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Study of the behavior of corroded steel bar and convenient method of repairing

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Abstract This paper presents an experimental investigation into the residual strength and mechanical properties of corroded reinforcing bare bars. An attempt has been made to describe firstly the impressed current technique which is commonly used for accelerating reinforcement corrosion. The study compared between two methods of repairing the corroded steel bar, the first one which mostly used by painting the half surface area of corroded bar; and the another one by coating the full surface area of corroded bar. The experimental results show that, the corrosion process alters the external surface of steel bar due to pitting, the residual cross-section of the corroded bar is no longer round and varies considerably along its circumference and its length so the residual diameter is better defined by loss of weight. The rate of corrosion has been calculated by two terms, the term of mass loss rate (MR) and the term of penetration rate (CR). The mass loss rate decreased for fully coated bars by 1.7–2 times than half coated bars showing the importance of fully coating bars in corrosion repair. Finally, the reliability of using the galvanostatic method in research work was represented by comparing between the real time and the accelerated time to reach a certain degree of corrosion.

Introduction

Corrosion of steel reinforcement is one of the major causes inducing deterioration of reinforced concrete structures. Corrosion is considered to initiate when the chloride concentration around the reinforcement reaches a threshold to cause dissolution of the protective film. When the corrosion of steel bars develop significantly, it not only affects the structural serviceability by cracking, or even spalling of the concrete cover, but also has an impact on the structural safety by decreasing the load-bearing capacity of reinforcement concrete members, which is of great concern to both owners and users of the structural building. The corrosion of steel bars in concrete is an electrochemical process that; involves both chemical reaction and current flow with anode and cathode occurring simultaneously on the reinforcement surface. A series of subsequent

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oxidation reactions converts the ferrous hydroxide into hydrated ferric oxide (rust). It is clear that, since the corrosion of reinforcement starts transforming the iron into rust, it must affect the residual capacity of corroded steel bars.

The majority of the previous researches mainly concerned with the mechanism of corrosion and its local effects on bond with concrete, rather than its effect on the mechanical properties of corroded reinforcement. Relatively little attention has been devoted to the residual capacity of corroded reinforcement. In all reported experimental investigations, either a single bare bar or bars embedded in concrete were adopted as test specimens. On the basis of experimental results from tension tests, Maslehuddin et al. [1] reported that up to 1.1% corrosion in air hardly changed bar strength. By using the measured smallest sectional area of corroded bars, Palssom and Mirza [2] also reported that the average nominal yield and ultimate stresses of reinforcement with less than 10% loss of cross-sectional area were similar to those with more than 30% sectional loss, and that even a slight increase in the yield strength was noted in pitted specimens.

In contrast to Maslehuddin et al. and Palssom and Mirza, Andrade et al. [3] proved that corrosion decreased bar strength significantly. By using the average cross-sectional area determined by the measured weight loss, it was noted that 10% corrosion decreased the yield and ultimate strength by 4.5% and 3.3%, respectively. Although the conclusions of Andrade et al. were obtained from a single bare bar, they were still supported by experimental results of Lee et al. [4], Saifullah [5], Morinaga [6] and Zhang et al. [7], whose test specimens were corroded reinforcement embedded in concrete. Du et al. [8] argued that, for corroded steel bars up to 16% corrosion, their residual yield and ultimate strengths decrease more rapidly than their average cross-sectional area and, therefore, their residual strength decreases significantly. They concluded also, for the same corrosion, the residual capacity of bare reinforcement and that corroded while embedded in concrete are similar. As a result of the long duration of the corrosion process in nature, Yuan et al. [9] compared between two techniques for accelerating the corrosion process; and reported that the corrosion characteristics of the steel bar under artificial climate environment or by using the galvanostatic method are similar to that of corrosion under natural environment.

Research significance

Repairing of corroded steel in concrete structures includes the following basic steps; cover removal, exposing the whole bar

Fig. 1 Universal testing machine.

Fig. 2 The data logger.

surface, rust removal and coating with suitable epoxy. Sometimes, in practical cases the concrete cover was removed and only exposes the half surface of the bar and is treated as before. This study presents an experimental investigation into the residual capacity and mechanical properties of corroded reinforcement with different diameters exposed to different degrees of corrosion. In addition comparing the efficiency of repairing the corroded steel bars treated by anti corrosive epoxy, either for coating the whole surface area of the bar or coating the half exposed surface area of the steel bar as may be done in practice.

Experimental program

A total of 48 single bare bar specimens were corroded and examined under tension test. The experimental program for the reinforced steel ribbed bars is divided into two groups. The first (Group A) consists of 36 test specimens; they were 27 corroded and 9 non-corroded control specimens. The variables investigated were reinforcement diameter and degree of corrosion. The test specimens were corroded to 10%, 20% and 30% corrosion degree with diameters 10 mm, 12 mm with specimen length of 500 mm and 16 mm with length 600 mm. Each corrosion degree has three samples of each diameter.

The second group (Group B) consists of 12 reinforcement steel specimens with diameters 10 mm, 12 mm with length 500 mm and 16 mm with length 600 mm. The steel bars were corroded firstly to 10% and 30% corrosion degree; each corrosion degree has two samples of each diameter. Then the corroded bars were cleaned of rust and coated with commercial coating material (Epozinc) for repairing the corroded steel bars. For the same diameter, one of the specimens is fully coated and the other one is partially coated with the same coating material via painting the half surface area of the steel bar for the same degree of corrosion. After that the fully and partially coated bars are exposed again for the same corrosion time. The uniaxial tension tests of the reinforcement specimens were performed using a Universal Testing Machine (Fig. 1). The load cell, electrical strain gauges glued to the bars were connected to the Data Acquisition System to collect readings every five second by means of a computer program that runs under the "PCD-30A" software (Fig. 2). The technique of accelerated and simulated corrosion was employed into groups.

Galvanostatic method for accelerating corrosion

Corrosion is a slow process in a natural environment, thus; the researchers have to simulate the nature of the oxidation reaction by using the galvanostatic method to accelerate the corrosion process in an artificially controlled environment. The method is impressed current technique for accelerating steel bar corrosion inside or outside the concrete. Hence, an electrochemical technique was adopted to accelerate the corrosion process of reinforcement as in Fig. 3, in order to achieve a significant degree of corrosion within a reasonable period of time and the easy control of the corrosion degree desired. As shown in Fig. 4, the circuit of corrosion resulting by applying the electrical potential (DC) using direct electric current impressed on a steel bar as the anode (+) and a stainless steel bar as the cathode (−), both immersed in 5% sodium chloride solution

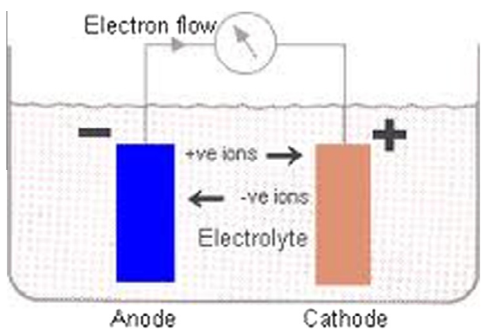

Fig. 3 The galvanostatic corrosion cell.

Fig. 4 The DC power supply used in corrosion process.

Fig. 5 The external surface of corroded bare bars.

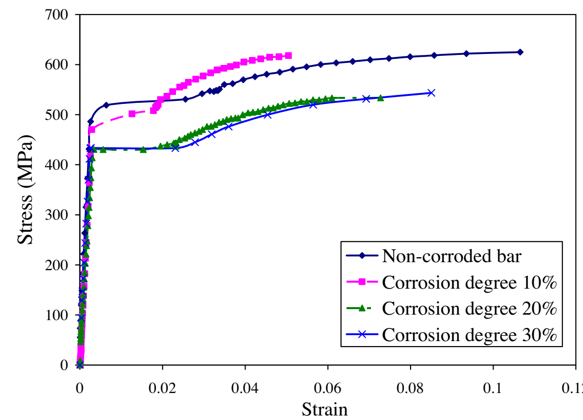

Fig. 6a Stress–strain curves of corroded bars with diameter 10 mm.

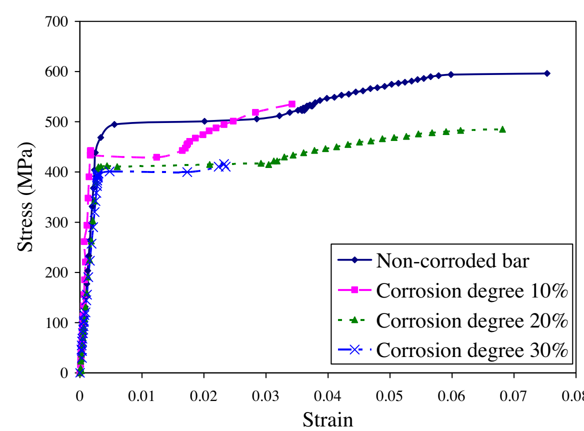

Fig. 6b Stress–strain curves of corroded bars with diameter 12 mm.

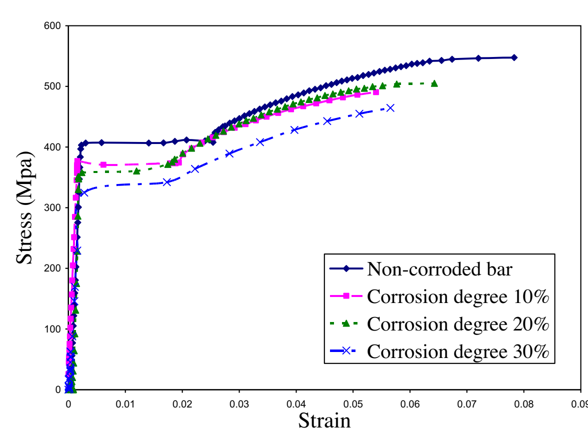

Fig. 6c Stress–strain curves of corroded bars with diameter 16 mm.

Table 1 Mechanical properties of corroded steel bars (group A).

Nominal bar diameter (mm)	Corrosion degree	Actual diameter (mm)	Yield load (KN)	Yield stress (Mpa)	Ultimate strength (Mpa)	Modulus of elasticity (kN/mm^2)	Yield strain	Ultimate strain	Elongation (%)
10	Non-corroded bar	10.05	38.55	486.21	625.07	$1.98 * 10^5$	0.0063	0.106	13.26
	10%	9.69	36.63	470.26	617.91	$1.87 * 10^5$	0.0028	0.0505	12.19
	20%	9.31	31.74	433.44	533.72	$1.83 * 10^5$	0.0026	0.072	10.10
	30%	8.88	26.83	430.62	543.61	$2.18 * 10^5$	0.0026	0.085	8.52
12	Non-corroded bar	12.6	52.97	468.59	596.25	$1.92 * 10^5$	0.0034	0.075	15.90
	10%	11.74	47.91	442.72	535.33	$2.28 * 10^5$	0.0017	0.034	15.13
	20%	11.52	42.22	405.27	485.22	$1.89 * 10^5$	0.0027	0.068	13.45
	30%	10.66	35.42	396.84	416.01	$1.79 * 10^5$	0.003	0.023	6.45
16	Non-corroded bar	16.25	81.01	403.12	547.57	$1.84 * 10^5$	0.0023	0.078	18.87
	10%	15.97	75.41	376.75	490.29	$2.19 * 10^5$	0.0016	0.054	15.80
	20%	15.26	65.44	357.98	504.97	$2.04 * 10^5$	0.0024	0.064	11.38
	30%	14.08	50.56	324.88	464.58	$1.95 * 10^5$	0.0028	0.056	9.75

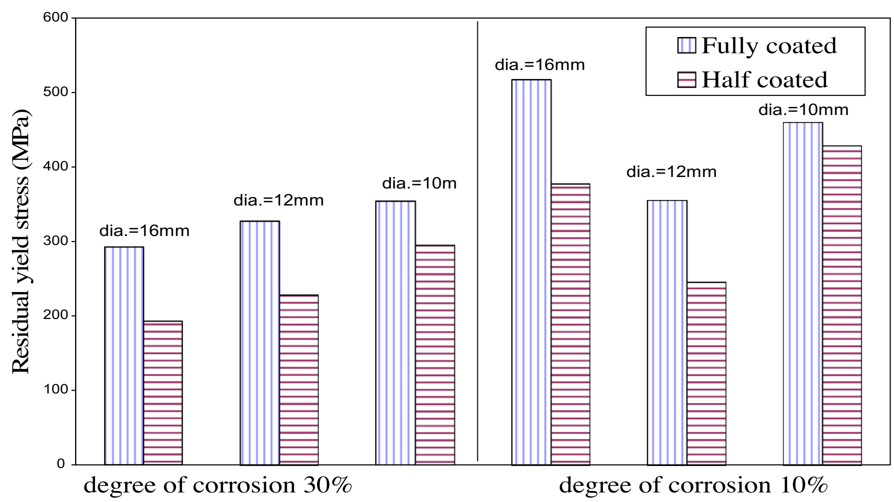

Fig. 7 The residual yield stress for fully and half coated steel bars with two different degrees of corrosion.

Table 2 Mechanical properties of corroded steel bars (group B).

Nominal bar diameter	Corrosion degree, %	Case of coating	Actual diameter (mm)	Yield load (Kn)	Yield stress (Mpa)	Ultimate strength (Mpa)	Yield strain	Ultimate strain
10	10	Fully	8.96	24.43	459.45	564.84	0.0032	0.0596
12			11.81	38.85	354.83	384.5	0.0026	0.022
16			15.38	50.81	517.03	711.68	0.0018	0.053
10	10	Half	8.33	16.98	427.95	526.12	0.0032	0.059
12			11.52	25.52	244.96	270.69	0.0019	0.0204
16			15.1	42.02	377.17	466.9	0.00172	0.0221
10	30	Fully	8.23	28.74	353.97	435.17	0.0032	0.059
12			10.11	26.22	326.83	354.17	0.0026	0.0269
16			12.51	54.32	292.53	376	0.00401	0.0226
10	30	Half	7.11	22.64	294.91	362.55	0.0032	0.059
12			9.04	14.62	227.94	251.88	0.00199	0.0204
16			10.175	34.53	192.92	267.11	0.00189	0.029

behaves as an electrolyte. The corrosion degree can be controlled by varying the current density and/or the time interval of the impressed current. The corrosion degree is defined by the weight of the bar before and after corrosion so; the duration of the corrosion process is related to the corrosion degree desired.

Corrosion degree $= (W_0 - W_1)/W_0 * 100$

where W_0 is the weight of bar before corrosion (g) and W_1 is the weight of the same bar after corrosion and rust removed (g).

Results and analysis

The external surface of corroded bar is shown in Fig. 5. In these subsequent figures, taking 10 mm diameter, as a typical example, ribbed reinforcement R10 and the last two digits in the bar notation refer to the degree of corrosion. Hence R1010 is a ribbed (R), 10 mm diameter (10), bar corroded to 10% corrosion degree (10). Fig. 5 indicates that, the external surface has been altered. With the increase of corrosion degree from 10% to 30%, the corrosion pits on the steel surface, increased in number and depth, expanded in size, and joined up with each other, and finally formed general corrosion. It is obvious that, corrosion of the reinforcement steel bar not only reduced its cross-section irregularly, but also altered the rib shape on a ribbed bar surface. Furthermore, corrosion penetration of reinforcement due to pitting varied considerably around its circumference along its length, an approximately round cross-section of reinforcement prior to corrosion process was changed into a section with a very irregular shape after corrosion.

Due to the irregularity in the shape in the corroded reinforcement along its length, the actual residual section of corroded bar is determined by the actual area of steel bar as follows:

Actual area $= W_1/(L * \gamma_{iron})$

where: W_1 is the weight of the reinforcement after corrosion and rust removed (g), L is the length of the specimen (mm) and $\gamma_{iron} = 0.00785$ g/mm^3.

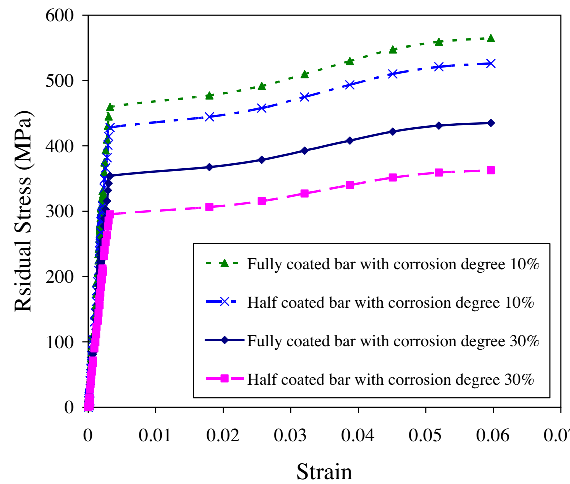

Fig. 8a Stress–strain curves for full and half coated 10 mm bars diameter.

Mechanical behavior of corroded bar

The mechanical behavior of corroded and non-corroded bars for Group A is shown in Figs. 6a–6c and Table 1. It is clear that, the yield stress decreased remarkably with the increase of corrosion degree for all tested diameters. Also, the modulus of elasticity (Es) shows no considerable changes between corroded and non-corroded bars.

Generally, as seen from Fig. 6 the length of the yield plateau is reduced for all diameters of corroded bars meaning that margin of elasticity is reduced due to the corrosion process.

Table 1 indicates that, with an increase of degree of corrosion, the yield load and yield stress of bare bars decreased

Table 3 Comparison between experimental and theoretical corrosion degree.

Group	Nominal diameter (mm)	Corrosion degree, %	Coating	Exp. MR (g/m^2)	Theo. MR (g/m^2)	Theo./Exp.
1	16	30	Non	358.00	386.10	1.08
	12			155.50	145.00	0.93
	10			120.00	138.30	1.15
2	16	30	Half	325.00	349.90	1.08
	12			130.00	139.00	1.07
	10			114.00	110.70	0.97
3	16	30	Fully	154.00	174.00	1.13
	12			78.00	86.50	1.11
	10			69.00	65.39	0.95
4	16	10	Non	102.00	91.26	0.89
	12			63.00	58.40	0.93
	10			40.00	51.16	1.28
5	16	10	Half	96.30	80.00	0.83
	12			46.00	57.10	1.24
	10			34.00	30.38	0.89
6	16	10	Fully	66.00	51.76	0.78
	12			28.00	35.39	1.26
	10			16.00	10.20	0.64
					Mean	1.01
					Standard deviation	0.17

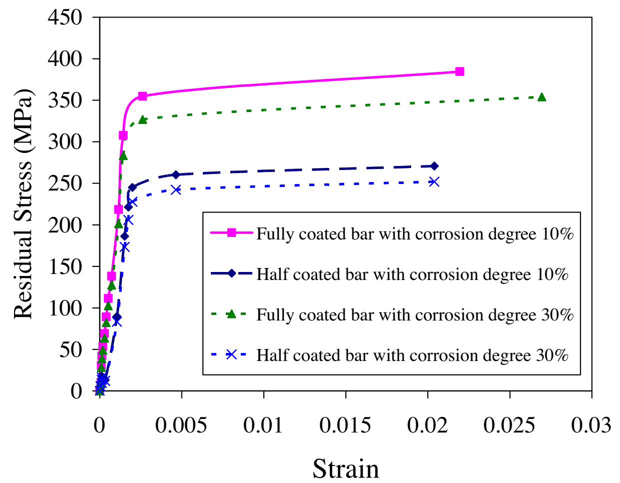

Fig. 8b Stress–strain curves for full and half coated 12 mm bars diameter.

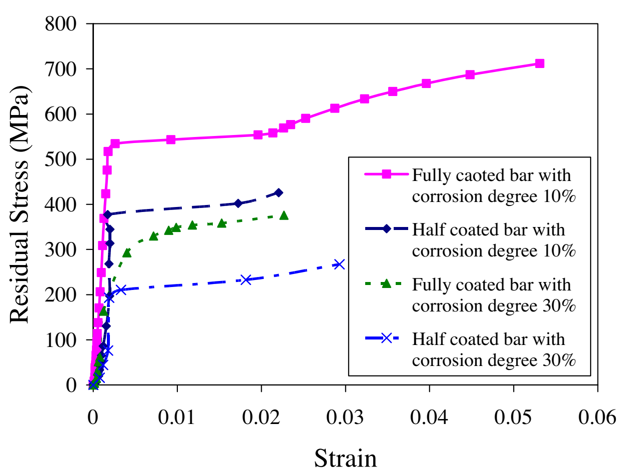

Fig. 8c Stress–strain curves for full and half coated 16 mm bars diameter.

more rapidly than do its diameters or its cross-sectional area. For the same degree of corrosion the residual yield stress of small bar diameter decreases much more than that of large diameter, meaning that the residual stresses decrease slightly with the increase of bar diameter.

Influence of method of coating on residual capacity of corroded steel bars

On reduction of reinforcement diameter it is possible to most accurately obtain results by direct measurements. On a corroded steel bars for R.C structure, parts of the concrete cover are spalled off, and the remaining bar diameter could be treated after removal of the rust layer. For less corroded steel of the structure where the cover is not yet spalled off, small parts of the cover could be removed at non-critical locations and afterward repaired. In most cases of corroded steel of R.C structures the treatment is only to the uncovered area of the steel bar, this study make a comparison between the repairing of the corroded steel bar by painting the whole surface area of the steel bar and painting half surface area of steel bar (Group B).

As seen in Fig. 7 and Table 2, the residual stresses of fully coated bars are greater than those of half coated bars by an average 26.5% for 30% corrosion degree. For corrosion degree 10% the residual stresses for fully coated corroded bars is greater than the half coated corroded bars by 21.1%. Repairing the full coating of the corroded bar surface area is better than the coating of half surface area. Figs. 8(a–c) represents the stress-strain curves for full and half coated corroded bars, with different corrosion degrees. The figures show that the yield stresses of fully coated bar diameter for different degrees of corrosion are higher than that of the case of half coating.

Table 2 shows the results of mechanical properties of fully and half coated corroded bars. For the same bar diameter, the fully coated bars yield stress is greater by 22% than the half coated bars.

Measuring of corrosion rate

The amount of corrosion is related to the electrical energy consumed, which is a function of voltage, amperage, and time interval. The amount of corrosion can be estimated by Faraday's law. Hence, the electric current I_{cor} can be estimated by surface area S of steel bar to be corroded and the equation I_{cor} = S* 0.01 to 0.02 mA/mm^2 (Yuan et al.) [10]. According to ASTM: G102-89 (Re-approved 1999) [11], the corrosion rate can be calculated by two terms, either in terms of penetration rate (CR) or mass loss rate (MR). The first step is to convert the measured or estimated current value to current density, by dividing the total current by the geometric exposed

Table 4 Comparison between accelerated and real time for corrosion process.

Nominal bar diameter (mm)	Corrosion degree (%)	Loss of diameter (mm)	Accelerated time (min)	Real time, day (year)
10	10	0.36	25	375 (1.03)
	20	0.74	45	770 (2.1)
	30	1.17	75	1217 (3.33)
12	10	0.86	30	1064 (2.9)
	20	1.08	70	1337 (3.66)
	30	1.4	90	1733 (4.75)
16	10	0.28	60	386 (1.06)
	20	0.99	120	1364 (3.74)
	30	2.17	190	2989 (8.2)

area of the electrode (steel bar) to the solution. It is assumed that the current distributes uniformly across the area used in this calculation. In the case of galvanic couples, the exposed area of the anodic specimen should be used. This calculation may be expressed as by ASTM G102 as follows:

$$CR = k_1 \frac{i_{cor}}{\rho} EW$$

$$MR = k_2 i_{cor} EW$$

$i_{cor} = I_{cor}/A$
CR = mm/y
MR = g/m^2 d, and
$K_1 = 3.27 * 10^{-3}$, mm g/μA cm y
$K_2 = 0.8953$, g/A m^2 d
$\rho = 7.85\ g/cm^3$ for steel
EW is the equivalent weight of element = 27.93 for steel.

The calculation of mass loss rate from electrochemical measurements as described above assumes that uniform corrosion is occurring. By comparing the mass loss rate (MR) for non-coated, half coated and fully coated corroded bars theoretically and experimentally as in Table 3; it is observed that; there is a good correlation between theoretical and experimental mass loss rates. For a certain corrosion degree the mass loss rate decreased as the bar diameter decreased whenever the corroded bar is coated or non-coated. By comparing the mass loss rate of the corroded bar for the same diameter, same corrosion degree but with different cases of coating; it can be seen that the mass loss rate decreased for fully coating bars for all bar diameters. For example, the mass loss rate (MR) for steel bar diameter 16 mm and corrosion degree 30% decreased by 1.1 times as half coated bar relative to non-coated bar, while it decreased by 2.3 times with respect to non-coated bar. The above conclusion shows the importance of fully coating bars in repair of corrosion. In the term of penetration rate (CR), which depends on the cross-sectional area of the steel bar to be corroded and by assuming a uniform distribution of the impressed current; the loss in bar diameter due to corrosion in the year can be calculated. The penetration rate for bar diameters 10 mm, 12 mm and 16 mm were 0.351 mm/y, 0.295 mm/y and 0.265 mm/y, respectively.

In order to calculate the corrosion rate in terms of penetration rate, the real time to reach a certain degree of corrosion can be calculated. The shown results in Table 4 indicate the importance of using the galvanostatic method as a technique for accelerating steel bar corrosion.

Conclusions

Based on the results of the experimental investigation, the following conclusions are drawn:

1- The corrosion process alters the external surface of the steel bar due to pitting. The residual section of corroded steel bar is no longer round and varies considerably along its circumference and its length, therefore the residual diameter is better defined by loss of weight.
2- The mechanical properties of corroded steel bars are affected due to corrosion. The yield stresses are reduced with an increase of corrosion degree, while the (Es) value did not remarkably change.
3- The yield plateau of corroded bars decreased with the increase of corrosion degree.
4- For a certain corrosion degree, the mass loss rate decreased by a decrease of the bar diameter whenever the corroded bar is coated or non-coated.
5- There is a good correlation between theoretical and experimental mass loss rate.
6- For corroded bars, the mass loss rate decreased for fully coated bar than half coated bar by an average from 1.6 to 2 times, showing the importance of fully coating bars in corrosion repair.
7- By comparing the accelerated time and the real time to reach a certain degree of corrosion, the galvanostatic method is a reliable tool in the research work.

Conflict of interest

The authors have declared no conflict of interest.

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