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Deterioration of Concrete

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Abstract **: Concrete is a hard composite material obtained by mixing the appropriate proportions of cement and aggregates (fine and coarse) with water, which in combination with steel reinforcement forms an excellent Civil Engineering material. Concrete, being good in compression and steel in tension, prove to be very strong and durable, if correctly designed and cast.**

The pH of concrete is very high (about 13 initially), providing a non-corrosive, durable alkaline environment to the reinforcement. But, many a times, due to various factors, the pH value of concrete reduces, inducing corrosion in the reinforcement.

There are many factors which lead to the deterioration of concrete. The most common factors which lead to the deterioration are the environmental factors (such as the salty environment, moisture and carbon dioxide), the materials and the casting procedures (such as improper concreting procedures, use of porous aggregates, use of aggregates from saline sources, use of saline water in concrete, poor vibration, improper cover to reinforcement, leaking formwork, use of porous and soft aggregates), structural design defects (such as improper design and detailing, settlement of structure), temperature (such as freezing and thawing, concrete subject to extreme temperatures) and improper use (such as change in use and loading on a structure).

A concrete structure undergoing the deterioration shows the following indicative signs: cracking, spalling, abrasion, stains, erosion, deflection, and corrosion. The most common factors leading to deterioration are the environmental factors leading to corrosion of reinforcement, improper use whereby overloading occurs on a structure and the construction procedures leading to porous concrete.

This paper presents the study of the various factors and their mechanisms leading to deterioration, their consequences and the rehabilitation of such structures.

1. INTRODUCTION

Deterioration is the process of degeneration or reduction in quality to an inferior state of a material. Concrete is an artificially created hard and composite construction material consisting of three primary ingredients cement, aggregates i.e. coarse aggregates and fine aggregates and water. When it is green, it may have admixtures added to it to improve the properties of the concrete mix. The aggregates comprise of about 70% of the total volume of concrete. The aggregates influence the workability of concrete. The properties of aggregates such as aggregate strength, pore structure, size, gradation, affect the strength of concrete.

Choosing good quality aggregates can give durable concrete. The pH of fresh concrete is about 12 to 13.5. The alkaline nature of the concrete forms a thin passivating layer around the steel reinforcement and protects it from reacting with oxygen and water or rusting.

Concrete is very good in compression, but is very weak in tension. Its tensile strength is about 10% of its compressive strength. Steel is very good in tension as well as compression. The thermal properties of steel are compatible with that of concrete. So, when steel is used in combination with concrete, the reinforced concrete so formed is an excellent building material capable of withstanding substantial loads.

The durability of a reinforced concrete structure depends upon its ability to withstand the various agencies which lead to the deterioration of concrete. Most often the term durability is linked with the compressive strength of concrete. But in recent times, it is linked with the permeability to chlorides and the other salts. Rapid Chloride Permeability Testing (RCPT) is now becoming a more acceptable parameter of durability testing. Basically the agencies which lead to deterioration of concrete can be summed up into physical, chemical and mechanical agencies. In order to achieve durable concrete, one must give proper attention to structural design, detailing, reinforcement placement, use proper construction material, use good construction practices and perform a good mix design.

The material property responsible to transfer the tensile or compressive stress from concrete to steel and vice versa is bond in concrete. Due to deterioration the bond between the steel and concrete, the load carrying capacity of the member is greatly reduced.

2. DETERIORATION OF CONCRETE

There are many factors which lead to the deterioration of concrete. The most common factors which lead to the deterioration are

1. The environmental factors
2. The materials and the concrete casting procedures
3. The structural design defects
4. The temperature and
5. The improper use of the structure

1. **The Environmental factors:** The various factors which can bring about the deterioration of concrete are the salty environment, moisture and carbon dioxide.

a) Concrete can deteriorate when it is exposed to aggressive environment such as sea water or salt spray, raw sewage, acids, groundwater, acid rain, condensation, etc. This could lead to various defects such as staining, corrosion of reinforcement, cracking and spalling. Salty water used in making concrete allows the salt crystals to be created on drying, which create excess pressure and damage the concrete from the inside.

b) De-icer salts penetrate inside the concrete during rains, and are found to damage the chemical structure of some aggregates leading to their deterioration.

c) The sea-water wetting the concrete surface, concrete structures storing salts, brine tanks, aquariums can easily be a source of salt from which Chlorides can diffuse into concrete. About 3.5% soluble salts are present in sea water and the concentrations of Na^+ and Cl^- ions are about 11000mg/L and 20000 mg/L respectively. As the chloride content in concrete increases, the anodic curve which maintains passivity gets altered and the oxidation of Iron occurs with the creation of Fe_2^+. The Fe_2^+ reacts with the Chloride ions (Cl^-) present in the moisture to form $FeCl_2$ (Ferrous Chloride) and FeOCl (Ferrous oxychloride). The $FeCl_2$ reacts with water to give Ferrous hydroxide and hydrochloric acid. The hydrochloric acid thus formed and availability of balance chloride ions generates a cycle for continual corrosion.

d) The carbonation is the formation of $CaCO_3$ in concrete. The concentration of CO_2 may vary from about 0.03% in non-industralised areas to about 0.3% by volume in industralised areas and large cities. The CO_2 finds its way in concrete through the concrete pores and due to leaching. When the atmospheric CO_2 dissolves in the cement pore solution, carbonic acid (H_2CO_3) is formed. The carbonic acid neutralises the alkaline calcium hydroxide (CaOH) to form calcium carbonate. The neutralizing of calcium hydroxide reduces the pH of concrete often to less than 8.3, and destroys the passive thin ferrous oxide film on the reinforcement to bring about the corrosion of reinforcement. The corrosion of reinforcement could bring about volume change by about 6 times. This leads to bond failure between reinforcing steel and concrete. Once concrete deterioration due to corrosion sets in, as more CO_2 is available, it is a continuous process and eventually leads to overall corrosion and deterioration of the whole member.

e) The water used for cooling towers, sewage, industrial effluents contains sulphates which can attack concrete. It is observed that the soluble sulphates in soils greater than 0.5% could lead to serious damage to concrete. Calcium sulphates react with hydrated calcium aluminate to form ettringite i.e. calcium sulphoaluminate. Sodium sulphate reacts with free calcium hydroxide to form calcium sulphate which reacts with aluminates to form calcium sulphoaluminate. The ettringite and calcium sulphate each have double the volume as compared to those of the original matter. The increase in volume creates a tremendous tensile stress on the surrounding concrete leading to its cracking.

2. **The materials and the concrete casting procedures:** The factors responsible for deterioration are: improper concreting procedures, use of porous aggregates, use of aggregates from saline sources, use of saline water in concrete, poor vibration, improper cover to reinforcement, leaking formwork, use soft aggregates.

a) Improper concreting procedures adopted can create pervious concrete. Poor vibration, improper cover to reinforcement, leaking formwork, lead to porous concrete being created with honeycombing and voids in the concrete. The moisture ingress in the concrete in the forms of gas, vapour or liquid, can serve as a catalyst to lead to corrosion of reinforcement. The strength of concrete achieved with concrete with porous aggregates is lesser than the normal concrete. The porous aggregates get deformed or crushed easily under service loads. It is observed that the porous aggregates absorb water. Water absorption of less than 1% has hardly any effect on creep and shrinkage of concrete. But, the aggregates with higher water absorption (greater than 2 to 3%) could impart higher drying shrinkage to concrete.

b) Concrete made with aggregates from saline sources or with the use of saline water allows the ions to react with the various components of concrete leading to the lowering of the pH of concrete, reducing the alkalinity and thereby exposing the reinforcement to the effects of corrosion.

c) Some aggregates contain siliceous materials which could react with the sodium and potassium hydroxides in the concrete to from a gel. The gel so formed could absorb water and swell excessively creating tremendous pressure and tensile stresses in concrete leading to its cracking. The cracks form openings to allow chlorides and sulphates inside, which could lead to further deterioration. This phenomenon is called Alkali Aggregate Reaction (AAR). The most common are the Alkali Silica Reaction (ASR) and the Alkali Carbonate Reaction (ACR). ACR occurs when the alkalis in concrete react with the fine grained argillaceous dolomitic limestone aggregates containing calcite and clay. ASR is a rare but serious form in which the reactive silica present in the aggregates reacts with the alkali hydroxides of concrete generated during the hydration of cement.

3. **The structural design defects:** are due to improper design and detailing, settlement of structure.

a) The overloading of a structure or its under-designing can bring about deflections and bending, and eventually cracking of the structural members.

b) Settlement of structures due to the settlement of soils due to consolidation, improper ground preparation, evaporation of moisture from foundation soil, fluctuations in water table, inadequate foundation design and construction can create yielding in structures.

c) Improper detailing of reinforcement can also lead to cracking in structures during its service period.

4. **The extreme temperatures**: create freezing and thawing in the concrete. The water or moisture which is contained in the inter particle voids, expands by up to 9% during freezing. When the concrete is saturated above the critical level during freezing, this moisture expansion produces osmotic and hydraulic pressures which are much greater than the tensile strengths of paste or aggregates, thereby accelerating the deterioration of pervious concrete.

Concrete can resist temperatures up to about 650^{o}C and steel up to 500^{o}C. The strength of concrete drops to about 80% at 450^{o}C and about 50% at 650^{o}C, though up to 250^{o}C, the concrete is generally not much affected by the temperature rise. In an eventuality of fire, when the temperatures go much beyond the 650^{o}C, expansion of steel occurs, causing increase in volume, loss in bond and decrease in tensile strength leading to spalling of concrete. On cooling down of such concrete, oxides which are formed due to heat get transformed into lime, thereby disintegrating the concrete.

5. **The improper use of the structure:** is one of the reasons leading to deterioration of concrete. The change in use and loading on a structure generates the moments and shears a structure is not designed for. Mechanical effects created by the improper use of a structure such as Abrasion, Erosion, Impact and Cavitations also bring about deterioration of concrete.

a) **Abrasion:** The abrasion caused by the harder material exercising friction on the concrete surface leads to the concrete surface being worn out and thereby exposes the internal core to the external agencies.

b) **Impact:** An impact given to a material for a particular duration of time leads to its deterioration, damage and reduction of strength.

c) **Erosion:** The phenomenon of erosion wearing out of the surface of concrete occurring due to agencies of nature such as water, wind, ice brings about the removal of the top coat or cover to reinforcement and exposing them to corrosion.

d) **Cavitation:** The cavitation phenomenon is generally created by the flowing water with speeds greater than 12m/s wherein turbulence is created, areas of low pressures are generated and vortexes erode the concrete surface.

3. EFFECTS OF DETERIORATION OF CONCRETE:

A concrete structure undergoing the deterioration shows the following indicative signs: cracking, spalling, abrasion, stains, deflection, and corrosion.

a) **Cracking:** Depending upon the cause of defect or deterioration every crack in concrete shall vary in depth, width, pattern and location. The cracks can be active or dormant.

Plastic settlement cracks may be i) fine type as seen on surface during the settlement of fresh concrete or ii) the wider type seen over the supports when settlement of foundations occur during setting of concrete.

Plastic shrinkage cracks are more or less parallel to each other, but rather shallower.

Drying shrinkage cracks are finer ones with random orientation.

Structural cracks are the well defined cracks occurring due to the crossing of the threshold of flexural, tensile, compressive or shear stresses. They may be diagonal in case of shear cracks.

AAR cracking, also known as map cracking is seen like a web or network of cracks on the surface.

b) **Spalling:** is the falling of pieces of concrete of varying size due to corrosion of reinforcement, local area overstressing, fire damage, overloading, impact, freeze-thaw action, and excessive relative movement of components due to seismic activity.

c) **Abrasion:** is the wearing out of the concrete surface leading to disfiguration.

d) **Stains:** are the patches generated on the surface of concrete due to leaching, or corrosion of steel reinforcement. The patches may be white in colour due to leaching or AAR, and brown coloured due to corrosion of reinforcement.

e) **Deflection:** is the sagging or bending of concrete members due to overloading, improper construction or steel corrosion and

f) **Corrosion:** is the result of reaction of steel reinforcement mainly due to attack of chloride ions and carbonation. Due to corrosion discoloration, extensive cracking and spalling occur in the concrete.

It is observed that the bond between the reinforcing steel and the concrete also reduces due to corrosion of the steel. At low levels of corrosion up to and less than 5%, the effect was beneficial to the bond between steel and concrete, but at levels above 5%, the bond capacity significantly reduced and the failure mode of concrete changed from splitting to slippage of reinforcing steel out of the concrete.

4. PREVENTION OF DAMAGE TO CONCRETE

Good construction practices and sound materials form the key to durability of concrete. Also, proper structural designs, detailing and inspection need to be carried out for sustainable concrete.

The concrete made with sound aggregates with adequate amount of air entrainment tend to have better resistance against freezing and thawing. Due to the entrapped air, the generation of hydraulic pressures during freezing can be prevented. The solutions of linseed oil and flammable solvents help to reduce the damage caused by de-icing salts.

To avoid the sulphate attack, sulphate resisting cements could be used and the concrete be made with a low permeability, which could be achieved by use of low W/c ratio, proper vibration, use of Slag cement or Fly Ash cement and proper curing.

To avoid the chloride and the CO_2 attack too, the concrete should be have very low permeability, by use of low W/c ratio, proper vibration, use of Slag cement or Fly Ash cement and good curing.

The AAR generally does not occur when the total alkali content is less than $3kg/m^3$ of concrete. The AAR can be prevented by the use of non-reactive aggregates, low alkali cements having alkali content less than 0.6%, design the concrete mix to limit the total alkali content to be less than $3kg/m^3$ of concrete and by the use of supplementary cementitious materials such as Slag cement or Fly ash cement.

5. REPAIR METHODOLOGY

Before any repair is undertaken, the thorough assessment of the deteriorated structure should be carried out to evaluate the causes, extent of damage and the severity of the problem leading to deterioration of concrete. More often the number of causes leading to deterioration is more than one and efforts are needed to be made to identify all the causes. All the drawings, structural designs, specifications, construction notes, soil data pertaining to the structure should be studied thoroughly. Environmental factors responsible for deterioration should be considered. Core samples of deteriorated concrete should be taken to analyse the deterioration of concrete.

In case of corrosion, the corroded reinforcement is needed to be exposed by removal of concrete cover to identify the loss in the area of reinforcement due to corrosion. The design of the original structure should be compared with the one with the new prevalent sections to understand the reliability of the existing structure. The compatibility of the repair materials and the existing ones should be established.

Tests may be carried out on the concrete to verify the permeability, extent of cracks by use of ultrasonic tests, confirm the size of reinforcement and the cover by ultrasonic methods, etc.

Carbonation: In order to measure carbonation, expose the concrete surface afresh and spray with a phenolphthalein indicator solution. If the solution remains clear, the carbonation has occurred, else the pink colour of the solution would indicate the alkaline nature of concrete.

Chloride content: is measured by analyzing the liquid extracted from the concrete samples. The corrosion threshold for chlorides are about 0.4% of chloride by weight of cement and about 0.05% chloride by weight of concrete. Chloride specific ion electrode can be used to determine chloride content on field, whereas titration can be used in the laboratories to determine the chloride content.

Concrete resistivity measurements: In order to determine the amount of corrosion, concrete resistivity measurements can be carried out wherein a four probe resistivity meter can give the concrete resistance. This measurement can be used as an indicator to find if steel has lost its passivity and is corroded. Resistivity is calculated as the product of resistance and the electrode diameter. Low corrosion rate is assigned a value of 20 kilo Ohm cm resistivity and less than 5 kilo ohm cm is considered to be high corrosion rate.

Electrochemical potential measurements: of reinforcing steel also give an indication of corrosion risk of the steel. Measuring the potentials with reference to standard calomel electrode defines the amount of corrosion in steel.

In case of damage due to AAR, placing new compatible concrete by removing the deteriorated one is most often the best solution.

6. REPAIR OF CORRODED CONCRETE

After analyzing and evaluating the causes and extent of deterioration, the repair methodology follows, but more often no single method suffices. A combination of different methods needs to be worked out for better rehabilitation of the affected structure.

Patch repair methodology: Patch repairs give the advantage of rendering the structure safe, restoring back the appearance of the structure and prevent further corrosion. Proprietary patch repair materials may be applied as a) trowellable mortars wherein more number of coats may be applied on the concrete and primers for steel, b) free flowing micro-concrete which is placed into large forms and shutters and c) spray applied mortars by wet spraying of pre-mixed mortars. The different types of coatings for concrete available are: silicones, epoxy resins, polyurethanes, polyester, vinyl ester, acrylate, etc. The coatings should be judiciously applied as they alter the permeability properties and may affect if the structure is to be treated by desalination or re-alkalization.

The concrete surface needs to be prepared appropriately. All spalling concrete, loose and poor concrete must be removed either by ultra high pressure water blasting or by pneumatic hammers. Reinforcement should be thoroughly cleaned of concrete, and exposed to a length equal to the corroded length plus 100mm at both ends and to a depth of about 50mm beyond reinforcement within the concrete body. Wherever the reinforcement has got corroded, the same should be replaced with a good one with adequate laps. Patch repairs are generally not designed to take up structural loads. They also do not inhibit the corrosion occurring somewhere else in the member, but may promote it also due to it being an anode in corrosion phenomenon.

Cathodic Protection Method: Corrosion of a metal can be reduced by lowering the potential of metal such that its ions are prevented from moving out of the metal surface. So, the reinforcement needing the cathodic protection is connected to an electrically more active anodic material which allows the anode to corrode, or it is connected to the negative terminal of a suitable DC power source in an impressed current system, with the positive terminal connected to a suitable anode. All the reinforcement within the concrete has to be well connected to one another. The cathodic protection method is very expensive. Regular monitoring of the system is very important as high potentials will reduce the steel-concrete bond affecting the strength of concrete.

Desalination: also known as electro chemical chloride extraction works on the principle that when concrete containing chloride ions is placed in an electrolyte between two electrodes, the negatively charged ions (Cl^-) will move towards the anode and leave the concrete, if the anode is set outside the concrete and the current is high. Depending upon the amount of desalination required and the chloride content, it can take between 1 to 3months for about 50 – 90 % of chloride removal. Desalination is preferred wherever the chloride contamination is widespread, and occurs at a lower depth and where the steel reinforcement is closely spaced.

Re-alkalization: is a process similar to desalination wherein alkaline sodium carbonate solution is drawn into concrete from an electrolytic medium on surface. Re-alkalization normally takes about 3 to 7 days and is used where the contamination of concrete is due to carbonation.

Crack Repair: If the concrete itself has got deteriorated due to cracks, after the analyzing and evaluating the cause of deterioration, the cracks are to be cleaned of loose debris and the pressure injecting techniques can be used to inject with epoxy resin and then sealing it at the top with generally render it durable.

7. CONCLUSION

Concrete is a relatively new material which is very useful in the civil engineering industry. There are many factors due to which the concrete can get deteriorated. Majority of the factors linked to the process of construction and the construction materials. The environment also accelerates the deterioration of concrete. The most important factor creating major damage to concrete is corrosion.

In India about 2 lakh crore losses are incurred due to corrosion of steel. In U.S. it is estimated at $ 1 trillion. The damage and losses are extensive.

The assessment, evaluation and repair make it imperative for a better understanding of the deterioration methodology and their performance under different environmental conditions. Repair methods can be carried out but the compatibility of the substrate and the repair coats should be maintained. Different methods such as patch repairs method, cathodic protection method, desalination, re-alkalization and crack repair are available, but all come at a very high cost.

It is best if the good construction practices are followed in concreting, sound materials are used and proper design and detailing is carried out. Apart from these, if the structure is put to proper use than most of the concrete structures will require little maintenance.

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