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The Effect of Reinforcement Diameter on Accelerated Corrosion Level in Concretes

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Abstract To increase the tensile strength of reinforced concrete structures, strengthening steels of different diameters are placed in the concrete. The diameter of the reinforcing steel to which placed in the concrete may decrease due to electrochemical reactions. Therefore, the determination of corrosion rates in structures is vital for solving this problem. As the corrosion rate increases, flexibility and ultimate load carrying capacity decrease. In this study, reinforcing steel of ø12, ø14, and ø16 diameters was placed in the middle of the concretes and subjected to an accelerated corrosion test by applying a 30 V direct current (DC). When DC was applied to concrete, weight loss values, crack widths, compressive strengths, tensile strengths, and micro examination results were compared. As a result, it has been seen that the corrosion rate decreased as the diameter of the reinforcement steel increased. Another result obtained from this study is that the corrosion level could be predicted by measuring the current flow over the reinforcing steels. It has been observed that microcracks occur much less than when ø14 reinforcement was placed compared to ø12 and ø16 reinforcements were placed in concretes.

Keywords Accelerated Corrosion, DC Current, Corrosion Level, Concrete, Diameter

1. Introduction

It is known that the tensile strength of concrete is low. For solving this problem, the different diameters of reinforcement steels are placed in reinforced concrete constructions. Corrosion of reinforcing steel is one of the main factors causing the deformation of concrete structures [1-2], especially buildings directly exposed to NaCl solutions. The reinforcement steels to which placed in concrete may corrode over time and depend on various factors. For old buildings, it is very important to determine the corrosion level of the reinforcement steel placed in the concrete. In some cases, electro-chemical reactions occur due to the corrosion of the reinforcing steels in concrete structures [3-12]. Accelerated corrosion depends on the geometry and shape of rebars. It also depends on the fluid properties such as temperature, ph, salinity, and salts compositions [13-14]. When the reinforcement in the concrete corrodes, it causes critical structural problems [15]. Eventually causes the collapse of construction [16-17]. In recent years, researchers have conducted a monitoring technique to determine the corrosion level of steel bars [18]. In previous studies, reinforcement steels were exposed to corrosion using three laboratory techniques. These are accelerated corrosion using natural exposure [19-21], artificial climatic environments [22-25] and Accelerated corrosion using AC and DC. This study is vital for determining the corrosion rate of structural steel directly exposed to NaCl solutions such as seawater. This research is also important for determining the corrosion level of old buildings before they collapse and taking precautions. This study purposed to investigate whether corrosion rates could be predicted by measuring the current intensities passing over on different diameter construction steels.

2. Material and Method

2.1. The Materials Used and their Properties/Features

In preparing the concretes, CEM I 42.5 R type cement was used [26]. The physical and chemical features of cement are shown in Table 1. Potable tap water was used in the concrete mixture. In the experiments, S420 class reinforcing steels with ø12, ø14, and ø16 diameters and minimum yield strength of 420 MPa were used as reinforcing steel.

Table 1. Physical and chemical features of cement [26-27]

Content (%)	CEM I 42.5 R
CaO	63.6
SiO_2	19.6
Al_2O_3	4.72
Fe_2O_3	3.27
MgO	1.91
Na_2O	0.34
K_2O	1.06
SO_3	4.72
Cr_2O_3	0.04
TiO_2	0.41
KK	2.69
Specific weight	3.10
Fineness, cm^2/g	3308

2.2 Production of the Specimen and the Experiments Conducted

Concrete production was carried out with 300 dosages (weight of cement in concrete for 1 m^3 production). The water/cement ratio was designed as 0.60, and the mixing process was carried out with a 250-liter concrete mixer. While the concrete was being produced, the dry mixture was first made, and then the water was added and continued to mix for 5 minutes. The prepared concrete was placed in polyester cube molds whose sizes are 15cm x 15cm x 15cm. The component of concrete per cubic meter is shown in Table 2. The mixture calculations were designed by determining the saturated surface dry weights of the aggregates. Concretes were designed as crushed sand (0-4 mm), crushed stone medium aggregate (4-11.2 mm), and crushed stone coarse aggregate (11.2-22 mm). The specific gravities of crushed sand, crushed stone as fine, and large coarse aggregate were determined as 2.68 gr/cm^3, 2.69, and 2.70 gr/cm^3, respectively. One percent (1%) hyper plasticizer was added to give fluidity to the concrete.

After the prepared concrete was placed in molds, reinforcement steels with diameters of ø12, ø14, and ø16, respectively were inserted into the middle of the samples. The samples were produced as three pieces from each series. The total length of the reinforcing bars was designed as 20 cm before they were used in experiments. 13 cm of the reinforcing steel was embedded in the concrete. The samples were kept in room condition for one day, and then they were removed from the molds and cured with standard curing conditions in water saturated with lime for 28 days (Figure 1). Approximately 90% of the hydration reactions in cement-based materials can be realized after 28 days of curing. Then, the junction points of the bars and concrete were coated with epoxy. DC power supply (whose capacity is 30 V) was used for the accelerated corrosion mechanism. The samples were placed in a 3.5% NaCl solution, and a 30 V DC was applied until cracks occurred in the concretes (approximately 14 days). An amperemeter was used to measure the currents passing over the reinforcements steels inside the concrete. A computer was used for saving data. Data were recorded every 60 seconds. A view of the accelerated corrosion mechanism is shown in Figure 2.

Figure 1. Curing of concrete for 28 days

Figure 2. Accelerated corrosion mechanism

Concretes to which applied accelerated corrosion test were placed parallel to the cracks in the compression testing machine and pressure tests were performed (Figure 3). Compression strength tests were applied to samples in 3 groups. These samples are control samples without rebar, samples with including rebar, and samples including rebars used for accelerated corrosion test. Steel tensile tests were applied to the reinforcement steels that were removed from the concrete (Figure 4). Steel tensile tests were made on corroded and control rebars.

Table 2. Component of concrete per cubic meter [26-27]

W/c	Cement (kg)	Water (lt)	Crushed sand (0-4mm)	Coarse aggregate (4-11.2mm), (kg)	Coarse aggregate (11.2-22mm), (kg)	Hyper plasticizer (lt)	U.V.W (t/m^3)
0.60	300	180	1036	302	550	3	2.37

Figure 3. Comprassive strenght test on concrete

30 V DC stress intensity was applied to concretes containing steel in different diameters for approximately 14 days. After the accelerated corrosion test, the steels in the concrete were removed. After the accelerated corrosion test, the last diameters of steels were measured with a caliper (Figure 4).

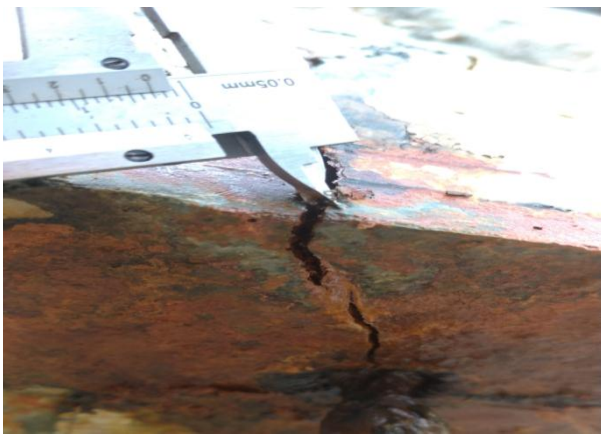

Figure 4. A view of after corrosion test

3. Discussion and Results

3.1. Current Pass through at Different Diameters of Reinforcement Steels

30 V DC stress intensity was applied for almost 14 days to the reinforced steels, whose diameters are ø12, ø14, and ø16 placed inside the concrete, then were put into a 3.5% NaCl solution. Figure 5 compares the electric current passage on reinforcement steels (ø12, ø14, and ø16) placed in concrete. When Figure 5 was examined, it was concluded that as the diameter of the reinforcement decreased, the intensity of the current passing over the reinforcement steel increased. The same results were obtained conducted by Hocaoğlu and Topçu [28]. The sudden peaks were observed in Figure 5. It was thought that these peaks indicate the formation of corrosion products. The fact that the current passing over the ø14 reinforcement steel was lower than the other diameter reinforcement means that less corrosion reaction occurred.

3.2. Weight Loss in Accelerated Corrosion

Weight loss rate, diameter loss rate, and weight losses with Faraday's law for reinforcement steels are shown in Figure 6. The loss rate of Faraday's law was calculated as follows.

$$M = (I * t * Aw) / (n * F) \tag{1}$$

In the formula, M; The mass (grams) of dissolved metal or converted oxide, I; its current through the concrete (mA), t; Time (seconds), Aw; Atomic unit weight of iron (55,847 grams), n; Iron atom valency (since the generally formed rust is $Fe(OH)_2$; 2 or 3), F; It expresses the Faraday constant (96487 coulombs).

A caliper was used to determine the diameter loss of steel. After the corrosion test was completed, the corroded rebars were cleaned with Clarke solution, and the weight loss amounts in the rebars were determined. Weight loss of reinforcement steels whose diameters are ø12, ø14, and ø16 were measured as 17.85%, 20.07%, and 31.75%, respectively (Figure 6). As a result of accelerated corrosion on reinforced steel, a loss of weight and decreased diameters were seen. The diameter loss ratios of reinforcement steels (whose diameters are ø12, ø14, and ø16) were calculated as 43.55%, 31.51%, and 25.31%, respectively (Figure 6). At the end of the accelerated corrosion test, the mass losses of different diameters (ø12, ø14, and ø16) of rebars, according to Faraday's law, were calculated as 51.86, 48.11, and 49.36, respectively.

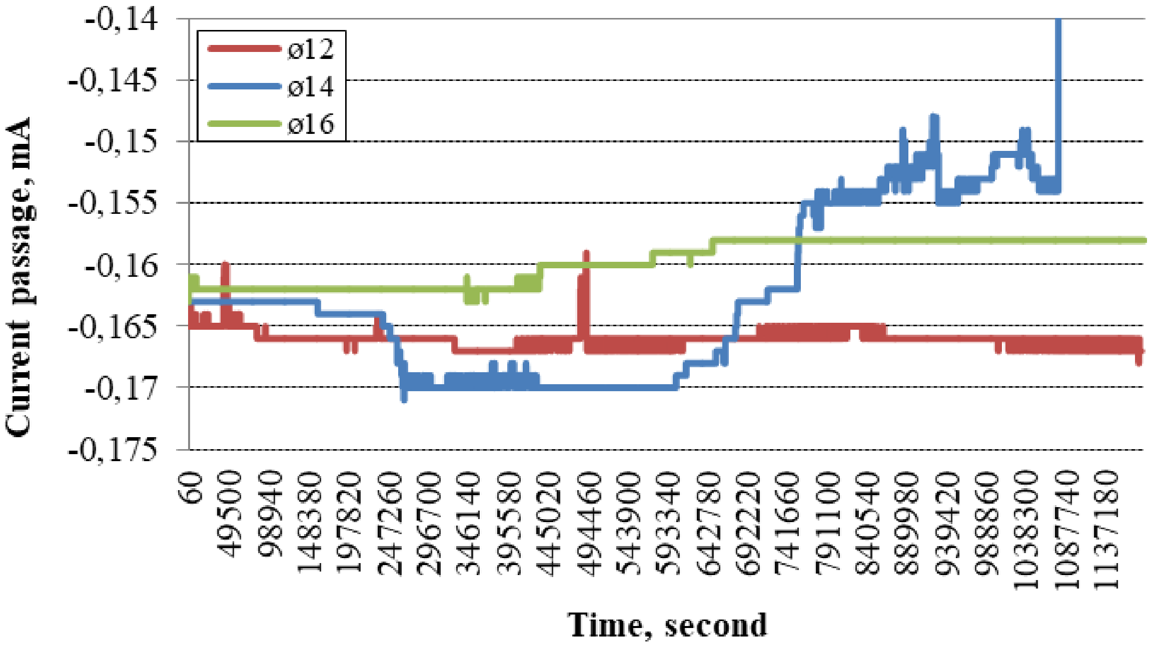

Figure 5. Electrical current passage on different diameters of reinforcement steels

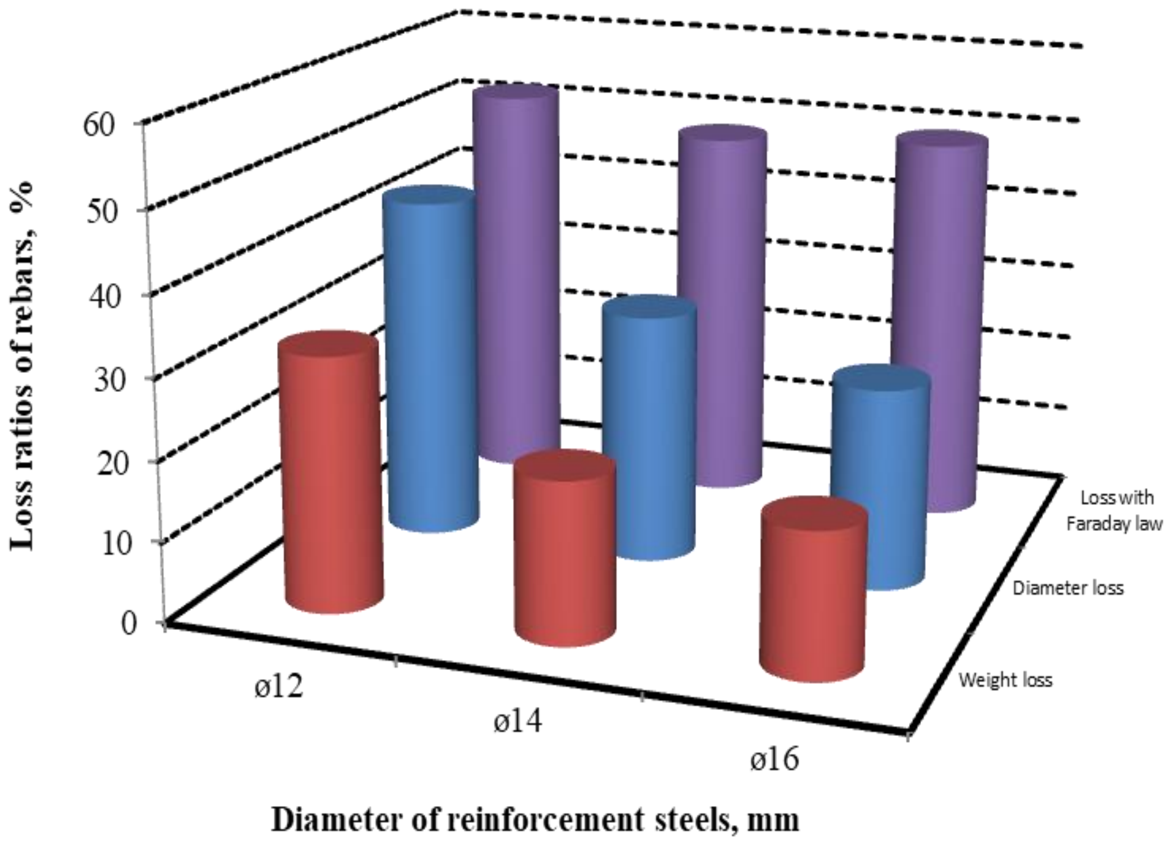

Figure 6. Weight loss- diameter loss and loss with faraday law ratios of rebars depending upon accelerated corrosion test

It has been observed that as the reinforcement diameter increased, the corrosion rates decreased. It was seen that corrosion in the diameter of the reinforcement steel of ø12 poses more risk than the others. At the end of the accelerated corrosion test, corrosion loss ratios of steels depending upon diameter are shown in Table 3.

Table 3. Corrosion loss ratios of rebars depending upon accelerated corrosion test

Diameter of steel	Corrosion loss ratio, %		
	Weight loss	Diameter loss	Loss with Faraday law (%)
ø12	31.75	43.55	51.86
ø14	20.07	31.51	48.11
ø16	17.85	25.31	49.36

3.3. Effect of Accelerated Corrosion Test on Crack Width

Figure 7 compares the corrosion ending times and crack widths of different diameters of rebars. The corrosion test was completed (end of the 14^{th} day) when a crack of approximately 0.27- 0.35 mm was formed in the concrete. The accelerated corrosion test was finished when the concrete cracks and the accelerated corrosion mechanism short-circuits. As a result of the accelerated corrosion test in concretes to which placed ø12, ø14, and ø16 reinforcement steels, the crack width has taken the lowest values in the concrete that placed ø14 reinforcement steel. This situation can be explained by the decrease of current passage in concrete, which placed ø14 reinforcement steel, especially when corrosion reactions begin. Accelerated corrosion tests on concrete that were placed ø12, ø14, and ø16 reinforcement steels have ended in approximately 14 days, 16 hours, 13 days 5 hours, and 14 days 17 hours, respectively.

Figure 8 compares the width of cracks in concretes to which placed different diameters of reinforcement steels at the last stage of the accelerated corrosion test (approximately on the 12th, 13th, and 14th days). It was observed that less cracking occurred in the concrete placed with ø14 steel compared to the concrete placed with ø12 steel. It was also observed that less cracking occurred in the concrete placed with ø12 steel compared to the concrete placed with ø16 steel. It was observed that the crack formation rate of the concrete to which placed ø14 reinforcement steel in the last stage of accelerated corrosion test is lower than the concretes to which placed other diameter reinforcement steel. This can be explained by that placed ø14 concrete takes lower negative current passage values. The crack widths formed in the concretes due to the accelerated corrosion test on the 12^{th}, 13^{th}, and 14^{th} days of the concrete with ø12, ø14, and ø16 reinforcement are shown in Table 4.

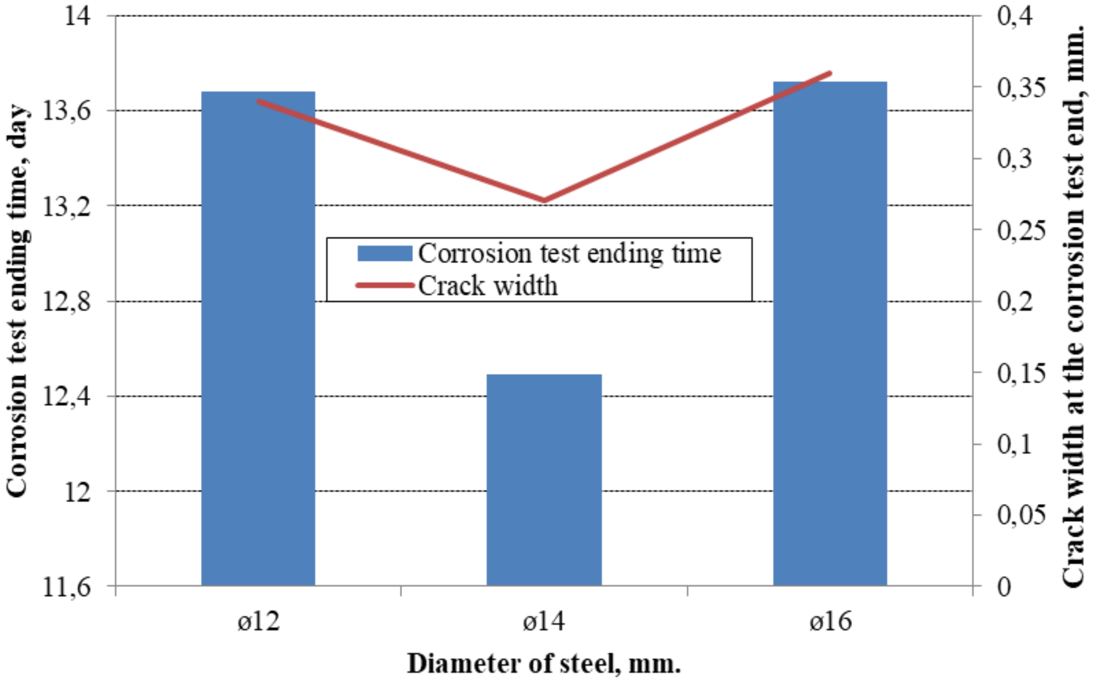

Figure 7. The corrosion ending times and crack widths of different diameters of rebars

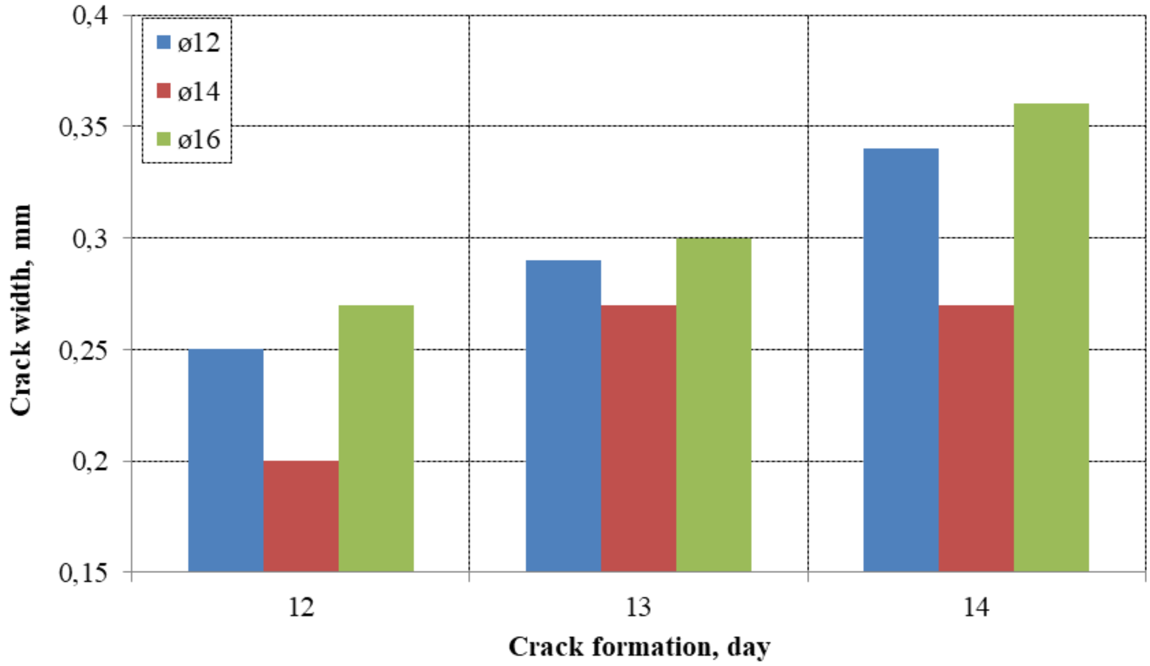

Figure 8. The width of cracks in concretes placed different diameters of reinforcement steel at the last stage of the accelerated corrosion test

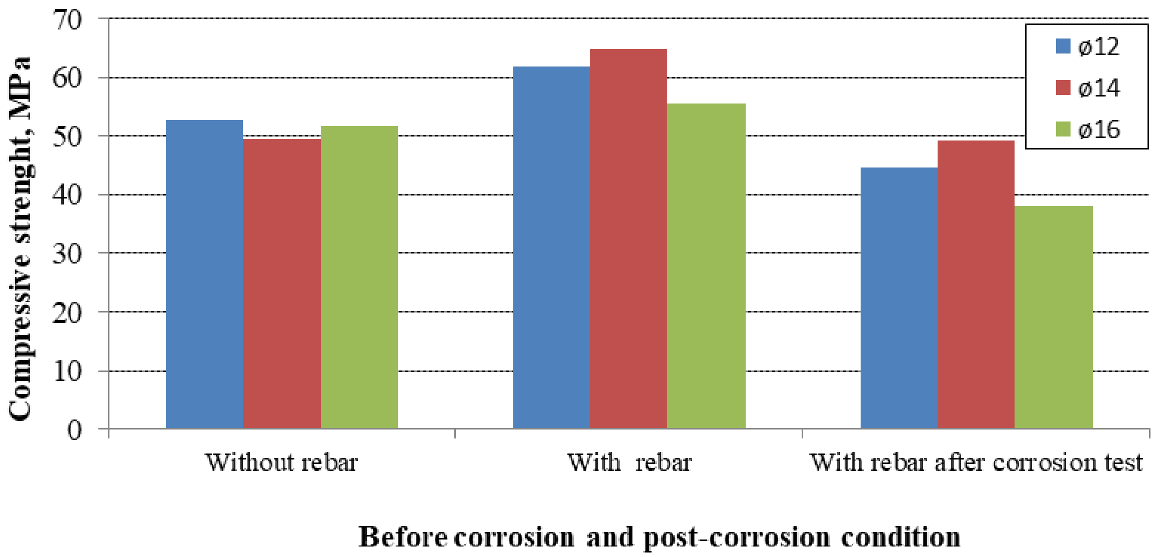

Figure 9. Change of compressive strength of the concretes in terms of DC application or not

Table 4. Comparison of crack formation in concrete after accelerated test application

Diameter of steel	The crack formation (mm) depending upon day		
	12	13	14
ø12	0.25	0.29	0.34
ø14	0.20	0.27	0.27
ø16	0.27	0.30	0.36

3.4. Results of Compressive Strength

Compressive strength is of great importance for cement-based composite materials. The high compressive strength of the cement-based material can also increase the service life of the structure. Figure 9 compares the compressive strength of concretes placed reinforcing steels of different diameters. In Figure 9, the first stun represents the control (rebar-free) concretes. The second stun represents the non-corroded specimens that placed reinforcement steel, and the 3rd stun represents both reinforced steel and accelerated corrosion test specimens. When ø12, ø14, and ø16 reinforcement steel diameters were placed in concretes, at the end of 28 days, the compressive strengths were approximately 20.51%, 26.52%, and 8.30% have taken higher values than the average of the control concretes. It was observed that the compressive strength of concretes to which placed ø14 reinforcement steel was higher than the compressive strength of concretes to which placed other diameter rebars; hence, it was thought the best adherence was achieved when ø14 reinforcement steel was placed.

As a result of the accelerated corrosion test, concretes to which ø12, ø14, and ø16 reinforcement steel were placed, 28-day compressive strengths of concretes were decreased by approximately 27.55%, 24.04%, and 31.29%. The compressive strength of the concrete in which the ø14 reinforcing steel was placed has taken at higher values than the concretes whose put other diameters of steel (ø12 and ø16). This can be explained by ø14 reinforcing steel has taken the lower negative value of the electrical current passage.

3.5. Results of Reinforcement Steel Tensile Strength

In this research, the rebars were placed in concretes and were put in a 3.5% NaCl solution, and a 30 V DC was applied for approximately 14 days. Then, the steels in the concrete were removed with the compressive strength test, and the tensile strength test was applied. Some investigations were tried to establish a relationship between reinforcement steel corrosion ratios and steel tensile strength. Moreno et al. [29] obtained the tensile strength of the 521.12 MPa for ø16 diameter of steel, which was corroded 15.21 ratio. In this study, with the 17.85 corrosion ratio, it reached 496.07 MPa tensile strength for the same diameter of steel. Figure 10 compares the tensile strengths of reinforcement steels depending on whether DC was applied. In general, it was observed that as the diameter of reinforcement steel increased, steel's tensile strength values were increased too (Figure 10). The tensile strengths of control reinforcement steels (ø12, ø14, and ø16) were measured as 570.18, 611.43 MPa, and 652.92 MPa, respectively. It was observed that when each diameter of steel specimens was exposed accelerated corrosion test, the tensile strengths were decreased. The tensile strengths of reinforcement steels (ø12, ø14, and ø16), which were exposed to accelerated corrosion tests, were measured as 438.83, 498.13 MPa, and 545.36 MPa, respectively. Decreasing tensile strengths of reinforcement steel can be explained by the cross-section losses occurring in diameters due to accelerated corrosion in the reinforcement steel.

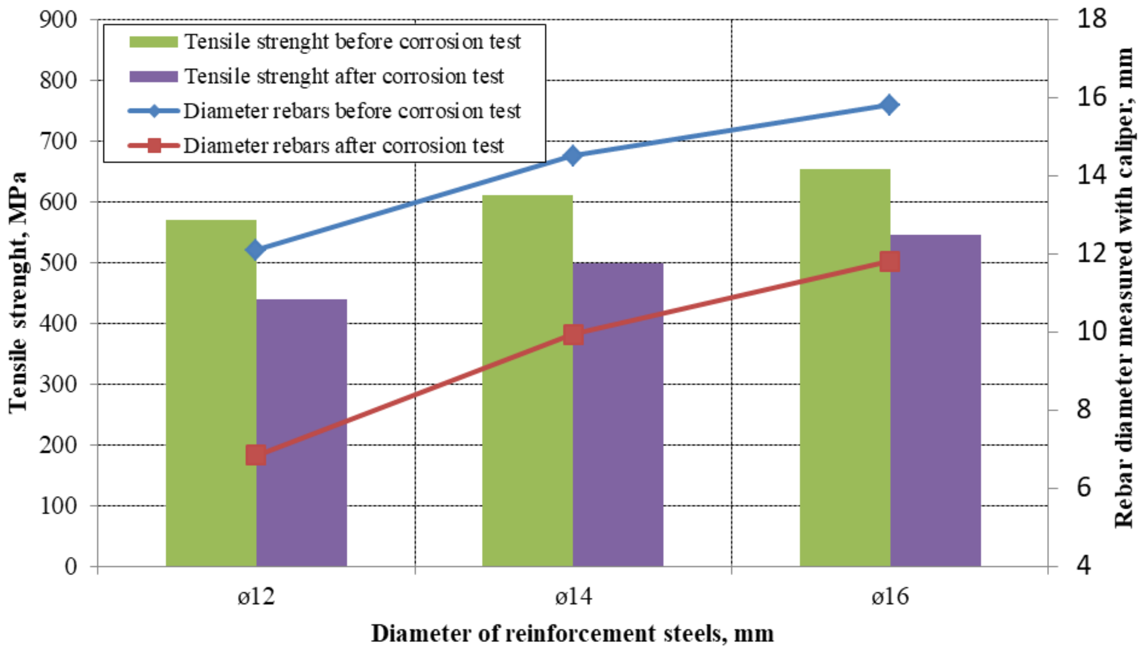

Figure 10. Comparing tensile strengths of reinforcement steels whose exposed to accelerated corrosion test or not

When the diameters of ø12, ø14, and ø16 rebars were placed into concrete and were put in a 3.5% NaCl solution, and constant 30 V stress intensity was applied, the tensile strength of rebars was decreased by 23.03%, 18.53%, and 16.47%, respectively (Table 5).

Table 5. Tensile strengths of reinforcement steels before and after accelerated corrosion test

Diameter of steel	Before corrosion	After corrosion
ø12	570,18	438,83
ø14	611,43	498,13
ø16	652,92	545,36

3.6. Prediction Diameter Loss Ratios with Applying DC Current

In the studies in the literature, it has been concluded that the corrosion level can be determined by using direct current in reinforced concrete [27-30]. This study investigated whether corrosion rates could be predicted by measuring the current intensities passing over on different diameter construction steels. To establish a relation between the first diameters of rebars and the first DC passage on concretes to which place ø12, ø14, and ø16 reinforcement steels. Figure 11 was prepared. The first current passages on concretes to which place ø12, ø14, and ø16 reinforcement steels were measured as -0.165 mA, -0.163, and -0.162 mA, respectively. It was observed that when the diameter of reinforcement steels was increased, the current passage on steels was raised too. In concretes to which placed reinforcement steel, when the first current passing over of the reinforcement steel is measured, information about its diameter can be obtained using the equation in Table 6.

The last current passage on concretes placed ø12, ø14, and ø16 reinforcement steels were measured as -0.166 mA, -0.154, and -0.158 mA, respectively. It was observed that when ø14 diameter reinforcement was placed in the concrete, the flow rate was lower than the other diameters of the steel (Figure 12). The fact that the lowest corrosion rate occurs in the concrete where ø14 reinforcing steel is placed can explain this situation. In concretes to which placed reinforcement steel and when the last current passage of the reinforcement steel was measured, information about its diameter can be obtained using the equation in Table 6.

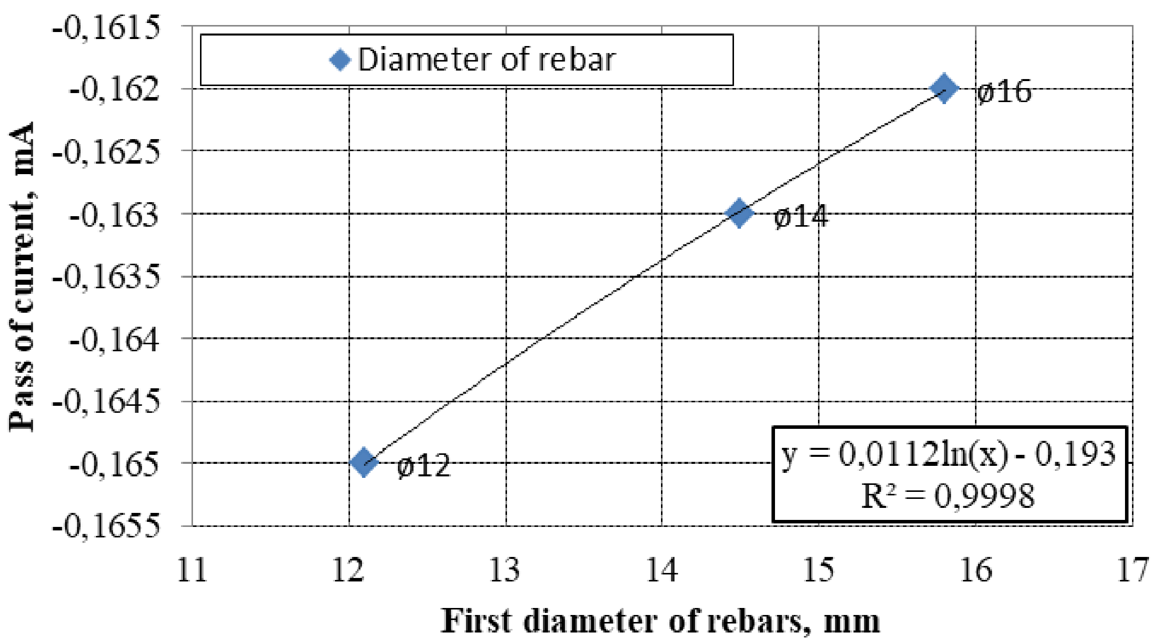

Figure 11. Relation between first diameters of rebars and first DC passage on concretes to which place ø12, ø14, and ø16 reinforcement steels

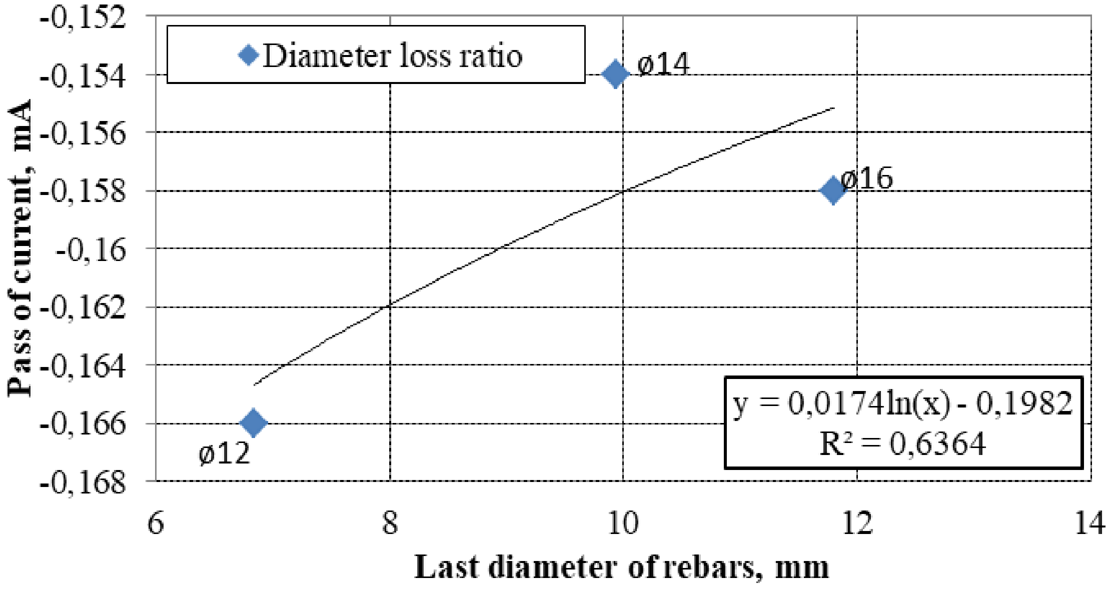

Figure 12. Relation between last diameters of rebars and last DC passage on concretes

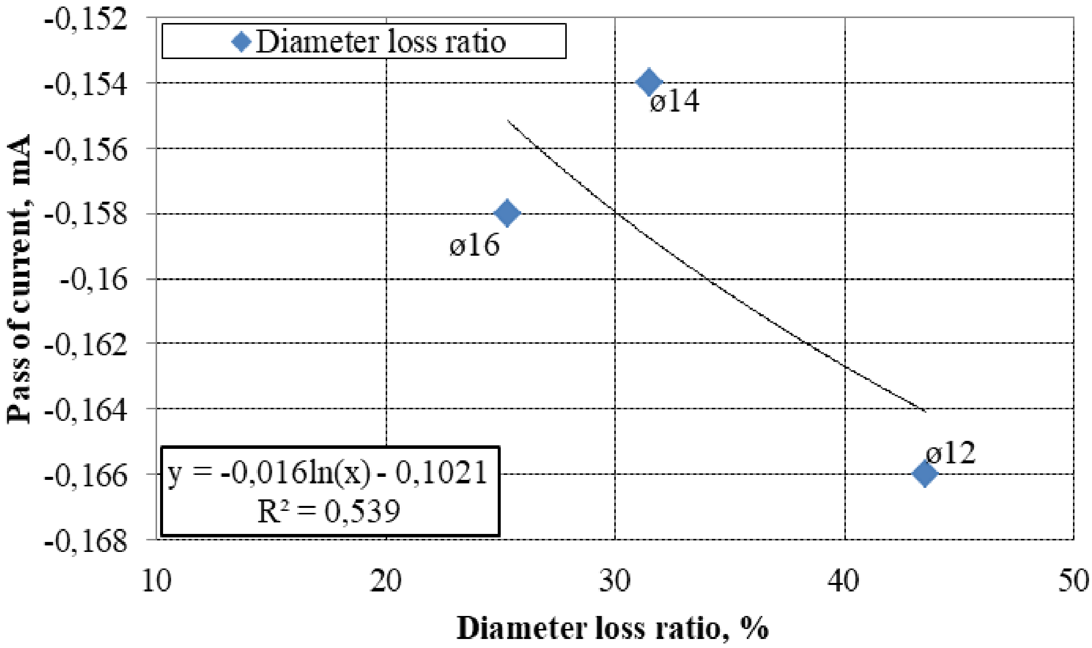

Figure 13. Diameter loss ratios of ø12, ø14, and ø16 reinforcement steels depending upon the accelerated corrosion test

Table 6. Equation and correlation coefficient for the relationship between corrosion ratio, first diameter, last diameter, and diameter loss of different diameters of steel

Prediction	Equation	R2
Prediction first diameter of rebars	y = 0,0112ln(x) – 0.193	0.9998
Prediction last diameter of rebars	y = 0.0174ln(x) – 0.1982	0.6364
Prediction diameter loss ratio of rebars	y = -0,016ln(x) - 0,1021	0,5390

The diameter loss ratios of ø12, ø14, and ø16 reinforcement steels were measured as 6.83%, 9.93%, and 11.80%, respectively (Figure 13). Diameter loss rates of steels can be estimated by measuring the current flow through the rebar (Table 6).

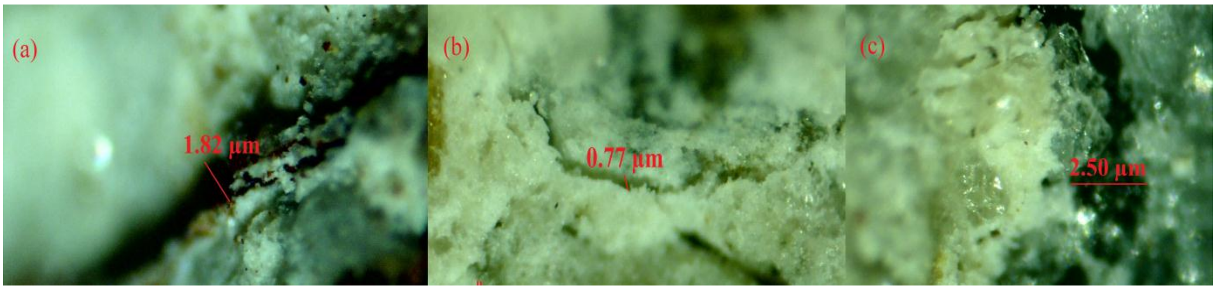

Figure 14. Microstructure views of the concrete to which placed different diameters of steel a- ø12, b- ø14, and c- ø16

3.7. Micro Examination of Concrete with Accelerated Corrosion Test

Microstructure photographs of 300-dosage concrete (28-day cured) with water/cement ratios of 0.60 and subjected to an accelerated corrosion test are shown in Figure 14. Microscope views were zoomed 1000x. In general, it was determined that when the diameter of steel was increased, the crack width increased too. It was seen that when Ø14 steel was placed in concrete, it had lower crack width than the other diameters. This situation can be explained as follows: when Ø12, Ø14, and Ø16 steel were placed in concrete, and current passage values were examined, concrete which had stuck Ø14 rebar has taken lover current passage values than the others.

Maximum crack width and crack area have been measured by the image program and shown in Table 7. When Table 7 was examined, the micro-crack areas of the concretes with ø12, ø 14, and ø16 reinforcement steels were measured as 6.059 μm^2, 1.640, and 8.022 μm^2, respectively.

Table 7. Maximum crack width and crack areas of concretes placed in different steels' diameters depending upon micro interview

Diameter of steel	Maximum crack width (µm)	Crack area (μm^2)
ø12	1,82	6,059
ø14	0,77	1,640
ø16	2,50	8,022

4. Conclusions

The diameters of the reinforcements steels in the concrete decrease due to corrosion reactions. Therefore, corrosion of reinforcement steel is one of the most critical problems in reinforced concrete buildings. Prediction of steel corrosion levels at the buildings is significant to prevent damage to the structures.

Several conclusions can be drawn from this study as follows:

- Corrosion in the diameter of the reinforcement steel of Ø12 poses more risk than the others.
- It was thought that the best adherence could be achieved when Ø14 reinforcement steel was placed in concrete.
- It was observed that when Ø14 steel was placed in concrete, it had lower micro-crack width than the other diameters.
- It was determined that the compressive strength of the concretes in which Ø14 reinforcement steel was placed had higher compressive strength than the concretes with other diameter reinforcement steel.The relationship between the first diameter of rebars, the last diameter of rebars, the diameter loss ratio of rebars, and the current passage on steels can be estimated using the equations in Table 6.

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