# Forensic Investigation of Concrete Structures and Structural Rehabilitation

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***Abstract*— The importance of integrity assessment of concrete structures, latest testing procedures and structural rehabilitation options available are not known to many in the construction profession. Apart from the physical characteristics, the corrosion status & potential and also the deterioration of concrete due to chemical attack are important aspects to be ascertained during the forensic investigation of structures. The presence of concrete defects like voids, honeycombs, spalls and cracking could be detected using techniques such as ultrasonic pulse velocity and ground penetrating radar methods. Concrete strength is generally determined using core testing, rebound hammer, ultrasonic pulse velocity, pull off, pull out test and son on. The corrosion potential and the extent of corrosion could be ascertained using half-cell potential and electrical resistivity methods. The reinforcement dimensions, orientation and concrete cover are determined using rebar scanners and the depth of carbonation effects could be measured using phenolphthalein indicator. Once the results of a structural concrete investigation are evaluated, those making decisions on the future of the structure being investigated have various options. These options could range from doing nothing, to complete demolition and replacement of the structure. In addition to the investigation methods and assessment, this paper discusses the selection and application of materials and methods for the protection, repair, and strengthening of concrete structures.**

## I. INTRODUCTION

Concrete, its components and its properties at various stages maturity can be tested in many ways. The concrete properties assessed by the methods referred to in this document range from strength to those associated with potential durability including capacity to protect embedded reinforcing steel. While some methods require extraction of samples for subsequent laboratory testing, the majority of test methods suggested can be applied directly to concrete in structures as in-situ tests.

The aim of the investigation and testing regime should be to obtain sufficient information on the condition of the structure to enable appropriate remedial steps to be taken. It is necessary to have a sound understanding of the underlying causes of the deterioration or lack of durability of a structure before setting out on a protection and repair programme. The changes which constitute deterioration can be the result of a number of factors, including the design of the structure, the standard of workmanship during construction, the materials used, the action of the environment during construction and in service and the loads acting upon the structure. Some of the test methods and the rehabilitation techniques described in this document are also applicable to the damages occurred to the structures caused by fire or structural problems such as overloading or impact damage.

Assessments are to be made of the defects in a concrete structure, in order to identify their causes and the ability of the structure to continue to perform its function, so that a suitable repair and protection option can be chosen.

## II. FACTORS AFFECTING DETERIORATION

The major causes of deterioration of structures are the following:

- In-built problems such as inadequate design, poor workmanship, the use of unsuitable aggregates or cement, or inappropriate concrete mix design.
- Features which appear during construction or shortly afterwards.
- Problems caused by the actions of the local environment on the completed structures

Deterioration may be due to a single cause but usually several factors are involved.

Most of the deterioration processes depend on the presence of water, the most important factor being the moisture state within the concrete rather than that of the surrounding atmosphere. Concrete takes in water from the environment more rapidly than it loses it and so the average internal humidity in the concrete is generally greater than the average external humidity. All chemical reactions are accelerated by increases in temperature and also due to temperature variations attributable to alternate cold and hot seasons. In general terms,, an increase in temperature of 10ºC causes doubling in the rate of reaction. Putting this way, the time taken to reach a particular condition will be halved by a rise in temperature of 10ºC, all other factors being equal.

The types of deterioration that occur in a concrete structure are most often related to its environment and these type environment related deterioration likely to occur in various types of structures are summarized in Table I.

## III. INVESTIGATION OF STRUCTURES

The aim of the investigation and testing regime should be to obtain sufficient information on the condition of the structure to enable appropriate remedial steps to be taken.

It is fortunate that many types of deterioration process lead to characteristic visible features such as distinctive crack patterns. This means that visual inspection can play an important part when starting an investigation. An early visual inspection can be extremely useful in obtaining information to assist in developing a full investigation & testing programme.

TABLE I. POSSIBLE CAUSES OF DETERIORATION

| Types of Structure | Possible cause of deterioration | Defect |
|---|---|---|
| Marine Structures | Chlorides<br>Sulfates<br>Marine creature | Corrosion of reinforcement particularly in the splash zone<br>Salt weathering/ loss of concrete section particularly in splash zone<br>Leaching/mechanical damage below water level |
| Bridges and highway structure | Chlorides from the environment (dust and condensation) | Corrosion of reinforcement particularly on upper deck surface and substructures where water leaks from above |
| Building | Carbonation<br>Chlorides | Corrosion of reinforcement on facades. Interior concrete carbonates but is unlikely to lead to corrosion unless there is a source of moisture<br>May be deposited in dust on facades. Can then be carried into concrete by condensation or leakage from air conditioning units. |
| Buried structure or Structures in contact with the ground | Sulfates<br>Chlorides<br>Salt weathering | Loss of concrete section<br>Corrosion of reinforcement, particularly just above ground level<br>Loss of concrete surface and later loss of section. |
| Ground Slabs | Chlorides | Corrosion of reinforcement in top mat because chlorides drawn through from the ground or because chlorides – contaminated soil or dust is blown onto them |
| Industrial Plants (including sewage treatment works) | Chlorides | Corrosion of reinforcement anywhere and saline water comes into contact with reinforced concrete; corrosion unlikely below water level where there is permanent contact with water and concrete remain saturated |
| Tunnels | Chlorides<br>Sulfates | Corrosion of reinforcement- will occur first near leaking joints<br>Loss of concrete section |
| Trafficked areas | Abrasion | Loss of concrete section |
| Trafficked areas | Abrasion | Loss of concrete surface |
| Sewer pipes | Sulfates | Loss of section by acid attack after sulfates converted to sulfuric acid by bacteria |

With the conclusions from the preliminary assessment of the cause of defects or deterioration in mind, the full investigation can be designed. The type of sampling and testing will be governed by the suspected form of defect or deterioration. The aim should be to try to fill in the gaps in the information on the structure. For example, if there has been significant loss of reinforcement because of corrosion, there will be a need to determine concrete strength and reinforcement size and spacing to permit a design check to be carried out.

If no drawings of the structure are available, the overall dimensions and the dimensions of the principal structural members should be measured and recorded. If drawings of the structure are available, the key structural dimensions should be checked against the as-built condition.

The investigation at site will concentrate on the physical and chemical properties of the concrete in both deteriorated and non deteriorated locations. Aspects of the investigation may also be influenced by the type of remedial treatment envisaged. For example, if cathodic protection is likely to be used, the resistivity of the concrete will need to be measured and the level of interconnection of the reinforcement established.

### A. *Selection of Sampling and Test Locations*

The sampling rate, type of testing and locations of test will vary from case to case. There are no general rules but there are some basic principles. It is important to consider the aims of the evaluation before measurements begin. As a simple rule no measurements should be taken or tests carried out if it is not known what the results will be used for.

Where possible, the spread of sampling and testing locations should include:

- members of different types e.g. columns, beams, slabs
- typical areas of each type of deterioration
- corresponding areas that are in good condition
- corresponding areas with different exposure conditions
- where appropriate, areas that have been previously repaired.

Selection of the locations for sampling and testing depends on the nature of the sample or test and the underlying purpose. Ease of access is also a consideration. It should be noted that the property may vary with the test position on an individual member. For example, the strength of concrete in a column varies with height because the concrete at the bottom will have been better compacted by the weight of wet concrete above than the concrete at the top. To obtain the mean value of a property the locations have to be chosen at random and the number of samples or tests has to be sufficient to give a satisfactory level of confidence.

If a particular defect is being investigated, samples may be extracted or test carried out at locations close to the areas of damage, with other tests and samples at undamaged locations for comparison. Sample locations may have to be chosen to avoid reinforcement or cracks (for example when extracting cores and dust samples)

## IV. IN-SITU TESTING & SAMPLING

During an investigation, different test methods may be used to provide information for condition assessment and prediction of future performance. These may be in-situ tests (destructive or non-destructive) or tests carried out on retriever samples. Some of these tests provide measurements that can be applied directly in the assessment (e.g. compressive strength of retrieved cores, carbonation depths) but in any cases the tests are only of value with reliable interpretation (e.g. rebound hammer, half-cell potential measurements, concrete resistivity).

Samples of concrete from structures are usually in the form of lumps, cores or dust obtained by drilling. All samples should be carefully labeled with a unique reference and marked to indicate their original orientation in the structure. They should be carefully packed to avoid contamination, deterioration or change in a relevant property. Lump samples and cores are usually wrapped in cling film and sealed in polythene bags. After wrapping and sealing, cores that are to be sent to the laboratory intact for further lab testing. Dust samples are usually sealed in small polythene bags.

General structural investigation tests being performed on concrete structures are as tabulated below in Table II.

TABLE II. VARIOUS FORENSIC INVESTIGATION TESTS

| Property under Investigation | Test | Interpretation of Results |
|---|---|---|
| Concrete strength | Cores | Direct |
| | Near Surface tests | Indirect |
| | Rebound Hammer | Qualitative |
| Concrete quality | Visual examination of cores & lump samples | Not applicable |
| | Ultrasonic pulse velocity | Indirect |
| | Petrographic | Direct/Indirect |
| | Ground Penetrating Radar | Indirect |
| Corrosion of reinforcement | Carbonation depth | Direct |
| | Cover depth | Indirect |
| | Chloride content | Direct |
| | Half-cell potential and potential mapping | Indirect |
| | Resistivity | Indirect |
| Integrity | Reinforcement location | Indirect |
| | Concrete porosity | Direct |
| | Initial surface absorption | Direct |
| | Water absorption | Direct |
| | Water permeability | Direct |
| | Ground Penetrating Radar | Indirect |

### A. *Concrete Coring*

Cores are cut using a rotary drill with a hollow barrel tipped with industrial diamonds. The barrel is cooled and flushed by water which is supplied to the barrel through a swivel. The drill motor is usually powered by electricity, hydraulics or petrol and is mounted on a slide on a vertical pillar attached to a base plate. The whole rig has to be firmly fixed in position and this is usually achieved by heavy weights, anchor bolts, vacuum pads or bracing against other parts of the structure.

Cores are cut in various diameters depending upon the purpose and considering minimal damage to the structures and avoid cutting reinforcement bars. Cores can, of course, be cut longer and trimmed to required size in the laboratory. Care must be taken in analysis when other than standard sized cores are taken, particularly if the size is small in relation to the maximum aggregate size. This may require calibration to verify conversion factors.

Apart from compressive strength, cores can also be used for visual assessment and petrographic analysis and can be sectioned or drilled to provide samples for chemical analysis. Core can also sued for the measurement of density. This provides a useful indicator of the level of compaction and degree of voidage, particularly if there are gross differences between samples. Through a combination of strength measurement, density measurement and visual inspection for excess voids, it many be possible to make a judgment about the likely cause of strength variations.

### B. *Dust Sampling*

Dust samples can be obtained rapidly with readily-available hand-held equipment. The use of dust sample is limited to various types of chemical analysis.

Dust samples are frequently obtained directly from structures using a hand-held rotary percussive drill with a 10, 12 or even 20mm diameter but. It may be necessary to drill a close pattern of holes to obtain sufficient material for analysis. The drill dust can be recovered using a plastic shroud around the but or using an angled plastic tube with a sample bag on the end. It is often of interest to investigate how properties vary with the distance inward from the concrete surface (for example where salts may be penetrated from an external source). In this situation, dust samples are recovered in increments at different depths.

### C. *Rebound (Schmidt) Hammer Test*

The rebound (Schmidt) hammer is one of the oldest and best known methods of comparing the surface hardness of concrete in different parts of a structure and indirectly assessing its strength. The rebound hammer should be considered as a means of determining variations of strength within a structure rather than an accurate means of determining strength.

The surface under test should be clean and smooth. Dirt and loose material on the surface can be removed using a grinding stone before the test. Rough surfaces cannot be tested as they do not give reliable results. It should be note that most of the testing standards state that the rebound hammer method is not generally considered to be a substitute for other methods of determining strength and that it is useful only as a preliminary or complementary method. If it is to be used as a means of assessing strength the correlation between rebound hammer reading and strength needs to be determined for the actual concrete under investigation.

The apparatus consists of a mass which slides on a plunger housed with a metal cylinder. At the start of the test the plunger is fully extended and the mass is attached to the end of the plunger remote from the concrete surface inside the cylinder housing. The mass is attached to the plunger by a catch with a self-release mechanism. The test is carried out by placing the end of the plunger against the concrete surface and moving the housing towards the concrete. This causes the plunger to retract into the housing and extends a spring connected to the mass and the housing. When the plunger is almost fully retracted the self-release catch is activated and the mass, under the action of the force from the spring, accelerates along the plunger in the direction of the concrete surface. The mass strikes an enlarged section of the plunger and rebounds. The rebound distance is measured on a sliding scale.

When using the rebound hammer at a location, 12 readings are normally taken from an area not exceeding 300mm x 300mm. The preferred method is to draw a regular grid of lines at a spacing between 20mm and 50mm and to use the intersection points as the test points. The average of the readings is taken, including abnormally high and low values, unless there is an obvious reason for discarding a particular value.

### *D. Ultrasonic Pulse Velocity Test*

Measurement of ultrasonic pulse velocity (UPV) is a means of assessing variations in the apparent strength of concrete. UPV equipment is also used for detecting the presence of voids, honeycombing or other discontinuities. The velocity of a pulse of ultrasonic energy in concrete is influenced by the elastic stiffness and mechanical strength of the concrete. As in the case of the rebound hammer, it is possible to develop an empirical relationship between pulse velocity and strength but his relationship is influenced by type of cement, type and size of aggregate, presence of reinforcement, moisture condition and age of concrete. To develop an empirical relationship it is necessary to test a significant number of cores or cubes of concrete similar to that being investigated in compression over a range of strengths and to also test them for ultrasonic pulse velocity.

The ultrasonic pulse velocity equipment consists of two transducers (heads) that are in the form of metal cylindrical heads, which are brought into contact with the concrete surface using grease or a suitable coupling medium. One head transmits an ultrasonic pulse into the concrete and the other receives it a few microseconds later. They are connected to a control box which contains a pulse generator, timing circuit and digital display. The display indicates the time for the ultrasonic pulse to travel between the transmitter and receiver.

The equipment is used by first calibrating the instrument against a cylindrical steel specimen of know properties. The transducers are held against opposite ends of the cylinder using coupling medium and the equipment is adjusted until the reading matches the standard figure for the cylinder.

The concrete surface has to be reasonably smooth. It may be possible to take readings on a rough surface by first placing small loads of plaster of Paris or quick-setting resin. Pulse velocity is calculated by dividing he distance between the centers of the transducers by the time which the pulse takes to travel between them.

The transducers can be used in three different configurations:

- Direct - in which the transducer and receiver are placed on opposite faces of a member and the pulse travels through the member.
- Indirect - in which the transducer and receiver are placed on the same face of the member and the pulse travels just below the surface
- Semi-direct - in which the transducer and receiver are placed on faces which are perpendicular to one another and the pulse travels across the corner

Direct transmission is preferred since maximum energy transfer is achieved and the accuracy of the velocity determined is dependent primarily upon the accuracy of path length measurement.

### *E. Near-Surface Strength Tests*

Various near to surface test methods can be used to assess concrete strength. Pull-out, pull-off, break-off and penetration resistance tests are described in BS 1881 : Part 207, Recommendations for the assessment of concrete strength by near surface tests. Briefly, the tests are as follows:

- The most common form of pull-out test is the internal fracture test which was developed by BRE. In this test a wedge anchor is pulled from a pre-drilled hole.
- The Capo (cut and pull-out) test uses an expanding insert in an under –reamed hole.
- Pull-off tests measure the force required to pull a metal block (dolly) from the concrete surface to which it has been attached using a high strength adhesive.
- The break-off test measures the transverse force required to break off a core drilled 70mm into the concrete surface.
- The penetration resistance (Windsor Probe) test is based on measuring how for a hardened pointed metal rod penetrates into a concrete surface when fired into it by a driver unit similar to a gun.

### *F. Reinforcement Depth & Position Scanning*

The depth of reinforcement below the surface of concrete can be measured using a covermeter. Covermeters are electro-magnetic or inductance devices consisting of a search head and a control box. Most modern equipment has a digital display and some systems have an audible output which increases in loudness or pitch as the search head approaches the position of a reinforcing bar. Older equipment may have an analogue output in the form of a needle sweeping across a graduated scale.

To check bar locations, the measuring head is moved slowly across the surface of the concrete. The display is observed until a minimum value is reached and the position of the head is noted –usually by marking the position on the concrete surface itself with a felt tip pen. The principal directions of reinforcement are generally fairly obvious from inspection and it is usual to move the search head along one of these with its long axis (in the case of a prismatic head) in the direction at right angles. Once the location of bars in one direction have been established, the search head is moved in the perpendicular directions between two previously marked bar positions and the locations of the other bars are also marked on the surface. Some manufactures produce digital models which can produce LCD representations of the bar layout which can be downloaded

### *G. Carbonation Depth*

Carbonation depth is assessed using a solution of phenolphthalein in alcohol. Phenolphthalein is an indicator which turns pink when in contact with alkaline concrete a values in excess of pH 9 and remains colourless when in contact with carbonated concrete which has a lower pH. The test is most commonly carried out by spraying the indicator on freshly exposed surfaces of concrete broken from the structure or on split cores. In either case the depth of carbonation is the depth of the clear zone at the surface. Alternatively, the powder from drill holes can be sprayed or allowed to fall on indicator-impregnated paper.

### *H. Half-cell Potential Survey*

Half-cell potential measurement is often carried out when reinforcement corrosion is suspected or evident. It is a measure of the electrical potential on the surface of the reinforcement and can be interpreted in terms of the likelihood of corrosion activity. It is only a qualitative measurement and may be affected by various factors. So care and experience are needed to avoid misleading results. The equipment consists of a half cell and a high-independence voltmeter. The half cell is a tube with a porous end, which contains a rod of metal in a saturated solution of one of its own salts e.g. copper in copper sulfate or silver in silver chloride. One terminal of the voltmeter is connected to the reinforcement and the other terminal is connected to the half cell. It is usual to take readings on a grid pattern on the concrete surface at either 500mm or 1000mm centers. The greatest corrosion risk is usually associated with areas in which the potential gradient is steep and where these occur the grid size should be reduced

### *I. Resistivity Survey*

Resistivity measurements are sometimes carried out in conjunction with half cell potential surveys to assist in the predication of the likelihood of corrosion. The most common techniques is to use a four probe or Wenner array. Four metal electrodes are inserted into shallow pre-drilled holes at equal spacing in a straight line on the concrete surface. An electrode spacing of 50mm is commonly used. A current is passed between the outer two electrodes and the potential drop across the inner electrodes is measured

### *J. Surface Absorption Test*

Various site tests are available to measure surface absorption or permeability of concrete. The most commonly used method is initial surface absorption test (ISAT).

The Initial Surface Absorption Test (ISAT) uses a plastic cap sealed to the concrete surface using modeling clay. The cap has a water area of 5000mm2. When working on a vertical surface the cap has to be kept firmly in position by bolting or some other means. To carry out the test, water is introduced into the cap via a connecting point and maintained at a head of 200mm using a filter funnel. A second connection point to the cap leads to a horizontal capillary tube. The connection to the reservoir is closed and the absorption is measure by observing the movement of the end of the water line in the capillary tube during a fixed period.

## V. LABORATORY TESTING

Laboratory tests of compressive strength, porosity, water absorption and permeability can be carried out on sections from concrete cores. The tests can be used to give a general assessment of concrete quality & strength or to provide parameters for use in estimates of remaining life.

A range of chemical tests can be carried out on sub-samples of concrete dust, obtained from cores or lump samples by drilling, sawing or grinding.

### *A. Core Testing for Strength*

When cores are received in the laboratory they may be examined for degree of compaction, cracks, voids, honeycombing and the presence of reinforcement.

If the cores are to be tested for strength, they have to be trimmed and the ends prepared so that they are flat and perpendicular to the longitudinal axis. This is achieved by grinding or, more usually, capping with high alumina cement mortar or a sulfur/sand mixture. After capping, the cores are stored in water until they are in a saturated condition before being tested in compression.

### *B. Dust Samples*

Dust samples are dissolved in acid (at the laboratory) and the resulting solution can be tested for chloride, sulfate or cement content by chemical means or ion-specific electrodes. (The cement content obtained from dust samples tends to be significantly less accurate than from lump or core samples). Chloride and sulfate content of solutions can be determined to a lower standard of accuracy using quick chemical methods.

### *C. Petrographic Examination*

Sub-samples for petrographic examination can be taken from lump samples of cores. The sub-samples are impregnated with resin, and surfaces, either polished sections or thin sections, are prepared by sawing, lapping and polishing. The prepared samples are examined by means of a petrological (geological polarizing) microscope, using either reflected or transmitted light. The lighting may be normal, ultraviolet or polarized. Petrographic examination can include determination of:

- Proportions of coarse and fine aggregates, cement paste and air voids
- Aggregate type, grading and shape
- Conditions of the aggregates
- Nature of the cement paste, including mineral additions such as pfa
- Bond between the aggregate and the paste
- Porosity of the cement paste
- Air entrainment

- Presence of deleterious material
- Depth of carbonation
- Cracks, voids and inclusions
- Evidence of sulfate attack, some forms of chemical attack and alkali-silica reactions

*D. Water Permeability*

The determination of water permeability of a concrete sample has little direct value in terms of predicting the performance of a structure, except in predicting water penetration. However, it is a useful indication of general quality. There are various methods for determining the water permeability but the most commonly used method is DIN water permeability method.

## VI. Structural Condition Assessment

Information obtained from the field investigation and laboratory testing as detailed above will need to be properly analysed to arrive at the root cause(s) of the structural distress identified. The following sections provide a rough guidance as to how to use the information gathered could guide us to underlying problems that in turn could guide us in deciding the most appropriate remedial actions to be taken.

*A. Visual assessment*

Visual assessment of deterioration can provide useful information when done in a rational, systematic manner but the data may come too late for cost-effective repairs. Rebar corrosion damage is often only fully manifest at the surface after significant deterioration has occurred. Early evidence of distress can sometimes be detected by an experienced engineer before major distress takes place.

*B. Delamination survey*

A hammer survey or chain drag is a simple method of locating areas of delamination in concrete. Hollow sounding areas can be marked up on the concrete or recorded directly in a survey form. Delamination surveys often under-estimate the full extent of internal cracking and should not be considered as definitive. Radar and ultrasonic instruments may provide a more sophisticated approach to locating areas of delamination, particularly at greater depths.

*C. Cover surveys*

Cover surveys are routinely done to locate the position and depth of reinforcement within a concrete structure. Covermeters use an alternating magnetic field to locate steel and any other magnetic material in concrete (note that austenitic stainless steels are non-magnetic). Covermeas -urements may be unreliable when:

- rebar is at deep covers (e.g. covers greater than 80 mm)
- measuring regions of closely spaced bars
- measuring differing bar types and sizes (unless specifically calibrated)
- other magnetic material is nearby (e.g. window frames, wire ties, bolts)

To ensure reliable cover depths from a survey, direct measurements of rebar depths should be made by exposing a limited number of bars. Calibration can then be made for site specific conditions such as rebar type, concrete and environmental influences.

*D. Chloride testing*

The presence of sufficient chloride at the surface of reinforcement is able to depassivate steel and allow corrosion to occur. Chlorides exist in concrete as both bound and free ions but only free chlorides directly affect corrosion. Measuring free chlorides accurately is extremely difficult and water-soluble chloride tests are unreliable, being strongly affected by the method of sample preparation. Further, bound chlorides may be released into solution under carbonating conditions or by dissolution, making all chlorides in concrete potentially corrosive. Table III provides an indication of the effect of chloride levels on probability of corrosion.

Table III. Qualitative Risk of Corrosion based on Chloride Levels

| Chloride Content (% by mass of Cement) | Probability of corrosion |
|---|---|
| < 0.4 | Low |
| 0.4 – 1.0 | Moderate |
| > 1.0 | High |

Limitations of chloride testing of concrete are as follows:

- presence of chlorides in aggregates may give misleading results
- chloride contents in cracks and defects cannot be accurately deter - mined
- slag concretes may be difficult to analyse with colorimetric titration methods
- relatively large samples are required to allow for the presence of aggregates

*E. Carbonation depth*

Carbonation depth is measured by spraying fresh concrete with a phenolphthalein indicator solution (1% by mass in ethanol/ water solution).

Phenolphthalein remains clear where concrete is carbonated but turns pink/ purple where concrete is still strongly alkaline (pH > 9.0). Carbonation moves through concrete as a distinct front and reduces the natural alkalinity of concrete from a pH in excess of 12.5 to approximately 8.3, with a pH level of 10.5 being sufficiently low to depassivate steel.

Environmental conditions most favourable for carbonation (i.e. 50 – 65 % R.H.) are usually too dry to allow rapid steel corrosion that normally requires humidity levels above 80% R.H. Structures exposed to fluctuations in moisture conditions of the cover concrete, such as may occur during rainy spells, are however vulnerable to carbonation- induced corrosion.

Limitations to carbonation testing are as follows:

- phenolphthalein changes colour at pH 9.0 whereas steel depassivation occurs at a pH of approximately

10.5, hence the corrosion risk is slightly under-estimated

- some concretes are dark (e.g. slag concretes) and a distinct colour change is difficult to discern visually
- phenophthalein may bleach at very high pH levels (e.g. after electro - chemical realkalization)
- testing must be done on freshly exposed concrete surfaces before atmospheric carbonation occurs

### F. *Rebar potentials*

Chloride-induced corrosion of steel is associated with anodic and cathodic areas along the rebar with consequent changes in electropotential of the steel. It is possible to measure these rebar potentials at different points and plot the results in the form of a 'potential map'. Measurement of rebar potentials may determine the thermodynamic risk of corrosion but cannot evaluate the kinetics of the reaction. Table IV shows the ranges of rebar potentials and associated risk of corrosion.

TABLE IV. QUALITATIVE RISK OF CHLORIDE-INDUCED CORROSION

| **Rebar potential (-mV, $Cu/CuSO_4$)** | **Qualitative risk of corrosion** |
|---|---|
| < 200 | Low |
| 200-350 | Uncertain |
| >350 | High |

Absolute values are often of lesser importance than differences in rebar potential measured on a structure. A shift of several hundred millivolts over a short distance of 300-500 mm often indicates a high risk of corrosion.

### G. *Resistivity*

Concrete resistivity controls the rate at which steel corrodes in concrete once favourable conditions for corrosion exist. Resistivity is dependent on the moisture condition of the concrete, on the permeability and inter-connectivity of the pore structure, and on the concentration of ionic species in the pore water of concrete. Table V provides the relationship between possible corrosion rate associated with various ranges of Resistivity.

TABLE V. LIKELY CORROSION RATE BASED ON CONCRETE RESISTIVITY

| **Resistivity (kOhm.cm)** | **Likely corrosion rate** |
|---|---|
| <12 | High |
| 12-20 | Moderate |
| >20 | Low |

## VII. REPAIR STRATEGIES

Various repair options are available and new technologies continue to make an impact in the field of concrete repairs.. Most of the repair strategies discussed here apply to carbonation and chloride induced damage to structural concrete, this being the most common, along with cracking induced by thermal/structural loading. The suitability and cost effectiveness of repairs depends on the causes and level of deterioration and specific conditions of the structure.

### A. *Patch repairs with mortar or concrete*

Before patch repairs are considered in this connection, it is important that the distinction between chloride and carbonation induced corrosion is appreciated.

As a general rule chloride-induced corrosion is far more pernicious and difficult to treat than carbonation-induced corrosion. This often dictates a completely different approach to repairing damage due to the two types of corrosion.

Carbonation-induced corrosion causes general corrosion with multiple pitting along the reinforcement. Carbonated concrete tends to have fairly high resistivity that discourages macro-cell formation and allows moderate corrosion rates. Steel exposed to corrosive conditions will therefore show signs of corrosion that can be easily identified (e.g. surface stains, cracking or spalling of concrete). Repairs are generally successful provided all of the corroded reinforcement is treated.

Chloride-induced corrosion is characterized by pitting corrosion with distinct anode and cathode sites. The presence of high salt concentrations in the cover concrete means that macro-cell corrosion is possible with relatively large cathodic areas driving localized intense anodes. High corrosion rates can be sustained under such conditions resulting in severe pitting of the reinforcement and damage of the surrounding concrete. Much of the reinforcement may be exposed to corrosive conditions without showing any signs of corrosion, this is particularly noticeable when corroded structures are demolished.

Localized patch repairs of areas of corrosion damage are popular due to their low cost and temporary aesthetic relief. This form of repair has limited success against chloride-induced corrosion as the surrounding concrete may be chloride-contaminated and the reinforcement is therefore still susceptible to corrosion. The patched area of new repair material often causes the formation of incipient anodes adjacent to the repairs. These new corrosion sites not only affect the structure but often also undermine the repair leading to accelerated patch failures in as little as two years. Consequently, it is necessary to remove all chloride-contaminated concrete from the vicinity of the reinforcement.

Patch repairs consist of the following activities that are briefly described below:

- removal of cracked and delaminated concrete to fully expose the corroded reinforcement
- cleaning of corroded reinforcement and the application of a protective coating to the steel surface (e.g. anti-corrosion epoxy coating or zinc- rich primer coat)
- application of repair mortar or micro-concrete or polymer concrete to replace the damaged concrete
- possible coating or sealant applied to the entire concrete surface to reduce moisture levels in the concrete

*B. Crack repairs*

Crack repairs constitute a major item of concrete repair and a wide range of materials is available for sealing and filling of cracks, including epoxies, polyurethanes, polyesters and methacrylates. The choice of the material will depend on the width of the crack and whether a structural bond is required and whether the crack is active (live) or passive. For example, epoxies are used when the structural bond between the cracked surfaces needs to be restored and polyurethanes are used when the crack repair is not intended to reinstate structural bond, but aims at sealing of cracks to probably ensure long term durability.

Most crack filling materials are applied under pressure, but it is possible to fill cracks in slabs by gravity. Crack filling under pressure is done by crack injection methods, where injection ports are stuck at regular intervals along the crack. Holes can be drilled at 45 degrees to the surface from offset positions so they intersect at the plane of the crack at depth. The cracks are sealed at surface using a quick setting putty. The resin is then applied under positive pressure in correct proportions. Injection starts at one end of the crack – for eg. In the case of vertical cracks, it starts from the bottom most port, resin being pumped till it comes out from the next port. The first port is then sealed and resin is injected at the second port and so on.

The alternative method is to use negative pressure or vacuum. This can give better control over the area of cracking which is being injected.

*C. Coating Systems*

A variety of coating and penetrant systems are available that are claimed to be beneficial in repairs of concrete structures. Barrier systems attempt to seal the surface thereby stifling corrosion by restricting oxygen flow to the cathode. In large concrete structures, corrosion control is theoretical ly unlikely due to the presence of oxygen already in the system. In practice barrier systems are generally ineffective due to the presence of defects in the new coating during application and further damage during service. Such an approach is more likely to promote the formation of differential aeration cells further exacerbating the potential for corrosion.

The application of a hydrophobic coating (sometimes referred to as penetrant pore-liners) may be used to reduce the moisture content of concrete and thereby electrolytically stifle the corrosion reaction. The drying action works on the principle that surface capillaries become lined with a hydrophobic coating that repels water molecules during wetting but allows water vapour movement out of the concrete, to facilitate drying. Hydrophobic coatings using silanes and siloxanes are gen rally most effective on uncontaminated concrete, free from cracks and surface defects. The feasibility of such an approach is questionable for marine structures where high ambient humidity, capillary suction effects and presence of high salt concentrations all interfere with drying.

The long-term effectiveness of hydrophobic systems applied to new construction is not known but some studies suggest reasonable performance over 10-15 years service.

*D. Migrating corrosion inhibitors*

Migrating corrosion inhibitors are generally organic-based materials that move through unsaturated concrete by vapour diffusion. Organic corrosion inhibitors such as amino-alcohols are believed to suppress corrosion by primarily being adsorbed onto the steel surface thereby dis - placing corrosive ions such as chlorides. The adsorbed organic layer inhibits corrosion by interfering with anodic dissolution of iron while simultaneously disrupting the reduction of oxygen at the cathode.

Migrating corrosion inhibitors are designed to move fairly rapidly through partially saturated concretes that allow vapour diffusion. Penetration has however been found to be poor in near-saturated concretes typically found in partially submerged marine structures.

*E. Electrochemical techniques*

Corrosion of reinforcement in concrete is an electrochemical process that occurs when embedded steel is depassivated by a reduction in concrete alkalinity or the presence of corrosive ions such as chlorides. Two repair techniques, electrochemical chloride removal and realkalization, attempt to restore passivating conditions by the temporary application of a strong electric field to the cover concrete region.

Realkalization is the process of restoring the original alkalinity of carbonated concrete in a non-destructive manner. The electrochemical treatment consists of placing an anode system and sodium carbonate electrolyte on the concrete surface and applying a high current density (typically $1A/m^2$). The electrical field generates hydroxyl ions at the reinforcement and draws alkalis into the concrete. Alkaline conditions may be restored in the concrete in as little as one to two weeks using the system.

Electrochemical chloride removal (ECR) is a more time-consuming and complex technique and its suitability needs to be carefully assessed. Chloride removal is induced by applying a direct current between the reinforcement and an electrode that is placed temporarily onto the outside of the concrete. The impressed current creates an electric field in the concrete that causes negatively charged ions to migrate from the reinforcement to the external anode. The technique decreases the potential of the reinforcement, increases the hydroxyl ion concentration and decreases the chloride concentration around the steel thereby restoring passiating conditions.

*F. Cathodic protection*

Cathodic protection systems (CP) have an excellent track record in corrosion control of steel and reinforced concrete structures. The principle of CP is that the electrical potential of the steel reinforcement is artificially decreased by providing an additional anode system at the concrete surface. An external current is required between anode and cathode that diminishes the corrosion rate along embedded reinforcement. The current may be produced either by a sacrificial anode system or using an impressed current from an external power source.

Sacrificial anode systems consist of metals higher than steel in the electrochemical series (e.g. zinc). The external anode corrodes preferentially to the steel and supplies electrons to the cathodic steel surface. Sacrificial anode systems are most effective in submerged structures where the concrete is wet and resistivity is low. Warm temperatures are also generally required for sacrificial CP systems (i.e. above 20 $^0$C).

CP systems more commonly use an external electrical power source to supply electrons from anode to cathode. The anode is placed near the surface and is connected to the reinforcement through a transformer rectifier that supplies the impressed current. Anodes may be conductive overlays, titanium mesh within a sprayed concrete overlay, discrete anodes or conductive paint systems. Anode systems are usually designed for a minimum service life of 20 years but may last in excess of 50 years.

### *G. Demolition/reconstruction*

Deterioration of reinforced concrete structures is often so advanced that demolition and reconstruction becomes viable. This option should only be considered as a last resort since the total cost (capital costs plus loss of service and temporary works) is usually well in excess of repairs costs. Corrosion damage is also generally confined to near-surface regions and engineers often over-estimate the extent of damage to corrosion-damaged structures.

Demolition and reconstruction is often preferred by engineers who have limited repair experience or lack confidence in new repair systems. It is crucial nevertheless that lessons are learnt from the old structure when designing the replacement.

## VIII. ECONOMICS OF REPAIRS

Repairs of reinforced concrete structures damaged by corrosion have often proved to be unsuccessful with further damage occurring after repair. Reasons for the poor performance of repairs include:

- lack of understanding of deterioration processes
- inadequate investigation and testing prior to repairs
- inadequate funds to undertake satisfactory repairs
- ineffective or inappropriate repairs being specified
- poor supervision and implementation of repairs on site

Repairs are not generally anticipated by owners and funds for repairs are nearly always extremely limited. Economics largely dictate the timing and scale of repairs but unfortunately only short-term costs are often considered. Whilst corrosion damage is to some degree unique to each structure some basic tenets hold for most cases.

Performance of the concrete structure prior to treatment often dictates the likely performance after repair. Structures with high levels of damage and rapid rates of deterioration require more substantial repair than those less seriously affected.

The timing of treatment is crucial since corrosion rates and damage increase with time. A structure that has been neglected and allowed to reach an advanced level of damage will not respond to 'quick-fix' solutions. Conversely a structure that is repaired early enough may be restored to full serviceability relatively cheaply.

The effectiveness of treatments in retarding corrosion is not equal and may range from highly effective to detrimental (e.g. cathodic protection versus patch repairs)

## IX. CONCRETE REHABILITATION CASE HISTORIES

The following gives a list of some of the major structural investigation and rehabilitation projects in the Sultanate of Oman, that the authors were involved in:

a) Preparation of the 5 Year structural rehabilitation strategy for the Oman Refinery- This involved investigation of large scale industrial structures damaged mostly by chloride induced corrosion in the marine environment.
b) Investigation, rehabilitation design and supervision of the Ministry of Higher Education Buildings at Al Khuwair – Involved structural rehabilitation of RC frames of multistoreyed buildings seriously damaged by carbonation and chloride contamination , mainly RC columns, particularly their sections near ground level. Entire bottom sections had to be replaced in the case of some of the peripheral columns, temporarily relieving column loads at lower sections with hydraulic jacks..
c) Investigation and structural rehabilitation design for the Ministry of Education, at various locations in Oman. This involved rehabilitation of reinforced concrete buildings damaged by various causes ranging from cracking due to structural over loading, thermal stresses, differential foundation movement due to swelling clays and carbonation and chloride attack on concrete.
d) Investigation, rehabilitation design and supervision of the head office building of Oman Telecommunications Company, Al Khuwair- This involved structural rehabilitation of a major multistoeyed concrete building that was damaged by water ingress in the basement and reinforcement corrosion from carbonation and chloride attack.
e) Investigation and rehabilitation design for various highway bridges in Oman– mostly involved dealing with defects in concrete during construction and thermally induced cracking of RC elements.
f) Investigation and rehabilitation design of various large scale Water Retaining Structures in various parts of Oman- Involved investigation of very large scale water reservoirs (with single reservoirs to the tune of 100 m x 100 m x 7m in size) – mostly addressed problems from early age thermal cracking and construction defects in concrete and related water leakage problems.

## REFERENCES

[1] The Concrete Society, CIRIA Special Publication CS 137, "Guide to evaluation and repair of concrete structures in the Arabian Peninsula", 2002
[2] The Concrete Society, Technical Report 31, "Permeability testing of site concrete: a review of methods and experience", 1987
[3] British Standards Institution, BS 1881: Part 207, Testing Concrete - Recommendations for the assessment of concrete strength by near-to-surface tests, 1992
[4] The Concrete Society, Technical Note 143, "Testing Concrete in Structures", 1992
[5] J.H Bungey, S.G Millard & M.G Grantham, "Testing of Concrete in Structures", 1982

[6] American Concrete Institute, ACI Committee 364.1-19,"Guide for Assessment of Concrete Structures before Rehabilitation", 2019
[7] JR Mackechnie and MG Alexander, Research Monograph 5, Repair principles for corrosion-damaged reinforced concrete structures, Department of Civil Engineering, University of Cape Town, South Africa,2001
[8] Concrete Society, Technical Report No. 54, Diagnosis of deterioration in vconcrete structures, DETR, UK,2000
[9] Archives of EIDC LLC, Structural Investigation and rehabilitation projects, Sultanate of Oman, 2008 – 2020