Concrete Structures Durability and Repair

by

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Abstract

Reinforced concrete exceptional durability is a major reason why it is the most popular structural material in many infrastructures around the world. Most concrete structures serve for several decades; therefore problems of concrete durability gradually arise. To insure that concrete structures perform functionally, it is necessary to maintain and inspect them regularly. The durability of the reinforced concrete structures generally depends on four major factors: structure design and construction, maintenance, concrete aggregates, and environmental conditions. The most common causes of concrete deterioration are carbonation, design and construction errors, alkali-aggregate reactions, freeze-thaw cycles, and corrosion. Each type of concrete deterioration has its own signs and characteristics. Choosing the best repair technique to address concrete deterioration requires specific analysis and tests to find the cause of the deterioration and the extent of the damage.

This study analyzes concrete structures inspection techniques to recognize the source of the problem and the part of the structure which has been affected. Choosing the most proper repair and strengthening techniques to prevent the structure from getting exposed to any further environmental and chemical are the next steps.

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A. Introduction

Extending the lifetime of concrete structures and structure durability are expected to become the most important aspects in design and construction. Concrete exceptional durability is a major reason why it is the most commonly used material for construction around the world. To insure that concrete structures perform functionally, it is necessary to maintain and inspect them regularly. The lifetime of a concrete structure such as a building, a bridge, or a pavement can be significantly extended when using different repair and durability techniques. Since concrete structures deteriorate to different degrees, considering the proper repair and durability method can extend the structures lifetime as well as prevent concrete from more deterioration. Extending the concrete structures service time reduces cost and saves time. As stated in different studies in developed countries, approximately 40% of infrastructures resources are spent on repair and maintenance while new constructions use the remaining 60%.

According to American Concrete Institute *durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion or any other process of deterioration. Durable concrete will retain its ordinal form, quality and serviceability when exposed to environment* [1].

Choosing the best repair technique to address concrete deterioration requires specific tests and analysis to find the cause of the deterioration and the extent of the damage. Repair and rehabilitation of damaged concrete improve functional performance, appearance, and structural integrity of the concrete structures. The major factors that cause deterioration or collapse of concrete structures are weather and chemical attacks such as freezing, moisture, corrosion, sulfates, acids; improper loading; and construction errors.

This study reviews concrete structure inspection techniques to identify the source of the problem and the part of the structure which has been affected. Choosing the most appropriate repair technique and material to prevent the structure from getting exposed to environmental and chemical attacks are the next steps. Finally, this study investigates various concrete strengthening techniques.

B. Review of Technical Literature

1 History of Concrete

The history of concrete development goes back several thousand years. Ancient Egyptians, Greeks and the Romans were the first people to use concrete as a construction material. The first so-called concrete material was made of lime. The limestones, which were used for making concrete, were crushed and burned. After that, sand and water were added to the mixture.

The precursor to concrete was invented in about 1300 BC when Middle Eastern builders found that when they coated the outsides of their pounded-clay fortresses and home walls with a thin, damp coating of burned limestone, it reacted chemically with gases in the air to form a hard, protective surface. This wasn't concrete, but it was the beginning of the development of cement [2].

1.1 The First Structures with Usage of Concrete

Concrete was used in structures for the first time around 6500 BC by the Nabataea trades or Bedouins who had a small kingdom in southern Syria and northern Jordan [2].

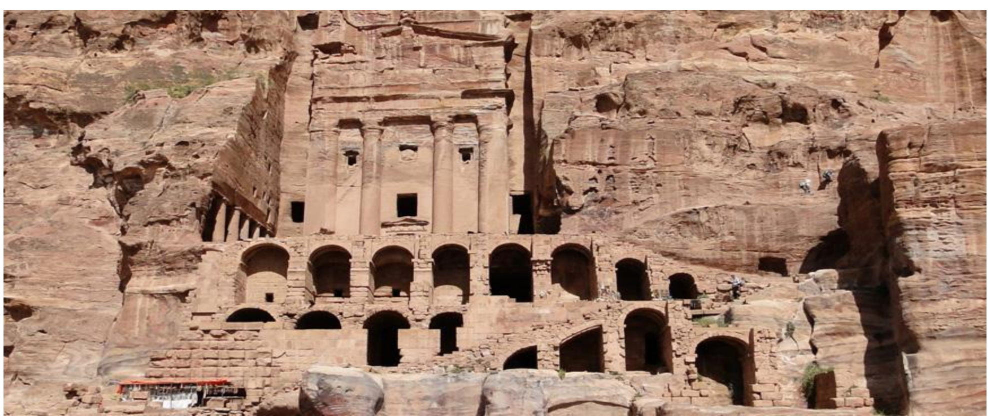
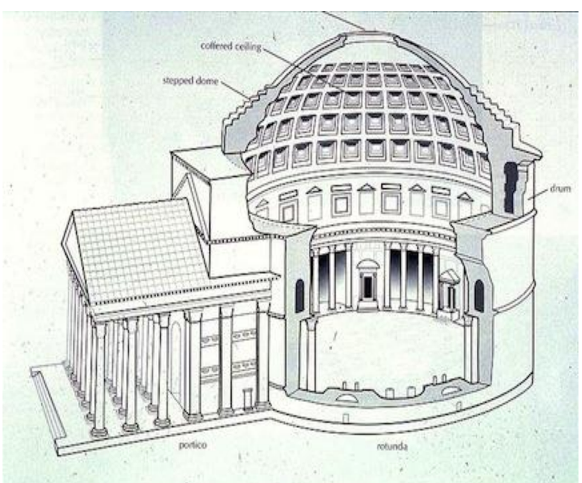


Figure 1.1 Old Nabataea Structure [2]

About 900 years later, concrete was used for the first time for floors in former Yugoslavia. The Egyptians used a mixture of mud with straw in building the pyramids around 3000 BC. The northern Chinese also used a mixture of cement in building boats and the Great Wall.

Romans were known for their development of pozzolanic cements and lightweight concrete in 200 BC. The roof of the Pantheon clearly shows the durability and strength of pozzolana cement which was made of lime, reactive volcanic sand, and water.

Built by Rome's Emperor Hadrian and completed in 125 AD, the Pantheon has the largest un-reinforced concrete dome ever built. The dome is 142 feet in diameter and has a 27-foot hole, called an oculus, at its peak, which is 142 feet above the floor. It was built in place, probably by starting above the outside walls and building up increasingly thin layers while working toward the center [2].



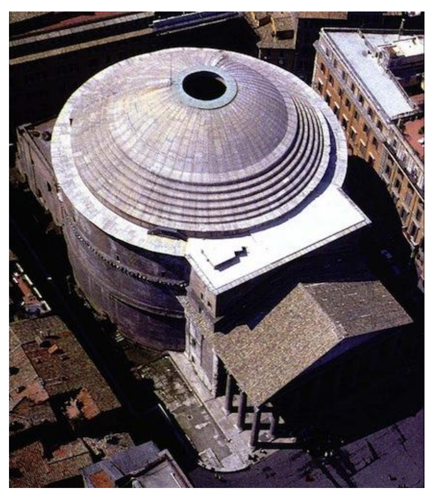


Figure 1.2 The Pantheon [2]

In 1756, John Smeaton produced hydraulic lime for cement with a new method. He constructed the Eddystone Lighthouse in Cornwall, England, which still stands there. Joseph Aspdin invented Portland cement in 1824. This fabrication procedure was done by burning finely ground chalk and clay in a kiln until carbon dioxide was removed. In 1897, François Hennébique built the first reinforced concrete frame building at Weaver`s Mill in Swansea, South Wales. Due to harsh environment the building 35 years later suffered major defects and therefore had to be repaired. As a result of the necessary repairs the building still stands in good condition [3].

Figure 1.3. Weaver`s Mill in Swansea, South Wales [3]

The first concrete street was built in 1891 in Ohio. The concrete that was used on this street has 8000 psi compressive strength and still serves the residential area [2].

Figure 1.4 Court Street in Bellefontaine, Ohio [2]

In the first years of using concrete as a new material in construction, the engineers expected that this material would need no maintenance. But after several years, they discovered that the concrete is not a maintenance-free material. Reinforced concrete structures useful life can be more than one hundred years. However, the concrete structures lifetime depends on various factors such as environmental conditions, maintenance of the structure, and the concrete components used to mix the concrete. Small changes in the amount of cement or water could result in huge differences of the concrete durability and the structure`s lifetime.

2 Most Frequent Problems of Concrete Structures

Concrete structures could get damaged due to several causes such as fire or explosion, chemical attacks, or structure overload, and loose their ability to perform functionally. Another common problem with concrete structures is deterioration. Freezing, corrosion of steel bars, erosion or sulfate environment are other causes of concrete structures deterioration. Design errors, construction problems, and the quality of concrete materials are also reasons for concrete structures defects.

There are four basic types of concrete problems based on the causes:

1. Chemical and Biological Attacks

   Concrete structures exposed to chemical or biological environment could get damaged. Acid and sulfate attacks are some of the most common causes for this type of concrete deterioration.

Figure 2.1 Damaged Concrete Foundation [4]

2. Mechanical Issues

   Loading the structure beyond its capacity and limits, explosion, and movement caused by settlement are some of the common reasons for concrete structures mechanical issues.

Figure 2.2 Broken Beam Caused by Overloading [5]

3. Concrete Reinforcement Corrosion

One of the most known reasons for concrete structures deterioration is reinforcing steel corrosion, which could lead to delamination and also decreases the structures ability to carry tension loads.

Figure 2.3 A Bridge Column Affected by Reinforced Steel Corrosion [6]

4. Physical Damages

Moisture, freezing and defrost, thermal damage, erosion and salt crystallization are major causes for physical damages of concrete structures.

Figure 2.4 Concrete Spalling [7]

2.1. Major Causes of Reinforced Concrete (RC) Structures Deterioration

2.1.1 Accidental Loading

Accidental loading is usually caused by explosion, collision impact, or earthquake and characterized as a one time event with a short and limited duration. In most cases, accidental loading leads to cracking or spalling the concrete.

2.1.2. Construction Errors

Adding too much water to the concrete mix, improper location and installation of reinforcing steel bars, movement of formwork, improper curing, poor concrete vibration, and poor alignment of formwork are most common causes for construction errors in concrete structures. The main factors for these kinds of problems are poor workmanship and carelessness. Therefore inspection, testing, and choosing an experienced contractor for the whole process of construction are some suggestions to avoid construction errors.

2.1.3 Design Errors

These kinds of problems are related to errors made during the design process and before construction. Poor design details, inadequate structural design, and insufficient steel reinforcement are typically common problems leading to concrete deterioration.

2.1.4 Chemical Attacks

There are different types of chemical attacks that can damage reinforced concrete structures. Acid attack caused by highly concentrated acids nearby the concrete is one of the most common chemical attacks. Another type of chemical attacks is sulfate attack. Sulfate attacks are usually caused by sulfates found in soil or water around the concrete. In sulfate attacks, concrete softens and loses its surface layers. Aggressive water attack is another type of chemical attacks. This is usually caused by the usage of water with low concentration of dissolved salts. The signs of acid attacks are cracking, staining, and spalling. Low water-cement ratio and appropriate surface coating are helpful to protect the reinforced concrete structures from these kinds of chemical attacks.

2.1.5 Alkali Silica Reaction

The reaction of aggregates containing silica with highly alkaline solutions forms a gel which is extremely expansive and could crack and break the concrete. The Pozzolanic reaction which happens in the mixture of slaked lime and pozzolanic materials has similar characteristics to the alkali–silica reaction. There is no special treatment for such affected concrete structures. Repairing damaged sections is possible, but the reaction will continue.

Figure 2.5 Alkali Silica Reaction [8]

2.1.6 Freezing and Thawing

The water volume increases by 9% when it freezes. This expansion of the water in moist concrete produces pressure and can exceed the tensile strength. On the long-term freeze-thaw cycles can cause scaling and cracking of the concrete. Air content in concrete must be between -1 to +2 percent of the target volume ratio to reduce the risk of freezing deterioration. Table 2.1 shows the target air contents in different weather conditions and aggregate sizes.

Table 2.1 Air Content for Various Aggregate Sizes [9]

	Air Content, %	
Nominal Maximum Aggregate size, mm (inch)	Sever Exposure	Moderate Exposure
9 (3/8)	7.5	6
13 (1/2)	7	5.5
19 (3/4)	6	5
25 (1)	6	4.5
37.5 (1 1/2)	5.5	4.5
50 (2)	5	4
75 (3)	4.5	3.5

2.1.7 Temperature Changes

There are two types of temperature change in concrete structures. It could be an internally-generated temperature change, usually caused by cement hydration, or an externally-generated temperature change such as fire or climate conditions. Usually concrete structures, which are affected by temperature changes, have thermal cracks and in advance cases spall or collapse.

2.1.8 Shrinkage

During construction, if the concrete mixture looses the capillary water and dries, concrete shrinkage will occur. Shrinkage in concrete structures could lead to an increase in tensile stress, which may cause cracking, internal warping, and structure deflection, even before the structure is subjected to any type of live load.

Figure 2.6 Shrinkage-Affected Pavement [10]

2.2 Corrosion of Reinforcements

Corrosion of reinforcing steel is the leading reason for deterioration of concrete structures. While steel corrodes, the resulting rust occupies a greater volume and this expansion creates tensile stresses, which causes cracking, deformation, and spalling.

Figure 2.7 Corrosion of Reinforcing [11]

Due to the properties of concrete, its ability to carry tension loads is low. Therefore, reinforcing steel helps the concrete to resist tensile loads. However in most cases, corrosion of the reinforcing steel reduces concrete structure durability. Hydration in concrete mixture produces a highly alkaline environment around the reinforcing steel with pH between 11and 13. This alkaline environment protects steel from corrosion.

> *For steel in concrete, the passive corrosion rate is typically 0.1 μm per year. Without the passive film, the steel would corrode at rates at least 1,000 times higher* [12].

The volume of the reinforcing steel increases while corrosion takes place. The forces caused by this increase in steel volume, cracks the concrete because the bond between the rebars and concrete becomes weak. Also when corrosion in concrete happens the effective cross sectional area of the steel bars decreases, which is another reason for deterioration of the concrete structures. Therefore, the structural safety of RC members will be reduced either by the loss of bond or by the loss of rebar cross-sectional area [12]. Corrosion development in concrete structures depends on various factors: existence of cracks, moisture, pH value, carbon dioxide and chloride attacks. In most cases well-cured concrete with low water-cement ratio and proper concrete surface coating will not experience steel corrosion. The causes of corrosion can be categorized as main external and internal factors.

I. External Factors

Steel reinforcement in concrete is usually affected by environmental attacks such as moisture, chloride and carbonation. Carbonation happens when carbon dioxide in the air penetrates in the concrete through the cracks and reacts with hydroxide to form carbonates.

$$CA\,(OH)_2 + CO_2 \longrightarrow CACO_3 + H_2O$$

As a result of this reaction the pH level in the concrete decreases to around 8, which helps reinforcement steel corrosion.

II. Internal Factors

Concrete mix quality, which includes water-cement ratio, size and grading of the concrete aggregates, plays an enormous role in concrete corrosion. Especially having aggregates with chloride salts in concrete could cause major corrosion issues. Another important element in concrete reinforcement corrosion is providing adequate protective layer (cover) to steel reinforcement. Table 2.2 shows the minimum concrete cover requirements to protect the reinforcement from corrosion [9].

Table 2.2 Minimum Concrete Cover Requirements

Cast-In-Place Concrete	**Min. cover, mm (in.)**
Concrete cast against and permanently exposed to earth	75 (3)
Concrete exposed to earth or weather: No. 19 (No. 6) through No. 57 (No. 18)	50 (2)
No. 16 (No. 5) bar, MW200 (W31) or MD200 (D31) wire	40 (1 1/2)
Concrete not exposed to weather or in contact with ground: Slabs, Walls, Joists	40 (1 1/2)
No. 43 (No. 14) and No. 57 (No. 18) bars	40 (1 1/2)
No. 36 (No. 11) bar and smaller	20 (3/4)
Beams, columns: Primary reinforcement, ties, stirrups, spirals	40 (1 1/2)
Shells, folded plate members: No. 19 (No. 6) bar and larger	20 (3/4)
No. 16 (No. 5) bar, MW200 (W31) or MD200 (D31) wire, and smaller	15 (1/2)
Precast Concrete	
Concrete exposed earth, weather:Wall panels: No.43 (No.14) and No. 57 (No.18)	40 (1 1/2)
No. 36 (No. 11) bar and smaller	20 (3/4)
Other members: No. 43 (No. 14) and No. 57 (No. 18) bars	50 (2)
No. 19 (No. 6) through No. 36 (No. 11) bars	40 (1 1/2)
No. 16 (No. 5), MW200 (W31) or MD200 (D31) wire, and smaller	30 (1 1/4)
Concrete not exposed to weather or in contact with ground: Slabs, walls, joists	30 (1 1/4)
No. 43 (No. 14) and No. 57 (No. 18) bars	30 (1 1/4)
No. 36 (No. 11) bar and smaller	15 (5/8)
Shells, folded plate members: No. 19 (No. 6) bar and larger	15 (5/8)
No. 16 (No. 5) bar, MW200 (W31) or MD200 (D31) wire, and smaller	10 (3/8)

Prestressed Concrete	
Concrete cast against and permanently exposed to earth	75 (3)
Concrete exposed to earth or weather: Wall panels, slabs, joists	25 (1)
Concrete not exposed weather or ground: Slabs, walls, joists Beams, columns:	20 (3/4)
Primary reinforcement	40 (1 1/2)
Ties, stirrups, spirals	25 (1)
Shells, folded plate members:No.16 (No.5) bar,MW200(W31)	10 (3/8)
MD200(D31) wire, and smaller	10 (3/8)
Other reinforcement	d_b but not less than 20 (3/4)

3 Most Important Signs of Concrete Structures Deterioration

There are different types of concrete deterioration. Each type of concrete deterioration has its own special characteristics and signs that depend on the cause of the problem and the severity of the damage. The most important sign of concrete structures deterioration is cracking. Other common signs of concrete deterioration can be classified as spalling, stain, excessive structural deflection, erosion, and corrosion.

3. 1 Concrete Cracks

Due to the nature of the concrete, most concrete structures have cracks, however all cracks are not normal and need more investigation. The direction of the cracks, the depth and width of each crack, also the cracks locations and pattern are important factors in concrete durability investigation and analysis.

Cracks on concrete structures can be active or dormant. Active cracks are in progress and deepen and widen which can facilitate moisture ingress causes further damages if they are not repaired.

3. 2 Concrete Spalling

It usually happens when the concrete losses the cover part of the reinforcement due to freezing and thaw or corrosion.

Figure 3.1 Concrete Spalling [13]

3. 3 Concrete Structural Deflection

Excessive structural deflection is one of the most common visual indications of concrete deterioration. Concrete members such as columns, beams, and slabs bend or sag when concrete material has been subjected to reinforcement corrosion.

3. 4 Concrete Stain/ Erosion

Usually alkali aggregate reaction causes stain, which is white powdery surface on concrete. Another major sign of concrete deterioration is erosion, which usually is caused by rain, wind, or water stream.

Figure 3.2 Concrete Stain [14]

4 Inspection of Concrete Structures

A detailed inspection at the beginning of the deterioration process will help select an appropriate and cost efficient repair method. There are several different methods of concrete repairs, therefore it is essential to first investigate the cause and evaluate the deterioration in concrete. After that the best repair option should be considered for each specific case accordingly to the inspection data and analysis. There are different factors that affect concrete durability. Generally evaluating the concrete structures is done in two steps. The first step is a preliminary survey and the second step is the detailed survey.

4.1 Preliminary Survey

The first step in conducting damage investigation is to determine when the last maintenance work has been done. The structure`s plans and documents need to be reviewed. The details about steel bars, structure foundation, concrete strength, the type of materials and the water-cement ratio should be considered. Visual inspection to determine cracks width and depth or spalling is the next important step in the preliminary survey. Measuring the cover of reinforcing steel and gathering other information and samples related to the concrete deterioration are essential to the detailed investigation.

4.2 Detailed Survey

The second step of concrete structures evaluation is to investigate details about the concrete deterioration cause and severity. Choosing the best repair method depends on how accurate the detailed investigation has been done. A detailed concrete condition survey is always necessary in order to correctly determine the extent and nature of any concrete structure problem. Concrete detailed survey includes diagnosis and lab tests.

5 Concrete Structures Examination and Test Methods

There are various methods of inspecting the concrete structures. A few of them are specially designed for concrete while others are common to other materials also such as steel. Each technique targets specific characteristics of the concrete or reinforcing steel. Some of the inspection techniques and tests focus on concrete quality, and others provide information about steel serviceability and condition. Therefore, choosing the precise inspection technique is a very important matter. There are several publications related to conducting a concrete survey and performing inspection techniques, some of which are listed below.

> *The American Concrete Institute have published a Guide for Making a Condition Survey of Concrete in Service, and the ACI Manual of Concrete Inspection which gives guidance on inspection techniques. Similar information is published by the Canadian Highways Authorities* [3].

Investigating the causes of deterioration in concrete structures can be done by two main categories of tests. Some test methods are classified as non-distructive tests (NDT) and others as partially distructive tests. These tests provide information about the cause and progress of the deterioration.

5.1 Visual inspection of Concrete Structure

Visual inspection is the simplest and the most important test for concrete structures. Cracks, voids, and damp patches can be detected with visual inspection. This activity needs to be done by a professional person, who has experience in concrete deterioration and is familiar with the critical parts of the structure. Visual inspection gives information about the type of concrete damage and in some cases it can also provide information about the causes. The visual inspection is also helpful to determine which type of non-destructive or destructive test should be used in the next steps of the investigation.

Figure 5.1 Visual Inspection of Concrete [15]

5.2 Rebound Tests

There is more than one method for testing the concrete surface hardness. The most commonly used method the standard rebound hammer or Schmidt Hammer test. Conducting this test on concrete is not expensive and can be done easily since the test is simple and quick. However, the results are not 100 percent accurate and could have 15 - 20 percent inaccuracy. The Schmidt hammer test results can be affected by various factors such as the shape and size of specimen, type of cement, moisture condition of the concrete and concrete surface condition. There are specific publications that provide standard guidelines for the application and interpretation to govern the standard rebound test, namely:

- ASTM C 805: Standard Test Method for Rebound Number of Hardened Concrete;
- BS EN 12504-2:2012: Testing Concrete in Structures - Non-destructive Testing Determination of Rebound Number.

Figure 5.3 illustrates a typical rebound test.

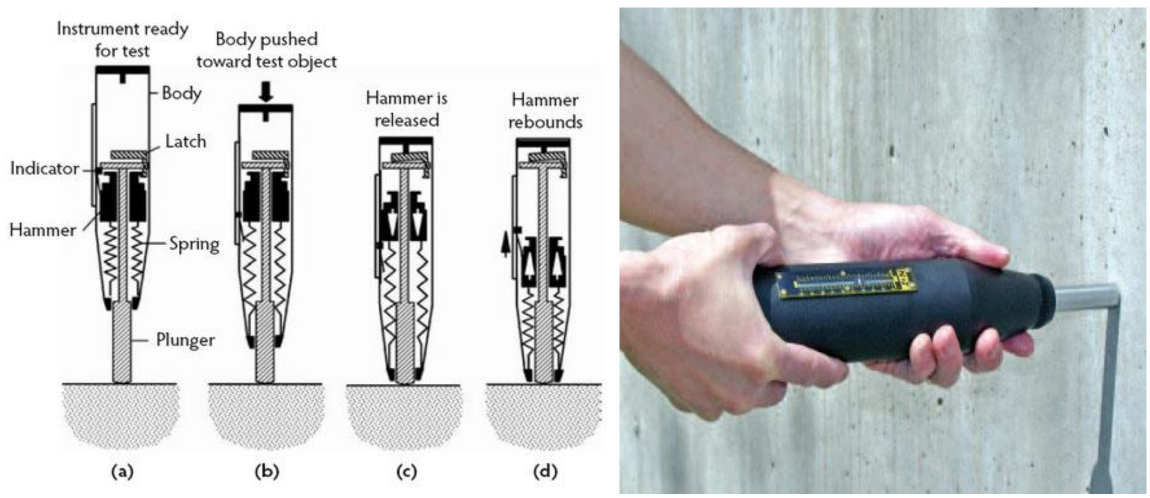


Figure 5.2 Schmidt Hammer Test [16]

5.3 Core Sampling

Another common method to determine the concrete quality is Core Sampling. This partially destructive method gives accurate information about the concrete quality. The samples are taken from concrete with a rotary cutting tool with diamond bits. The sample size differs from test to test but the height over diameter ratio should be more than 0.95 and should not exceed 2. The core sample should not be taken from the part of the concrete where reinforcement steel is located, since it affects the test procedure. Cover meter is a useful device to determine the steel bars location and avoid any conflict between the cutting tool and the reinforcement steel.

One of the most important advantages of this method is that the core sample can be used for several concrete tests such as chemical analysis, strength, density determination, petrographic test, AASHTO Chloride permeability test, and depth of carbonation of concrete. A number of factors can reduce the strength of the core sample and consequently affect the test results. Some of these factors are:

- The number of steel bars and their location in the concrete
- The age of the concrete when the sample is taken.
- The ratio of the sample diameter to the maximum size of the stones that was used in the concrete.
- The site`s environmental condition.

After taking the core sample it should be placed in water with temperature of 75 to 86 Fahrenheit for 2 days. Figure 5.3 shows the procedure and test samples.

Figure 5.3 Core Sampling [17]

5.4 Infrared Thermography

Infrared Thermography is another non-destructive testing method that provides exact and precise information about delamination and concrete defects. The temperature of the concrete surface could be different in the areas where the concrete has a defect. Therefore, with measuring the temperature with this device, deterioration spots in concrete can be located.

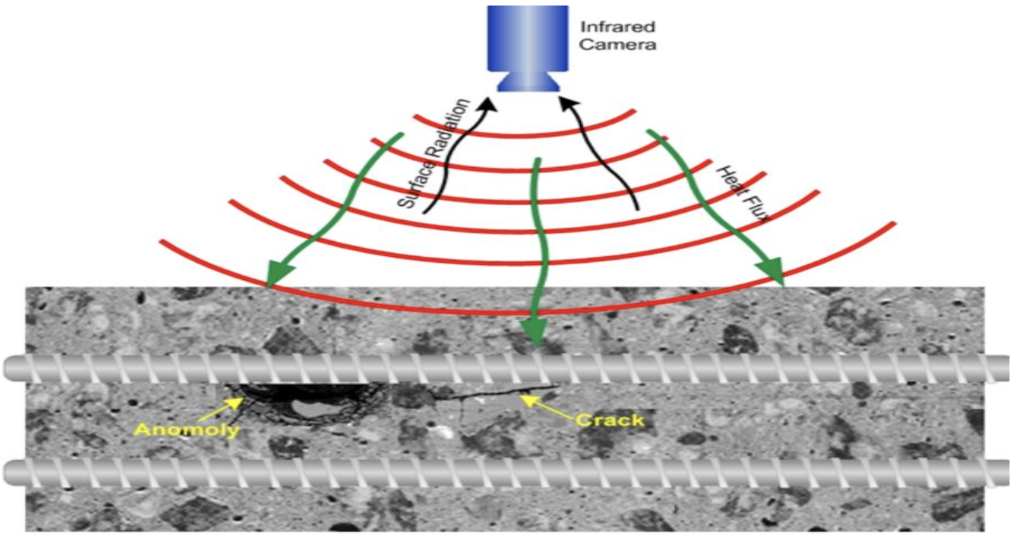


Figure 5.4 Infrared Thermography [18]

5.5 Load Testing of Structure

In this method, investigators measure structures deflection under loads. This type of testing provides information about the maximum strength and assures that the structure has the ability to resist the designed loads safely. There are various ways of loading the structures such as water, bagged sand, kentledge, certified steel weights, and hydraulic jacks. For small tests, steel weights are the most common material for loading. For bigger projects, water is the best choice since it has many advantages such as being easily available, low cost, accurate, and easy to use and remove. However, hydraulic jacks are the most practical tools for loading the concrete structures. They are not heavy unlike other materials, and are very compact.

5.6 Ultrasonic Pulse Velocity Method

This method of concrete investigation is based on the time of travel of an ultrasonic pulse passing through the concrete. The reinforcing steel in the concrete has a considerable effect on the results. Therefore, it is recommended to choose the parts of concrete that has no presence of steel bars. Another factor that can influence the accuracy of the test results is temperature. The temperature needs to be between 41 and 86 Fahrenheit. Table 5.1 shows the relationship between pulse velocity in different concrete qualities.

Table 5.1 The Relationship Between Pulse Velocity and Concrete Quality [19]

Pulse Velocity (km/second)	Concrete Quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

5.7 Cover Meter

Cover Meter is a device used to determine quickly and accurately the depth of concrete over reinforcement bars. It can also detect bar sizes, and the distance between the bars. Using the cover meter is one of the most popular methods in inspecting concrete and especially the steel reinforcement. This device has some disadvantages. One disadvantage is that the cover meter can locate the steel bars only in a limited depth of concrete. Another disadvantage is that the cover meter is not able to detect a large area of the concrete in a short period of time and is suitable to inspect only specific areas.

The advantages of this device are:

- The cost is very reasonable
- The device is unaffected by environmental influences
- It gives very accurate data
- Moisture and heterogeneities do not affect the process and results

Figure 5.5 Cover Meter [20]

6 Repair

The goal of repairing the concrete structures is to bring the concrete to its ideal shape and performance and to stop the progress of the deterioration. There are different types of concrete repair methods and materials. To choose the best and most effective concrete repair technique, the cause of deterioration and progress of damage must be considered.

Concrete structures deterioration repair methods can be classified in five major categories.

- Repair of cracks and concrete surface
- Spalling repair
- Repair of defect or overload
- Water proofing and protection of the structure
- Concrete structure strengthening

6. 1 Repair of Cracks on Concrete Surface

Cracks are the first and most common signs of concrete structures deterioration. Investigating the width, length and depth of cracks, also the pattern of the cracks and their location are essential to select the proper repair method. There are different types of concrete cracks repair methods. The depth, width and the cause of cracking are the most important factors to be considered for choosing the proper repair option.

6. 1.1 Injection of Epoxy

This method of crack repair is usually considered for cracks with a width of 0.002 inches or less. Since the epoxy strength under tension loads is very high, injection of epoxy is one of the most popular crack repair methods. In the epoxy injection repair method holes must be drilled along the cracks and then the epoxy should be injected to those holes under high pressure. This repair technique is highly effective to prevent moisture damage. Epoxy injection should not be used for wet cracks since it will not properly bind to wet concrete.

Figure 6.1 Epoxy Injection [21]

6. 1. 2 Dry Packing

This repair technique is usually used for filling deep and inactive concrete cracks, or repairing narrow slot cuts. In this method, low water-cement ratio mortar is hand placed into the cracks. This is the most economic repair option, which is absolutely not proper for active cracks.

Figure 6.2 Dry Packing the Dormant Cracks on the Concrete Wall [22]

6. 1. 3 Stitching

This method involves drilling holes along the crack on both sides and placing U shape staples (called stitching dogs) in those holes. In order to fill the holes and fixing the legs of the stitching dogs non-shrink grout or epoxy resin can be used.

Figure 6.3 Stitching [23]

6. 1. 4 Additional Reinforcement Steel

Steel bars usually No. 4 or No.5 with length of 18 to 30 inches are used in this concrete cracks repair technique. First holes should be drilled along the cracks and then the steel bars can be inserted and bonded into the holes and fixed with epoxy.

6. 1. 5 Drilling and Plugging

This concrete cracks repair method is usually applied to vertical cracks mostly in walls where there is access only from one side. This method is effective mainly for straight-line cracks. Holes, 2 to 3 inches deep, must be drilled at the center of the crack. Mortar plugs or form key with precast concrete are placed in the hole to have stronger bonds between the hole and the plug.

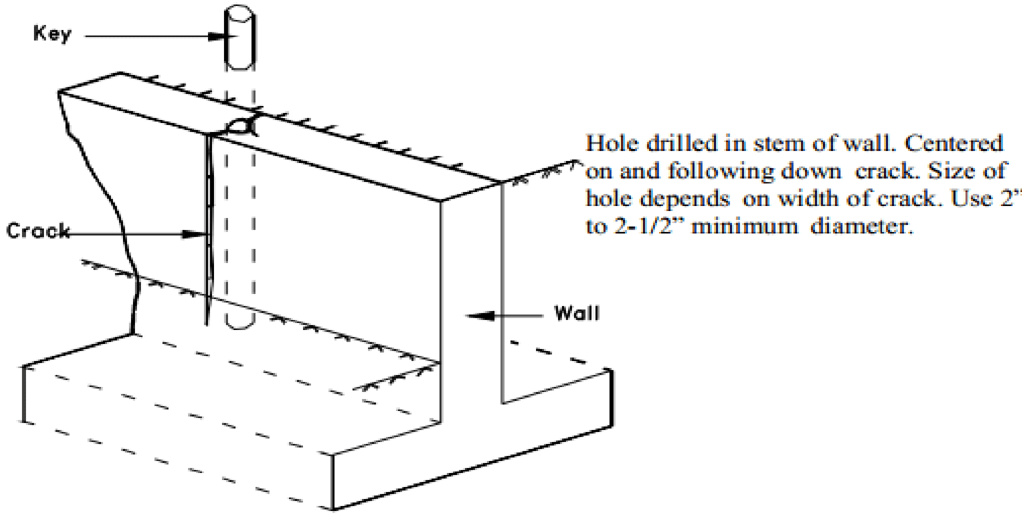


Figure 6.4 Driling and Plugging [24]

6. 1. 6 Routing and Sealing

This is one of the most common, simple, and economical methods, which can be used when structural replacement is not necessary. It is ideal for huge dormant cracks on horizontal surfaces. However, it can also be used for vertical surface cracks. This technique involves cutting and enlarging along the crack and then filling it with proper joint sealant. The sealing material could be epoxy, hydraulic cement, chemical gel or polymer.

Figure 6.5 Routing and Sealing [25]

6. 2 Spalling Repair

The reasons for concrete spalling are corrosion, improper slump of the concrete, or freeze-thaw cycles. To repair the spalling, first the deteriorated concrete should be removed. After cleaning the area and checking the steel bars, compatible patch material must be placed in the affected area. This material should create strong bond between concrete surfaces. Most common materials used to repair concrete structures spalling are:

- High strength concrete
- Rapid hardening cement
- Polymer concrete
- Epoxy, latex, or asphalt
- Shrinkage compensating concrete

6.3 Repair of Deflection and Overloading

Depending on the severity of the structure deflection, repair methods focus on strengthening the deflected members or replacing the damaged parts of the structure. This kind of concrete deterioration could have serious safety consequences and if it is not repaired it could result in structure failure. Most of the concrete deflection repair methods, which focus on strengthening, use materials other than concrete. Therefore, incompatibility between the concrete and the new repair material is an important issue. In order to reduce the risks of this kind of problems, it is necessary to maintain and inspect the structure regularly.

Strengthening the deflected concrete structures could be categorized as presented below:

- Enlargement
- Post tensioning and using steel plates
- Externally and Internally grouting
- Seismic strengthening using shear walls
- Shear strengthening
- Strengthening with Composite materials such as Fiber-Reinforced-Polymer

6.3.1 Enlargement

This concrete structures repair technique helps to increase the thickness of the concrete by pouring extra layers of concrete to the deflected areas. The most common issue with this repair method is the compatibility of the structure`s behavior. Therefore, bonding between the existing concrete and the new material must be strong. Epoxy concrete, latex concrete or low water and high strength concrete are some common materials for enlargement.

Figure 6.6 Enlargement [26]

7 Fiber-Reinforced Polymer Strengthening

Strengthening reinforced concrete with fiber reinforced polymer composites is one of the most effective solutions for the rehabilitation of the deteriorated concrete structures. Fiber-reinforced polymer composite was used for the first time in early 1940`. Mainly it was used in aerospace and naval applications. FRP composites have been used since the 1950` in architectural applications. At first, it was applied for restoration of historic buildings and then it became a very popular material for strengthening deteriorated structures. Compared to other concrete strengthening materials fiber reinforced polymer is very light weighted. It also has a high strength-weight ratio, it is easy to install, and usually has a good corrosion resistance. There are different types of FRP composites based on the material used in their structure. Glass-based fiber is the most common FRP type (GFRP). Other types are carbon fiber reinforced polymer (CFRP) and aramid fiber reinforced polymer (AFRP). Each of these materials has special features and characteristics. Selecting the most proper type of FRP depends on the condition of the concrete structure and also the type and extent of deterioration. [27]

Fiber-reinforced polymer strengthening can involve complex evaluation, design, and detailing processes. It requires a good understanding of the existing structural condition along with the materials used to repair the structure prior to FRP installation. The suitability of FRP for a strengthening project can be determined by understanding what FRP is and the advantages it offers, but more importantly, its limitations [28].

7. 1 Advantages and Disadvantages of Using FRP

The most important advantage of using FRP for strengthening reinforced concrete structures is the speed of application. Other advantages of using FRP composites in construction are

- lightweight
- high strength
- good resistance to corrosion
- easy installation
- high quality energy saving
- durability

Figure 7.1 Installing FRP on Beams [28]

Using fiber reinforced polymer disadvantages are:

- limited codes and standards
- restricted experience in applying FRP in construction
- low resistance against fire and other high temperatures
- harmful to the environment

7.2 FRP Products in Construction

Laminates, rods, and tendons are three major products of FRP composites in construction. The most common product of FRP is laminate which bonds to the surface of the concrete mostly in order to carry tension loads or prevent the buckling of the reinforcement. Rods and tendons are implanted in the concrete as substitute to reinforcing steel.

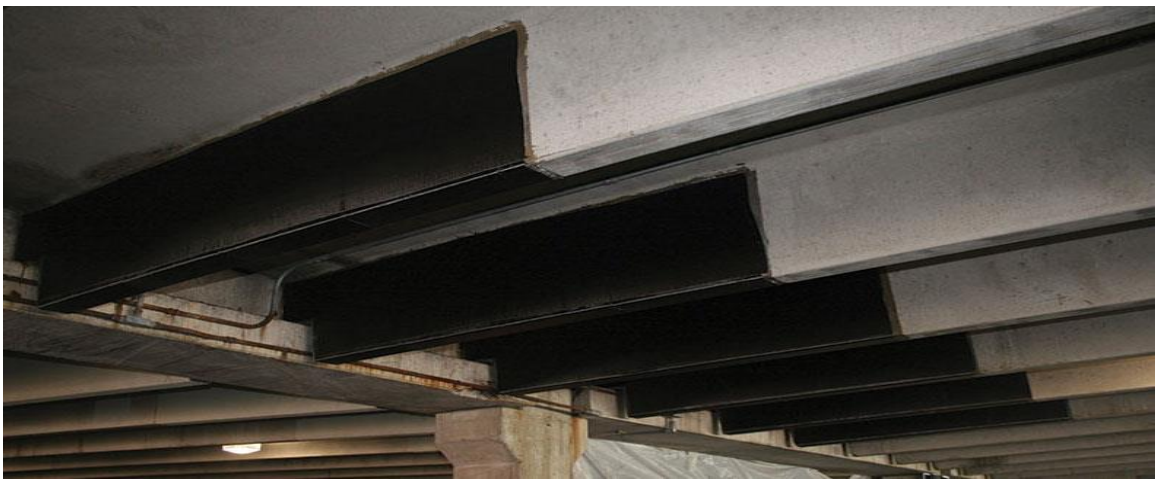


Figure 7.2 FRP Used on Beams [28]

7. 3 Fiber Reinforced Polymer Installation

There are different procedures for installing the fiber reinforced polymer composites. Manufacturers provide information and guidelines related to the installation process. The most important factors that affect the FRP installation are the concrete surface moisture and temperature. The bond between concrete surface and FRP sheets is very critical and should be proper in order to preform well. Therefore, all cracks or other problems on the concrete surface must be repaired before starting the installation process. Also prior to installing the FRP composites on the concrete structure, any corrosion of reinforcement steels must be repaired. Fiber reinforced polymer has the ability to resist high temperature up to 300 Celsius, which is not sufficient according to the various codes and standards. Therefore, in most cases considering proper fire protection for members repaired with FRP is necessary. The American Concrete Institute published some guidelines for materials selection, surface preparation, and installation of the repair materials [29].

C. Conclusion

Several factors affect the reinforced concrete deterioration. Most of the reinforced concrete problems are related to environmental attacks and concrete material composition. However reinforcing steel corrosion is the leading cause of reinforced concrete deterioration. Concrete surface proper coating and high quality concrete mixture are the most important aspects to avoid RC steel corrosion. Other common causes of concrete deterioration are overloading the structure, impacts, and freeze-thaw cycles.

Reinforced concrete, similar to other construction materials, is not a maintenance-free material. The progress of concrete deterioration differs from case to case and depends on various factors. To be able to reduce the risks of reinforced concrete structures deterioration, it is essential to maintain and inspect the structure regularly and examine the parts that are affected.

Based on this literature review the following conclusions can be drawn for reducing concrete deterioration.

- Provide adequate protection to the reinforcing steel with sufficient concrete cover.
- Use proper materials for concrete and avoid design and construction errors.
- Protect the concrete with coating and waterproofing.
- Maintain and repair small cracks on concrete from time to time with local patching or crack sealing.

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