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EFFECT OF CORROSION LONGITUDINAL STEEL BARS ON THE FLEXURAL STRENGTH OF RC BEAMS

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ABSTRACT

The main objective of this research is to investigate the effect of corroded steel bars on the ultimate flexural capacity of reinforcement concrete beams. The experimental work consists of four RC beams with dimensions (150×200×1200) mm tested under two-point concentrated loading. The major parameter of the current research is corrosion period (5,10,20) days. The amount of longitudinal and transverse reinforcement, concrete strength and, the other parameters were kept constant for all samples. The comparisons between specimens are based on the visual cracking loads, ultimate loads, deflection, cracks pattern and mode of failure. Results showed that visual first cracking load, and ultimate loads of corroded RC beams were decreased with increase corrosion durations relative to the control beam as a result of the corrosion process. The mode of failure was flexural failure for all specimens. Corrosion caused decreasing percentage in weight of steel bars and cross-sectional area of longitudinal steel bars. This percent increased as exposure time to corrosion process increased by 8.5% and 28.39% for 20 days respectively.

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تأثير تآكل قضبان الحديد الطولي على مقاومة الانحناء في العتبات الخرسانية المسلحة

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الخلاصة

الهدف الرئيس من هذا البحث هو التحري عن تأثير تآكل حديد التسليح الطولي (الرئيسي) على مقاومة الانحناء للعتبات الخرسانية المسلحة. البرنامج العملي يتألف من أربعة عتبات خرسانية مسلحة بأبعاد (150×200×1200) ملم فحصت تحت تأثير أحمال مركزة. شملت المتغيرات الرئيسية المعتمدة في البحث الحالي فترة التعرض لعملية التآكل (5, 10, 20) يوم. كمية حديد التسليح الطولي والعرضي ومقاومة الانضغاط للكونكريت وغيرها من المتغيرات ثابتة بالنسبة للنماذج. المقارنة بالنتائج بين جميع العينات اعتمدت على حمل الشق المرئي والحمل الأقصى والهطول للحمل الأقصى وانماط التشقق واطوار الفشل. من خلال الفحص العملي أوضحت النتائج بأنه أحمال الشق الأول المرئي والاحمال القصوى للعتبات الخرسانية المسلحة المتآكلة تتناقص بزيادة فترة التعرض للتآكل نسبةً الى العتبة المرجعية كنتيجة لعملية التآكل. نمط الفشل كان فشل انحناء لكل العينات. عملية التآكل سببت نسبة تناقص في وزن حديد التسليح ومساحة المقطع لحديد التسليح الطولي. هذه النسبة تزداد كلما زاد زمن التعرض لعملية التآكل بـ (8.5 %) و (28.39%) لـ (20 يوم) على التوالي.

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1. INTRODUCTION

Corrosion can be defined as a chemical or electrochemical reaction between a material, usually a metal, and its environment which produces a deterioration of the material and its inherent properties. This is one of the biggest global problems which could be attributed to the exposure of reinforced concrete to chloride salts or the carbonization of the concrete cover. Corrosion leads to the formation of pits or holes on the steel surface which invariably reduces cross-sectional area and reduction of strength capacity, Vavpetič (2008) [25].

The strength of steel-reinforced concrete greatly depends on the adequacy of the bond between the concrete and the steel reinforcement. Bonding is enhanced by adhesion and frictional resistance between the steel-concrete interface. The durability of reinforced concrete largely depends on the surrounding environment and exposure conditions, Sakr (2005) [22].

There are two major divisions of corrosion according to their appearance on the steel bar, generalized and localized. The former takes place in corrosion which spreads uniformly along the steel bar, where the latter is otherwise known as pitting corrosion usually formed as isolated pits along the steel bars, Tahershamsi (2016) [24].

Moreover, the third cause of corrosion in reinforcing steel is bacteria which is mostly seen with steel bars used in foundations. The demerit of corrosion is that it shortens the useful life of building structure and reduces the period of validity and the operational efficiency. This takes place slowly and steadily with the resulting losses exceeding the perceived expectations, AL- Agha (2006) [4].

The capability of steel bars to carry the tension was reduced with respect to the increase in loss of cross-sectional area, Ahmed (2018) [3]. The compressive strength was reduced in respect to increasing corrosion degree, where for concretes with large uniform graining and lower w/c percent (high compressive strength) was observed that the corrosion degree is lower, Shayanfar et al. (2016) [23].

Hassan (2013) [17] studied the effect of accelerated corrosion of tension reinforcement on the reinforced concrete beams bending behavior. The experimental method was made up of twelve square reinforced concrete beams with dimensions (150×150×1000) mm, 10 mm dimeter for bottom tension and the compression zones, 8mm stirrups dimeter with 70 mm c/c spacing for shear reinforcement. The variables in this study mix proportions and corrosions degree. The mix proportions used which include (1:1.2:1.7), (1:1.5:2.2) and (1:2:3), together with three corrosion degree (simple, moderate, heavy). The study was divided into three groups, with each group containing four beams. Each group contain one beam that is not corroded used as reference beam or control, while the remaining were the three beams corroded for different periods of 15,30and60 days. Hydrochloric acid (HCl) solution was used with 10% volumetric percentage. Current density of 0.6 m A/ cm^2 was used and thereafter the four-point loading tests were conducted on the specimens. The results showed that reduction in the ultimate capacities for the corroded specimens containing different mix proportions and mid –span deflections proportioned to corrosion degree. The maximum loss in ultimate load was 36% for beam in group two having heavy corrosion degree for the mix (1:1.5:2.2). Maximum loss in mid-span deflection for beam in group one was recorded with heavy corrosion degree for mix (1:1.2:1.7).

Wang et al. (2014) [26] investigate the comparative analysis of flexural behavior of corroded beams using different types of steel bars as a case study. The experimental matrix contains twenty-two RC rectangular beams with dimensions (200×300×2400) mm which was simply supported with 2100 mm clear span. Four variables were considered, the type of steel bars (smooth and deformed), the diameter of reinforcement (20,22) mm for longitudinal tension zone, corrosion loss, and concrete cover (25,30,35) mm. The accelerated corrosion technique was used. Two groups of RC beams based on the type of longitudinal reinforcement were used. The group (LA) contained deformed bars while group (LB) is made up of smooth bars. The concrete compressive strength for two groups (LA) and (LB) were 34.55 MPa and 39.84 MPa, respectively. The beams were immersed in a 5% NaCl solution and current density of 1.8 mA/cm^2. The results showed that corrosion has a more significant effect on the flexural behavior deterioration in beams with smooth bars than in beams with deformed bars, corrosion decreasing with reinforcement size.

Ahmad (2018) [3] studied the residual flexural capacity of corroded reinforced concrete beams. The experimental program contains four reinforcement rectangular beams with dimensions (100×150×1200) mm. These were casted using concrete with compressive strength of 30 MPa. 2Ø8mm (longitudinal rebar) at tension and compression zone were used, 6mm stirrups with 100 mm c/c spacing (shear reinforcement). One non-corroded beam was used as reference or control and three beams after curing were shifted to accelerate corrosion tank containing 5% NaCl solution for different periods. Direct current was thereafter supplied to the reinforcement cages. The results showed that the increase in the corrosion percentage leads to a corresponding drop in the flexural capacity.

2. EXPERIMENTAL METHODS

2.1 Materials

The normal concrete (NC) mixes used in this research. **"Table 1"** presents a brief description of the used materials. Reinforcing steel bars that are used deformed rebar with a nominal diameter of 6mm and 8mm. The bar properties are shown in **"Table 2"** which conform to the ASTM A615 requirements [5].

2.2 Experimental Program

The experimental program included testing of four simply supported beam specimens, one of them is control beam and three beams were exposed to three corrosion periods (5,10,20) days. One beam for each period. **"Table 3"** shows the full details of the tested beams.

2.3 Beam Specimens Details

For all specimens, the cross-section is 150mm in width, 200mm in depth, and the overall length is 1200mm, with a clear span of 1100mm. 2Ø8mm steel bars were used in the longitudinal direction in the lower part. 2 Ø6mm steel bars were used in the longitudinal direction in the upper part to assist the formation of the required steel frame, as well as 6mm diameter steel bars as stirrups at 80mm center to center. **"Fig.1"** shows the details of the reinforced concrete beams that were tested in this study.

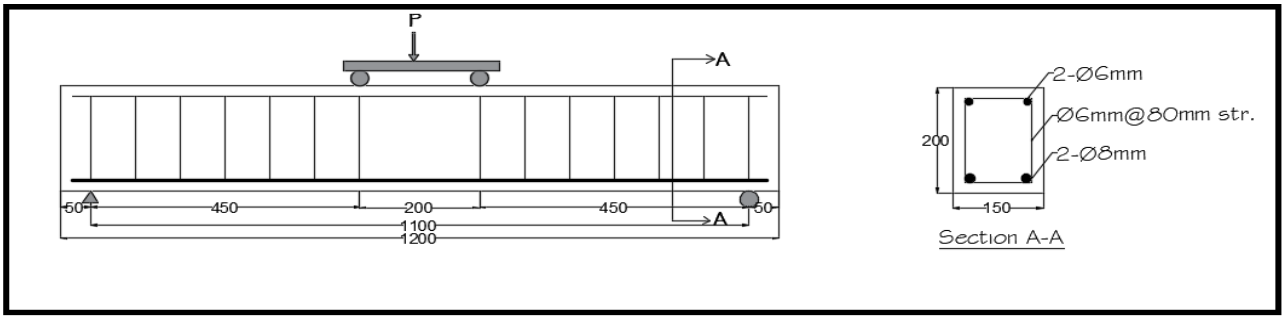

Fig.1: Dimensions and Reinforcement Details of Tested Beams

2.4 Concrete Mix Design

The material mix proportions stated in **"Table 4"** is used in this work. The workability for the normal concrete mix was tested by slump test according to BS1881: part2,1970 [15].

2.5 Concrete Mixing and Curing

Mixing procedure is important to achieve the required workability and homogeneity of concrete mix. The mixing process was done under the Iraqi standard specification of 280/1992 [20] with the aid of an electric mixer. **"Fig.2"** showed casting specimen.

The following mixing procedure is recommended:

1. Preparation and weighing of the mixture materials (cement, coarse aggregate, fine aggregate, water).
2. The mixer basin is moisturized with water to prevent the absorption of the mixture water and that influences the mixing ratios.
3. Put the coarse aggregate in the mixer basin first and then add the fine aggregate and cement in a dry state and mix for two minutes.
4. Add water to the mixer and leave it for two minutes.
5. Stop the mixer and clean the sides of the basin and then mix for two minutes to get a homogeneous mixture.
6. After 24 hours, beams and another specimen (cubes, cylinder, and prism) are demolded and cured.

Fig.2: Casting of RC Beams

2.6 Mechanical Properties of Normal Concrete (NC)

The control specimens were mixed and casted to determine the mechanical properties of the concrete mix, see **"Fig.3"**. Three cubes (150mm×150mm×150mm) were examined in accordance with BS1881: part116 ,1989 [16], three cylinders (150mm × 300 mm) were examined in accordance with ASTM C496-96 [6] and three prisms (100mm × 100mm × 500mm) tested accordance to ASTM C78 [13], to determine the compression strength, splitting strength and modulus of rupture respectively. The test results are shown in "Table 5".

Fig.3: Control Specimens after Testing

2.7 Corrosion Cell

In this research, accelerated corrosion method was used according to Li et al. ,2018 [21], for three different periods (5,10,20) days with current density of (1 mA/ cm^2). Dual power supply model (PS 303-2) with a maximum current of 3A and voltage of 30V used to supplied current for specimens in the corrosion basin, according to sample dimension (surface area for longitudinal steel bars) used (0.8A). A stainless steel plate was used as a cathode electrode and located under each beam, where longitudinal steel bars for each beam with an average two bars used as an anode electrode. 5% from pure salt (NaCl) as a percentage from the volume of basin was used. **"Fig.4"** shows the corrosion cell during operation.

Fig.4: Corrosion Cell Operation

Table 1
Description of Materials

Material	Descriptions
Cement	Ordinary Portland cement (Type I) produced by Mass factory, compatible to the Iraqi specification No.5 /1984 [17]
Coarse Aggregate	natural gravel from Al-Zwyah town at north of Tikrit, the maximum nominal size was recorded as 12.5 mm and compatible to the Iraqi specification No.45 /1984 [18]
Fine Aggregate	Fine aggregate river sand from Al- Zwyah town at the northern area of Tikrit , compatible to the Iraqi specification No.45 /1984 [18]
Water	Clean tap water (using for mixing and curing)
Steel bars	Deformed steel bars (8and 6)mm diameter

Table 2
Test Results of Steel Bar Reinforcement

Bar Diameter (mm)	Yield Stress f_y (MPa)	Ultimate Stress f_u (MPa)	Modulus of elasticity Es (MPa)
8	400.96	602.98	210000
6	389.93	568.79	210000

Table 3
General Details and Variable of the Tested Beams

Beam Symbol	Type of Beam	Corrosion Period (days)
Ref.1	Control Beam	----
C5	Corroded Beam	5
C10	Corroded Beam	10
C20	Corroded Beam	20

Table 4
Mix Proportion

Cement (Kg/m^3)	Coarse aggregate (Kg/m^3)	Fine aggregate (Kg/m^3)	Water (Kg/m^3)	Slump (mm)
378.22	910	805.8	176.6	90

Table 5
Mechanical Properties for Concrete Mix

Compressive strength f_{cu} (MPa)	Splitting tensile strength f_{st} (MPa)	Modulus of rupture f_r (MPa)
40.8	3.5	4.6

2.8 Beam Test

All beam specimens have been tested as a simply supported beam under static loading with two concentrated loads applied at the two-third points of the beam. The beam specimens have been placed on the machine with a clear span (1100) mm. Universal testing machine with a load capacity (5000) KN and a rate of loading (1.75) KN/sec was used for testing beams. The deflection has been measured at mid-span of the beam specimens by using a dial gauge of accuracy (0.01mm) at every load stage. The loading continued until the failure of beams.

2.9 Determination of Corrosion

After testing the corroded beams in flexure, breaking it. The corroded reinforcing steel bars were washed by using kerosene oil to remove rust particles from the steel bar. Two calculation methods were used to know losses by corrosion for steel bars, weight loss method and loss in cross sectional area, Li, et al. ,2018 [21], see **"Table 6".**

2.9.1 Weight Loss Percentage

In this method, the steel bars are weighed before and after the corrosion process and then the weight loss percentage is calculated ($\omega\%$) by the following equation:

$$\omega\% = \frac{w1-w2}{w1} * 100 \quad ..... (1)$$

where w1, w2 are the weight of steel bars before and after corrosion respectively.

2.9.2 Sectional Area Loss

According to Li, et al. 2018 [21], sectional area loss for the steel bars before and after the corrosion process was estimated by measuring six different places in every steel bar, (average diameter) and then the area of each average diameter was calculated.

3. RESULTS AND DISCUSSION

During the experimental program, test results of the control and corroded reinforced concrete beam specimens were including; effect of corrosion process on the visual cracking loads behavior, ultimate loads, and load-deflection response at mid-span. As well as cracks pattern, mode of failure, weight loss percentage and sectional area loss were observed. The test results are presented in **"Table 6"**.

3.1 Visual Cracking Load ($P_{vcr.}$)

"Table 6" illustrates the visual cracking load values before and after the corrosion. The test results show that the visual cracking loads for corrosion periods 5,10 and 20 days are decreased respect to control beams, but for corroded RC beams increased as the corrosion periods increased by percentage (9.04, 7.34, and 4) % respectively.

3.2 Ultimate Loads

All beam specimens have been tested up to failure. The recorded ultimate loads of the tested beams are presented in **"Table 6"**, the test results show that the ultimate loads for corrosion periods 5,10 and 20 days decrease about (2.44, 11, and 16) % respectively, compared with the control beam due to damage of corrosion.

3.3 Load- Deflection Relationship

The load versus mid-span deflection curves of the tested beams at all stages of loading up to failure have been drawn in **"Fig.5"**. Each curve was initiated in a linear form (the beam is in the elastic state), then changes to a nonlinear form with varying slope after the visual cracking was initiated. Then, the third interval starts when the deflection increases very fast with small increase in the applied load up to failure. The deflection at mid-span for ultimate loads decreased about (9.32 ,24.65, and 36.65) % for (5,10,20) days respectively relative to the control beam, see **"Table 6"**.

3.4 Cracks Pattern and Mode of Failure

The mode of failure and cracks-pattern for the corroded RC beams were different according to their exposure harmful conditions. The crack pattern for all the tested beams is shown in **"Fig.6"** and the failure modes of all the tested beams are presented in **"Table 6"**.

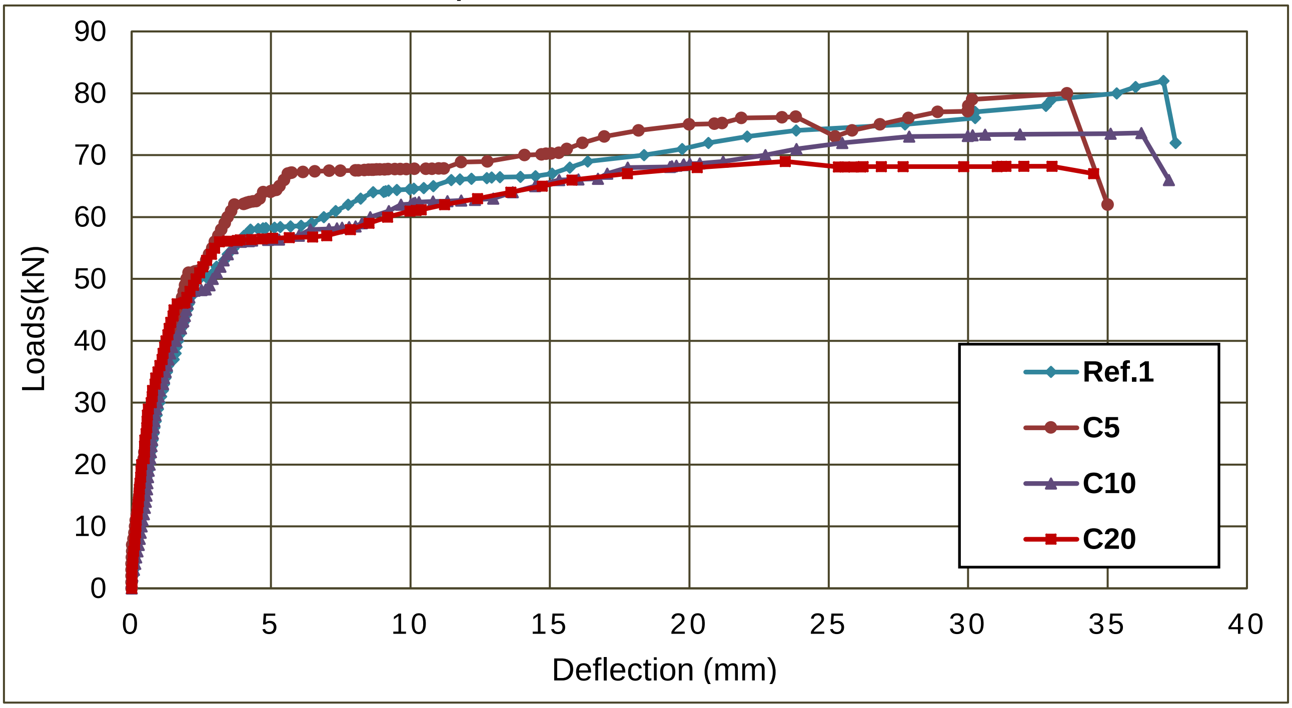

Fig.5: Load - Deflection Curves for Control and Corroded RC Beams at 5,10, and 20 Days

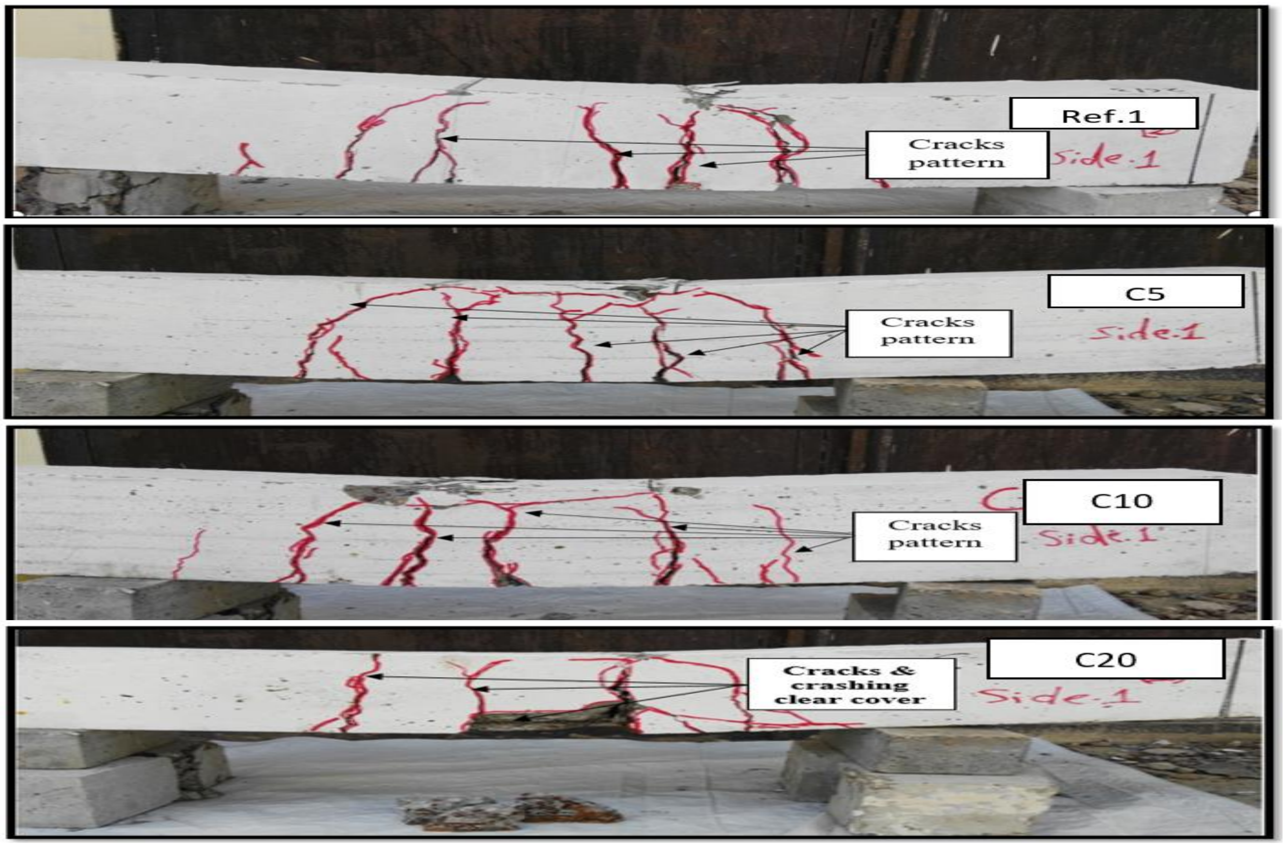

Fig.6: Cracks Pattern and Mode of Failure for Control and Corroded RC Beams at 5,10, and 20 days

3.5 Weight Loss Percentage %

Weight of the reinforcement steel bars after the corrosion process for 5,10 and 20 days respectively decreased in respect to control beam by (872, 850, 846, and 798) grams. The percentage of the weight loss in respect to the original steel bars before exposure to corrosion conditions is illustrated in **''Table 6''**.

3.6 Sectional Area Loss

Sectional area for steel bars after the corrosion process for 5,10 and 20 days respectively decreased in respect to control beam as shown in **''Table 6''**.

Table 6
Test Results of Beams specimen

Beams Symbol	Loads (KN)		Deflection (mm)		Cracks & Mode of Failure	Weight loss Percentage %	Sectional Area Loss (mm^2)
	$P_{vcr.}$	$P_{ult.}$	$D_{vcr.}$	$D_{ult.}$			
Ref.1	35.4	82	1.28	37.00	Tension Cracks (Flexural Failure)	0	49.76
C5	32.2	80	0.94	33.55	Tension Cracks (Flexural Failure)	2.5	41.97
C10	32.8	73	1.09	27.88	Tension Cracks (Flexural Failure)	3	40.83
C20	34.0	69	0.86	23.44	Tension Cracks (Flexural Failure)	8.5	36

4. Conclusion

Based on the results obtained from the experimental work, the following conclusions can be drawn:

1. Firstly, visual first cracking loads, and ultimate loads of corroded RC beams were decreased with the increase of corrosion durations relative to the control beam as a result of corrosion process by percentages (9.04, 7.34, and 4) and (2.44, 11, and 16) % respectively.
2. Deflection in mid-span for ultimate loads decreased for corroded RC beams relative to the control beam due to reduction of ultimate capacity by (9.32 ,24.65, and 36.65) % for 5,10, and 20 days, respectively.
3. The mode of failure was flexural failure for all specimens.
4. The cracking pattern for corroded RC beams spread in two-point loads and shear span. With increased exposure to corrosion process the number of cracks increased, and then caused crashing cover of concrete with increase in loading because reduction in flexural capacity as a result of corrosion of the main reinforcement for RC beams.
5. Accelerated corrosion process caused decrease in weight of steel bars by (2.5,3,8.5) % and cross-sectional area of longitudinal steel bars by (17.37 ,18.78, and 28.39) % for 5,10,20 days respectively.

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