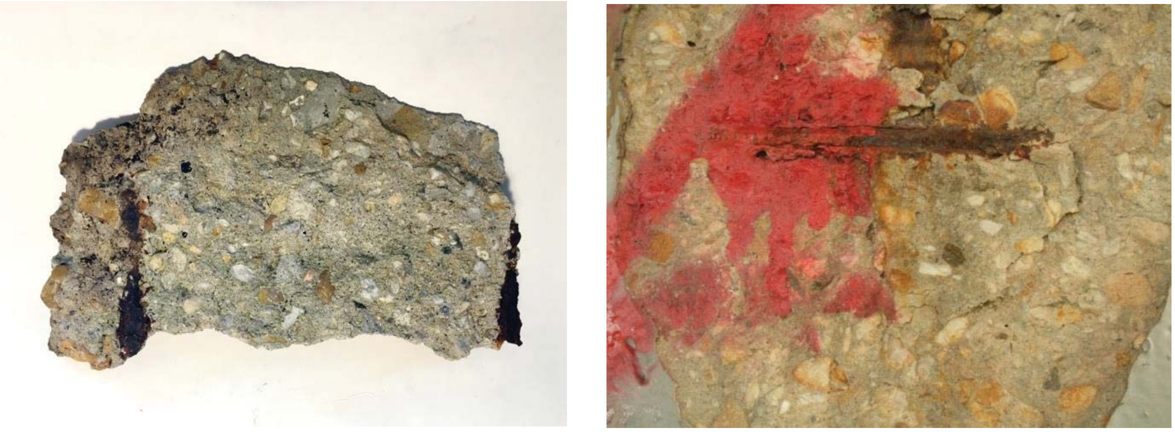


Figure 3: Left photograph shows a concrete piece fallen from the concrete column of the bridge at Denbigh, VA. Infusion of iron oxide takes place in the porous structure of the concrete and fine cracks are seen all over the surface. Right photograph shows the fine cracks in concrete layers, prior to the spalling of layers.

Figure 4: Photographs of a concrete block tested in the laboratory. Fine cracks originate from the reinforcing steel bar, owing to the development of corrosive layers around the steel bar. Also, the infusion of iron oxide around the porous structure of the concrete is seen in the photograph, which influences the resistivity of the concrete. Traces of silicone grease used in coupling AE probes are seen around the steel bar.

Microcracking of concrete layer generates stress waves and are detected by AE sensors. The magnitude and frequency of the stress waves are related to acoustic properties of the steel and concrete and also to the dimensions and the corrosion rate. The contamination of concrete with iron oxides lowers the electrical resistivity of concrete.

Measurement of AE

Elfergani, et.al. (7) have carried out experiments to understand the mechanism of AE emission during corrosion of reinforced steels in concrete. Continuous acoustic emission (AE) monitoring is applied to a cyclic wet and dry test of reinforced concrete beams (16,17). The onset of corrosion and the nucleation of corrosion-induced cracks in concrete are successfully identified, and then cross-sections inside the concrete specimen are observed by an electron probe micro analyzer (EPMA). Results of AE parameter analysis are compared with the corrosion mechanisms observed by EPMA. Further, a relation between kinematical information of AE sources and nucleation of micro-cracks inside is identified by the SiGMA (18) analysis and observed by the stereomicroscope. From these results, AE is found to be a promising technique to quantitatively evaluate the corrosion process in concrete due to expansion of corrosion products, at an early stage, is demonstrated.

In our experiments, a multichannel AE system, Sensor Highway II manufactured by Physical Acoustics Corporation Ltd. has been chosen (Figure 7) for measurement. AE sensors manufactured by Vallen Systeme and Physical Acoustic Corporation Ltd. were employed. Figure 5 shows some of the sensors used in the experiments. Vallen VS900-RIC is a wideband sensor, with built-in preamplifier. Sensor WD, made by Physical Acoustics is a wideband sensor, which uses an external preamplifier. Sensor R6I-AST (60 kHz), manufactured by Physical Acoustics is a narrow band sensor, with built-in preamplifier. Narrow band sensors give higher sensitivity and effectively excludes external noises which will be useful in capturing very weak AE events. AE signals arising from corrosion activity involves wide range of frequencies, depending upon the mechanism of corrosion. In this way, wideband sensors will be appropriate in capturing information due to all kinds of corrosion activities.

Concrete absorbs acoustic waves greatly, compared to metallic materials. The AE signals becomes absorbed in concrete, as the waves travel in concrete. It becomes essential to mount sensors very close to the suspected regions of corrosion to capture corrosion events effectively. Absorption of acoustic signal increases with the frequency of signal. In this way, high frequency signals will be lost, relatively in short distances of travel in concrete, unless the sensors are mounted sufficiently close the corrosion sites. Figures 8 and 9 show the concrete block mounted with five AE sensors.

AE Parameters

AE signals are quantized in various parameters based on the features deduced from the waveforms of the AE burst. Figure 6 shows some of these parameters. In this study parameters such as amplitude, energy, rise-time, average frequency, waveform and spectral power density of the wave have been considered in characterizing the AE signal. Energy analysis and the frequency spectrum analysis for each waveform are found to be more significant of AE emissions during the corrosion activity (20).

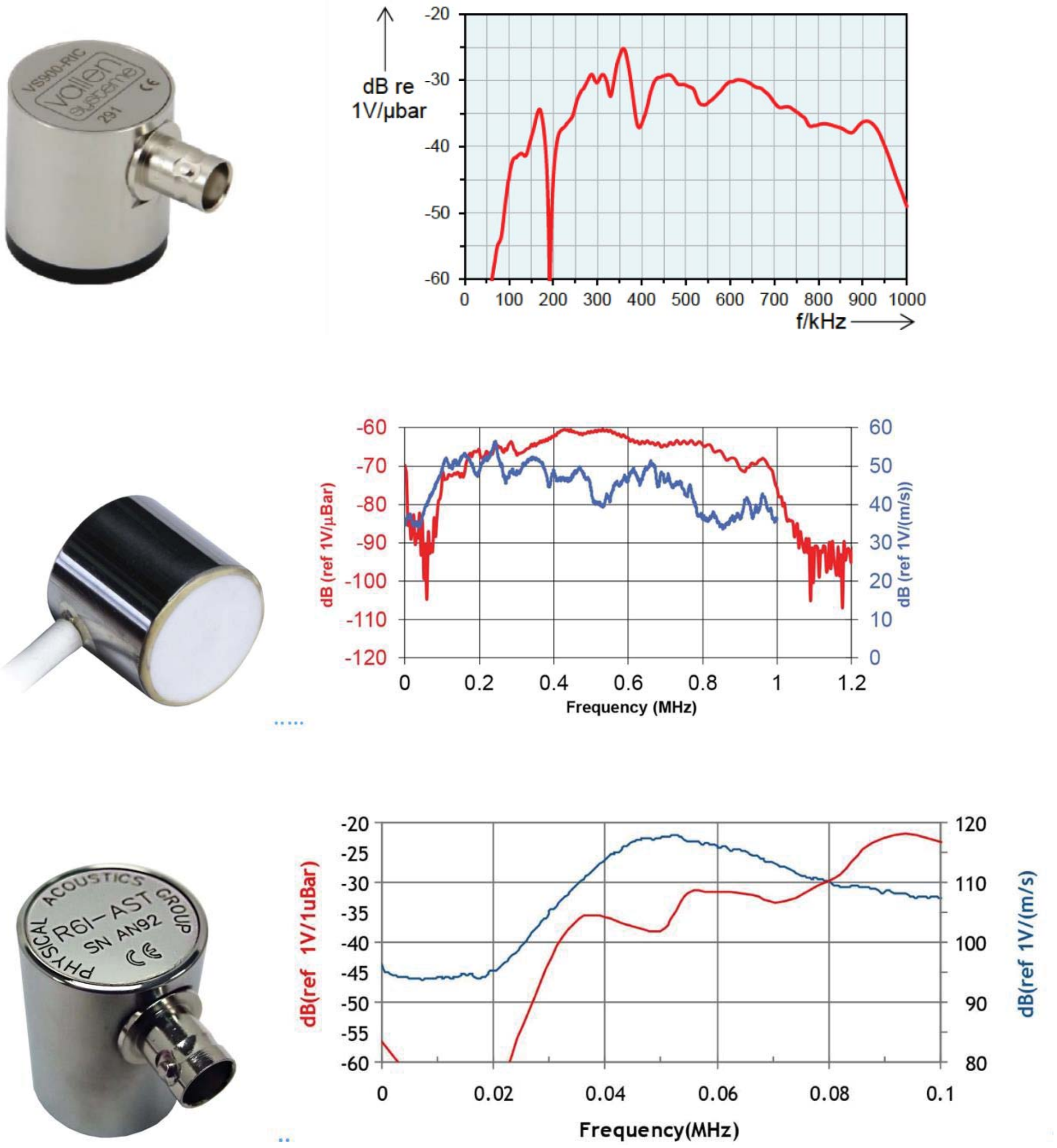


Figure 5: Photographs of some of the AE probes used in the experiments. The first two probes are wide band probes, with frequency response extending to 900 kHz and the third probe is a resonant probe (60 kHz) that provides better sensitivity.

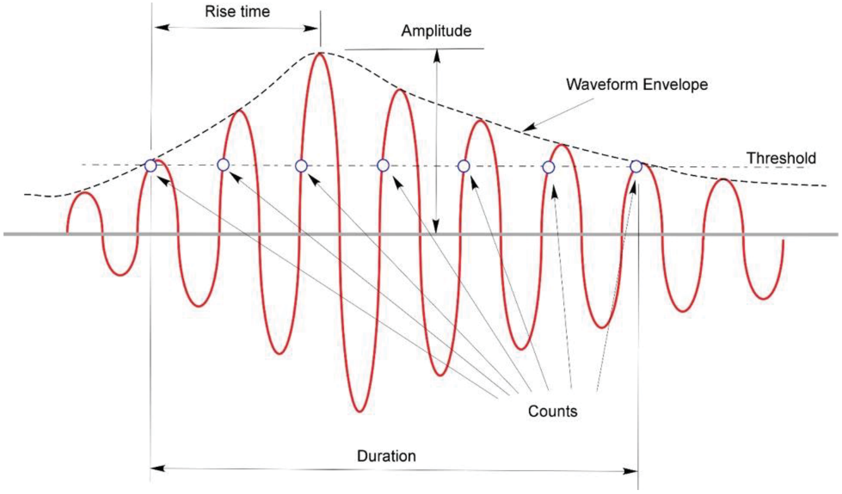


Figure 6: Diagram of a typical AE burst, which is a transient signal. The signal rises to a peak amplitude with a 'Rise-time' and decays in time. The signal, in most cases are not repetitive. Each waveform detected by the sensors is known as Hit. The signal parameters are quantitatively expressed as amplitude, energy, rise time, etc. as shown in the diagram.

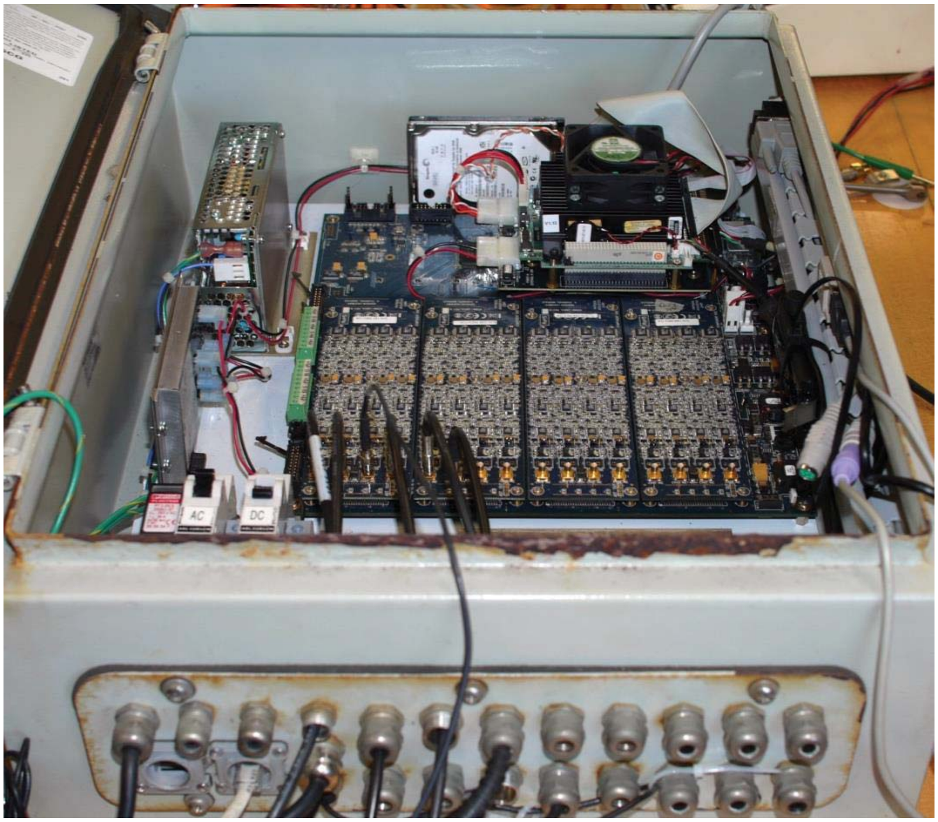


Figure 7: Photograph of the AE instrumentation, "Sensor Highway II", manufactured by Physical Acoustics, which was used in the studies.

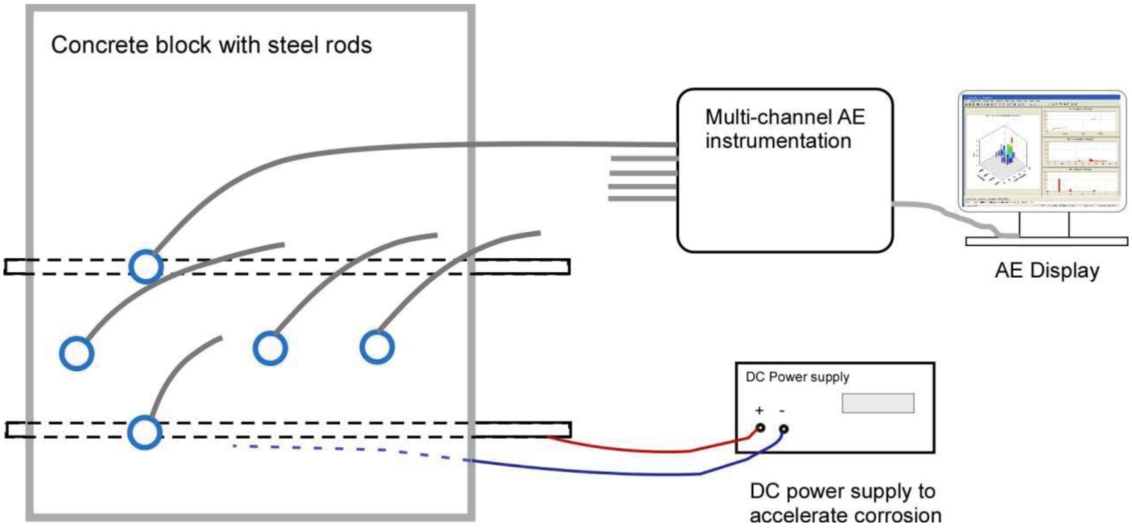


Figure 8: Experimental setup used in the corrosion studies conducted on the concrete block fabricated in the laboratory. The concrete block is embedded with electrodes to accelerate corrosion of the steel bar.

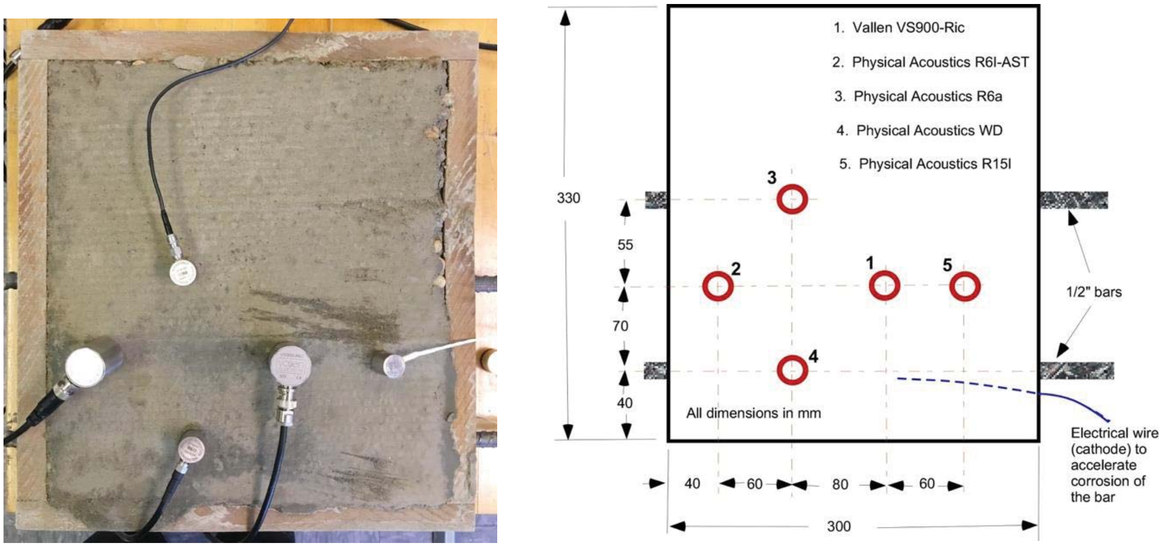


Figure 9: Photograph on the left shows the concrete block with the AE probes. The figure on the right shows the details of the concrete block with the positons of the probes and the steel bars. All dimensions are in mm, unless specified in the diagram.

Acoustic energy

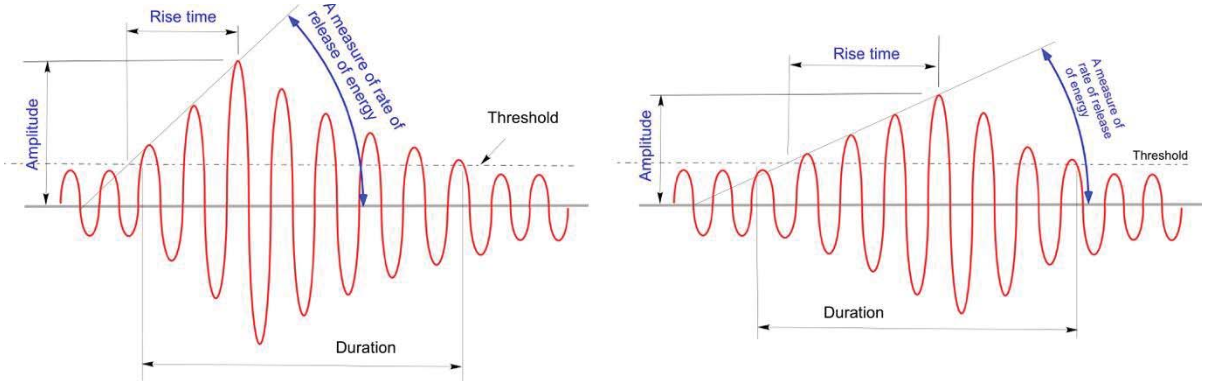
AE signals recorded over a 24-h period were converted into energy per second (23). Even though the parameter was an indicative of the corrosion activity, the AE energy per hour between successive days was found to be irregular. At low corrosion rates the duration of monitoring will significantly influence the accuracy of detection. Due to the irregular nature of the emission, only a couple of high-energy AE hits are required to distort the data collected within a 24-h period. The total AE energy recorded over a finite period can only indicate an approximate range of corrosion activity. Due to the low corrosion rate, only a relatively small number of processes occur within each 24-h period, consequently the variations in energy that occur naturally between each microfracture are not averaged out hence distorting the cumulative values. It is evident that the temperature and hence time of year, has apparently little influence on the ability of AE to detect corrosion of steel in concrete. Whilst the maximum energy per second increases at higher temperatures there is no clear relationship between temperature and AE Energy.

Rise time

Jones and Friesel, (21), have reported that in monitoring for the stress-corrosion cracking, use of rise time along with event rate, and amplitude could be used to discriminate among valid and invalid events. Ohtsu et.al (22) have reported that the measurement of rise time/amplitude (RA) and average frequency was successfully adopted to monitor tensile cracks generated due to expansion of corrosive products.

Rate of release of energy

It has been reported that the rate of release of energy, as indicated in the figure 10, is an indication of the mechanism of the release of energy. A higher rate of release of energy is a typical behavior of the tensile failure while a relatively slow rate of release of energy is an indicative of the shear mode of failure, which represents the failure due to corrosion phenomena. The rate of release of energy, thus is related to rise-time, amplitude and also the average frequency of the AE burst. In our studies, we consider the ratio of rise-time/amplitude in relation to the average frequency of the signal to classify the signal as one that could have propagated due to a corrosion phenomenon.



a) b)

Figure 10: AE waveforms with shorter and longer waveform for the same amplitudes. a) shorter rise-time is expected from a tensile event or due to the propagation of a crack b) longer rise-time is probably due to shear event, similar to some of the corrosion activities.

Resistivity testing

Concrete is a porous material that absorbs moisture; it allows the infusion of salt and carbon-di-oxide to takes place and the concrete structure becomes vulnerable to corrosion. Very porous concrete at high degrees of saturation has a higher hydraulic conductivity than denser concrete at lower water contents. Higher hydraulic conductivity allows for soluble ions from deicing salts and other sources to more easily infiltrate the porous concrete (25). Consequently, the rate of corrosion increases as chloride ions migrate at faster rates toward the reinforcing steel and accumulate in higher concentrations within the concrete.

Corrosion rate is found to be strongly dependent on the electrical resistivity of concrete, which is influenced largely by temperature and the internal relative humidity of the concrete, as shown in figure 11 (26). Electrical resistivity measurement is used to evaluate the status of corrosion vulnerability of reinforced concrete. It is a measure of the electrical conductivity in the concrete structure. The ohmic resistance of concrete may change significantly from very high values of a few Mega ohms in dry concrete to about several hundred ohms when the concrete is fully saturated with electrolytes.

Also, the presence of micro cracks on the surface and sub-surface of the concrete will be indicated by the measurement of resistivity. So also, infusion of corrosive products from reinforcing steel to the cement layers will affect the measured resistivity of the material.

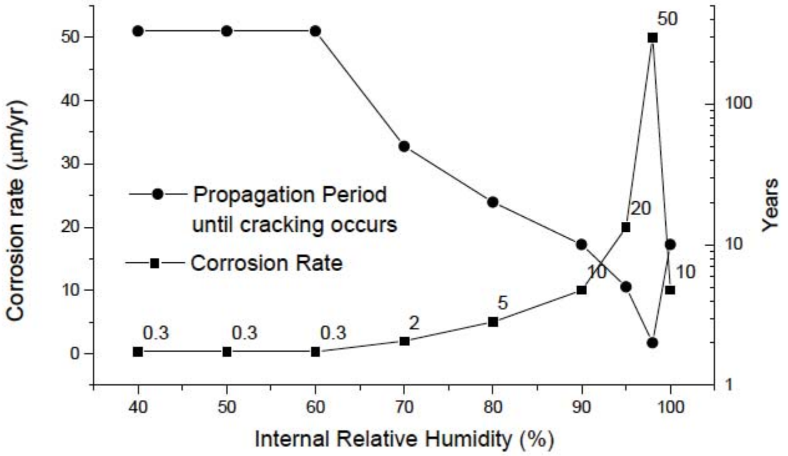
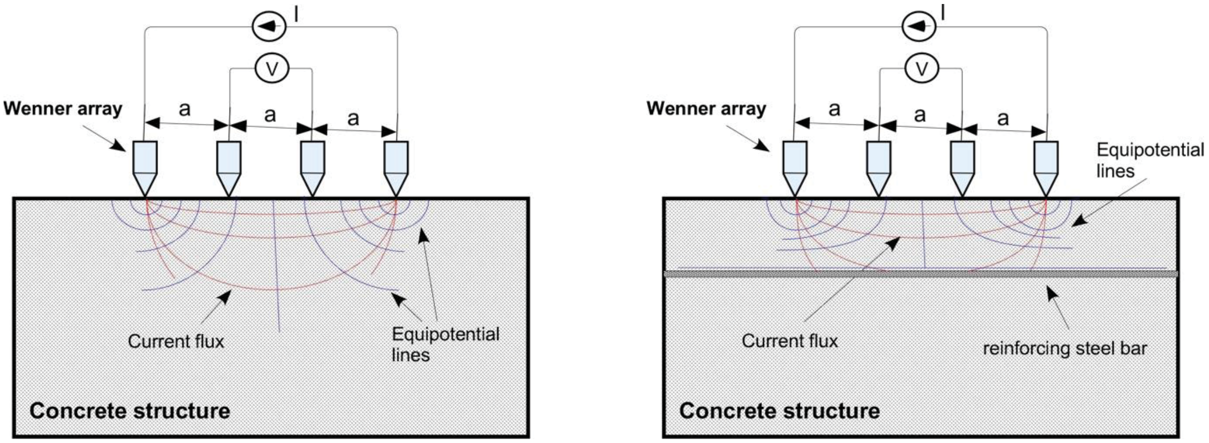


Figure: 11: Influence of relative humidity on corrosion rate in carbonated concrete (26)

Figure 12: Photograph of the Wenner array probe fabricated in the laboratory for the measurement of resistivity in the concrete block

Wenner Array

The resistivity of concrete is measured using a four-probe method. In order to carry out the measurement from the surface probe arrangement is chosen in form of Wenner array, as shown in Figure 12. The probe has four contact points (electrodes), which is held onto the concrete surface. Care must be taken to ensure proper surface contact between the probe and the concrete surface. Current is passed through the outer electrodes and the voltage is measured across the inner electrodes to calculate the resistivity. The method reduces the measuring error due to contact resistance between the electrodes and the concrete surface.



a) Distribution of current flux b) influence of the steel rod on the current flow

Figure 13: Wenner array is used to measure the resistivity of concrete structure to assess the vulnerability of concrete structure to corrosion.

Resistivity is given by, $\rho = 2 \pi a (E/I)$

Where, ρ = resistivity, ohm-m

a = electrode spacing, m
E = voltage across inner electrodes, V
I = current through the outer electrodes, A

Tests have been performed to investigate the resistivity of concrete in various conditions (17). Moist concrete typically shows a resistivity of 100 ohm-m, while oven-dried concrete exhibits a resistivity of 240 Mohm-m. Corrosion is almost certain to occur when resistivity measurements are less than 50 ohm-m. When resistivity measurements are between 50 and 120 ohm-m, corrosion is probable. The corrosion is unlikely to occur when resistivity measurements are in excess of 120 ohm-m. Corrosion is unlikely to occur when the resistivity exceeds 200 ohm-m. In addition, the study states that resistivity values between 50 and 100 ohm-m are needed to induce corrosion. Reduced resistivity may occur due to the absorbed electrolytes in the porous and moist concrete giving rise to an increased chloride ion concentration in the vicinity of the steel reinforcement.

While resistivity testing shows promise as an effective non-destructive method, there are no well-established standard to which measurements can be compared with. That is, although numerous suggestions have been reported, a consensus has not yet been reached regarding appropriate threshold resistivity values. Further research is needed to establish levels of resistivity that are reliably linked to corrosion potential and occurrence. Another deficiency is that the resistivity of concrete is most sensitive to near-surface conditions rather than to conditions in the vicinity of the reinforcement. Figure 13 shows how resistivity values will be influenced by the nearby conducting materials. Therefore, resistivity testing cannot be used as a primary testing method; it can, however, be used to provide information to supplement other testing methods. Periodical measurement of resistivity on the same structure will indicate any change in the conductivity of concrete compared to previous measurements; this will alert the NDT personnel in taking extra measure of care.

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DISCUSSION OF RESULTS

Acoustic Emission Testing

The concrete block prepared for laboratory testing has two embedded steel rods. One of the rods is arranged to induce electrochemical corrosion with the use of a surrounding cathode. A pair of copper wires was placed close to the rod for this purpose, so that accelerated corrosion in the steel rod can be carried out. Sodium chloride solution was applied near the steel rod to induce corrosion.

AE sensors were mounted on the concrete block with silicone grease as the couplant. A multichannel AE instrumentation as shown in the figures 7 and 8 was employed in the experiment. AE signals were monitored continuously. The instrumentation could be operated remotely, so as to adjust the threshold levels of the AE instrumentation, so that influence of external noises can be excluded.

During the early stages of experimentation, the corrosion process was very slow and no appreciable signals arising from corrosion could be detected, during the test period. A dc current with a current density of about 10 μA/mm^2 was applied between the steel rod and the buried copper wire, with the steel rod as the anode. This will result in accelerated corrosion in steel. Corrosion activities could be detected in several tests.

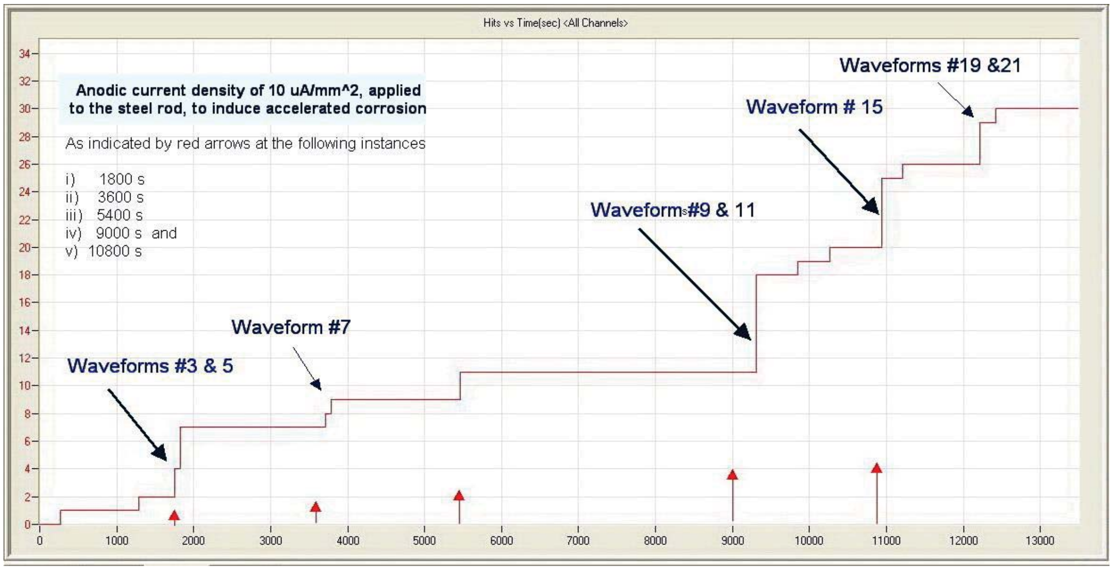


Figure 14: AE activity during the test is shown in the figure. AE hits increase with time during the test. Periodically a DC current was applied to accelerate corrosion at different time intervals, as indicated by red arrows.

Figure 14 shows the AE activities during the test, with an intermittent application of dc current at a current density of about 10 $\mu A/mm^2$. The two copper wires, which were placed on the two sides of the steel rod, were held together as the cathode and the steel rod itself as the anode. Electrochemical corrosion took place apparently with the evolution of gas bubbles around the electrodes and the generation of corrosion products formed around the steel rod. Stresses build up during such events and localized cracks can form in the highly stressed regions which will contribute to the strong emission of acoustic signals.

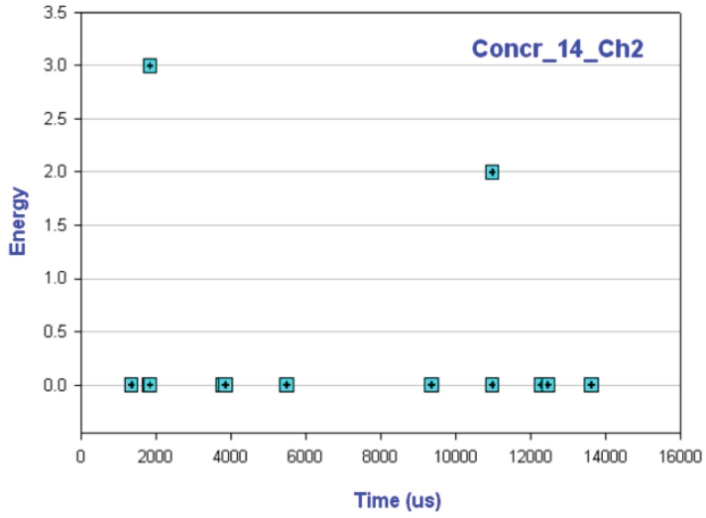
It was observed that whenever the DC current is stopped the emission activities slowly fades away with time. Thus, during the induced corrosion processes evolution of gases take place, causing bursts of bubbles contributing to AE signals and probably collapse of gas bubbles by way of diffusion through the pores of the concrete may take place. Also, strong build of stresses, due to bulging of steel rods with layers of corrosion products will cause strong emissions of AE signals due to cracking in concrete layers.

AE signals are transient bursts that occur during each event. The signals are not reproducible. In order to deduce a meaningful quantitative result, AE signals are expressed as parameters such as counts of pulses, duration of the burst, energy of the burst, amplitude, rise-time, energy, etc. In this study, on the detection of corrosion activities the interest is to identify an effective parameter that represents the corrosion activity, with least ambiguity. Corrosion mechanism, as such involves several stages of activities

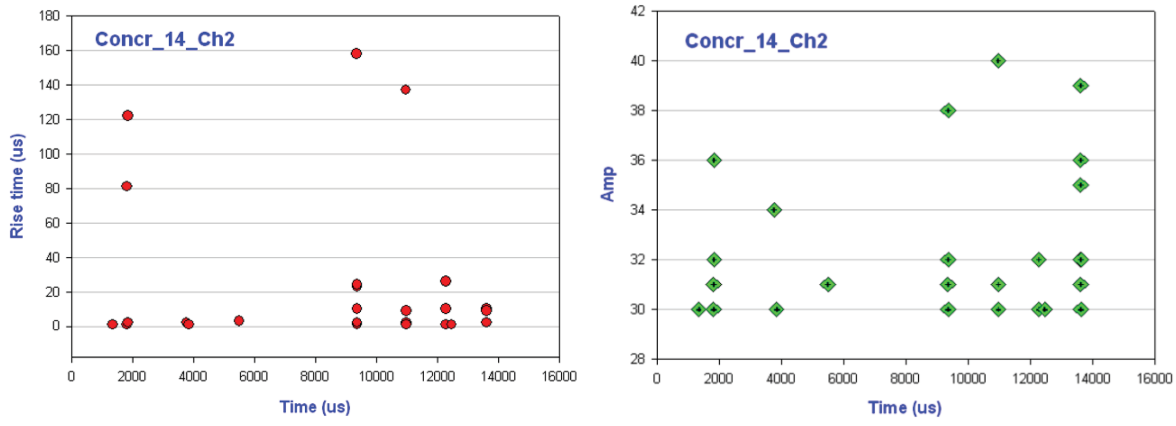
Corrosion process is an anodic reaction, with $M \rightarrow M^{n+} + n.e^-$

In the case of steel, compounds of Fe^{++} and Fe^{+++} form.

Corrosion process is an exothermic process and evolves heat and by-products of gases evolve. In our experiment, the application of DC current additionally contributes to localized heating. Gases develop in the vicinity of steel and try to exit through the pores of concrete. These processes produce localized stresses and shocks of stresses, as the gases find a way to move away. Also, the corrosion products are more voluminous and cause severe stress in the corrosion site, resulting in localized or propagated cracks in concrete. As a result, corrosion process results in steps of tiny events, which will be reflected in the emitted acoustic signals and their waveforms. Also, the spectral content of the emitted signal will correspond to the massive nature of the materials involved in the corrosion process.



a) AE activity plotted as energy of bursts with time



b) Plot of Rise-time with time

c) Plot of amplitude with time.

Figure 15: Plots of AE parameters for the test shown in figure 14. Three important AE parameters are taken up for the study, as given in figures 15a, 15b and 15c.

Figure 15 depicts the three parameters of the AE signals of the test described in figure 14. The three parameters are, a) energy, b) rise-time and c) amplitude. Figure 16 is the plot of the Rise-time/Amplitude for the same test. It has been reported by some researchers, that the parameter ratio of rise-time/amplitude is a better indicator of the corrosion activity. Accordingly AE emission occurred at 1800s, 9000s and 10800 s time periods could be due to corrosion activity.

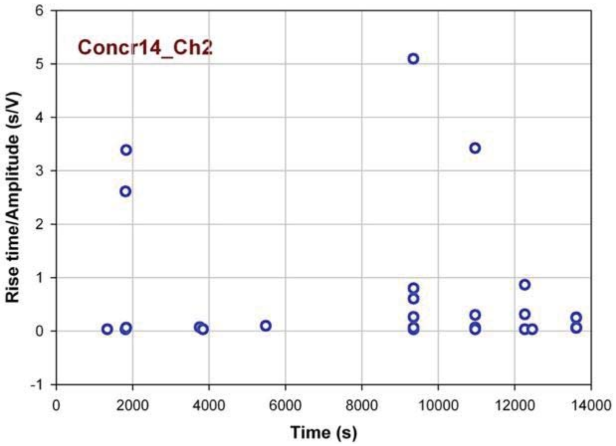


Figure 16: Ratio of rise-time to the amplitude for each burst is plotted to relate to the corrosion activities. The data are deduced from the plots given in figure 15.

On studying the waveforms, the waveforms are either single burst of damped waveform or superposition of several waveforms. Figure 10 shows how waveforms have a relatively shorter rise-time of longer rise-time, based on the mechanism of the emission of the signal. Shorter rise-time is an indicator of higher rate of release of energy, generally due to tensile stress release event. The longer rise-time waveforms are expected arise due to release of shear stresses, which are expected to arise due to the corrosion events. Again, the classification of waveforms is based on the average frequency of the AE burst signal. Figure 25 is a plot of data points of the various AE emissions as Average frequency versus Rise-time/Amplitude. An arbitrary dividing line is drawn to qualitatively distinguish between the AE signals arise due to release of tensile stresses and AE signals released due to the corrosion activities.

The waveforms and the frequency spectral density of the waveform are given in figures 17 to 24 for various events. AE signals evolved during the test described in figure 14 involve emission of signal due to corrosion as well as due to other activities, such as vibration and mechanical shock, from the surrounding. Based on the proposed classification given in figure 25, waveforms shown in figure 20 and 21 are probably due to corrosion activities. Another qualitative difference observed in the AE signals is that external disturbances generally results in a simple damped vibration, involving a narrow band of frequencies, while corrosion activities can involve a wide distribution of frequency components, depending upon the size of bubbles, size of corroded products that detach from the steel rods, etc.

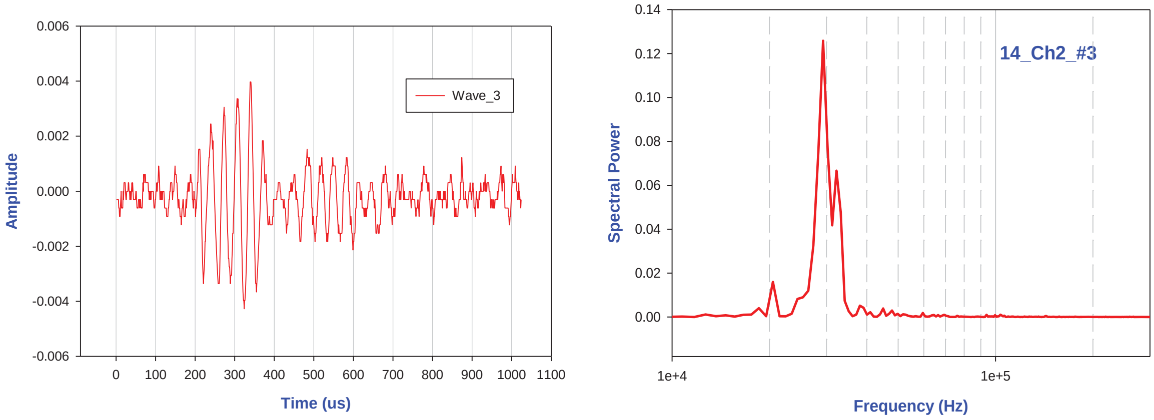


Figure 17: Plots of waveform #3 and the corresponding frequency spectrum of the AE burst at each instance.

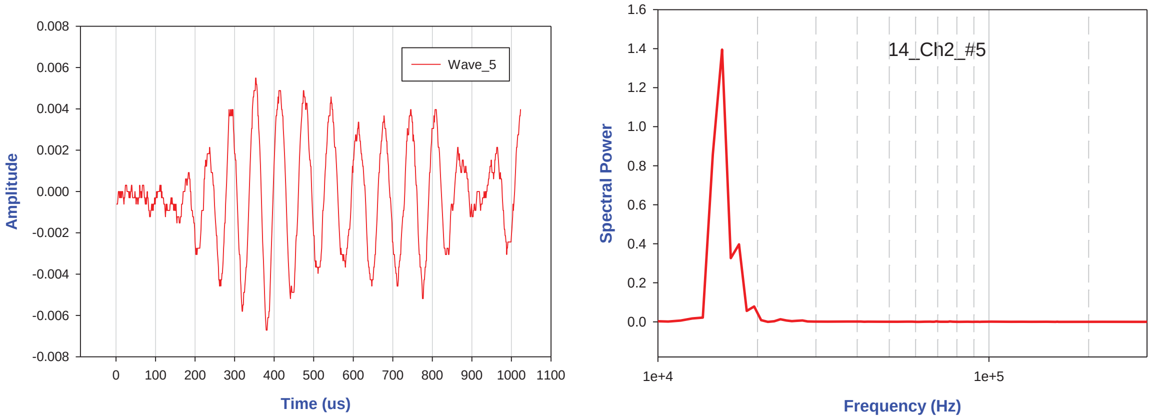


Figure 18: Plots of waveform and the frequency spectrum of the AE burst at each instance.

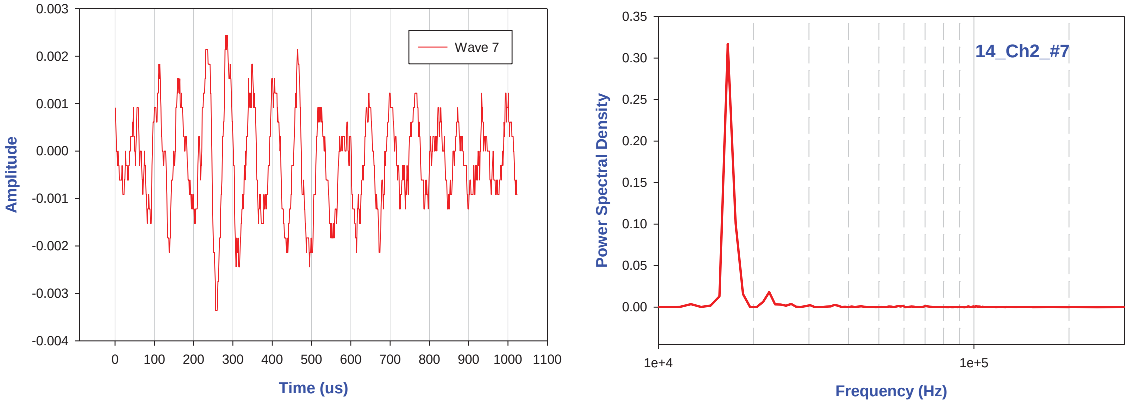


Figure 19: Plots of waveform and the frequency spectrum of the AE burst at each instance.

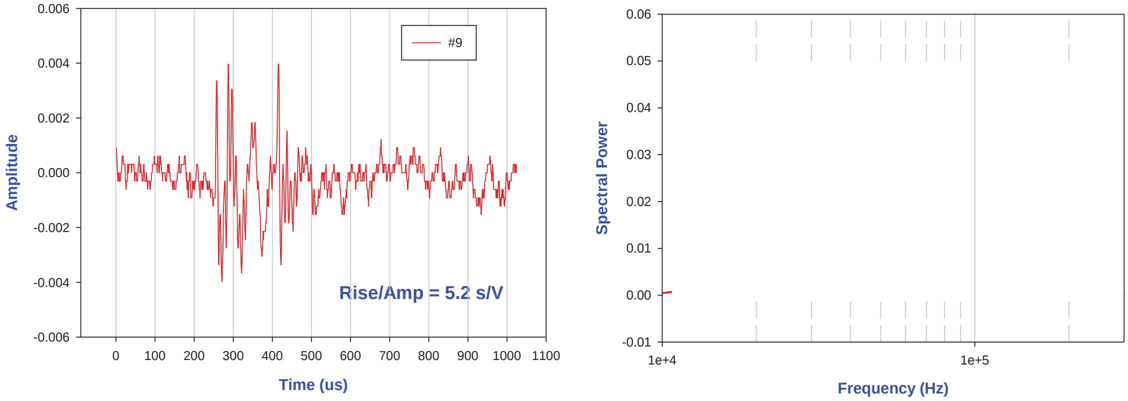


Figure 20: Plots of waveform and the frequency spectrum of the AE burst at each instance.

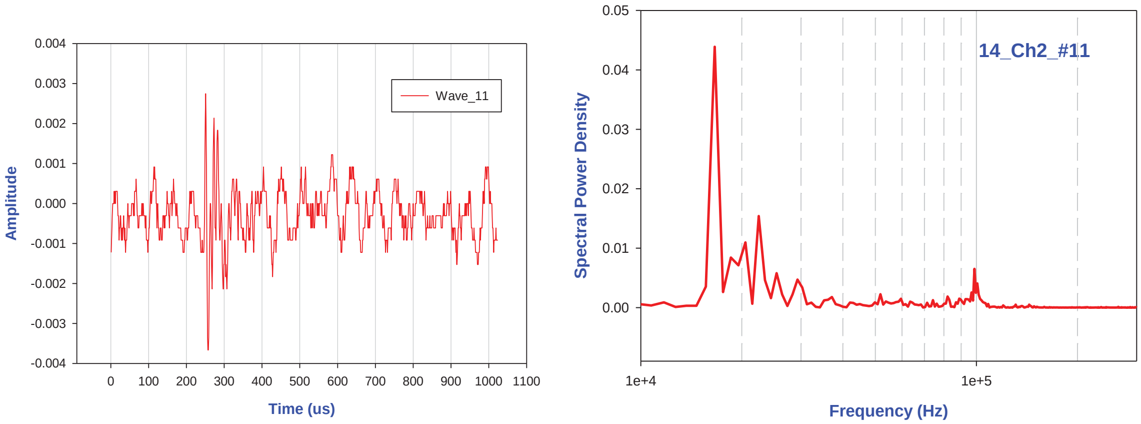


Figure 21: Plots of waveform and the frequency spectrum of the AE burst at each instance.

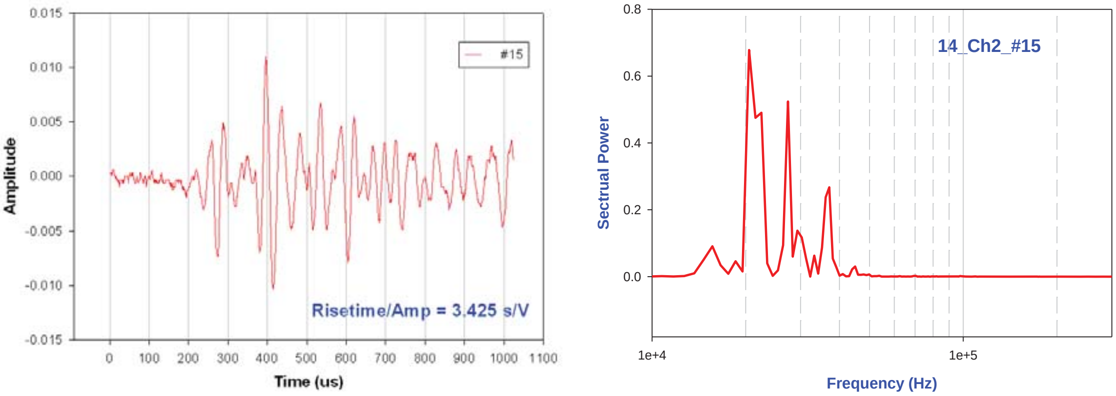


Figure 22: Plots of waveform and the frequency spectrum of the AE burst at each instance.

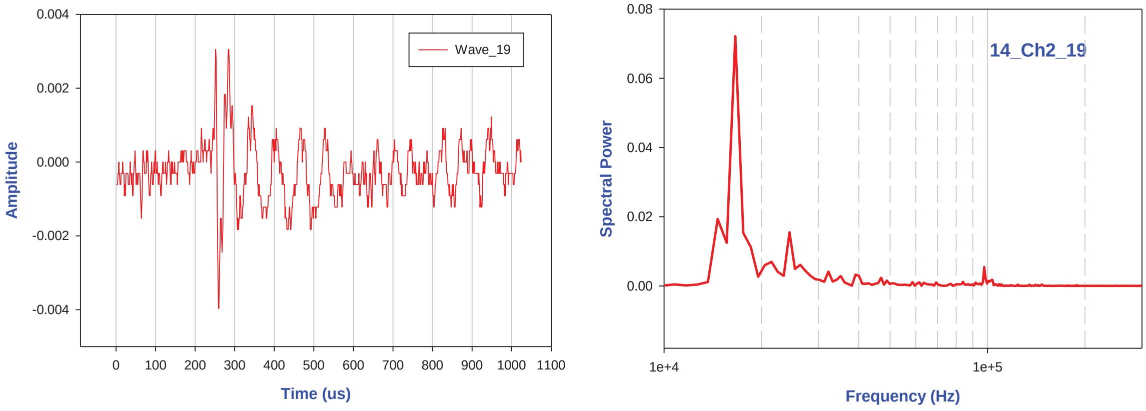


Figure 23: Plots of waveform and the frequency spectrum of the AE burst at each instance.

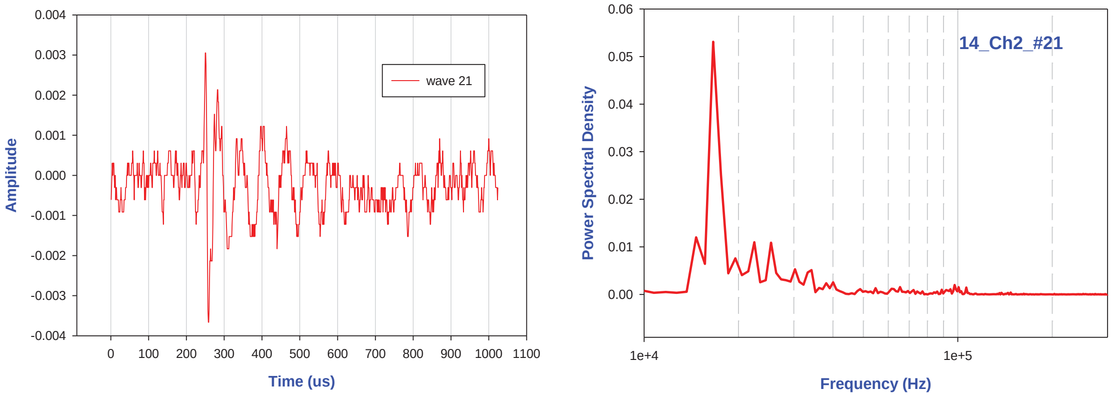


Figure 24: Plots of waveform and the frequency spectrum of the AE burst at each instance.

Figure 14 describes a corrosion test, with successive stages of activities. It indicates instances at which corrosion was induced by way of applying DC current, as shown by the red arrows in the diagram. That is at time instances of 1800 s, 9000 s and 10800 s, DC current was passed, for 300s. The figure also indicates the waveform numbers of the AE signals picked up by the AE instrument. The waveform and the frequency spectral plot for each event are given in figures 17 to 24. It is expected that some of these emissions are due to corrosion activity and some are due to external events, not relevant to corrosion.

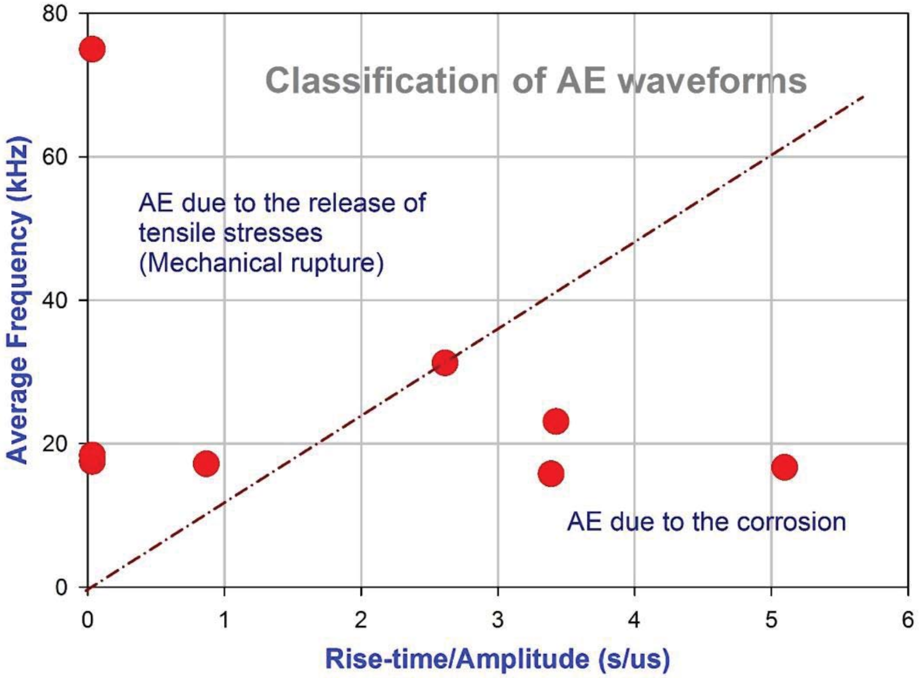


Figure 25: Classification of waveforms based on the average frequency and the ratio of rise-time to amplitude. The plotted area is divided into two regions to qualitatively differentiate between the AE emission due to sudden release of tensile stresses and release of AE signals due to the release of shear stresses. Corrosion process involves emission corrosion products and which can induce localized shear stresses.

CONCLUSIONS

AE technology is useful in detecting corrosion activities in reinforced concrete structures. There are several industrial applications where AE technology is adopted to monitor corrosion activities in structures, such as storage tanks used in corrosion environment.

In implementing AE technology in concrete structures of Highway bridges, there are some difficulties. Widely varying ambient noises arising from traffic situations will greatly interfere with the AE data. Reliable methods of interpreting the measured AE signals need to be evolved.

Careful judgment has to be applied in selecting the sensor spots in structures. In positioning the AE sensors in concrete structures two aspects need be considered. First, concrete highly absorb acoustic signals, especially, the high frequency components will be lost if the AE sensor is far away from the location of the corrosion activity. Concrete poses additional problems compared to steel structures, in that, the concrete structures attenuate the AE signals greatly, which demand that more number of sensors need to be used, to cover a wide area of the structure. AE signal that arise from corrosion activities carry a wide range of frequency components. In order to preserve the high frequency components, it becomes necessary to mount the sensors close to the corrosion prone locations; metallic coupling-horns may be considered, if necessary.

Commercially manufactured AE systems provide several useful parameters for analyses of data. It is up to the end users to identify the most relevant parameter for interpretation of the test results. In current research efforts three parameters have been analyzed, to interpret AE signals from corrosion activities. The characteristics of the AE burst or the AE waveform can indicate the nature of mechanical activity in concrete that generated the AE signal. The ratio of rise-time to amplitude is one of the parameters to consider identification of corrosion activity. The ration to the average frequency of AE burst to the rise-time/amplitude ratio appears to provide a more reliable assessment of corrosion activity.

Resistivity measurement on concrete surfaces will help in identifying condition of concrete as to whether it is prone to corrosion. Resistivity measurement can identify the absorption of carbon dioxide and sodium chloride in concrete which create a condition that promotes corrosion in reinforced structures. However, the surface condition of the concrete and the moisture level and temperature in the environment will influence the test result and careful judgement has to be carried out in interpreting the test results. Resistivity measurement alone cannot provide the status of integrity of concrete structures, but it will complement the test results from AE monitoring in assessing the status.

Vulnerability to corrosion can be identified using the resistivity technique and the ongoing corrosion activity can be monitored by AE technique. Resistivity measurements may have to bae carried out periodically to assess the condition of concrete. Use of both the NDT methods will help in preventing corrosion damages in reinforced concrete structures.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration
VDOT	Virginia Department of Transportation
MR&R	Maintenance, rehabilitation and repair
ASNT	American Society for Nondestructive Testing
NDT	Nondestructive Testing
AE	Acoustic Emission
UT	Ultrasonic testing
Hz	Hertz
dB	Decibel

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