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Effect of Corrosion on the Flexural behaviour of one-way Slabs under Two-Point Loading

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Abstract

The effect of corrosion on five concrete slabs was studied for a period of 25 days, where the rate of corrosion and loss was determined by the cross-sectional area of each model for a period of five days until the last model reached 25 days in the corrosion basin. Three models were selected to be reference models with weak, medium and strong corrosion rates, and its flexural behaviour was studied while applying two-point loads. The deflection was also measured in each model. The stiffness and toughness index were also determined for the purpose of knowing the behaviour of these corroded slabs under high loads and which of them will fail first. The results showed that the corrosion rate was (11, 26, and 40) % for each level of corrosion, respectively. From the results of the applied load, the highest resistance to failure was in the slab with a low level of corrosion, and the lowest resistance was in the slab with a high level of corrosion. Also, the loss in weight and cross-sectional area for each period of corrosion increased at a non-linear rate due to the weakness occurring in the reinforcement steel.

Introduction:

Steel in concrete is typically shielded from corrosion by the intensely alkaline environment that is produced around it. Iron oxides are produced at the contact between steel and concrete, serving as a passive coating that prevents corrosion. However, because the volume occupied by the corrosion products is around six times bigger than that of the original steel, any remaining corrosion or cracks in the concrete surface can speed up the rate of corrosion [1-3]. Thus, one of the main issues affecting the resilience and usability of reinforced concrete structures is corrosion. It happens as a result of the interaction between the surrounding environment, which includes chemicals, oxygen, and moisture, and the steel reinforcement. The process of corrosion can result in structural collapse by causing cracking, spalling, and a loss of integrity. The presence of chlorides, carbonation, pH level, and exposure to harsh conditions are some of the variables that might affect corrosion. The use of protective coatings and cathodic protection systems, appropriate material selection, routine maintenance and inspection, and design and construction methods are examples of preventive measures [4, 5].

Universal and restricted corrosion are the two primary types of corrosion that can affect a steel bar in reinforced concrete. The formation of isolated pits along the steel bars is a characteristic of pitting corrosion, sometimes referred to as localized corrosion. Generalized corrosion, on the other hand, disperses evenly across the steel bar [5, 6]. It is important to remember that the thickness of the concrete covering the steel reinforcement and the quality of the concrete both affect the passive layer's stability. They have an impact on the system's ability to keep out strong chemicals, which tend to alter the pore water's composition in ways that jeopardize embedded steel's passivity and consequently cause significant corrosion [7].

Loreto *in* 2011 [8] used linear polarization to study reinforced concrete steel bar corrosion. The relationship between concrete deterioration, fracture width, and residual strength was examined. Start phase length, aggressive agent penetration, and cover depth determine concrete cover life. Design considerations for exposure determine cover depth. Rapid specimen aging measured tensile strength, cracking depth, and corrosion. Concrete cover tensile strength was measured using the Brazilian split test. Calculated start and finish times using concrete diffusivity and residual life. Thus, concrete durability was best assessed by a short corrosion test. Pozzolan cement penetration was more resilient than chloride penetration. A study found that fracture breadth and corrosion rate decrease tensile strength. The study also matched accelerated test findings to natural exposure to assess lab vs. field exposure. A forecasted study indicated that thickening the cover extends lifespan by 25 years. While, Taher Shamsi in 2016 [9]. A theoretical and experimental study examined reinforced concrete structure longevity with respect to chloride permeability, concrete cover, and hardening. Reinforced concrete samples treated with 5% NaCl were tested for corrosion resistance using ten curing processes. The study had two parts: an accelerated corrosion test on 80 concrete prisms with a steel bar and 50 concrete cylinder compressive strength and chlorine permeability tests. To maintain 12 volts, samples were wired parallel to each other and powered by a direct current (DC) power source with the cathode (-) instead of the anode (+). The specimens were submerged in 5% NaCl to witness corrosion's commencement, splitting, and damage. The findings showed that specimens with higher chloride permeability and lower concrete cover had initiation periods from one to 53 days. Concrete cover effects on corrosion initiation periods were 1.5, 5, 14, and 37 days for 20 mm, 30 mm, 40 mm, and 60 mm coverings, respectively. Raising the concrete cover from 20 mm to 60 mm delayed cracking for 3, 9, 18, and 43 days.

Lou Chang in 2008 [10] tested concrete slabs reinforced with corroded and uncorroded bars. A four-point load configuration evaluated 70 slabs reinforced with 10 mm bending bars. Key factors were corrosion and bond length. Bond lengths were 10–440 mm, and corrosion was 0%–4.6% diameter loss. Extracting corroded bar test data from another study predicted slab moment capacity. The results show that rusted reinforcing slabs are predictable. Like pull-out tests, minor corrosion enhances slab flexural strength. Once bar diameter loss exceeds 2%, capacity reduces significantly. Data shows bond breakage causes most instant capacity reduction. When, Lubna B. Mahmood *in* 2023 [11] Examine how concrete cover thickness impacts longitudinal reinforcing steel corrosion in short circular high-performance concrete columns. The data showed that increasing concrete cover thickness from 10 to 20- and 30-mm reduced reinforcing steel weight loss by 12.47, 11.82, and 11.26 percent. Reinforcing steel cross-sectional area loss dropped 77.44, 64.00, and 57.75%. Bearing capacity decreased 29.07, 25.25, and 32.23 percent for 10-, 20-, and 30-mm clear coverings compared to control columns. According to experimental study Yaroslav Blikharskyy 2021 [12] found that corrosion damage did not affect strength characteristics when samples were subjected to a statically applied tensile strain in a hostile environment. Both strain and area reduction decreased simultaneously. Due to cyclic loads in a hostile environment, the fatigue limit drops to 20–24%

of the original samples' yield strength. This is two to three times lower than undamaged sample fatigue limits.

In this study, the effect of corrosion on the flexural behaviour of reinforced concrete slabs was investigated. Three periods of corrosion were studied: the corrosion of the reinforcement steel is weak, moderate, and strong, and each level has its consequences and effects on the reinforcement. The results showed that by increasing the number of days, that is, by increasing the level of corrosion, the ability to slab is supported by the stability of the cover and the diameter of the iron used.

Materials and Methods:

Materials:

The materials relied on and their properties are as follows:

1. Cement: Ordinary Portland Cement type I were used [13].
2. Fine Aggregate: The necessary concrete mix design is made from river sand with a maximum size of (4.75) mm and a fineness modulus (F.M=2.62) that satisfies IQS No.45 [14] specifications.
1. Coarse Aggregate: The concrete mix design satisfies the IQS No.45 '[14]' standards by using river gravel with a maximum size of 12.5 mm and a rounded partial form.

Table 1 shows Mix design details according to ACI 211.1 [15].

Table 1. Mix Design proportion

Ingredient	W/C	W	C	F.A	C.A
kg/m³	0.45	160	350	850	1040

2. Steel Reinforcement: Steel bars with a diameter of (6) mm is used for slab reinforcement. As shown in 'Table 2', the stress testing results for steel bars satisfy ASTM A615 [16].

Table 2. Steel Bar Reinforcement Test Results

Bar Diameter(mm)	Yield Strength (MPa)	Ultimate strength (MPa)	Elongation (%)
6	476	560	10.7

According to ACI 318-14, ρ should be not less than 0.0018. First check the slab dimension needed for minimum steel ratio (ρ) (ρ = 0.0018, 4 longitudinal steel bars of 8 mm with 100mm spacing).

The cross-section of each specimen measures 110 cm length,40 cm width and 7cm in depth with clear cover thicknesses 25mm. 4 Ø6 mm steel bars were used, with spacing of 100mm and bar length of 105 cm, shown in Fig. 1.

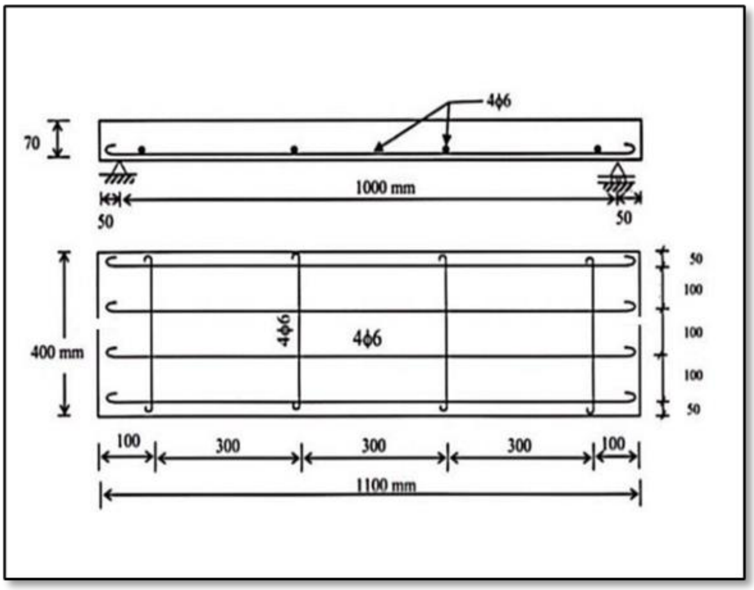


Fig. 1. *Slab Details (dimensions, steel diameter, and spacing)*

Experimental program:

This work was conducted under the effect of three major parameters:

1. Weak Corrosion (11% losses).
2. Moderate Corrosion (26% losses).
3. Sever Corrosion (40% losses).

Four reinforced one-way slabs were casted and cured for seven days, one is a reference and three specimens were exposed to corrosion in a special corrosion basin equipped with power supplies (see 'Fig. 2') with DC, where a plate was placed under the models to act as a cathode and the models to act as an anode for the purpose of completing the electrical circuit and obtaining the results of electrolysis (corrosion) with sodium chloride of 5% (NaCl).

a *b* *c*

Fig. 2 *(a. corrosion basin, b. power supply, and c. NaCl used)*

Slab Test:

As seen in Fig. 3, a detailed sketch of the test, a two-point load test was used to test the slabs. The slabs were simply supported with two loads applied at 333.3 mm from the supports over a span of 1100 mm. Using a displacement control testing device, the loads were applied. An LVDT was used to measure the mid-span deflection and a load cell was used to measure the load. Additionally, crack patterns were observed. 'Fig. 4' and 'Fig. 5' shows the samples during testing.

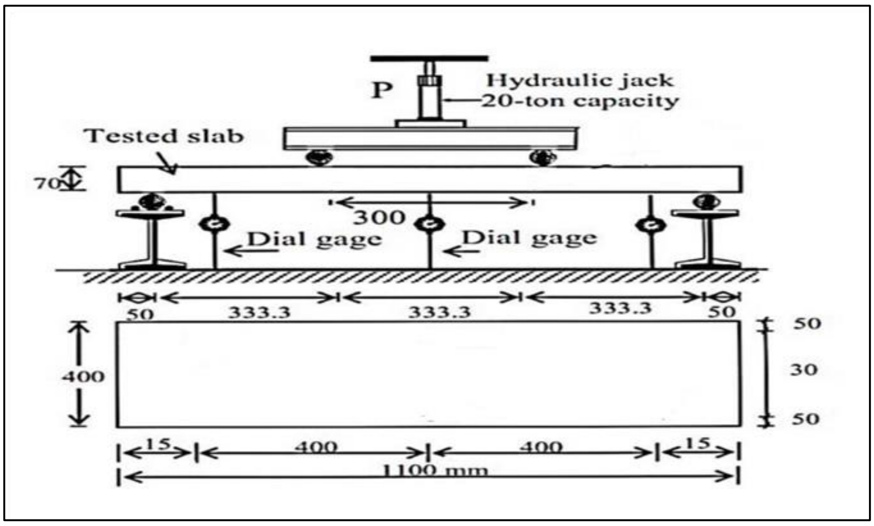


Fig. 3 *Test Setup*

a *b*

Fig. 4 *Slab Test*

Determination of Corrosion:

The rusted reinforcing steel bars were cleaned with kerosene oil to remove any remaining rust particles after the damaged slabs were tested and found to be unsatisfactory. Two methods were used to measure the amount of corrosion that happened in the steel bars; the cross-sectional area loss and the weight loss method. Li *et al.* (2018) [18] used these methods:

Weight loss percentage

The weight loss method was used to calculate the oxidation loss of the steel bars. To calculate the percentage weight loss, first weigh the bars both before and after the corrosion process. Then, use equation (1) to get the weight loss as a percentage:

$$W\% = (w1-w2)/w1*100\% \quad .... (1)$$

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

Surface Area loss

To determine the loss in surface area of the bar before and after corrosion, we relied on the weight before and after corrosion, and from it the area was calculated as shown in the equation below:

$$A_2 = (A_1\, W_2)/W_1 \quad ... (2)$$

Where A1 and A2 are the steel bar area before and after corrosion respectively. 'Table 3' show the weight loss and surface area loss for corroded slabs.

Table 3. Corroded slab details

Slab Symbol	weight before corrosion (g)	Area before corrosion(mm^2)	weight after corrosion(g)	Area after corrosion(mm^2)
S1	231.42	28.26	195.66	23.8
S2	231.42	28.26	162.65	20.4
S3	231.42	28.26	133.50	16.3

Result and Discussion:

The main and secondary bars, respectively, were weaker as a result of the rebar's loss of weight and area due to corrosion, which has major ramifications for rebar. Additionally, the steel bar that was directly linked to the electrical circuit observed a higher percentage of weight loss than the other bars. Because of the steel's initial strength, the loss rate was about 11% during the first ten days. However, throughout the course of the second period, the corrosion rate grew by 15% as a result of the steel's weakness and inadequate resistance to the corrosion. In the remaining interval, the loss rose in non-linear proportions as the number of days grew. Each of the three periods that were used as a basis for the corrosion percentages is displayed in 'Table 4, from which the corrosion was categorized into three groups: weak corrosion, moderately severe corrosion, and strong corrosion. As shown in 'Fig. 5', the flexural behaviour for each specimen were expected due to corrosion. The three corroded specimens showed an increasing in the maximum load from 15.2% to 18.65 to 39.9% as a result of loss weight for each level.

Table 4. Corrosion rate for each duration

Slab Symbol	Number of days	% Corrosion
S1	10	11
S2	17	26
S3	24	40

According to the results shown in Table 4, the corrosion rates were classified as follows in Table 5.

Table 5. Corrosion Classification

Number of days	% Corrosion	Classification
10	11	Weak
17	26	Moderate
24	40	Sever

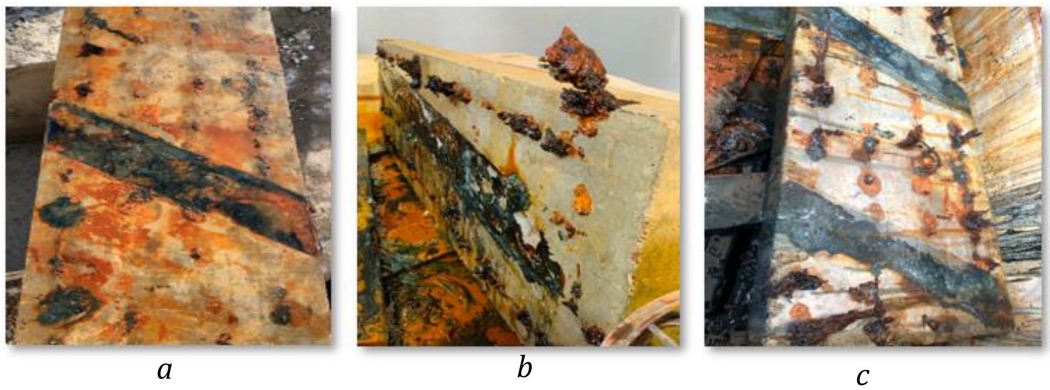


Fig. 5 *(a. weak corrosion, b. moderate corrosion, and d. sever corrosion)*

Overall load–deflection behaviour and maximum loads

Figure 6 depict the typical load-deflection behaviour of slabs with corroded and uncorroded reinforcement. Fig. 8 illustrates how corrosion affects the flexural behaviour of reinforced concrete slabs. It is evident from the load deflection curves (stress-strain curves) in Fig. 6 that corrosion reduces the load capacity at high deflections, the maximum load, and the post-cracking flexural stiffness. This figure also illustrates how toughness is impacted by corrosion. The results in Table 6 show that there were significant variations in the maximum load magnitude for medium and high degrees of corrosion. This suggests that corrosion-induced loss of bond at the interface, rather than loss in the bar region, is the main cause of the strength and stiffness loss in the reinforced concrete slabs examined in this work. The maximum loads that were achieved through experimentation are shown in 'Table 6, for the conditions of low, medium, and high corrosion, respectively.

Table 6. Maximum Loads for Tested Slabs

Slab Symbol	Classification	Max. Load (KN)
Reference	No Corrosion	20.4
S 1	Weak Corrosion	17.3
S 2	Moderate Corrosion	16.26
S 3	Sever Corrosion	12.60

Flexural Stiffness

Flexural stiffness is how much material resists bending when subjected to a force. It`s influenced by factors such as the material`s modulus of elasticity and its geometry, including its moment of inertia [19, 20]. It could be calculated by finding the factor "k" (slope of stress-strain curve in the elastic region (see in Fig. 6) as shown in equation (3).

$$\boldsymbol{K} = \frac{\boldsymbol{P\ max}}{\boldsymbol{D\ max}} \quad \ldots (3)$$

Where P_{max} is the maximum failure load and D_{max} is the maximum failure deflection.

It was shown that stiffness index decreased with increasing corrosion rate for the tested slabs as shown in Fig. 7 (a).

Flexural Toughness

Flexural toughness is the material's ability to absorb energy during repeated loading or multiple applications of bending forces. It represents the capacity to withstand multiple stresses without significant loss in the material's flexural properties. It is primarily expressed in terms of energy per unit distance (joules per meter) [21, 22]. Toughness can be calculated by measured as area under load deflection curve, from zero to the ultimate value of failure, as shown in Fig. 6. In the current investigation, Microsoft Excel was used to measure the area under the load-deflection curve (Toughness). The results show that increasing corrosion levels will increase the absorb energy (Toughness) as shown in Fig. 7 (b).

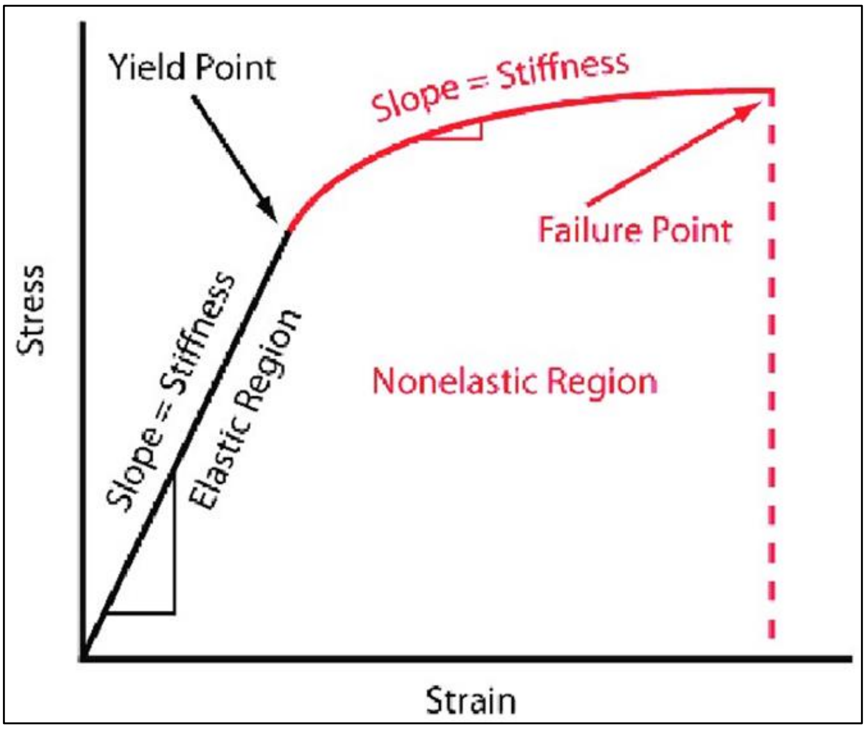
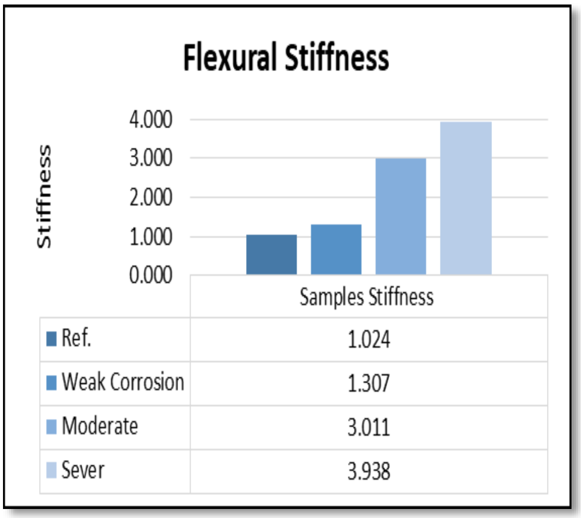
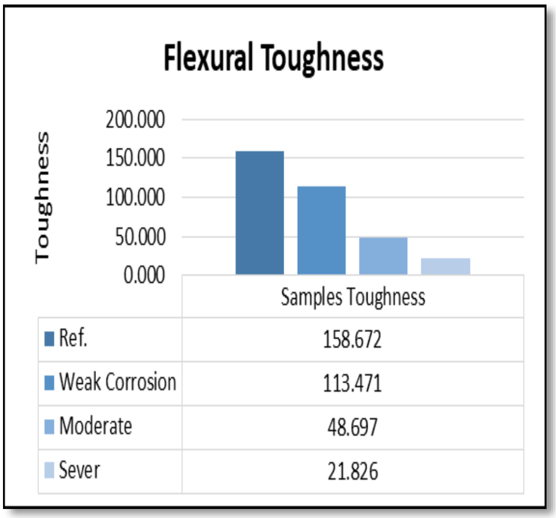


Fig. 6. *Ductile Material Stress-Strain Curve*

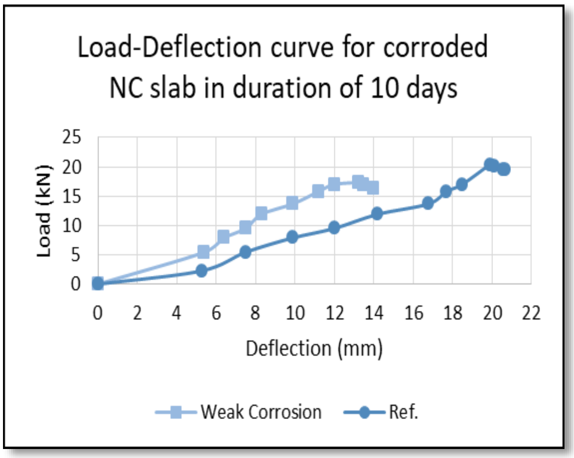


a

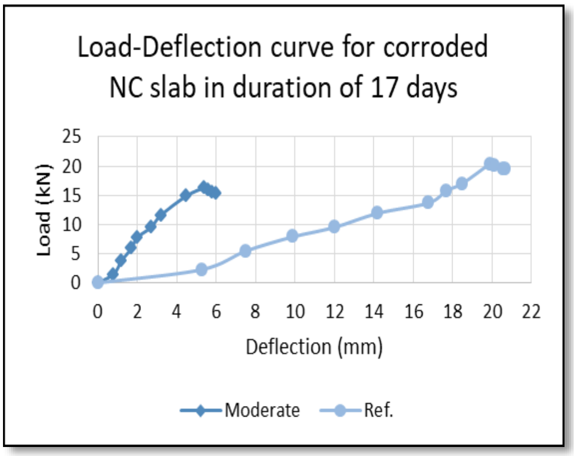


b

Fig. 7 *(a. Flexural Stiffness and b. Flexural Toughness)*



a



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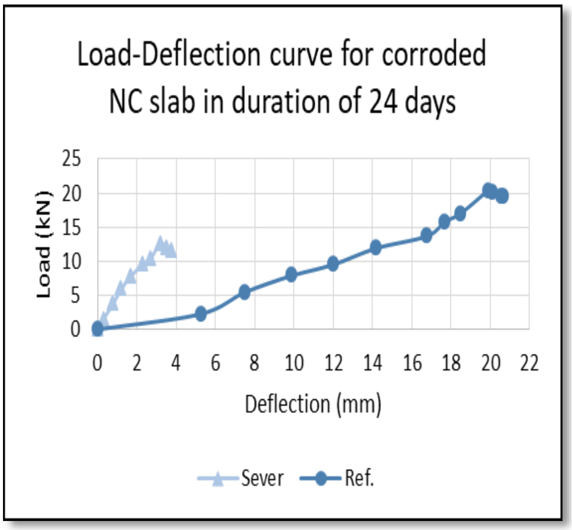
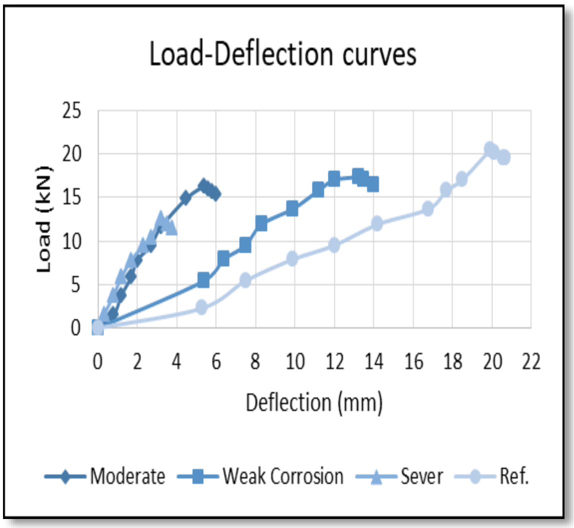


c



d

Fig. 8. *Load-Deflection Curves for the three specimens*

Conclusions:

The results show that the behaviour of the slabs with corroded reinforcement can be anticipated rather well and that the slab's flexural capacity rises somewhat with a little degree of corrosion. The findings support the theory that the primary cause of the decrease in moment capacity is bond breakdown. The experimental findings from this investigation allow for the following deductions to be made:

1. The results confirm the theory that the loss of tension force capacity due to bond degradation is more important than force loss resulting from a decrease in the cross-sectional area of bars.
2. As the diameter of the reinforcement increases, corrosion declines. So using big diameter was a suitable option for structural safety.
3. For structural toughness, raising the cover is usually advised.
4. Low corrosion percentages will not always have a negative influence on the strength of a reinforced concrete structure, and the length of corrosion up to a defined limit may be included in the usable life of a structure.
5. Cracks enable more water to enter, accelerating corrosion of anodic steel bars by increasing the current that passes through them
6. The application of accelerated corrosion process resulted a reduction in bars weight and cross section areas.

References

1. Broomfield, J. P. (2023). *Corrosion of steel in concrete: understanding, investigation and repair*. Crc Press.
2. Physical Assessment for Concrete Bridge Components Relative Reinforcement Corrosion. (1997). SHRP Workshop December.
3. El-Jazairi, B., Berke, N. S., & Grace, W. R. (1990). The use of calcium nitrite as a corrosion inhibiting admixture to steel reinforcement in concrete. *Corrosion of reinforcement in concrete*, 571-585.
4. Fu, X., & Chung, D. D. L. (1998). Effects of water-cement ratio, curing age, silica fume, polymer admixtures, steel surface treatments and corrosion on the bond between concrete and steel reinforcing bar. *Materials Journal*, *95*(6), 725-734.
5. Rodrigues, R., Gaboreau, S., Gance, J., Ignatiadis, I., & Betelu, S. (2021). Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring. *Construction and Building Materials*, *269*, 121240.
6. Vavpetič, P. (2008). Corrosion in concrete steel. *Kamnik*, 1-16.
7. El-Reedy, M. (2007). *Steel-reinforced concrete structures: Assessment and repair of corrosion*. CRC press.
8. Loreto, G., Di Benedetti, M., Iovino, R., Nanni, A., & Gonzalez, M. A. (2011, April). Evaluation of corrosion effect in reinforced concrete by chloride exposure.

In *Nondestructive characterization for composite materials, aerospace engineering, civil infrastructure, and homeland security 2011* (Vol. 7983, pp. 119-128). SPIE.

9. Tahershamsi, M. (2016). *Structural effects of reinforcement corrosion in concrete structures*. Chalmers Tekniska Hogskola (Sweden).
10. Chung, L., Najm, H., & Balaguru, P. (2008). Flexural behavior of concrete slabs with corroded bars. *Cement and Concrete Composites*, *30*(3), 184-193.
11. Lubna B. Mahmood, Assim M. Lateef (2023) ; Effect of Cover Thickness on the Corrosion Degree of Longitudinal Steel Bars in Reinforced High-Performance Concrete Circular-Short Columns under Concentric Loading.
12. Blikharskyy, Y., Selejdak, J., & Kopiika, N. (2021). Corrosion fatigue damages of rebars under loading in time. *Materials*, *14*(12), 3416.
13. Iraqi standard specifications No.5. (1984). Portland Cement. The Iraqi Central Organization for Standardization and Quality Control, Planning Council. (In Arabic).
14. Iraqi standard specifications No.45. (1984). Aggregates from Natural Sources for Concrete and Building Construction. The Iraqi Central Organization for Standardization and Quality Control, Planning Council. (In Arabic).
15. Dixon, D. E., Prestrera, J. R., Burg, G. R., Chairman, S. A., Abdun-Nur, E. A., Barton, S. G.,
16. & Lee, S. H. (1991). Standard practice for selecting proportions for normal, heavyweight, and mass concrete (ACI 211.1-91). Farmington Hills: ACI.
17. Standard, A. S. T. M. (2018). ASTM C33/C33M–18 Standard Specification for Concrete Aggregates. *West Conshohocken, PA*.
18. Li, H., Li, B., Jin, R., Li, S., & Yu, J. G. (2018). Effects of sustained loading and corrosion on the performance of reinforced concrete beams. *Construction and Building Materials*, *169*, 179-187.
19. Timoshenko, S., & Gere, J. M. (1987). Theory of Elastic Stability (2nd ed.). McGraw-Hill.
20. Beer, F. P., & Johnston, E. R. (2012). Mechanics of Materials (6th ed.). McGraw-Hill.
21. Popov, E. P. (1998). Engineering Mechanics of Solids (2nd ed.).
22. Callister, W. D., & Rethwisch, D. G. (2014). Materials Science and Engineering: An Introduction (9th ed.).
23. Ashby, M. F., & Jones, D. R. H. (2011). Engineering Materials 1: An Introduction to Properties, Applications, and Design (4th ed.). Butterworth-Heinemann.