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Corrosion Damaged Lightweight Concrete

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Abstract: This paper presents the aspects of lightweight concrete durability in view of reinforcement corrosion and its implications on the integrity of structural concrete members. Mechanisms of deterioration related to the heterogeneous nature of concrete are discussed. Modern techniques for inspection, durability assessment procedures, maintenance & restoration programs, as well as preventative systems are demonstrated.

Keywords: reinforcement corrosion, Lightweight concrete, Ultrasonic pulse velocity.

1. INTRODUCTION

Although a vast majority of lightweight concrete structures have performed satisfactorily during their service life, there are nevertheless significant problems that occur in many structures, and the causes are often related to lightweight concrete durability. Although the durability of lightweight concrete is a matter of high concern however; the existing balance between the requirements of both strength and durability in the codes of practice is heavily shifted towards strength criteria. Indeed for lightweight concrete construction some aspects of durability are automatically met with adequate cube strength, but the connection between the performance of concrete in service and the strength of sample cubes is far from direct. Lightweight concrete comprises graded range of aggregate particles bound in a strong paste of cement particles hydrated with water thus, contains pores of varying permeability to both liquids and gases. The durability of the hardened lightweight concrete relates to the inherited permeability of the heterogeneous matrix and to the interfacial microstructure of its constituents.

Lightweight concrete can be defined as a type of concrete which includes an expanding agent in that it increases the volume of the mixture while giving additional qualities such as nailbility and lessened the dead weight. It is lighter than the conventional concrete. The use of lightweight concrete has been widely spread across countries such as USA, United Kingdom and Sweden

Loss of durability, known as concrete deterioration, is rarely found to be a result of one isolated cause. of Lightweight concrete can suffer from various mechanisms of deterioration such as alkali-silica reaction, sulfate attack, leaching, and freezing & thawing. Moreover, environmental processes may cause salts, oxygen, moisture or carbon dioxide to penetrate the concrete cover and eventually lead to corrosion of the embedded steel reinforcement. Rebar corrosion is the undesirable reaction that takes place at the steel/concrete interface leading to significant loss in the bar diameter and accumulation of the corrosion products at the steel/concrete interface with significant reduction in the load carrying capacity of the composite section.

In general, the study of reinforcement corrosion in lightweight concrete structures may be organized into four groups:

1. Laboratory/based research on the mechanisms of steel corrosion.
2. Field studies on corrosion damaged structures.
3. Test methods and systems for monitoring rebar corrosion in lightweight concrete structures.
4. Evaluation of the corrosion protection materials and techniques.

However, large parts of the work done so far were directed towards the basic mechanisms of reinforcement corrosion and corrosion protection. Little research was utilized to develop valid expressions for the mechanical performance of corrosion-damaged structures, which in urgently needed for better design of effective and economic remedial work.

In thin paper the author addresses the following subjects:

1. Corrosion Damaged Lightweight Concrete -- The Mechanism.
2. Assessment 0f Corrosion Damaged Lightweight Concrete.
3. Repair of Corrosion Damaged Lightweight Concrete.
4. Protection of Lightweight Concrete Elements against Electrochemical Corrosion.

2.CORROSION DAMAGED LIGHTWEIGHT CONCRETE - THE MECHANISM

For a reinforced Lightweight Concrete member to function under external loading conditions, load transfer has to be maintained by virtue of the bond between concrete and the reinforcing steel, otherwise the member will fail to induce its own force equilibrium.

Reinforcement corrosion reduces the bond strength to an extent that serious consequences with respect to the member's load carrying capacity may arise. The effect of corrosion on bond strength may be explained in terms of reduction in the degree of bar confinement caused by an Opening of longitudinal cracks along the reinforcement and significant changes at the steel/concrete interface, mainly loss of roughness and development of flaky layer of corrosion products. The changing conditions at the steel/concrete interface lead to reduced stiffness of the composite and the load carrying capacity being reduced to critical levels. This problem became more pronounced since the introduction of the ultimate strength design approach and the wide-scale employment of high strength steel in the construction industry in recent years.

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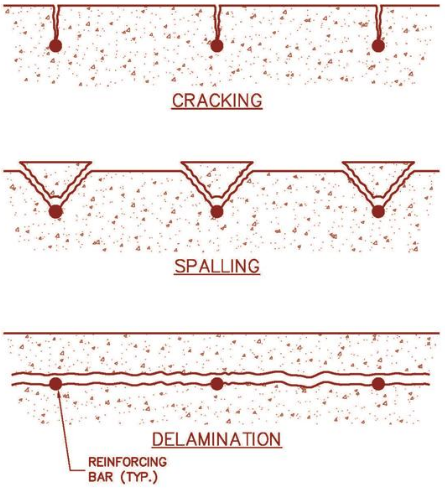

Fig.(1): Common Failure Mechanisms

It is well established that the high level of pH (between 12 and 13) in the concrete environment provides adequate protection to the steel reinforcement against corrosion as a passive film on the metal surface is formed. Corrosion initiates when this passivity is no longer maintained. Passivity breakdown could be a result of chloride ions ingress into the hardened concrete and/or to several other processes such as the carbonation of the concrete cover zone. Corrosion of steel reinforcement in lightweight concrete structures is characterized by three successive stages, the initiation stage, the propagation stage and the final stage. Initiation times relate to the diffusivity of C02 gas and/or the Cl- ions into the hardened concrete. While propagation rates are controlled by the changes in the electrode polarization. Concrete reaches its final stage when it reaches a certain degree of deterioration and repair work is deemed necessary.

3.ASSESSMENT OF CORROSION DAMAGED LIGHTWEIGHT CONCRETE - PARAMETERS & TECHNIQUES

If carried out by experienced personnel, visual survey in perhaps the most important, and certainly one of the most useful and informative parts of any inspection program. However, in most cases detailed inspection is normally needed in pinpoint the critical parts, the causes of distress and the actual performance of the structures. Such information is crucial to provide early warning against failure and to design the appropriate maintenance strategy. Breathtaking research & development is going on to develop and upgrade monitoring devices that are accurate, inexpensive, long-lasting, easy-to-install and non-obstructive to occupants. The following is a brief description of some inspection techniques.

3.1 On-Site Mechanical Evaluation of Strength

On-site mechanical evaluation of strength employs special techniques known as “near to surface tests" to estimate the mechanical strength of the lightweight concrete on the basis of non-destructive tests performed on the lightweight concrete cover zone. Although widely spread, such techniques are unlikely to produce results of accuracy better than ±8 MPa at 95% confidence. However, near-to-surface techniques are useful for the assessment of surface durability. All the tests are described in BS 1881 part 201.

3.2 Ultrasonic Pulse Velocity Testing

The behavior of the ultrasonic pulse into lightweight concrete relates to the density and the elastic properties of the lightweight concrete medium as per the following equation

$$V= \sqrt{\{Ed\,(1-v)/p\,(1+v)\,(1-2v)\}}$$

V	Ultrasonic pulse velocity
p	Lightweight concrete density
v	Dynamic Poison‘s ratio of lightweight concrete
Ed	Dynamic elastic modulus of lightweight concrete

As Ed is closely related to lightweight concrete strength, the measured velocity, V, is used to estimate the strength and to identify the locations of defects in lightweight concrete. Methods of conducting pulse velocity surveys are given in BS 1881 part 203 and in ASTM C597- 83.

3.3 On-Site Permeability Tests

The most familiar method for testing the permeability of lightweight concrete o-site is the initial surface absorption test (ISAT), described in BS 1881 part 208. Other test methods are discussed in the Concrete Society technical report No.31. No absolute figures for concrete permeability can be obtained on-site. All of the test methods are generally used on comparative basis only.

3.4 On-Site Determination of the Lightweight Concrete Cover

Lightweight concrete cover to reinforcement can be determined by means of cover meter in accordance with BS 1881; part 204. Provided the diameter of the steel bar is known, the depth of the lightweight concrete cover is indicated by the change in the inductance of the iron—cored inductor, as it is moves in the proximity of the reinforcing steel. Moisture content if the lightweight concrete cover zone affects the accuracy of the cover meter with as high as 10.42% relative standard deviation.

3.5 On-Site Determination of the Carbonation Depth

The normal method of determining the depth of carbonation of lightweight concrete is to spray a freshly exposed concrete surface with phenolphthalein made up as 1% solution in alcohol/water. Phenolphthalein changes color over the pH range 8.3 →10. A pink surface indicates a carbonation-free surface, while carbonation will be associated with the colorless areas. Details and procedures of the test are given in the Building Research Establishment information Paper IP 6/81.

3.6 Chloride Content in Powder-Drilled Samples

Powder-drilled samples of hardened lightweight concrete are normally taken in order to determine the chloride content of hardened lightweight concrete by means of titration, such as potentiometer titration against silver nitrate solution. It is normal to take powder gradient samples at various depths, usually 2-25mm, 25-50mm, 50-75mm, 75-100mm etc. so that chloride penetration profiles with depth into the lightweight concrete can be plotted. Powder sampling is described in the Building Research

Establishment information paper IP 21/86. Powder-drilled samples are also used for determining sulfate profile in lightweight concrete.

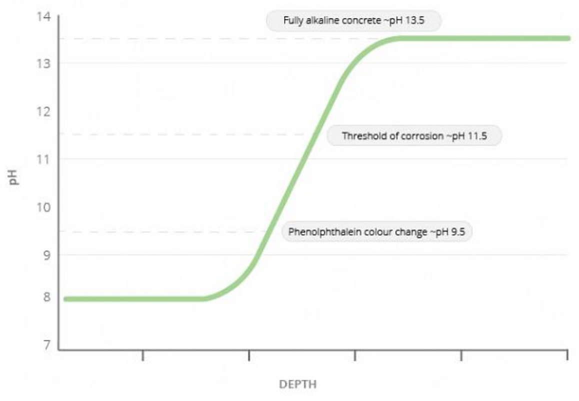

Fig.(2):Relation between PH and the depth of carbonation

3.7 Half-cell Potential Mapping

Half-cell potential mapping on lightweight concrete surface is successfully used to delineate the anodic and the cathodic areas of reinforcement and to identify the probable extent of the ongoing corrosion. especially in areas where no surface evidence exists. The technique was pioneered in the USA and is covered by ASTM51. The leaf apparatus basically comprises a rigid Perspex tube containing a copper rod immersed in saturated copper sulfate solution. The rod passes through the end of the tube, where it is provided with an electrical terminal. The face of the tube usually incorporates a 20mm diameter porous plate above which is a sponge pre-wetted with copper sulfate solution. Connecting the terminal to a suction of exposed reinforcement and pressing the sponge in contact with the lightweight concrete surface provide electrical continuity. The potential difference between the steel reinforcement and the copper rod in the half-cell is then recorded. Ewins and Das presented a modified device that comprises electrolytic half-cell in contact with a wheel to be rolled along a path and obtain a continuous scan of the potential of the full cell, usually presented as equi-potential contour maps. By convention, potentials are considered negative when measuring the steel with respect to the copper. High negative potentials usually correspond to areas of on-going damage and also to particularly wet areas. Experience, particularly in the USA, has shown that potential measurement more negative than -350 mV indicates a 90% probability of an active corrosion site. On the other hand, potential measurement less negative than -200 mV indicates a 90% probability of a passive site. However, between these potentials, complimentary test are needed to predict the extent of corrosion activity with confidence.

There are several possible factors that may affect the half-cell potential measurements as shown in the following table:

Effecting Factor	**Magnitude of Effect (mV)**
1-Carbonation of surface	±250 → 450 mV
2-Salt concentration	Up to 250 mV
3-Changes in original water/cement ratio	±100 mV
4-Moisture content in the concrete	±70 mV
5-Stability of the Voltmeter	±6
6- Electrical connections	±7
7-Reproducibility of the RE	±10
8-Thermal Coefficient of the RE	1 mV per 0C
9-Electrolyte concentration in the RE	±40 mV

3.8 Testing of Lightweight Concrete Resistivity

As reinforcement corrosion proceeds, a pattern of flowing electrical current develops within the concrete, and the magnitude of which is directly related to the rate of corrosion at the anode. Since the conductivity of the adjacent lightweight concrete has its control on the flow rate of the developed current, measurement of the lightweight concrete conductivity (or inversely the lightweight concrete resistivity) may indicate the extent of the corrosion process in the steer reinforcement. The four-probe Wenner method is commonly used in practice. It involves four contact probes to be inserted into the lightweight concrete cover to a depth of 6mm with a spacing of 50mm between the probes. An alternating current is then passes between the outer electrodes and the resultant difference in potential between the inner electrodes is measured. In practice the resistivity r is calculated as follows:

r	lightweight concrete resistivity (ohm cm)
a	Spacing between the probes (cm)
E	Potential drop between the inner electrodes (mV)
I	Current flow between the outer electrodes (mA)

Correlation of resistivity against probability of corrosion is given as follows:

r >12000 ohm cm → Corrosion is impossible
5000 > r > 12000 ohm cm → Corrosion is probable
r < 5000 ohm cm → Corrosion is favorable

The presence of the steel reinforcement may itself cause an error in the measurement of the lightweight concrete resistivity by providing an electrical short circuit. However, adjusting the probe spacing to be less than the depth of the lightweight concrete cover could eliminate this error.

3.9 Testing of Core Samples

Visual examination as per the procedures described in ASTM C42-84A.

Physical testing to determine the compressive & tensile strength of lightweight concrete, as per the procedures described in BS 1881: Part 120, BS 6089 and Concrete Society Technical Report No.11.

a. Physical testing to determine the density of lightweight concrete, as per the procedures described in BS 1881: part 114 and Concrete Society Technical Report No.11.

b. Physical testing to assess pore structure in lightweight concrete, as per the procedures described in the BS 1881: Part 122 and ASTM C642-82.

c. Chemical Analysis to determine the cement and aggregate content, cement type, aggregate grading, original water content, chloride and sulfate content (total acid soluble), and alkalis content (such as potassium and sodium oxide). BSI 1881: parts 6 & 124 cover the chemical analysis of hardened concrete. Test procedures are reviewed in the Concrete Society Technical Report No.32 and the BRE Information Paper IP 21/86.

d. Petrography Examination to assess the mineralogy and microstructure of the hardened lightweight concrete by means of section microscopic analysis, microprobe analysis, X-ray diffraction and infrared spectroscopy, according to Eric procedures described in ASTM C856-83. Petrography Examination is useful to identify and diagnose the following:

I. Mix constituents, i.e. the type and amount of aggregate, cement and cement replacement materials
II. Concrete quality
III. Concrete deterioration mechanisms, such as Sulfate attack, frost damage and alkali-silica reaction.

4. REPAIR OF CORROSION DAMAGED LIGHTWEIGHT CONCRETE

4.1Repair Requirements

The objectives set for structural repair are to ensure additional service life for the repaired element and to match the long-term serviceability of the remainder of the structure. Long-term performance of the repair work depends on the following:

a. The overall strategy set to repair the cracks, construction & dilatation joints, the concrete cover zone and the treatment of the lightweight concrete surface.
b. The quality of workmanship.
c. The characteristics of the repair material in terms of the following:
    i. Stiffness (elastic modulus of elasticity)
    ii. Free shrinkage properties
    iii. Creep properties
    iv. Dimensional stability
    v. Early bond characteristics to the lightweight concrete substrate
    vi. Protection against corrosion it provides to the embedded steel

4.2 Repair Strategy

As per RILEM 124-SRC and EN 1504, the set strategy for repair of corrosion-damaged concrete comprises the following elements:

a. Repair the cracked locations by either of the following methods as appropriate:
    i. Injection
    ii. Routing and sealing
    iii. Stitching
b. Coating the steel reinforcement
c. Reinstating the lost passivity with appropriate patching mortars
d. Limiting the moisture content of the lightweight concrete by means of hydrophobic impregnation or by the application of barrier materials based on either of the following as appropriate:
    i. Asphalt
    ii. Bituminous emulsions
    iii. Coal tar
    iv. Chlorinated rubber
    v. Epoxy resins
    vi. Neoprene
    vii. Plasticized PVC
    viii. Polyester resins
    ix. Polyurethane resins
    x. Polyvinyl butyral
    xi. Acrylic resins
    xii. Special composites, such as bricks and mortars

It is very important to note that re-establishing the lost passivity by means of patching mortars may result in local protection of the reinforcement however, incipient anodes are created and failures occur adjacent to the repaired zone. Therefore, optimal repair requires the employment of suitable cathodic protection system on the repaired element.

4.3 Repair Material

From the viewpoint of long-term load sharing between the repair material and the substrate, repair materials based on standard lightweight concrete technology may offer some advantages compared with special formulations. Repair materials at significantly high strain capacity at maximum load may lead to rapid decrease in the effective elastic modulus, thus structural interaction (continuous redistribution of load from the substrate) becomes impossible in the long-term. Repair materials of stiffness greater than the substrate lightweight concrete will experience less cracking during the shrinkage period (early age) and provide efficient structural international.

If the repaired reinforced lightweight concrete beams undergo further corrosion attack after repair, their long-term structural performance is strongly influenced by the properties of the repair material itself. Low ultimate flexural strength and high deflection under service loading result when the cover zone is repaired with a material of low strain capacity, low tensile strength, high stiffness, high flexural strength and low permeability. Effective repair work requires relatively ductile repair materials to be employed in order to allow dissipation of corrosion products and eliminate excessive disruption of bonding at the reinforcement interface. If high stiffness and high-flexural strength repair materials are used, these properties need to be combined with relatively high permeability and ductility to provide optimal long-term structural performance. The incorporation of large coarse aggregate content offers one method of improving ductility and increasing permeability.

Sand-cement mortars were always a fair choice as repair materials However, the limited durability of such materials led to the employment of resin-based mortars as complimentary systems. Despite their relatively high cost, resin-based systems have performed satisfactorily when

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used in appropriate situations. Their inherited characteristics of superior adhesive bonding capability, rapid development of high strength and outstanding chemical resistance allowed the engineers to choose from a large variety of high quality systems. Indiscriminate use of resin-based materials in the repair works may lead to unfortunate experience.

The literature includes extensive research on the adverse effect of temperature rising during the reaction of resin materials. As well, the effect of shrinkage in the resin binder as well as the difference between the coefficient of thermal expansion of the resin mortars and the concrete substrate are points of concern when monitoring the performance of the repaired sections under conditions of thermal cycling.

The American Concrete institute issued paper 515.1R-79 to summarize the repair methods for concrete surface defects as follows:

a. Small surface voids & rutted cracks
  I. Portland cement grout
  II. Epoxy, urethane, or resin latex with inert fillers
b. Large surface voids and rutted cracks
  I. Dry-pack Portland cement mortar
  II. Polymer (latex or epoxy) modified Portland cement mortar
  III. Polymer (epoxy or acrylic) concrete
  IV. Concrete
  V. Shotcrete
c. Holes (repair in confined area)
  I. Hydraulic cement and aluminum or iron powder with oxidizing agent
  II. Expansive Portland cement compositions

5.PROTECTION SYSTEMS AGAINST CORROSION OF STEEL IN LIGHTWEIGHT CONCRETE

The basic objective of corrosion-protection systems is to prevent aggressive agents, mainly chlorides, from attacking the surface of the reinforcing steel. Some systems function by providing a physical barrier while others work by chemically, or electrically, stabilizing the steel surface. The commonly used systems in the lightweight concrete industry may be summarized as follows:

5.1 Corrosion Inhibitor

Corrosion inhibitors involve the addition of certain species into the lightweight concrete mix to modify the steel/environment interaction in favor of metal passivity. Corrosion inhibitors are either film-forming types or medium deactivating types. The important aspects in the study of corrosion inhibitors in lightweight concrete industry have been the extent of inhibition provided by the specific inhibitor to the embedded steel, the rate at which the inhibitor is consumed, the type of attack if inhibition fails, and the effect of the inhibitor on lightweight concrete strength. The effect of the inhibitor on lightweight concrete strength is considered to be the most important aspect in view of structural engineers, who favor the practice of coating the steel bars with strong inhibitive slurry (made of 2-10% sodium benzoate in a slurry coating) rather than general incorporation of admixtures into the lightweight concrete mix. However, zinc oxide used as adrnixture proved to be effective in lightweight concrete exposed to seawater with no adverse effect of the structural performance of the lightweight concrete elements. Sodium nitrite also proved to be effective in the case of carbonation-induced passivity breakdown. Calcium nitrite is used on a wide scale as an inhibitor as well as an accelerator accepted by ASTM C494 for admixtures.

5.2 Coating of Concrete Surface

Protective coating systems are widely used in the lightweight concrete industry as physical barriers against the ingress of corrosion agents into the concrete mass. Thermoplastics (such as bitumen-based materials) are widely used as bonded lining- overlays. Latex modified concrete (LMC) overlays show outstanding performance as corrosion barriers. Silan and acrylic coatings give satisfactory protection against moisture penetration. Polymeric coatings and polymer concrete, such as polyurethane-based and epoxy-based give excellent protection against corrosion of the embedded reinforcement provided that careful selection of the resin binder, adequate surface preparation, and proper mixing and placing techniques are furnished.

5.3 Waterproofing Agents

Waterproofing agents improve the resistance of lightweight concrete to water absorption, hence limiting its moisture content and decelerate the process of reinforcement corrosion. Waterproofing agents are pore filling or water repellent that present in powder, paste or liquid forms. Pore-filling alkaline silicates, notably silicate of soda, aluminum and zinc, are chemically active and widely used to accelerate the setting time of lightweight concrete, thus rendering it more impervious at an early age.

Chemically inactive pore filling materials, such as chalk and Fuller‘s earth, are introduced with the mix constituents as an aid to workability to improve the lightweight concrete density. A material in the water repellent class is, soda and potash soaps. Lime, alkaline silicate, or chloride maybe added to promote their chemical activity within the lightweight concrete. Chemically inactive materials, such as calcium soaps, resin, vegetable oils, waxes and coal, tar residues and bitumen may also act as pore blocking agents.

5.4 Modified Reinforcement Bars

Protection against reinforcement corrosion may be achieved by modifying the steel surface properties or by using alternative materials as reinforcement. Coating the reinforcing bars with solvent-based and Chemical-curing types, such as polyurethane, acrylic polymer solutions, modified polyolefin and coal-tar epoxy are widely used, particularly in the repair works. Fusion-bonded epoxy coating provides considerable protection to the steel reinforcement against corrosion. However, detailing the reinforcement bar in the concrete formwork may induce mechanical disturbance of the coat, and corrosion spreads from the points of defect. New grades of micro-alloyed steel are introduced in the lightweight concrete industry as corrosion-resistant reinforcement bars of acceptable mechanical properties. Fiberglass reinforced plastics have recently been introduced in the market in the form of bars for concrete reinforcement. On the expense of initial coast, their lightweight, ultimate corrosion resistance and non-magnetic properties of these materials make them a better alternative than steel in some concrete applications. The literature indicates some success in the use of galvanized steel as reinforcement bars.

5.5 Re-Alkalization

Lightweight concrete re-alkalization is an electrochemical process that hampers the process of reinforcement corrosion by drawing chloride ions out of the contaminated concrete and restoring the high pH level.

Re-alkalization is achieved by applying a potential across a temporary anode, external to the lightweight concrete, and an internal cathode - the reinforcing bar. The affected lightweight concrete may be restored in a period between 10 days to 10 weeks, depending on the cause and the extent of corrosion. Low current densities (around 0.1 to 0.2 amp/sq. ft.) successfully remove the chloride from the areas immediately around the steel bars without causing damage.

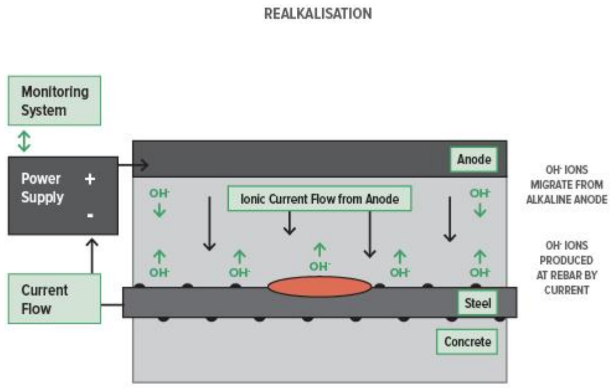

Fig.(3): Re- Alkalization

5.6 Cathodic Protection

Cathodic protection systems of impressed current devices and sacrificial anodes are successfully fitted to pre-stressed concrete pipelines, bridges, car park decks, storage tanks and buildings. Using minute current densities protects relatively large structures, as small local corrosion cells are progressively reversed to the passive state. The use of CP in lightweight concrete industry is controlled by the availability of engineered anodes. Several systems based on fixed anodes and conducting paints are commercially available, and the choice is related to initial cost, life expectancy and maintenance cost. Metal oxide coated titanium mesh in sprayed lightweight overlay is widely incorporated in impressed Current systems, Zinc-zinc sulfate, silver-silver chloride, molybdenum-molybdenum oxide, lead-lead oxide cells, and graphite electrodes are used as embedded reference cells, however, the graphite electrodes are proved to be of high stability with time and perform satisfactory under temperature variations and high chloride contents.

Several criteria are new available for assessing the extent of protection provided on-site. Instantaneous off potential is commonly used criterion, defined as the potential obtained within one second (not less than 0.1 second) following interruption of the direct current to the anode system. If the Instantaneous off potential value is made more negative than -250mV when the current is switched on, with reference to a silver/silver chloride half-cell placed on lightweight concrete surface, and then the steel immediately below is probably protected. Another criterion defines the potential of - 770 mV (with reference to a silver/silver chloride half-cell placed on concrete surface) as the safe level of protection, irrespective of the humidity and chloride content in lightweight concrete.

6.CONCLUSION

Through proper evaluation, design, and installation, lightweight concrete repairs can be made that perform as well as the surrounding materials. A comprehensive evaluation will identify the areas that require repair as well as assist in identifying possible sources of the damage. By understanding the extent and source of the damage incurred, a suit able repair using the most appropriate materials can be designed. Only through proper preparation and execution will a repair be successful. Many of the repair materials used have specific requirements that must be carefully followed to produce a quality repair.

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