NDT ASSESSMENT OF CONCRETE STRUCTURES : LIMEHOUSE LINK TUNNELS

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ABSTRACT

Assessing the durability of concrete has become an important function of engineer's responsibility for maintaining concrete structures. Bridge engineers have been at the forefront of emerging technology relating to their durability, as bridges are particularly susceptible to deterioration due to often-harsh environments. With the growth of non-destructive testing (NDT) over the past 25 years a bewildering array of tests has appeared. Within the industry detailed knowledge of the tests has not always kept pace with the growth, as engineers have struggled to keep abreast of increasing complexity. Because of this testing quality and interpretation of results have suffered, compounded on occasion by insufficient knowledge of such specialised techniques by those supervising the work. Appropriate advice is not readily available being spread amongst many different specifications and references some of which outdated.

In order to make the step from knowing, for example, that destructive contaminants are present in the concrete, to selecting the best methods for repair, engineers require guidance on techniques available both for condition assessment and for interpretation of the data.

This paper discusses NDT techniques available to assess the condition of structures and provide the fullest information enabling effective repair strategies to be developed show casing current methods attempting to manage the inevitable deterioration of concrete structures.

INTRODUCTION

The appropriate, long term solution to the problem of deteriorated and distressed concrete should start with a visual inspection, which may yield invaluable information affecting the choice of methods and location of test points.

Following this and with the correct techniques selected and the appropriate analyses carried out then the ‘real cause’ of deterioration should be apparent. It is all too often the case that the corrosion damage is first evident in an area of low cover. However, only thorough and methodical investigation can establish if the low cover is the main cause or merely coincidental and perhaps a more deep-seated problem exists. Once the real cause or combination of circumstances that have enabled the deterioration to start have been identified then a full assessment of the damage be made and an effective repair program started.

This is not the sort of work that can simply be passed on to the nearest available body in the office. Experience in the knowledge of the processes in question and expertise with the various tools and means of investigation and analysis are essential if a correct investigations is going to be made and accurate interpretation placed on the resultant data. Where possible wide dissemination of the resultant information should be encouraged so that the industry as a whole may learn from past mistakes and avoid recurrence of most of these problems in future structures.

The investigation process should not be a costly exercise and may account for less than 5% of the total repair contract value. However, it is frequently seen by those funding the project as an area where savings can be made.

PLANNING AN INVESTIGATION

A limited inspection would only be expected to determine the causes of specific areas of deterioration. Extending this further would examine representative areas of both deteriorated/distressed and visually sound concrete. An ultimate investigation would extend the scope to identification, diagnosis and scheduling of all defects requiring remedial treatment, although unfortunately this seldom occurs due to budgetary/time constraints.

Most often it is the case that the test engineer is required to determine the integrity of a structure given minimal information on the structure fabric, design data, etc. with the expectation of providing all the answers. Another frequent occurrence is where a contractor is required to carry out repair works and during these works a scant regime of testing is required. The contractor merely sees this as an unnecessary evil, hoping that test results fall within the specification criteria enabling the work to proceed onto the next phase.

This is amplified in a statement from the British Standards, which all too well sums it up.
‘*As a general rule the cheapest and quickest suitable test methods will have been chosen*’.

It is generally the case that the required property cannot be measured directly. However, properties can usually be assessed using a combination of different techniques. For instance, a bridge will be unique and have its own specific areas of potential weakness. The assessment therefore requires planning and a thorough understanding of the suitability of specific techniques and their application. Deterioration of concrete will vary from member to member, orientation and elevation, orientation of elevation and severity of environment. A fundamental part of any investigation therefore must include verification of details of materials used in a building or structure.

The preliminary investigation in the form of a visual assessment is fundamental and should be treated accordingly. It should be carried out with much attention to detail as incisive evidence may be obtained. Considerations such as the design, workmanship, environment, weather patterns, physical damage, wear and erosion.

The simplest assessment may require complementary techniques as usually the findings from a single test method present more questions than answers.

ASSESSMENT TECHNIQUES

Durability has been given considerable attention in the past 25 years because of the premature deterioration of some reinforced concrete structures. Typical of highway structures – Department of Transport, Departmental advice note BA 35/90 ‘Inspection and repair of concrete highway structures’ is used throughout England as a general and efficient way to assess structural condition. This standard suggests a regime of testing and outlines areas of potential deterioration, although one should quantify each structure on its own merit. The majority of the testing techniques specified are well known throughout the industry, although the analyses and interpretation is sometimes cloudy owing to contradictory findings.

Cover Depth

Concrete cover to reinforcement is a major controlling factor in the service life of structures that are required to resist the effects of carbonation and chloride ingress. Failure to achieve the specified cover depth is probably the greatest single factor influencing premature corrosion of reinforcement that in turn is probably the principal form of deterioration of concrete structures. Surveys of cover achieved in practice have shown that the specified cover is frequently not achieved. In one such survey of 25 sites carried out for the BRE it was found that failure to achieve the specified cover is ‘an extensive and chronic rather than sporadic problem' with 15% of the cover measurements not meeting with the absolute minimum requirements of the designer. However the reasons for non-compliance are complex and manifold, with no single, simple solution.

Chloride ion Gradients

Mostly originating from road salts, sea water and sea spray this requires the obtaining of a dust or lump sample for laboratory analysis, though on site test apparatus is available. The interpretation of the results obtained is complex following conflicting recommendations of contaminant through BA, BRE and TRL criteria. The properties of the concrete, type steel will each have an impact on interpreting results. It may be prudent to expose reinforcement where values approach high risk levels. Additional testing such as half-cell, cover, resistivity, carbonation would provide a bigger picture enabling more assured recommendations.

Half-Cell Electropotential

Developed in the early 60's the widely used corrosion potential measurement technique (using standard reference electrode commonly known as 'standard half cell) for steel structures such as pipe lines buried in soil or submerged in water, is equally suitable for assessing the corrosion state of steel reinforcement in concrete. Now the technique is routinely used worldwide and various national and international standardizing authorities have adopted this as a proven NDT method for determining the risk of reinforcement corrosion. This is however a measure of probability and should be complemented with chloride sampling as high potentials could indicate a more chloride contaminated concrete.
Notwithstanding this a high potential does not indicate a particular high rate of corrosion activity and it is recommended that resistivity and linear polarisation is also carried out to determine corrosion rates.

Surface Resistivity

The time at which corrosion of steel may commence and the rate at which it may proceed is dependent upon properties of the cement paste and the permeability of the concrete. Since the electrical conductivity of the concrete is an electrolytic process, which takes place by ionic movement in the aqueous pore solution of the cement matrix, it follows that highly permeable concrete will have conductivity and low electrical resistance. Thus, knowledge of the electrical resistance of concrete can provide a measure of the possible rate of corrosion of steel embedded. In order to determine an actual corrosion rate this test should be used in conjunction with linear polarisation to provid an insight into the severity of any corrosive activity.

Linear Polarisation Technique (LPR)

The corrosion rate is probably the nearest the engineer can get to measuring the rate of deterioration of reinforcement within concrete. LPR method is based on the fact that near to the natural (corrosion) potential, the relationship between applied current and polarisation is approximately linear.
There are various ways of measuring the rate of corrosion including AC Impedance and electrochemical noise. However these techniques are not field worthy for the corrosion of steel in concrete. It is possible with varying degrees of accuracy to measure the amount of steel dissolving and forming oxide (rust). This is done directly as a measurement of the electric current generated by the anodic reaction.

AAR/ASR

Sulphate attack in concrete has been known to occur when sulphate solutions (derived either from a constituent in the concrete such as aggregate or from external sources such as groundwater) react with the calcium aluminate hydrates present in the hardened cement to form the hydrated calcium sulfoaluminate known as ettringite which can occupy over twice the volume. Recent investigations of concrete structures have identified another form of sulphate attack that has taken place in concretes that were specifically designed to provide sulphate resistance. In this type of deterioration sulphate solutions react with calcium silicate hydrate phases in the presence of calcium carbonate ions within the hardened cement paste to form the mineral thaumasite. This mineral is a more complex salt than ettringite and forms at low temperatures (below 15C) and is associated with the presence of finely divided limestone sometimes used as filler, though limestone aggregate may also promote the reaction. Thaumasite formation renders the cement paste soft with concomitant loss of strength and disintegration of the concrete.

Similarly Alkali aggregate reaction which is a more complex and currently less well understood problem relies at least in one of its forms on the presence of excess water to form the expansive gel which disrupts the concrete structure and gives rise to the characteristic map cracking of the surface. Despite opinions to the contrary in the 70’s and early 80’s AAR is now also accepted as a British problem though to date only silicate aggregates are known to be affected in the UK and this problem is more properly known as ASR. Caution is needed in its diagnosis because it is possible for frost damage or plastic shrinkage cracks to cause very similar crack patterns on the concrete surface. Furthermore the crack patterns resulting from ASR are often influenced by the structure itself following the lines of reinforcing steel etc, and mimicking in some cases the type of cracking more commonly associated with structural movement. A further point to consider is that ASR is a finite process and will stop when one or other of the necessary reagents is used up i.e. free alkalis or reactive aggregates. The reintroduction of one or other of these components during any repair could restart the reaction in the body of the material.

Specialised Techniques

Impulse radar, also known as ground radar, has traditionally been used for geophysical surveys to study rock formations and even to measure glacial and polar ice cap thickness. However, more recently impulse radar is being employed by civil engineers to investigate the integrity of concrete structures and to locate sub-surface pipes and ducts. The principle of impulse radar is similar to that of marine sonar, except that a very high frequency electromagnetic pulse, instead of an acoustic source or pinger, is used to generate a high resolution 'cross section' of the ground or structure being investigated. Pulses of electromagnetic energy are transmitted directly into the surface of the structure. When the pulse reaches a boundary between electrically contrasting layers (i.e. between concrete and air), part of the signal is reflected back to the receiver antenna and part is transmitted through the interface. The waveform received corresponds to multiple reflections from multiple layers.

Analysis of data is complex and requires knowledge of both signal analysis and material properties. Like all indirect testing techniques, the accuracy can be improved greatly if data can be correlated with direct measurements.

CASE STUDY: LIMEHOUSE LINK TUNNEL

The construction of Limehouse Link Road Tunnels commenced in 1990 by Balfour Beatty-Fairclough joint venture and was completed in 1993. The tunnel is approximately 1500m in length with zero inspection chainage located at the west entrance. The tunnel passes under the Limehouse Basin, fed by the fresh water Regent Canal between inspection chainage 150 and 500. The tunnel at around inspection chainage 850 passes under the Limekiln Dock that is linked to the Thames River, hence the water above the tunnel has a variable degree of salinity. A plain rectangular box tunnel approximately 1.8km long with twin bores 10m wide separated by a central wall. The box is 7.8m high with a depth below ground generally between 6-8m. The scheme connects the highway at Limehouse with Aspen Way near West India Quay in the London Docklands.

Construction was by the cut-and-cover technique with top down construction using diaphragm walls and cast in situ roof and base slabs. Ground conditions are complex over the route of the tunnel with made ground overlaying Thames gravel, London clay, Woolwich and Reading beds, Thanet sands and Chalk bedrock. In addition the tunnels passes under the Limehouse Basin Limehouse Cut Limehouse Dock and the Docklands Light Railway.

The main defects present within the structure are joints in the diaphragm walls, which have shown varying degrees of water and silty fines ingress. Similar ingress is observed occurring through cracking in walls and soffit.

Long Term Condition Assessment

In 1993, a system comprising 6 monitoring probes measuring Rate of Corrosion in Concrete (ROCC) was permanently installed by another company within the tunnel structure. In 1999, a further 6 probes were installed by Testconsult Limited. The ROCC system is an automated corrosion rate measurement system that consists of two components: a probe measurement interface and a computer to control the measurement and store results. The measurement system returns results for corrosion potential and corrosion rate.

The corrosion rate measurement is obtained using three-electrode linear polarisation resistance (LPR) technique. The interface uses a potentiostat to control the potential of the probe test element with respect to a reference electrode or reference element and measures the current required to control this at a level of 20mV more anodic than the natural corrosion potential. The current is passed between the test element and a third auxiliary or counter electrode element.

Control of the probe and storage of results is handled by the psion walkabout hand held computer. The software allows the results to be tagged against the user entered location data as well as the date and time at which the measurement was recorded.

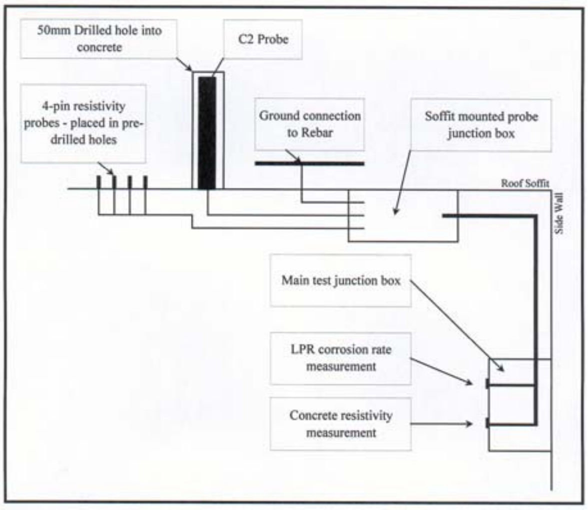

Figure 1 : Type C2 Dual Probe Schematic

The probe Type C2 is a dual probe, assembled and grouted into a cored hole, enabling permanent monitoring of corrosion potentials and providing information on corrosion trends and changes occurring throughout the structure with time. Each probe comprised a silver/silver chloride/potassium chloride (Ag/AgCl/KCl) reference electrode specifically designed for permanent embedment in concrete, a stainless steel auxiliary electrode, and a ground connection to the main rebar cage. The type C2 probe incorporating 4-pin resistivity probes is wired into a main test junction box situated on the wall of the tunnel enabling measurements to be taken when required without the need for access platforms, tunnel closures etc.

Figure 2 : Type C2 Probe Monitoring Point

From visits carried out over a period of eight years readings taken provide an insight into the behavior of concrete at each probe location. Figure 3 shows a typical graph obtained for corrosion rate against time, illustrating the gradual decline in corrosion rates over the past decade.

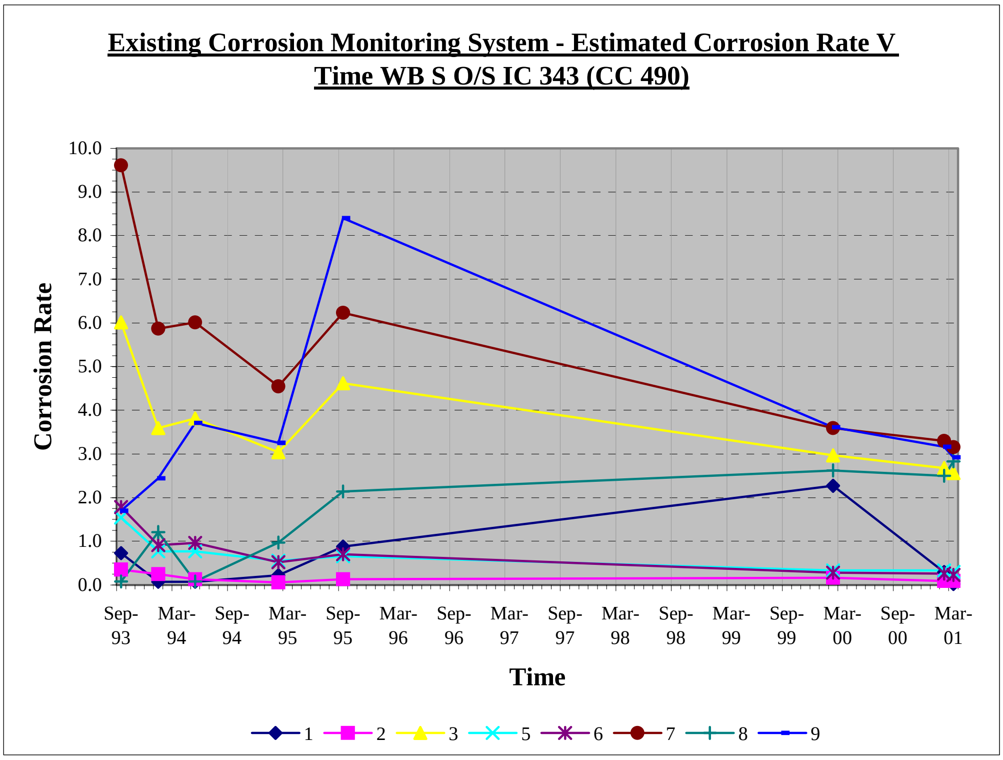

Figure 3 : Corrosion Rate versus time - Limehouse Link Probes

CASE STUDY: DONCASTER NORTH BRIDGE

The Doncaster North Bridge, currently under construction by Amec Civil Engineering, will form an integral part of the urban traffic scheme spanning the River Don, main line railway lines, a minor road and Canal close to the town center. The bridge is a 600m steel composite viaduct, with reinforced concrete piers and column heads and reinforced concrete deck. As a requirement within the specification a monitoring system is to be installed requiring "half-cell potential and corrosion monitoring equipment comprising passive and active half-cells together with resistivity.

A system comprising a series of 34 embedded probes for the determination of the corrosion rate of embedded test electrodes as well as the actual reinforcing steel is currently being installed by Testconsult. The system is to be connected and controlled via a computer network connected to a modem to enable data acquisition and analysis at a remote PC. In addition to 'Rate of Corrosion Monitoring', displacement of bridge abutments is also to be measured at 2 locations using fleximeters linked within the system. The monitoring system is designed to have a continuous operating design life of 60 years plus with minimal maintenance.

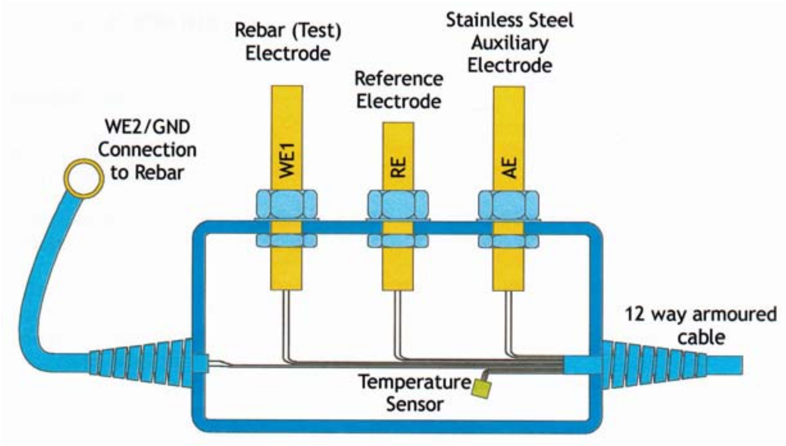

Figure 4 : Rate of Corrosion Probes - Doncaster

Rate of corrosion sensors (probes) are to be installed in 34 locations with additional displacement transducers at the abutments to measure deflection. Instrumentation and Monitoring of the structure will enable remote logging and give an early warning of any potential problematic areas. The monitoring system will measure and record Corrosion (half-cell) potential, Corrosion rate of embedded steel, temperature and resistivity. By obtaining corrosion monitoring data it is possible to assess the condition of the bridge remotely and plan remedial works more effectively that will become necessary during the life of the structure.

CONCLUSION

There is a wide range of NDT techniques available to provide the engineer with information and data to assess and predict durability. The correct interpretation however is sacrosanct and therefore the limitations, as well as the advantages of specific tests should be acknowledged. The responsibility lies with the NDT Specialist having relevant experience in the physics of the tests and knowledge of the materials involved to provide the expertise to enable the engineer to achieve the assessment objective.

The engineer should be provided with as much information as possible to enable him to choose the 'right' techniques. The list is becoming ever more extensive and confusing for the engineer who traditionally has been the specifier for the works and is tasked with preparing a bill of quantities for the investigation. In addition the technologies are advancing at such a pace that the British Standards and other bodies find it difficult to keep their advice current.

There is little published guidance, presented in laymen's terms that is available to help the engineer in the selection of methods. Trade associations do exist to promote particular technologies but they do not stress the importance of other techniques that may be equally suitable of which could be used in parallel to provide more information. What is required is a multi disciplinary approach where the investigations specialist can advise on the ways of achieving the objectives based on an understanding of the physics of the NDT tests and knowledge of the materials involved.

Reliance on a single method of test may generate uncertainty and consequently get that particular technique an unjustifiable bad reputation. This has happened with techniques ranging from the simple rebound hammer to impulse radar. Often expectations for some techniques exceed the practical capabilities.

Notwithstanding this it may prove prudent when designing structures to incorporate systems that would provide assistance in the future for anticipating maintenance repair. This may be in the form of corrosion management systems and stress management systems which will provide the engineer with real information to allow for better judgement in assessing the condition of structures.

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