BAU Journal - Science and Technology

Volume 2 | Issue 1
ISSN: 2706-784X

Article 4

December 2020

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Recommended Citation

Abou Shakra, Jana; Joumblat, Rouba; Khatib, Jamal; and Elkordi, Adel (2020) "CORROSION OF COATED AND UNCOATED STEEL REINFORCEMENT IN CONCRETE," *BAU Journal - Science and Technology*: Vol. 2 : Iss. 1 , Article 4.
Available at: https://digitalcommons.bau.edu.lb/stjournal/vol2/iss1/4

CORROSION OF COATED AND UNCOATED STEEL REINFORCEMENT IN CONCRETE

Abstract

Corrosion of reinforcing steel is the one of the main causes of deterioration in reinforced concrete structure. During the initial stage of corrosion, the steel volume increases. This creates tensile stresses in the concrete, which can eventually lead to cracking, delamination, and spalling. This potential risk of corrosion in a structure is quite unpredictable. Therefore, this paper examines the influence of accelerated corrosion on the bond between concrete and the coated and uncoated steel bars. The bar coating consisted of epoxy rich in zinc. Six concrete mixes were prepared. Three mixes had cement contents of 300, 400 and 500 Kg/m3 and a water cement ratio of 0.4. In the rest of the mixes, cement was replaced with 10% silica fume and the water to binder ratio was 0.5. The reinforcing bars were placed inside concrete cylinders. After curing for 3 days, the specimens were immersed in a 5% NaCl solution for 7 days while a DC current of 5V flowed through them using a portable power supply. Different tests were conducted such as the accelerated corrosion test (ACT), the pull-out tests, compressive strength, and weight loss. The results show that coating the steel bars while lowering the water cement ratio with the addition of silica fume, reduces the effects of corrosion in reinforced concrete specimens

Keywords

accelerated corrosion, coated bars, corrosion, silica fume

1. INTRODUCTION

Corrosion of steel reinforcement is the main cause of deterioration of reinforced concrete structures. It is usually caused by the presence of deicing salt or chloride ions found in soiled aggregates or aquatic environments (Abosrra et al., 2011). Corrosion causes the concrete cover to crack after corrosion products are developed and the cross section of steel bars gets depleted (Kivell et al., 2012). This depletion is induced by several elements related to the concrete properties; steel's external form condition, surrounding environment, exposure period, and the addition of supplementary cementing materials (Song et al., 2008). Concrete samples with high W/C ratios have a greater volume of cavities and capillary pores which causes higher diffusion rates, whereas concrete with low W/C ratio and penetrability can withstand chlorides' intrusion into the steel bars, supplying a blockade against the oxygen access and thus, prolonging the time of corrosion origination (Chen et al., 2013). Also, with increased curing duration, chloride permeability decreases, resulting in a reduction in concrete permeability and corrosion consequently (Ghanem et al., 2018).

Reinforcing steel in concrete is normally protected from corrosion by the passive film formed at the steel/concrete interface inside the alkaline cementitious matrix (Cabarera, 1996). The steel defensive passive layer is damaged and vulnerable steel areas dissolve in the existence of chloride and other triggering agents. This passivation can also be eradicated either by a reduction in the pH value ($pH < 9$) due to carbonation, or the presence of chloride salts, which initiates an extensive corrosion of the reinforcing steel and in the long run spoils the concrete (Zhou et al., 2014). Corrosion has a big impact on the material weakening the bond among the material (Du et al., 2005). At the same time, it also affects the mechanical properties of the material such as the tensile strain, hardness etc. Apart from this, corrosion also has an impact on the safety factor. Corrosion has the capacity to bring serious damages to different concrete structures such as bridges, buildings, sanitary and water amenities, and others (Kelestemur et al., 2010).

The well-known bridge collapse at Pt. Pleasant, West Virginia, USA, killed 46 in 1967 and has been credited to stress corrosion cracking (Lichtenstien, 1993). Large sums of money are spent each year to compensate for these reparations caused by the spalling of concrete caused by corrosion cracking. Adding to the financial losses sustained, public safety is similarly risked, reaping lives as the example shows above. Industries raised the funds to examine different ways to avoid corrosion as to diminish the rate of substituting the corroded material (Roberge, 2019). The issue here is that the development of rust and other corrosion products encompasses a significant volume increase, which implies that the volume of corrosion products increases that of original steel bar (Asami et al., 2003). Consequently, extensive stresses are generated around corroded steel bars leading to probable cracking, spalling of concrete cover, and a decrease in the bond between steel/concrete and eventually lowering the serviceability of concrete constructions. This causes a dangerous situation for the people who are using the structures (Teply et al., 2012). Thus, when concerns rise about the durability of the structure, it is commonplace to take measures against corrosion attacks (Eldarwish et al., 2001). El-Darwish et al. (1997) reported adequate performance of concrete containing up to 30% (by volume) of ground steel slag as partial cement replacement when exposed to either sodium sulfate, magnesium sulfate solution or seawater. In addition, the incorporation of silica fume in reactive powder concrete was found to improve the durability properties when the cementitious materials content ranging from 800 kg/m^3 to 1090 kg/m^3 (Kurdi et al, 2001). Similar results on the durability improvement using cement replacement materials were obtained elsewhere (Khatib, 2009; Khatib et al. 2013; Khatib et al. 2014; Mangat et al. 2006)

Hence our study is carried out to determine the effect of the bar coating (epoxy zinc rich) on corrosion where half the samples are coated to test its resistance to corrosion and to determine the bond loss between the steel bar and the concrete. Also, the study focuses on the effects of different cement content (300, 400, and 450 Kg/m^3) and effect of addition of 10% silica fume by weight of cement on corrosion. The corrosion resistance has been evaluated by pull-out tests, compressive strength, and weight loss after conducting the accelerated corrosion test (ACT) where specimen are immersed in a 5% NaCl solution for 7 days and a constant current flows through them using a portable power supply.

2. EXPERIMENTAL

2.1 Materials

Ordinary Portland cement of specific gravity of 3.15 and silica fume of specific gravity 3.2 were used for the concrete mixes in this study. Fine aggregate (natural sand) of specific gravity 2.63 and coarse aggregate of specific gravity 2.77 and of maximum size of 19mm were used in the concrete mixes.

2.2 Mix Proportions

Concrete mixes were prepared using water cement ratios of 0.4 and 0.5. The ratio of coarse aggregate to the total aggregate was 60%, whereas the ratio on fine aggregate to the total aggregate was 40%. Silica fume ranging from 0% to 10% were added as a substitute to cement while casting concrete mixes. In the mixer, all concrete mixes were initially dry mixed for 3 minutes. When the desired workability was obtained, it was placed in moulds and vibrated on a table vibrator. The specimen was stored for a 24-hour period at room temperature before demolding and curing. The details of concrete mixes are shown in table 1 below.

Table 1: Concrete mix proportions with and without silica fume

Mix	Binder (Cement + Silica fume)		Water (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Fine Aggregate (Kg/m^3)	W/C	Unit Weight (Kg/m^3)
	Cement (Kg/m^3)	Silica fume (Kg/m^3)					
M_{300}	300	0	120	1144	763	0.4	2327
M_{400}	400	0	160	1096	723	0.4	2379
M_{450}	450	0	180	1110	740	0.4	2480
S_{300}	270	30	150	1132	756	0.5	2338
S_{400}	360	40	200	1081	722	0.5	2403
S_{450}	405	45	225	1078	718	0.5	2471

* Where M represents the mix with its corresponding cement content with no addition of Silica Fume, and S represents the mix with its corresponding cement content with the addition of Silica Fume.

2.3 Specimen Preparation and Testing

In this experimental study, specimens were prepared and evaluated as per relevant standards, as shown in figure 2 below.

2.3.1 Compressive strength

After 7 days of waster curing at 20C, the compressive strength was conducted according to ASTM C39 15ae1. Cylindrical specimens of 15cm in diameter and 30 cm in length were used to conduct the compressive strength test.

2.3.2 Pull-out test

The pull out test was performed on cubes of 15 cm in size in order to assess the bond between the steel and concrete. The testing conformed to ASTM A944. Cubes were cured in water at 20C for 7 days before testing. In this test each cube was placed in a steel mould sketched in figure 1 where the load was applied axially on the steel bar and the mould. The bond strength σ_b was calculated by equation 1 given below .

Eq. (1)

$$\sigma b = \frac{F}{\pi DL}$$

Where F is the tensile force at failure, D is the diameter of the steel bar, and L is the length of the steel bar embedded in the concrete.

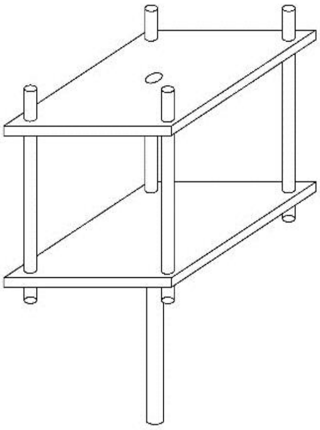

Fig.1: Sketch of the steel mould used in the pull – out test
Reference: Designed by the author, July 2015

2.3.3 Accelerated corrosion test

The accelerated corrosion test was performed on eight cylindrical specimens (15cmx30cm). Two specimens contained an uncoated steel bar no. 16, two specimens contained a coated steel bar no. 16, two specimens contained uncoated steel bars no. 20, and two samples contained coated steel bars no. 20. The specimens were immersed in a 5% NaCl solution with a constant current flow through them using a portable power supply. After 7 days, all cylinders were removed for inspection of cracks. Mass loss was calculated. In addition, crack number, length, and width was also recorded to enable comparison between the specimens.

Fig.2: Compressive strength, pull out, and accelerated corrosion tests
Reference: Photographed by the author November 2015

3. RESULTS AND ANALYSIS

3.1 Compressive Strength

Figure 3 shows the compressive strength for the various mixes. Each value is the average of two replicate specimens. The results presented in the study are the average of these two values in Figure 3. There is a systematic increase in compressive strength as the cement or binder content in the mix increases. There is an increase of 64.82% and 47.2% when the cement or binder content varies from 300 to 450 kg/m3 for mixes with and without SF respectively. Concretes containing silica fume had a lower compressive strength compared with those without SF. This is due to the higher water/binder ratio in the mixes containing silica fume of 0.5 compared with water/binder ratio of 0.4 for the other mixes.

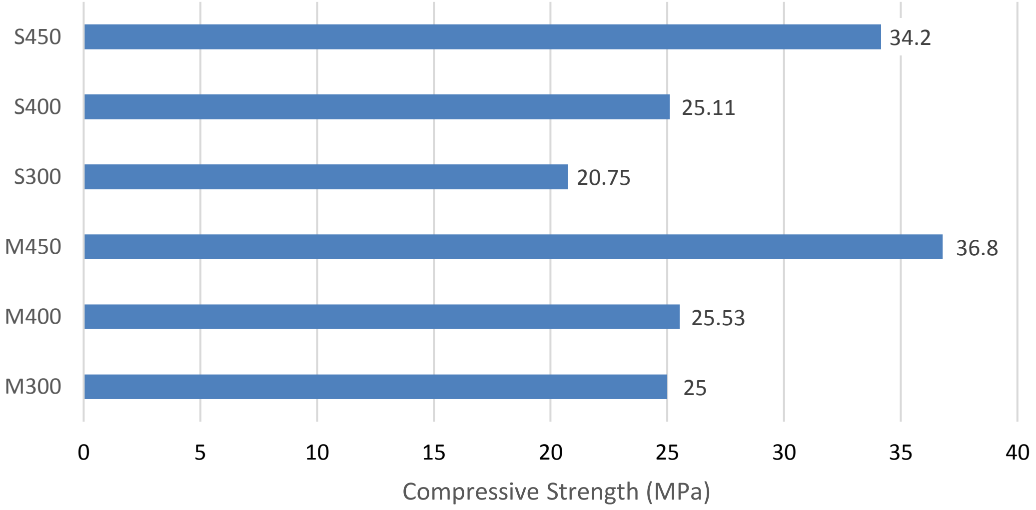

Fig.3: Compressive strength of the different mixes at 7 days

3.2 Pull-out Test

The pull-out strength of coated and uncoated bars for the various mixes are shown in Figures 4 and 5 for mixes without and with SF respectively. Two replicate specimens were tested, and the average is shown in the figures.

Mixes having cement or binder content of 300 kg/m^3 (M_{300} and S_{300}) and water/cement ratio of 0.4 and 0.5 respectively, showed similar results. The coated bars showed higher pull-out strength than those which are coated. Results show that the greater the bar diameter, the higher the bond strength.M_{400} at water cement ratio of 0.4 scored higher pull out strengths than M_{300} and S_{300}. Coated samples showed lower strengths than the uncoated samples and little difference between the strengths of the samples with no. 16 and no. 20 bar diameter was detected as seen in figures 4 and 5. S_{400} at water cement ratio of 0.5 showed lower strengths than M_{400}. But as figures 4 and 5 show, the coated samples showed lower strength than the uncoated samples similar to M_{400}. As concerning the mixes M_{450} and S_{450} at water cement ratio of 0.4 and 0.5 respectively, the samples scored the highest bond strength between all the mixes, but also the uncoated samples showed higher bond between concrete and steel than coated samples. The difference between the no. 16 and no. 20 bar diameter samples was considered insignificant.

Thus, it was inferred that mixes with the highest cement content showed higher pull-out strengths. Also, the epoxy rich in zinc coating reduced the bond between the steel bar and concrete resulting in lower pull-out strengths.

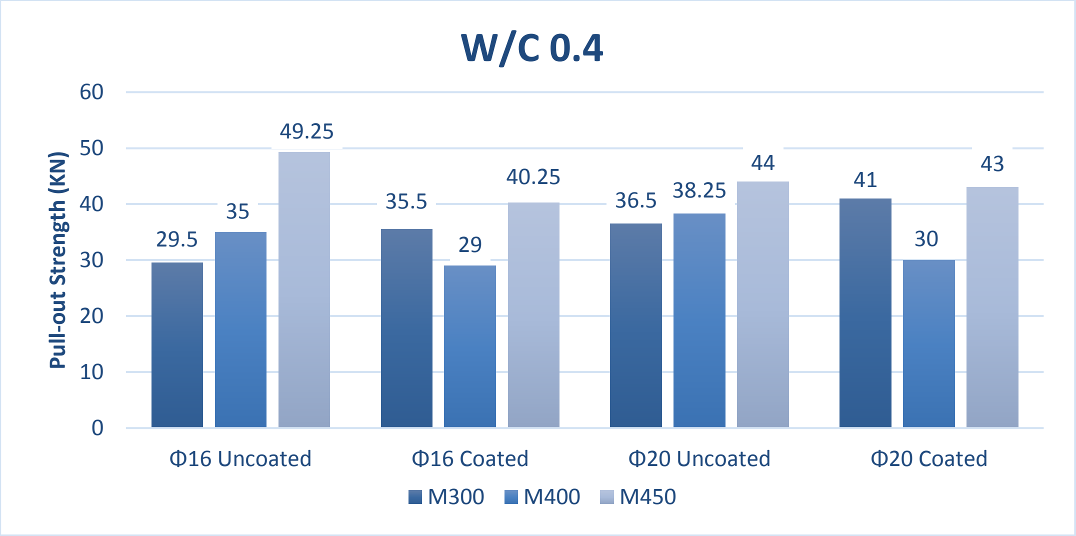

Fig.4: Variation of pull-out strength of mixes without silica fume with respect to water cement ratio 0.4

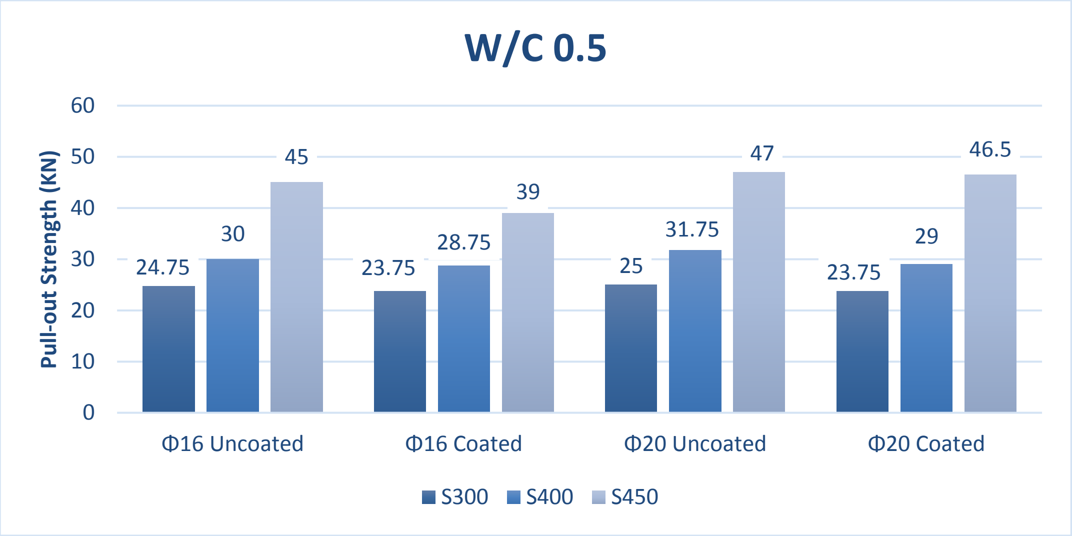

Fig.5: Variation of pull-out strength of mixes containing silica fume with respect to water cement ratio 0.5

3.3 Mass Loss From Accelerated Corrosion Test

The % mass loss for different mixes M300, M400 and M450 is shown in Figure 6 and for the other mixes is shown in Figure 7. The mass loss for uncoated bars was significantly higher than those coated. However, the mass loss in coated bars is nearly negligible. The presence of silica fume in the mixes reduced the % mass loss, even though these mixes were prepared at a higher water/binder ratio.

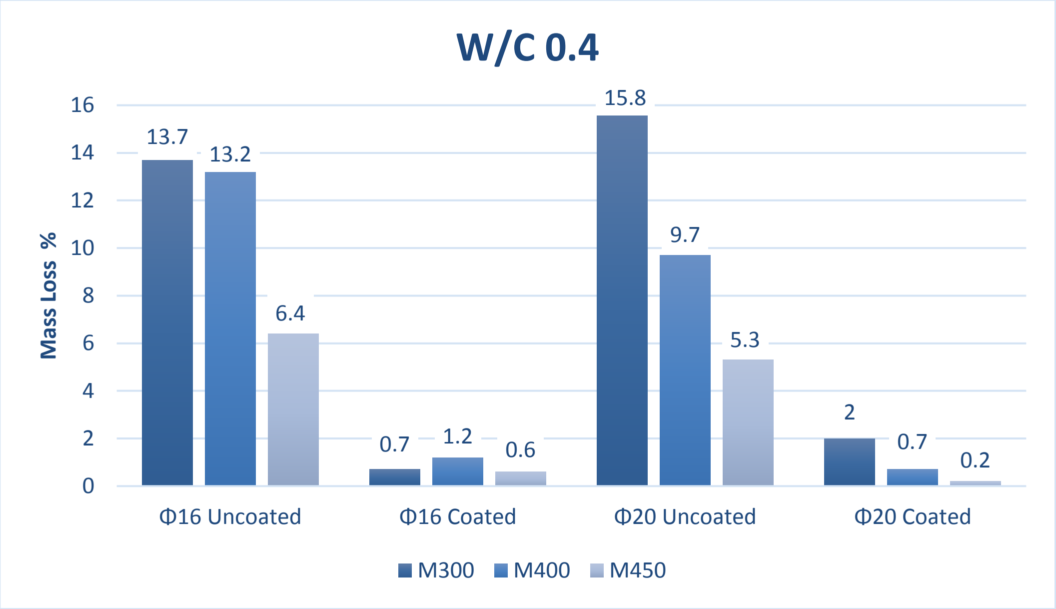

Fig.6: Variation of mass losses of coated and uncoated steel bars at water cement ratio 0.4

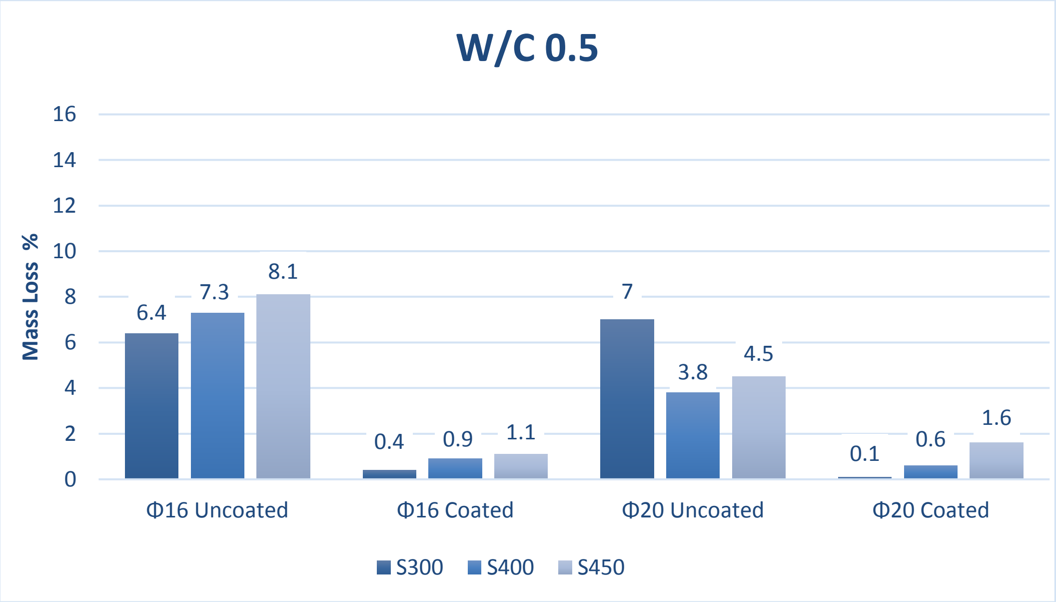

Fig.7: Variation of mass losses of coated and uncoated steel bars at water cement ratio 0.5

3.3.1 Crack number, length, and width

Two cracks were observed in M_{300} in average for each of samples no. 16 and 20 uncoated each of approximate length of 16cm and width of 3mm, and only fine cracks were spotted in samples no. 16 and 20 coated of length of 3cm and width of 0.2mm.

Whereas in S_{300}, an average of two cracks in samples no. 16 and 20 uncoated each of approximate length of 19cm and crack width of 6mm, and an average of one crack was seen in the coated samples with crack length of 5cm and width of 3mm, as recorded in figure 8.

An average of two cracks was spotted in M_{400} in no. 16 and no. 20 uncoated samples of approximate length 13cm and width 1mm, whereas in the uncoated samples, no cracks were spotted .

An average of two cracks was spotted in S_{400} in samples no. 16 uncoated of approximate length of 13cm and width of 1mm, and an average of three cracks in samples no. 20 uncoated of length of 13cm and width of 1mm, whereas in the uncoated samples, no cracks were seen, as shown in figure 8.

Three cracks in average were seen in M_{450} for each of samples no. 16 and 20 uncoated of length of 10cm and width of 1mm, and no cracks were spotted in samples no. 16 and 20 coated. Whereas, an average of two cracks was spotted in S_{450} in samples no. 16 uncoated of length of 9cm and width of 1mm, and an average of 4 cracks in samples no. 20 uncoated of length of 8cm and width of 0.5mm, whereas in the uncoated samples, no cracks were seen.

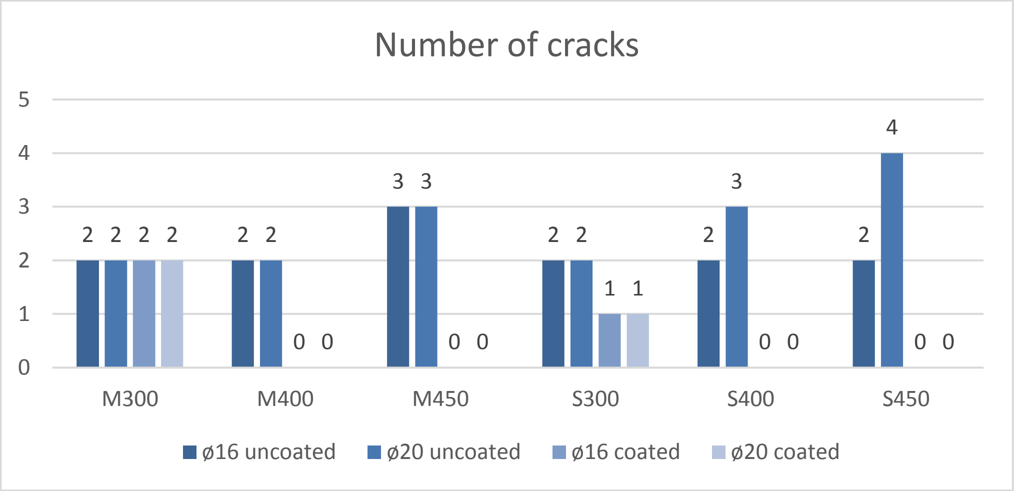

Fig.8: Variation of crack number in each sample of the different mixes

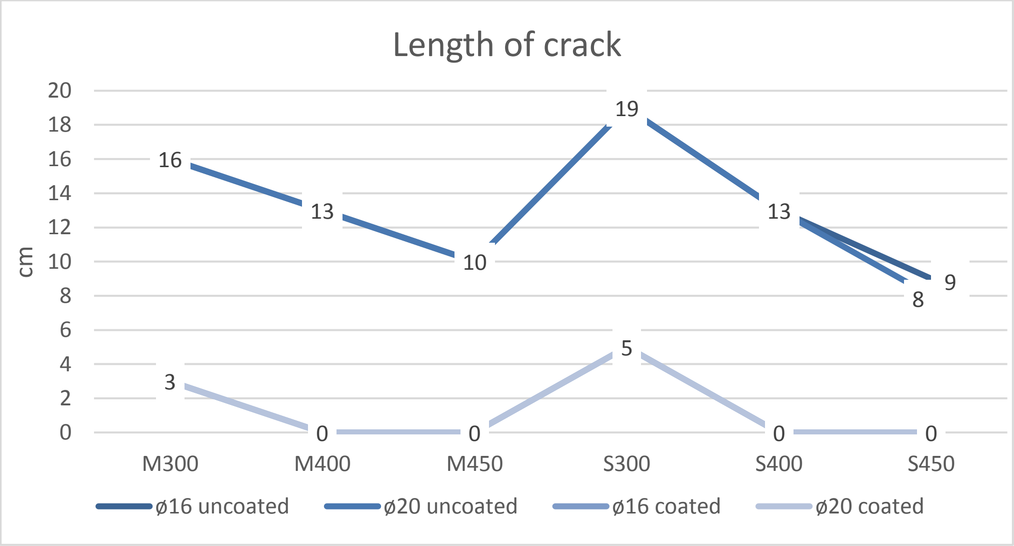

Fig.9: Variation of crack length in each sample of the different mixes

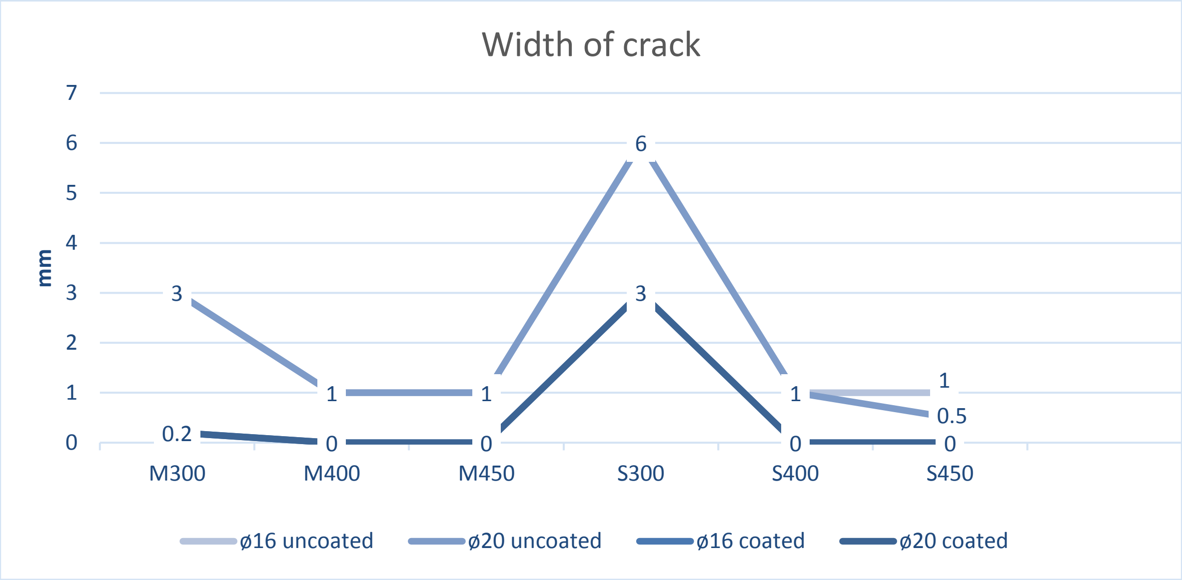

Fig.10: Variation of crack width in each sample of the different mixes

4. CONCLUSIONS

In the present study, the corrosion of coated and uncoated samples with and without silica fume (0 and 10%) was evaluated by carrying out an accelerated test. Different concrete mixes were considered with cement contents of 300, 400, and 450 kg/m^3 and varied water/ binder ratio (0.4 and 0.5). Compressive strength, pull-out, and accelerated corrosion tests were performed according to the relevant standards. Based on the results and analysis, several conclusions are derived:

A. The bond strength and the mass loss are reduced for coated bars. Also, the number, length, and width of cracks were reduced, which implies that coating reduces the corrosive attack on the steel bars.
B. Having concrete with higher cement ratio and lower water content lowers the corrosion rate, due to lower diffusion caused by the decrease in volume of capillary pores present in concrete.
C. The lesser the diameter of the steel bar, the lower attack of corrosion. Since it takes the chlorine more time to destroy the inert film formed at the steel/concrete seam.
D. The water cement ratio exhibited as the central element controlling the chloride ions passage. This effect is attributed to the permeability of concrete, because the lower the water/cement ratio is, the lesser the mass loss of the steel bars which results in lower percentages of corrosion .
E. The addition of silica fume in concrete presented a reduction in weight loss bars, where the degree of loss is proportional to the water cement ratio. The use of silica fume tends to be more advantageous for concrete with lower water/cement ratios and less effective for high values of the water/cement ratios.

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