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Effect of Carbonation on Existing Reinforced Concrete Building

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Abstract: Concrete is one of the most important materials that is being used on the earth for the purpose of construction. It has innumerable uses in our day-to-day life. The deterioration of concrete occurs in three main forms physical, chemical, and corrosion. One of the major forms of environmental attack is when carbon dioxide diffuses into the concrete and dissolves in a pore solution to form carbonic acid, which neutralizes the alkalis in the concrete pore solution and combines with calcium hydroxide to form calcium carbonate causing a decrease in the pH of concrete pore solution. A reduction of pH to a lower level causes loss of passivity and initiates corrosion of reinforcement which leads to cracking and fragmentation of concrete and corrosion of the reinforcing steel and a subsequent reduction in the strength, serviceability, and aesthetics of the structure.

This paper presents the results of the field and an experimental investigation of the accommodation building at the National Cancer Institute in Sabratha. Site inspection and destructive tests were conducted including the effect of carbonation diffusion. The results showed the depth of carbonation exceeds the location of steel bars in most element structures. It is also indicated that the compression strength of concrete decreases with the depth of carbonation increase. However, the density of concrete increases with a carbonation depth increase. Evaluation of the building is necessary and important due to the advanced age of the existing structure. This evaluation leads to either rehabilitation or removal as a result of the spread of corrosion in most of the structural elements of the building.

Keywords: Carbonation diffusion, corrosion, compressive strength, reinforcing steel, concrete density.

1 Introduction

Reinforced concrete is considered to be a cost-effective material. Due to the availability of its raw materials and its adaptability to all conditions, it is a cheap material. Its most important attributes include an alkaline environment that protects the embedded reinforcement from rusting. Nevertheless, many environmental conditions have contributed to the deterioration of buildings made of this concrete, particularly those of low quality. Rebar rust has been identified as the primary cause of this degradation, which may lead to the collapse of these buildings in partial or complete terms with time [1].

Concrete is generally the strongest, most stable, and least expensive, the critical dimensions usually being the cover over reinforcement, the minimum space between reinforcement components, or the depth of a slab. Ordinary Portland cement is extremely alkaline, mainly because of its normal lime content but also because some cement contains appreciable concentrations of sodium and potassium salts. These alkalis are progressively neutralised by the absorption of carbon dioxide from the atmosphere. This Carbonation and the loss of alkalinity are mainly important in relation to the durability of steel reinforcement, as it is the alkalinity that prevents steel corrosion in concrete. The corrosion of iron and steel is a form of oxidisation that commonly occurs in the presence of air and moisture when it is known as 'rusting' [1].

Steel is most widely used and the most serious problems are associated with steel corrosion. The high alkalinity of the cement paste surrounding the steel reinforcement normally inhibits corrosion, but the alkalinity is progressively lost by carbonation and steel corrosion can eventually develop. A reasonable period of freedom from corrosion is normally achieved by specifying a minimum concrete cover over the reinforcement, although the life that this achieves will depend upon the density of the concrete and the porosity of the aggregate. Carbonation due to the absorption of carbon dioxide from the atmosphere is the most important and inevitable form of chemical damage that affects concrete.

Concrete constructed in areas close to the sea is more susceptible to deterioration, as the humidity of the air contains carbon dioxide that can penetrate through the cracks in the concrete and cause the reinforcing steel to rust, which in turn splits the concrete cover, exposing the reinforcing steel to further corrosion [2]. This is one of the main reasons that the accommodation building in the Sabratha was exposed to cracks and deterioration of the concrete structural elements.

This deterioration may be rapid if inappropriate materials are used or work is carried out that does not comply with technical specifications and professional principles [3]. This paper presents the results of the field inspection and laboratory tests, the reasons that led to the spread of rust in the steel reinforcement in the structural elements of the shelter building, and recommendations to avoid such deterioration of the concrete.

2 Carbonation

The primary cause of loss of alkalinity in concrete is atmospheric carbon dioxide (CO2). Other acid gasses will attack the cement paste in concrete at the surface but CO2 is unique in its ability to react with the cement without damaging it but changing the environment around the steel making it susceptible to corrosion. Concrete is permeable and allows the slow ingress of the atmosphere; the CO2 reacts with the alkalis (usually calcium, sodium and potassium hydroxides), neutralising them by forming carbonates and sulphates, and at the same time reducing the pH value. If the carbonation front penetrates sufficiently deeply into the concrete to intersect with the concrete reinforcement interface, protection is lost and, since both oxygen and moisture are available, the steel is likely to corrode. The extent of the advance of the carbonation front depends on the porosity and permeability of the concrete and on the conditions of the exposure. For dense concretes, permeability and porosity are related to cement types and content, water/cement ratio, aggregate grading, degree of compaction, and adequacy of curing. It is normal to accept, in the long term, a degree of carbonation in the concrete according to the above factors of porosity, permeability, and degree of exposure. To provide the steel with an effectively permanent protective alkaline environment, therefore it is necessary to ensure that the depth of cover to the reinforcement nearest the surface is sufficiently greater than the depth of carbonation penetration [3], [4], [5].

3 Background on the accommodation building of the National Institute for Oncology in Sabratha

The National Institute is located in Sabratha, Libya. The institute's buildings were completed in 1982. The national institute for oncology is considered to be one of the most important centers in the country for oncology research in general and the Western region in particular. It consists of several distinct departments and buildings as shown in Figure (1).

Fig. (1): The general location of the accommodation building at the Oncology Institute in Sabratha

The accommodation building at the National Institute for Oncology, the subject of this study, is considered one of the largest components of the institute. It consists of four floors, with an area of 800 square meters on each floor and a capacity of 120 beds. The building was then constructed by the Union of Arab Contractors Construction Company as part of the components of Sabratha General Hospital, which the company began building in the year 1982.

4 Methodology

To determine the deterioration of the concrete structure and the reinforcement of the accommodation building, field visits were made to identify the problems, the most important of which were the corrosion of the reinforcement and the disintegration of the concrete. Through field inspection, core sampling locations were marked to include the various structural elements of the building, as shown in Figures (2), (3), and (4), and laboratory tests were carried out to determine the concentration and penetration of carbonation into concrete.

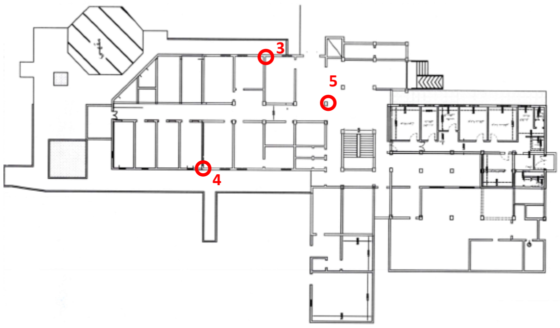

Fig. (2): Locations of samples taken from the ground floor

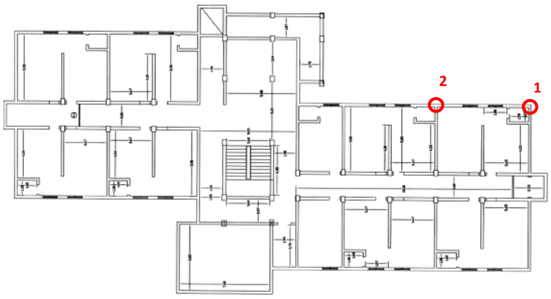

Fig. (3): Locations of samples taken from the first floor

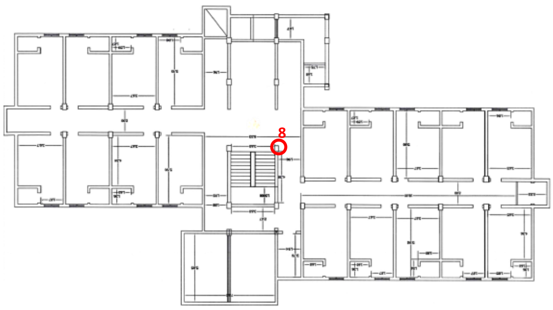

Fig. (4): Locations of samples taken from the third floor

5 Site Inspection

The site investigation helps determine the extent of deterioration of the concrete structure through indicators that may appear from the decomposition of building materials in the concrete structure, and the appearance of cracks of various shapes. The site inspection included the structural elements that make up the building under study, including slabs, columns, beams, and not including the foundations. Through field examination, it became clear that the reinforcing steel had reached an advanced degree of rust as a result of its exposure to environmental influences, represented by moisture and harmful carbon dioxide penetrating the concrete and reaching the reinforcing steel, thus deteriorating the concrete. The following are the forms of this deterioration and the factors that help it occur:

5.1 Through observation, it was noted that the thickness of the concrete cover was not sufficient to protect the reinforcing steel in most of the structural elements, especially the ceilings, as it reached less than 1 cm. In the tested external columns, the thickness of the concrete cover for the main steel ranged from 1 cm to 2.5 cm, according to the American code for such buildings near the sea, the concrete cover is 4 cm for diameters of rebar less than 20 mm and 5 cm for diameters of rebar from 20 mm to 50 mm [4]. This resulted in the exposure of the rebar to an environment full of chloride salts and moisture, and thus the concrete cover fell and peeled off significantly, as shown in Figures (5) and (6).

Fig. (5): The thickness of the concrete cover ranges from 1 cm to 2.5 cm for the columns

Fig. (6): The thickness of the concrete cover is less than 1 cm in the slabs

5.2 Corrosion of the reinforcement steel occurred in the external columns of the northern facade of the building, such that this corrosion led to the separation of the concrete cover in some places and its fall, with the spread of the corrosion of the reinforcement steel to include all floors of some columns, as shown in Figures (7), (8), (9), and (10).

Fig. (7): Severe deterioration of all columns of the northern facade facing the sea

Fig. (8): Severe deterioration of all columns of the northern facade facing the sea

Fig. (9): Corrosion of reinforcement steel for a column on the ground floor with a concrete cover of up to 1.5 cm and links less than 1 cm.

Fig. (10): Spread of corrosion of reinforcement steel for the same column on the third floor.

5.3 There is also widespread corrosion of the steel reinforcement of the slab, especially on the third floor, as shown in Figure (11) and Figure (12).

Fig. (11): The concrete cover of the slab on the third floor fell as a result of corroded steel reinforcement

Fig. (12): Corrosion of the reinforcement steel and the collapse of the concrete cover of the slab on the second floor

5.4 The bottom of the columns is exposed due to the presence of stagnant water on the floor, which in turn causes corrosion of the reinforcing steel, Figure (13), and Figure (14) show the effect of sewer and sewage pipes on the columns near the toilets.

Fig. (13): Corrosion of steel due to leakage of sewer and sewage pipes

Fig. (14): Corrosion of reinforcing steel and spalling of the concrete cover which is less than 1 cm

6 Field and laboratory tests

The type, locations, and number of targeted tests were determined through site inspection of the accommodation building. This program included field and laboratory tests to evaluate the structural efficiency and condition of the rebars. The following tests were conducted:

6.1 Determine the locations of the reinforcing bars

A survey of concrete surfaces was conducted with a micro cover meter surface sensor per British specifications (BS 1881: Part 204:1988) [6]. The survey aims to determine the locations of the reinforcing bars in preparation for extracting the cut concrete samples (concrete cores). In addition, to measure the concrete cover. The value of the concrete cover ranged from 10 to 25 mm, and Figure (15) shows the use of the device.

Fig. (15): Using a cover meter to indicate the location of reinforcement before taking core

6.2 Core extraction

This test is considered one of the most important field tests to measure the strength of concrete. Although it is destructive, the rest of the devices give a close indication of the resistance of the tested concrete. In addition to knowing the quality of the internal concrete and its depth. Among its disadvantages is that it only allows the extraction of a limited number of concrete cores due to their impact on the safety of the structures and the difficulty of obtaining samples free of reinforcing steel in dense concrete members. During use of this test, the extraction process was preceded by determining the locations of the reinforcing bars to avoid it, the locations of the samples were tested so that they do not affect the structural efficiency of the relevant elements, and then the test was conducted on the extracted iron-free core samples per British European Standard (BS EN 12504: Part 1:2004) [7]. The samples were weighed before the test was performed. Then the density of their concrete was determined according to British specifications BS EN 12390: Part 7 [8] .

Figures (16), and (17) show the process of extracting concrete cores, and Figure (18) shows testing extracted cores.

Fig. (16): One of the places where drilling concrete cores are extracted

Fig. (17): Extracting concrete core

Fig. (18) Testing cores

6.3 Carbonation test

A test that determines the extent of penetration of carbon dioxide gas into the concrete and shows the area that has lost its basicity as a result of the carbonation process. It is considered very important and useful in determining the causes of rusting of embedded reinforcement in concrete. This test was performed on six concrete cores extracted from the structure of the building. The test was conducted by spraying the samples with a phenolphthalein solution in the laboratory after wrapping them well immediately after extraction. This solution becomes a light pink color on surfaces when the pH is above a value of 9.5 when the concrete is alkaline, and becomes gray or blue on surfaces that have lost their basicity. So, if no coloration occurs, carbonation has taken place and the depth of the carbonated surface layer can be measured. This test was conducted on samples extracted from columns, under the British European Standard BS EN 12390 Part 10:2018 [9], and BS EN 14630: 2006 [10]. Figure (19) shows the cores and the extent of carbon dioxide penetration into the concrete after spraying it with a phenolphthalein solution.

Fig. (19-1): Carbonation depth for Sample 1

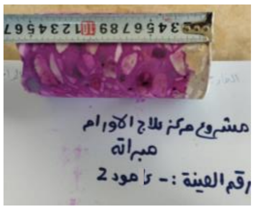

Fig. (19-2): Carbonation depth for Sample 2

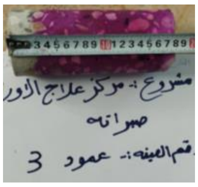

Fig. (19-3): Carbonation depth for Sample 3

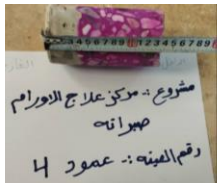

Fig. (19-4): Carbonation depth for Sample 4

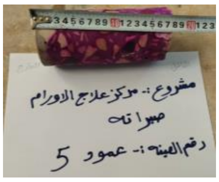

Fig. (19-5): Carbonation depth for Sample 5

Fig. (19-6): Carbonation depth for Sample 8

Fig. (19): Spray the phenolphthalein solution on the concrete and measure the depth of carbonation

7 Results and Discussions

7.1 Depth of Carbonation

The carbonated area remains colourless whereas the non-carbonated area changes to purple red. The carbonation depth was measured at the edge and the Table (1) shows the obtained results.

Table (1): Shows the results obtained from the carbonation test

Sample No.	Sample Location	Depth of Carbonation (mm)
1	First Floor-Northern Facade	28
2	First Floor-Northern Facade	24
3	Ground Floor-Northern Facade	33
4	Ground Floor-Southern Facade	42
5	Ground Floor-Entrance Hall	17
8	Staircase Room	19

The tested samples clearly showed that most of them, particularly samples 3 and 4, were penetrated by carbonation after being sprayed with phenolphthalein solution. After using the Standard Division, the depth of carbonation was found to be between 21 and 31 mm, based on measurements taken between 17 and 42 mm. This depth of carbonation went beyond the location of reinforcement steel. Samples 3 and 4 were collected from the north and south sides of the structure, respectively. This indicates that for a variety of reasons, the carbonation disperses throughout most of the structure elements. One of the reasons is leakage of the water and sanitary system of the building, which allows for enough moisture to cause corrosion in most of the steel bars of the structural elements, particularly slabs where the concrete cover is too low compared with the minimum allowable concrete cover.

7.2 Compressive Strength and Density

The obtained results of the compressive strengths of concrete specimens are presented in Table 2 and Figure 20. In addition, it shows the concrete density of the tested samples. The range of compressive strength is 37 MPa to 60 MPa and the average is 49 MPa. The strength of concrete is considered acceptable for this type of concrete structure after approximately 42 years from the date of its construction.

Table (2): shows the results of the density test for concrete core samples

Sample No.	Sample Location	Compressive Strength (MPa)	Density (Kg/m3)
1	First Floor-Northern Facade	30.60	2480
2	First Floor-Northern Facade	58.44	2555
3	Ground Floor-Northern Facade	56.01	2474
4	Ground Floor-Southern Facade	41.64	2669
5	Ground Floor-Entrance Hall	60.23	2537
8	Staircase Room	25.50	2452

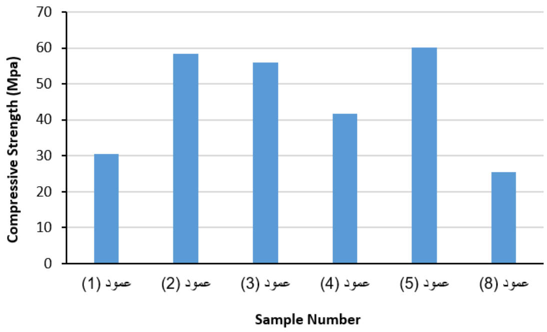

Fig. (20): Compressive strength of tested samples

Figure 21 shows the relationship between the carbonation depth and the compressive strength. It shows that the depth of carbonation decreases with an increase in compressive strength. This approach appears to be very logical since both carbonation and compressive strength are significantly controlled by the pore structure of concrete. However, these relations depend on the type of cement and curing [11]. Figure 22 shows the calibration.

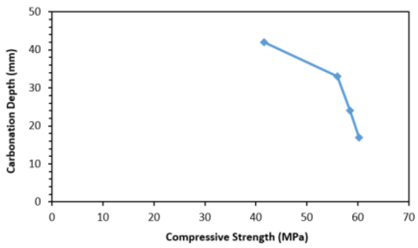

Fig. (21): Relationship between carbonation depth and compressive strength for various concretes

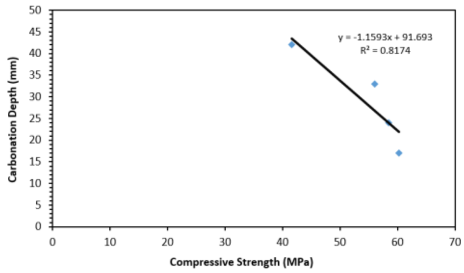

Fig. (22): Calibration equation of Carbonation depth VS Compressive strength

The carbonation makes the plain concrete more durable because it makes the concrete denser, decreases the whole porosity, and increases the sulphate resistance and alkali-aggregate resistance but in reinforced concrete, the value of pH will fall from 13.5 to 8.3 due to this reason the steel losses its passivity which in turn leads to corrosion as well as cracking and concrete spalling [12].

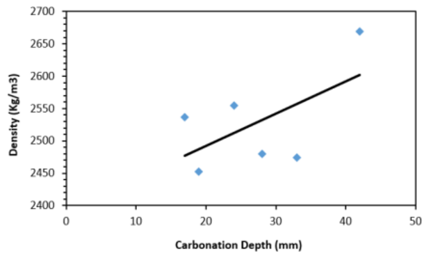

Fig. (23): The relationship between Carbonation depth and Concrete density

Figure 23 shows, the general trend of the relationship between the depth of carbonation with the density of concrete is positive. But its fall in the PH of concrete which reduce the passivity layer on the steel which in turn leads to corrosion as well as cracking and concrete spalling.

8 Conclusions

Through the results of field and laboratory tests and a site inspection of the accommodation building at the Oncology Institute in Sabratha, concrete deterioration of most of the structural elements was revealed, and they can be listed as follows:

8.1 The lack of sufficient thickness of concrete cover to protect the reinforcing steel in most of the structural elements as a result of non-compliance with what is recommended by the relevant standards and specifications in such a marine environment, and even non-existence in some places, helped to corrode the reinforcing steel bars by the access of moisture and oxygen to those bars.

8.2 Corrosion of steel reinforcement contributed to the deterioration of concrete in most structural elements, as we found spalling and fall of the concrete cover, the appearance of straight and perpendicular cracks in ceilings, vertical cracks on the sides of some columns at the location of the reinforcing bars anchored to the sides of the columns, and horizontal cracks at the ends of some beams next to the main reinforcing steel.

8.3 For this type of building was constructed in 1982, the average compressive strength (49 MPa) of specimens is considered acceptable.

8.4 The depth of carbonation exceeded the location of the steel bars in most of the structure elements. Carbonation diffusion increases the spread of corrosion of reinforcement steel, which will lead to the risk to the safety of the accommodation building.

8.5 The strength of concrete decreases when the depth of carbonation increases.

8.6 The general trend of the relationship between the depth of carbonation with the density of concrete is positive. But its fall in the PH of concrete which reduce the passivity layer on the steel which in turn leads to corrosion as well as cracking and concrete spalling.

8.7 Neglecting regular maintenance led to significant deterioration of the concrete, which resulted in the difficulty of implementing the treatment and its high cost, and sometimes resorting to removing some structural elements and re-implementing them.

9 Recommendations

9.1 Expedite the implementation of the appropriate treatment of the building due to the widespread corrosion of the steel reinforcement, so that the problem can be monitored and to avoid the high cost of treatment.

9.2 Removing concrete around corroded steel bars and implementing impermeable concrete to prevent carbonation diffusion. This is done by following a maintenance program to ensure and control quality in all stages of implementing the treatment program and not neglecting periodic maintenance.

9.3 Conduct periodic inspections of the building, carry out appropriate and prompt treatment in the event of any damage, and avoid random maintenance.

9.4 Choose a specialized contractor with good experience in such maintenance work, under intense and careful supervision by specialized engineers to ensure the quality of treatment implementation.

Acknowledgment

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