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Pull-Out Behavior of Steel Bars Exposed To Accelerated Corrosion and Embedded In Different Concrete Mixes

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ملخص:

في هذا البحث تم دراسه تأثيراستخدام اسمنت خبث الافران (CEM-III/A) المصنع في احدي الشركات المحليه وخليط من نفس نوع الاسمنت مع نسبه 20% من الرماد المتطايرعلي قوه الاقتلاع و النقص في قطاع حديد التسليح المستخدم داخل الخرسانه المسلحه المصنعه من هذه الانواع قبل و بعد التعرض لعمليه الصدأ بواسطه اختبار التيار المؤثر ومقارنه النتائج مع مثيلتها من الخرسانه المصنعه من الاسمنت البورتلاندي العادي (CEM I). تم استخدام عدد 432 عينه ذات شكل اسطواني تحتوي علي قضيب حديد تسليح وحيد في المنتصف علي ان يكون جزء منه داخل الخرسانه و اخر بالخارج و ذلك في اختبار التيار المؤثر لبحث تأثير كل من : اختلاف سمك الغطاء الخرساني واختلاف نسبه المياه الي الاسمنت و نوع و كميه الاسمنت المستخدمه و مده التعرض لاختبارالتيار المؤثر(التعرض للصدأ). تم دراسه تاثير الصدأ من خلال الفقد في قوه الاقتلاع للتسليح و التاكل و نقص القطاع لقضيب حديد التسليح في العينات الاسطوانيه . تم تأكيد و ربط النتائج من خلال اختبارات مقاومه الضغط للخلطات الخرسانيه المستخدمه ونتائج التيارالكهربي المقاس في اختبار. هذه الدراسه اثبتت ان استخدام انواع الاسمنت المذكوره سابقا في صناعه الخرسانات المسلحه تزيد من ديمومه الخرسانه من خلال (التقليل في التيار المار بها و تقليل الفقد في مقاومه الاقتلاع و تقليل الفقد في حديد التسليح) معتمدا في ذلك علي سمك الغطاء الخرساني و نسبه المياه الى الاسمنت

Abstract

In this research work, the pullout behavior of steel bars- embedded in different concrete mixtures- was investigated after various exposure periods to accelerated corrosion condition. The investigated concrete mixtures were made of local manufactured Egyptian slag cement (CEM-III/A), and (CEM-III/A) partially replaced with 20% of fly-ash. On the other hand, the influence of different water/binder ratios and binder content, for the investigated concrete mixtures, in addition to the steel concrete cover were also considered. The influence of corrosion exposure on the pull out force and the steel bar cross sectional area was investigated before and after corrosion exposure. All these results were compared with the case of using ordinary Portland cement (CEM I) concrete mixture. A total of 432 lollipop specimens were exposed to impressed corrosion current technique. The corrosion is quantified by measuring the pull-out force loss and rebar diameter loss. The results were correlated to: compressive strength for the used concrete mixtures and the impressed current values. This study proved that the using the aforementioned blended cement types -in reinforced concrete- enhanced the concrete corrosion protection and hence providing less pull-out force loss and diameter loss depending on concrete cover and w/b ratio.

Introduction

The embedded steel rebar profile surface and the geometry of the ribs along its length will evaluate the amount of mechanical interlocking bond, adhesion, and friction that can be generated between rebar and concrete, where the force transfers between the ribs

and the concrete keys thus the ultimate bond strength is reached and the behavior of reinforced concrete member is influenced. Bond strength of corroded rebars remains available as long as the confinement around the rebar is not completely impaired. This phenomenon is fundamental because it influences many aspects of the behavior of reinforced concrete such as cracking, deformability, instability and others [1,2]. Bond loss between the embedded steel rebar and the surrounding concrete is expected result due to the cracking and spalling of the concrete cover caused by the corrosion products on the bar surface lead to confinement loss, bond strength reduction at the (ITZ) interfacial transition zone, and friction component reduction of the bond strength. Also the ribs deterioration of deformed rebar causes a significant reduction of the interlocking forces between the ribs of the bars and the surrounding concrete where the interlocking criteria is a primary and mainly mechanism of the bond strength, since a 2% diameter loss could lead to 80% bond reduction [3] when no confinement provided by concrete cover reduction in bond strength appear [1,2].
Different test types investigate the bond force, where the most popular one is the pull-out test due to its ease of preparation, and fabrication and simplicity of test procedure, Hence, pull-out test would be adequate for studying the effect of different parameters on bond strength such as comparison of different concrete mixtures cast with deferent (cement content, cement type, and w/b ratios). Also the effect of concrete cover at the various corrosion levels [1]

New cement types are being promoted with many objectives among them: cost saving, environmental protection; which means the decreasing of the emissions of carbon dioxide which contributes to the global warming problem, and conserving the resources, and decreasing the energy consumption which is needed for cement clinker production [4,5,6]. Therefore, using a mixture of cement clinker and other alternative materials – such as ground granulated blast-furnace slag (GGBS) or fly ash (FA) - in concrete production helps to partially address economic and environmental problems corresponding to the use of cement clinker. It also improves some properties of both fresh concrete (increase: cohesion and workability, the setting time; and reduce: bleeding, segregation and, etc.), [5,10,11], and hardened concrete (reduce permeability and porosity; and increase the long-term strength) [5, 9, and 10]. Five main different groups introduced a total of (27) different cement types are in the new Egyptian standard specification for cement (ESS 4756/2006) [11]. With intentions to enhance concrete performance and reduce the environmental impact of cement industry; the use of these (5) different cement groups is promoted. Additionally the Egyptian standard is very close to British standards (BS EN 197-1:2011) [12] in the way of cement classification.

Corrosion of embedded steel rebars in concrete structures is often not uniform. Corrosion areas depends on the environmental and material conditions such as the availability of moisture, oxygen, chloride ions, carbon dioxide, and the efficiency of the electrical path resistivity through the concrete which is depends on physical concrete properties[13,14,15,16]. The most famous corrosion types are general (uniform) corrosion, and pitting (localized). The most direct effect of corrosion is the reduction in reinforcement diameter and cross-sectional area. This may have a significant effect on the safety and integrity of the concrete structure if the loss of section is severe and the working stresses in the reinforcement are high. Additionally, Corrosion of steel produces an insoluble chemical by-product commonly known as rust products, which have volume 3–8 times greater than the original metal volume [17,18]. This generates expansive stress around corroded embedded steel rebars causing cracking, spalling, and delamination of the concrete cover and bond loss between steel rebars and concrete, which further accelerates corrosion and thus reducing the serviceability of concrete structures.[6,13,15,17,18,19].

The impressed current method for lollipop specimens is one of the most famous and reliable corrosion acceleration methods and it has many advantages, such as obvious saving in time and cost, providing different (RFT diameter- length of RFT exposure – concrete cover). Additionally it is considered as the easiest way of (carrying –moving – transporting) the specimens. One advantage over other techniques is the ability to control the rate of corrosion by changing the resistivity, oxygen concentration and temperature. The process of steel corrosion in both accelerated and normal corrosion techniques is similar [6,19].

The objective of the present work is to studying the pull-out behavior of corroded rebar for lollipop specimens by impressed current technique using different parameters, which are (different; cement type, and cement content, w/b ratio, compressive strength, concrete cover; and time of exposure).

1. Experimental program

1.1. Materials

Two Local Egyptian cements which are Ordinary Portland cement (CEM I 42.5N), Blast Furnace Slag Cement (CEM III/A 42.5N); and a lab manufacturing cement consist of Blast Furnace Slag Cement (CEM III/A 42.5N) and locally available Fly ash (FA) Class-F according to ASTM C618 [20] with a mixing ratio of 4:1 were used as different binding materials. Coarse and fine aggregate complying with ASTM C33 [21], and ES: 1109/2002 [22] limits - were used for concrete lollipop specimens. The used coarse aggregate was dolomite with maximum nominal size of 10mm, where the specific gravity was 2.657 and 2.7 for coarse aggregate and sand respectively. The used aggregate was in saturated surface dry condition and complying with ECP 203-2007[23] limits. A super-plasticizer (SP) with a specific gravity of 1.19, and pH value 8.3 were used to achieve the desired fairly constant workability in all concrete mixtures.

1.2. Concrete mixtures proportions

A total of eighteen mixtures were designed with two different (w/b) of 0.45 and 0.55, and three different binder contents (350, 400, and 450 kg/m^3), with different percentage of (SP) which was chosen according to trial mixes to achieve constant slump which is about (12cm to 17cm). Concrete mixtures were cast with the aforementioned different cementitious sources and mixture’s proportions are given in Table (1). The abbreviations used in the study for labeling the mixtures were; (C) Stands for control mixtures cast with ordinary Portland cement (CEM I 42.5N), (S) stands for mixtures cast with slag cement (CEM III/A 42.5N), and (SFA) stands for mixtures containing (CEM III 42.5N + 20% FA), (35, 40, and 45) stand for binder contents (350, 400, and 450 kg/m^3), (A, and B) stand for 0.45, and 0.55 w/b ratios. The slump test was performed according to ECP 203-2007 [21] within 2 minutes after mixing.

Table 1. Concrete mixtures proportions (kg/m^3) and measured slump

Mixture ID	CEM I	CEM III/A	FA	Sand	Aggregate	Water	SP (%)	Slump (cm)
C-35-A	350			646.06	1292.1	157.5	2.5	12
C-40-A	400			612.16	1224.3	180	2.0	12
C-45-A	450			578.28	1156.5	202.5	1.5	17
C-35-B	350			615.14	1230.3	192.5	1.5	12
C-40-B	400			576.83	1153.7	220	0.5	15
C-45-B	450			538.52	1077	247.5	0.0	17
S-35-A		350		646.06	1292.1	157.5	2.3	12.5
S-40-A		400		612.16	1224.3	180	2.5	13
S-45-A		450		578.28	1156.5	202.5	1.0	12.5
S-35-B		350		615.14	1230.3	192.5	1.0	14
S-40-B		400		576.83	1153.7	220	0.3	17
S-45-B		450		538.52	1077	247.5	0.0	18
SFA-35-A		280	70	646.06	1292.1	157.5	1.5	17
SFA-40-A		320	80	612.16	1224.3	180	1.3	17
SFA-45-A		360	90	578.28	1156.5	202.5	0.5	17
SFA-35-B		280	70	615.14	1230.3	192.5	0.6	13
SFA-40-B		320	80	576.83	1153.7	220	0.0	20
SFA-45-B		360	90	538.52	1077	247.5	0.0	22

1.3. Concrete specimens preparation

Lollipop concrete specimens with (5cm, and 10cm) diameter were designed to provide two different concrete cover thicknesses which are (1.9cm , and 4.4cm) with embedded rebar length of 15cm. To eliminate the rebar corrosion at the lollipop specimen end, six cm length of the rebar were zinc rich coated such that 3cm are on the embedded part and the other 3cm are on the free part, this coated area is the weakest and highest probability affected area by exposure and this coating will prevent promotion of excessive corrosion at the end of the rebar embedded length as shown in Fig. (1). Cubes with (15*15*15cm) dimensions were also cast for compressive strength test.

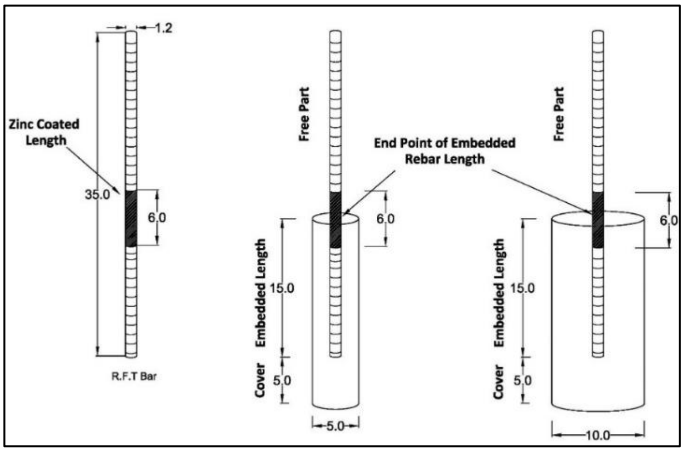


Figure 1. Schematic diagram of lollipop specimens design (dimensions are in cm)

1.4. Compressive strength test

Cube specimens are tested in compression at the ages of (7, 28, and 58 days) to determine the different concrete mixtures mechanical behavior.

1.5. Accelerated corrosion test by impressed current technique

The aim of impressed current tests was examining the corrosion performance of reinforced concrete specimens showed in figure (1). In this test, the embedded rebar in lollipop specimens acted as an anode and a stainless steel plate acted as a cathode. The electrolyte is 5% sodium chloride solution (NaCl). A constant voltage of 12V is applied from the external direct current (DC) power supply source between anode and cathode. The electric current (mA) was recorded every 12-hours for the lollipop specimens during the exposure period. Specimens with small cover (1.9cm) had exposure periods of (1, 3, and 7days), whereas, the large cover (4.4cm) specimens had exposure periods of (3, 7, and 20days). The schematic diagram of Fig. (2) showed the test arrangement and the current reading technique in detail (A), impressed current technique test setup shown in Fig. (3).

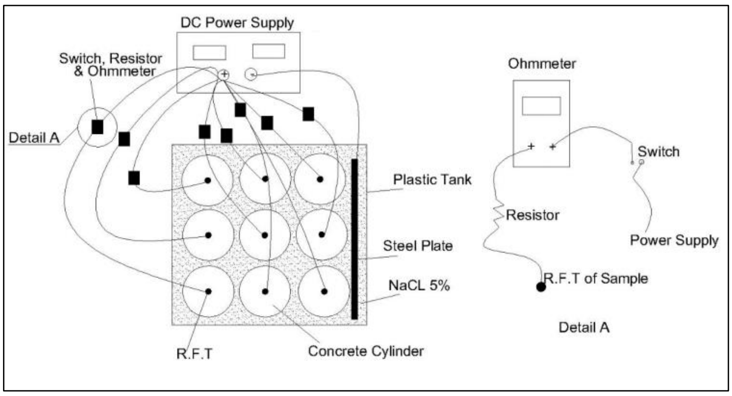


Figure 2. Schematic diagram of impressed current test method

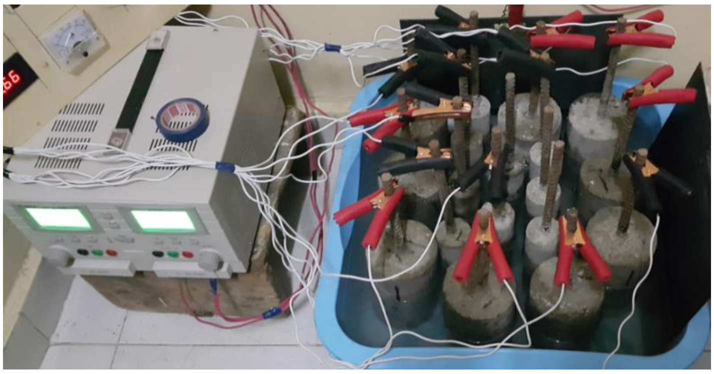


Figure 3. Impressed current technique test setup

1.6. Pull-Out test

Average of three lollipop specimens from each different size of concrete cover thickness (1.9, and 4.4cm) for all concrete mixture in table (1) were represented the result of pull-out test. The test results were divided in to two groups; first group was for the control specimens, which were tested after 56-days of curing without any exposure conditions. However the second group was tested also after 56-days of curing with addition of different time for chloride exposure periods according to the size of the embedded steel rebar cover as mentioned in section (1.5). Fig. (4) showed lollipop after accelerated corrosion.

Figure 4. Lollipop specimens after different exposure times

1.7. Determination of maximum rebar diameter loss

The embedded steel rebar in concrete lollipop specimens was extracted and cleaned in hydrochloric acid (HCl) using the wire brush to remove all corrosion products and then washed twice with distilled water and then dried. Fig. (5) showed a set of rebars exposed to corrosion current for different periods before and after cleaning. The minimum diameter of each rebar was measured by Vernier caliper device and compared with the original size which provided the percentage of maximum rebar diameter loss.

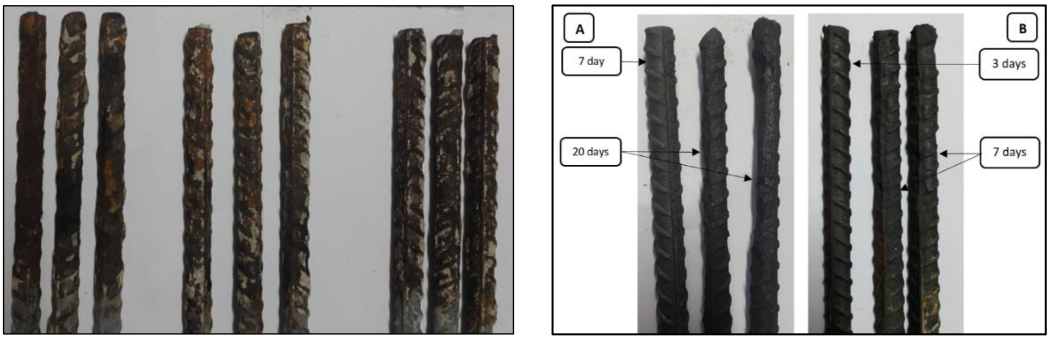


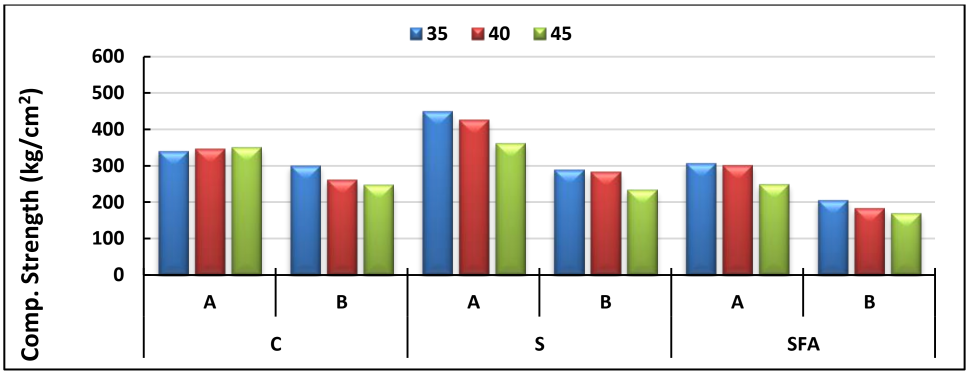
Figure 5. Extracted rebars from lollipop specimens before and after cleaning

2. Results and discussions

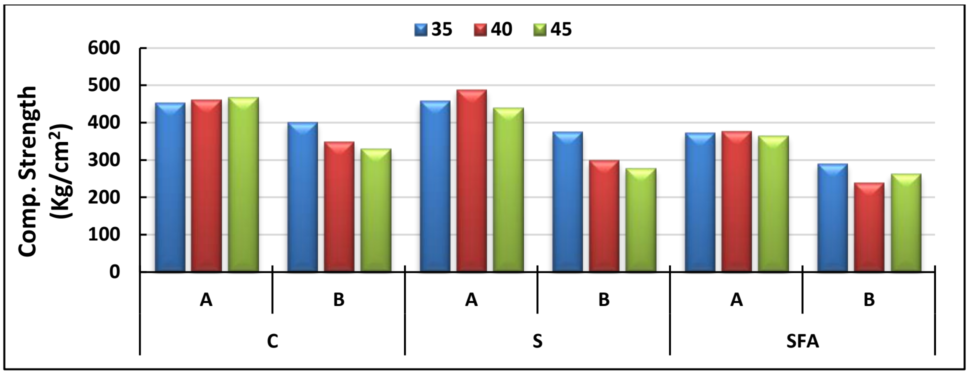
2.1. Compressive strength

Figure 6 (a, b, and c) showed the compressive strength of different concrete mixtures in different ages (7, 28, and 56-day). According to the compressive strength results for concrete mixtures cast with 0.45 w/b ratio and (CEM III/A) were 23% to 47% higher than results from (CEM I), and (CEM III/A + 20% FA) respectively in the early age 7-days, where there is no any significant difference between the results from concrete mixtures cast with (CEM I), and (CEM III/A), however it was higher than results from mixtures cast with (CEM III/A + 20% FA) in later age 56-Day. Increasing the w/b ratio from 0.45 to 0.55; the compressive strength results for concrete mixtures cast with (CEM I) showed the highest results in the earlier age (7, and 28days), but there is no significant difference between results for concrete mixtures cast with (CEM I), and (CEM III/A) in the later age 56-Day, also increasing the w/b ratio lead to decreasing all the compressive strength results for concrete mixtures cast with different cements. On the other hand, increasing of w/b ratio from 0.45 to 0.55 led to decreasing the compressive strength after 56-day by (19 to 32%) for CEM I, (12 to 30%) for (CEM III/A), and (30 to 37%) for (CEM III/A + 20% FA) depending on cement content.

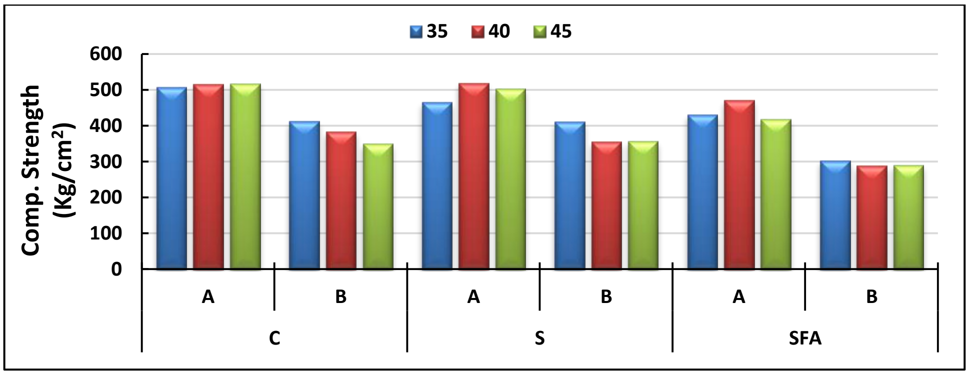
Concrete mixture cast with (CEM III/A + 20% FA) showed the minimum compressive strength results in all ages (7, 28, and 56) Days compared with the other results of concrete mixtures cast with (CEM I) and (CEM III/A) regardless of the w/b ratio.



(a) Compressive strength results at 7-days



(b) Compressive strength results at 28-day



(c) Compressive strength results at 56-day

Figure 6. Compressive strength test results

2.2. Impressed current readings

Figures (7.A through 7.F) show the influence of changing the cement type on the corrosion current profiles for all the 5cm diameter specimens. In addition, these figures are classified according to w/b ratio and binder contents. Referring to the aforementioned figures, no significant difference was observed in the current profiles of mixtures made of (CEM III/A) or (CEM III/A+ 20% FA) binders. Although, the corrosion current profiles of mixtures made of CEM I were always upper bounded that of the two blended cements in case of w/b ratio 0.45 as shown in Figures (7A, 7B, and 7C). However there is no significant difference between the three types of cement in case of w/b ratio 0.55 as shown in figure (7D, 7E, and 7F). On the other hand, for the 10cm-diameter specimens, no significant difference was found for the corrosion current profiles mixtures made of (CEM III/A), and (CEM III/A+20% FA) binders which were upper bonded by that of mixtures made of CEM I regardless the w/b ratio as shown in Fig. 8 (A through F).

Figures (9.a) and (9.b) show the average corrosion current values for 5cm and 10cm diameter specimens respectively which were clearly reduced due to using (CEM III/A) or (CEM III/A+ 20% FA) binders instead of (CEM I). These reduced current values emphasized the enhancement role of using either high slag cement alone or after partial replacement with 20% fly ash on the concrete corrosion protection under chloride exposure environments. In addition, more protection improvement was achieved for the case of using more concrete cover (i.e. 5cm vs. 10cm diameter specimens).

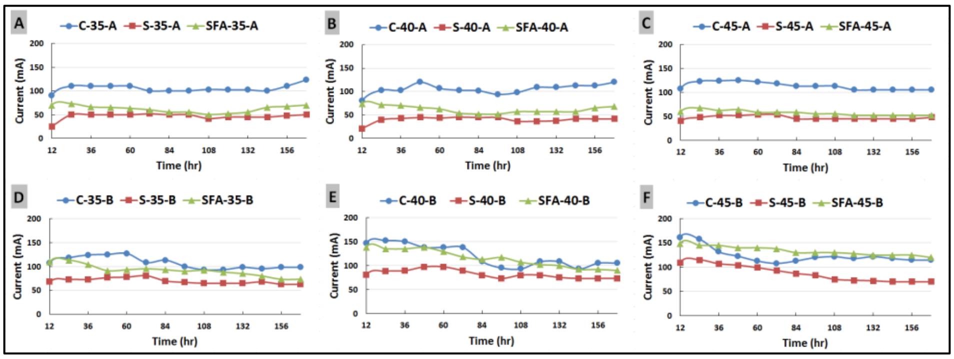
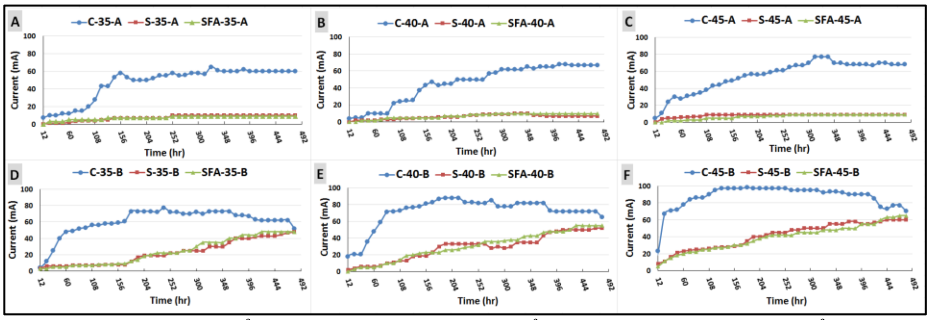


Figure 7. Current profiles for all 5cm- diameter specimens



A: binder content = 350 kg/cm^3, w/b = 0.45, **B:** binder content = 400 kg/cm^3, w/b = 0.45, **C:** binder content = 450 kg/cm^3, w/b = 0.45, **D:** binder content = 350 kg/cm^3, w/b = 0.55, **E:** binder content = 400 kg/cm^3, w/b = 0.55, **F:** binder content = 450 kg/cm^3, w/b = 0.55

Figure 8. Current profiles for all 10cm- diameter specimens

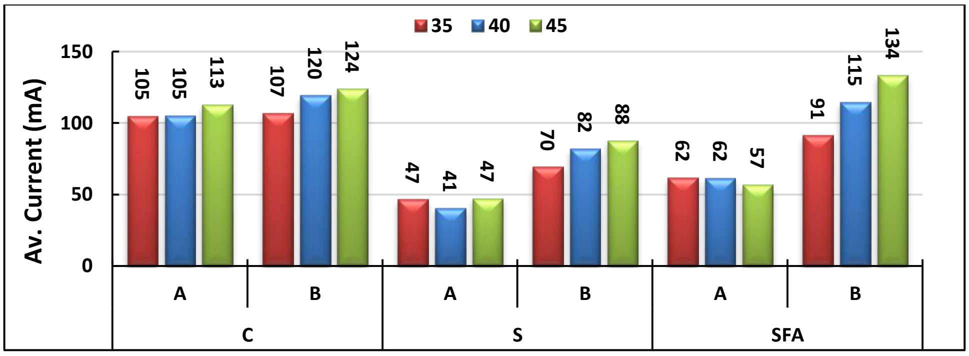


Figure (9.a) Average of measured current for 5cm lollipop specimens

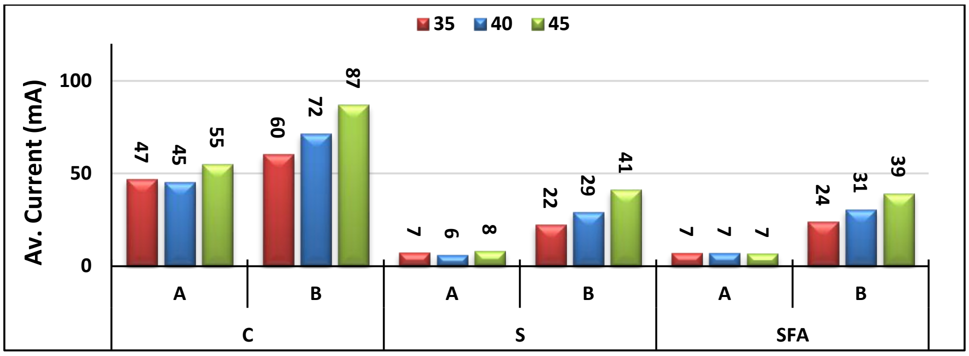


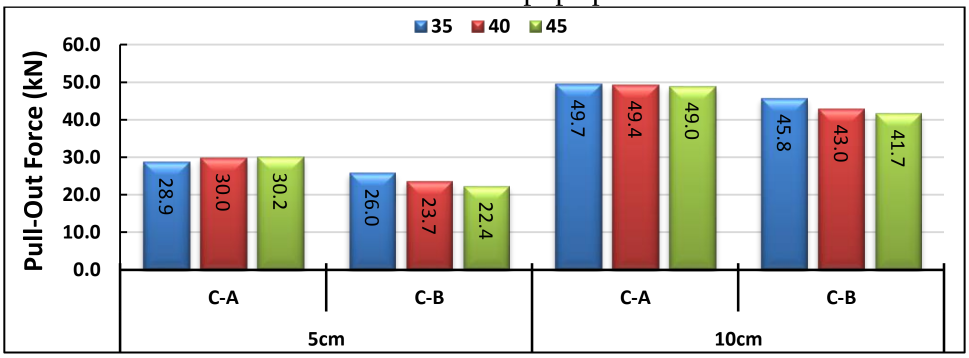
Figure (9.b) Average of measured current for 10cm lollipop specimens

2.3. Pull-Out test results

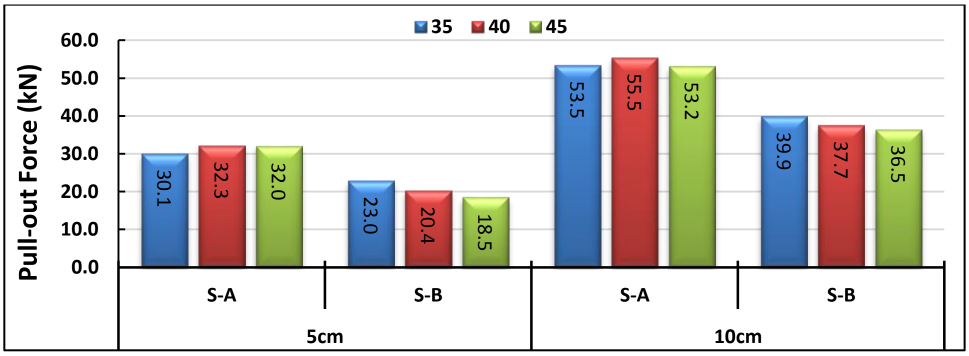
2.3.1. Control specimens test results

For all concrete mixtures cast with; (CEM I), (CEM III/A), and (CEM III/A + 20% FA), and regardless of lollipop specimens diameter. there is no significant or slightly adversely affect when the binder content increasing on the measured pull-out force results cast with 0.45 w/b ratio. On the other hand, binder content increasing led to pull-out force result decreasing when 0.55 binder ratio used as shown in Fig. (11).

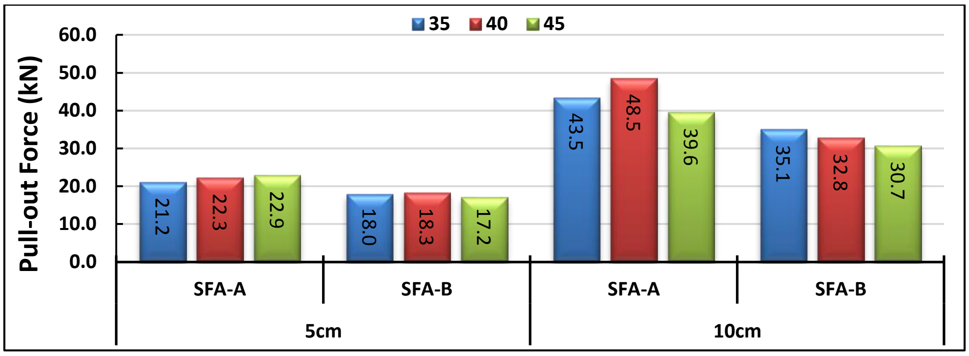
Increasing the diameter of lollipop specimens from 5cm to 10cm with 0.45 w/b ratio used led to pull-out force increase by (64, 70, and 117%) for (CEM I), (CEM III/A), and (CEM III/A + 20% FA) respectively. However, the increase percentage was around 80% for all aforementioned cement types when w/b ratio was 0.55 as shown in Fig. (10). Pull-out force for concrete mixtures cast with (CEM III/A) and w/b ratio 0.45 gave the highest results regardless to lollipop specimens diameter. On the other hand the concrete mixtures cast with (CEM III/A + 20% FA) gave the lowest pull-out force regardless to w/b ratio or binder content or lollipop specimens diameter.



(a) (CEM I) Mixtures

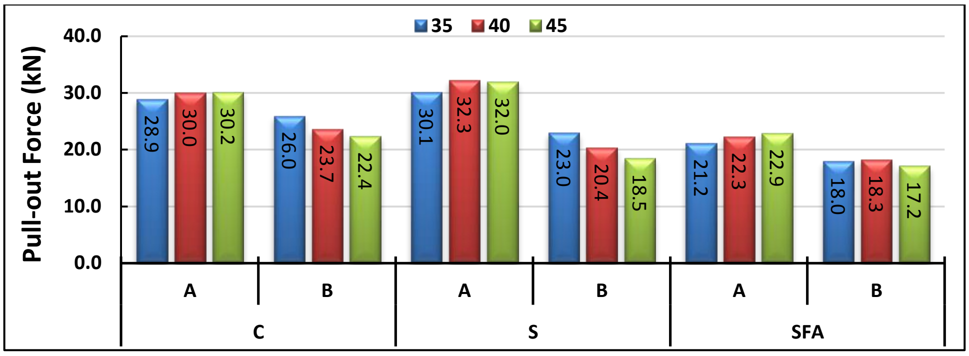


(b) (CEM III/A) Mixtures

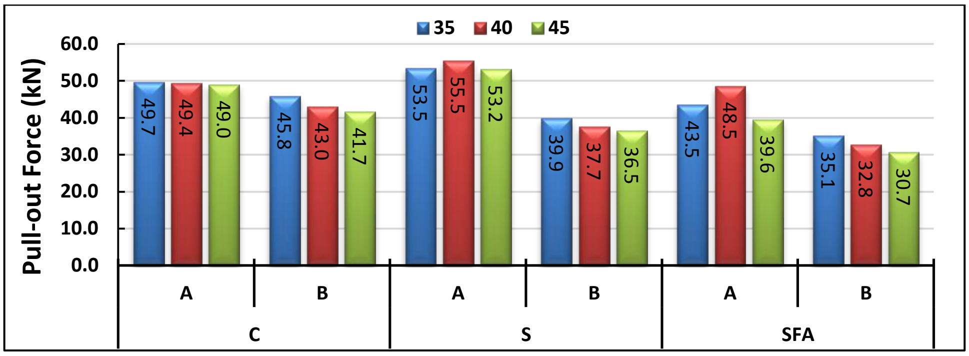


(c) (CEM III/A + 20% FA) Mixtures

Figure (10) Influence of Binder Content and w/b Ratio on Pull-Out Force Results



(a) Lollipop specimens with 5cm diameter



(b) Lollipop specimens with 10cm diameter

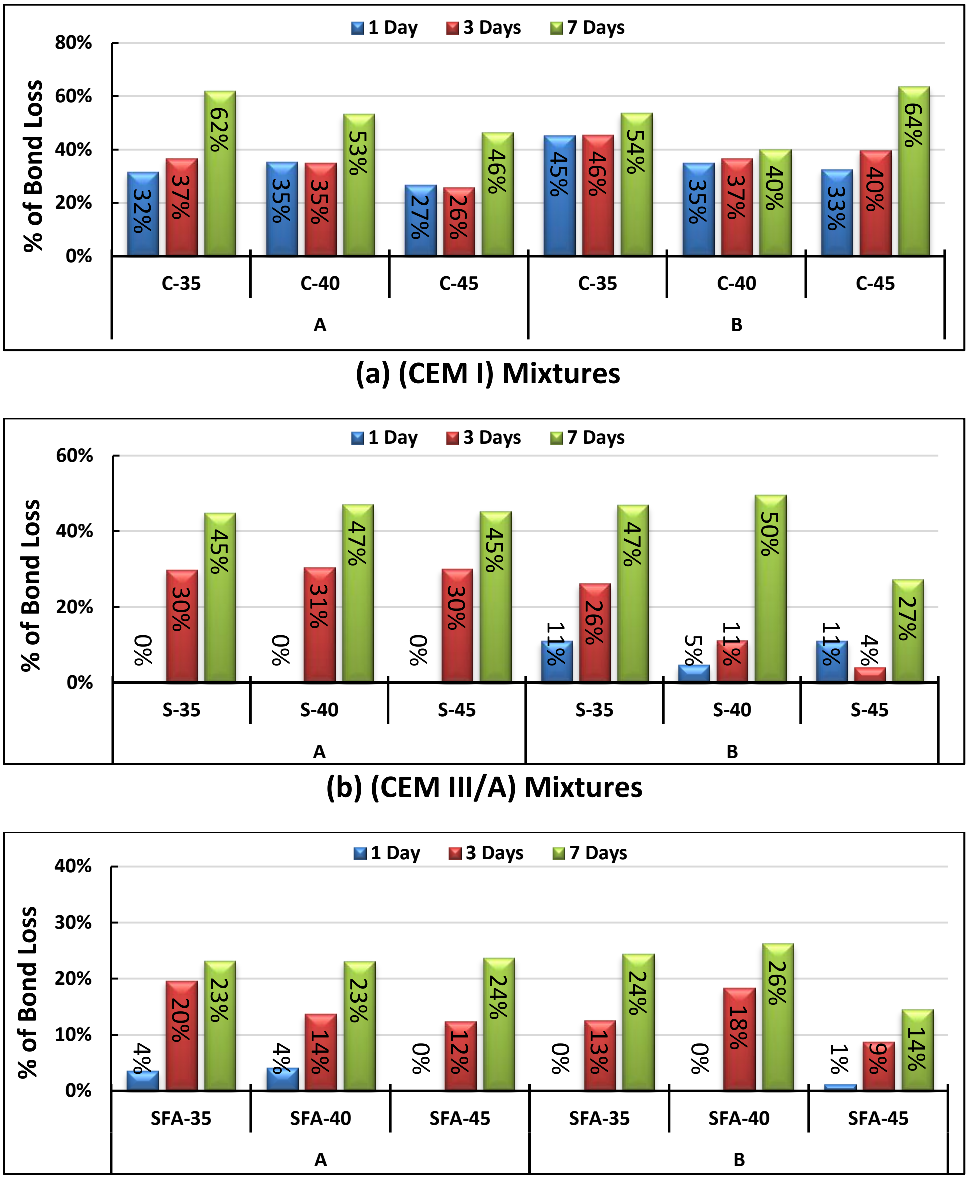
Figure (11) Pull-Out force for concrete mixtures cast with different cement types

2.3.2. Corroded rebar specimens test results

For all concrete mixtures cast with; (CEM I), (CEM III/A), and (CEM III/A + 20% FA) and regardless of cover thickness, w/b ratio, and binder content. The increasing of chloride exposure time by impressed current technique led to decrease of rebar-concrete bond as shown in Fig. (12, and 14).

Concrete mixtures cast with (CEM III/A), and (CEM III/A + 20% FA) constant rebar-concrete bond loss percentage regardless to binder content, w/b ratio, and cover thickness except the 20-days exposure bond loss values which increased drastically as shown in Fig. (12b, 12c), and (14b, 14c). Additionally the using of (CEM III/A), and (CEM III/A + 20% FA) in concrete mixtures led to a reduction in rebar-concrete bond loss percentage as shown in Fig. (13, and 15), however by increasing the cover thickness from 1.9cm to 4.4cm; (CEM III/A), and (CEM III/A + 20% FA) gave the same rebar-concrete bond loss percentage Fig. (15).

In lollipop diameter specimens 10cm with 0.45 w/b ratio used; there is no rebar-concrete bond loss in concrete mixtures cast with (CEM III/A) or (CEM III/A + 20% FA) regardless to binder content, where the mixtures cast with (CEM I) had around 45% decrease in bond loss at the end of exposure time (20-days) as shown in Fig.(15).



(c) (CEM III/A + 20% FA) Mixtures

Figure (12) Bond loss due to exposure time for lollipop specimens (5cm)

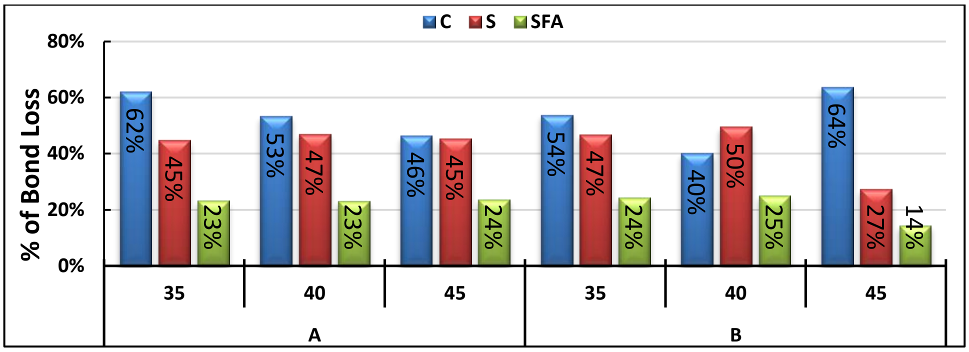
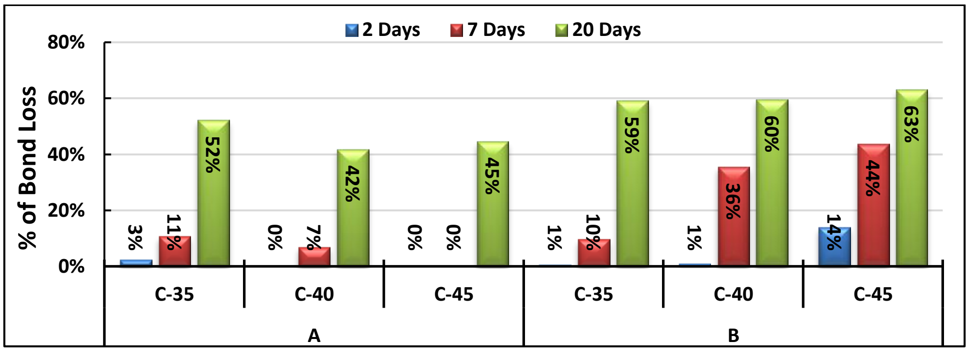
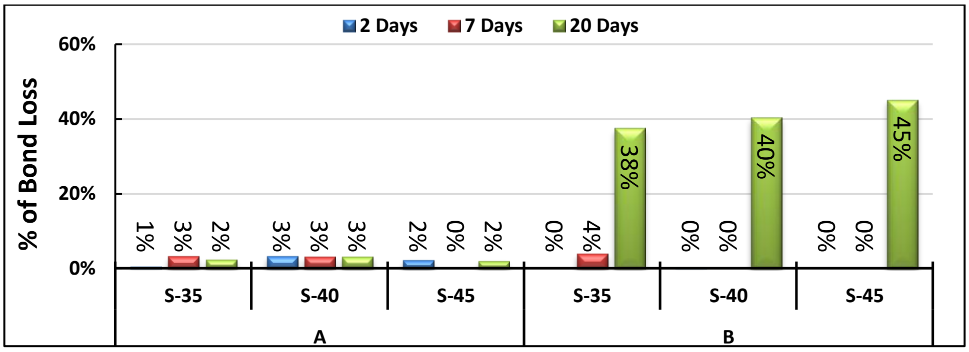


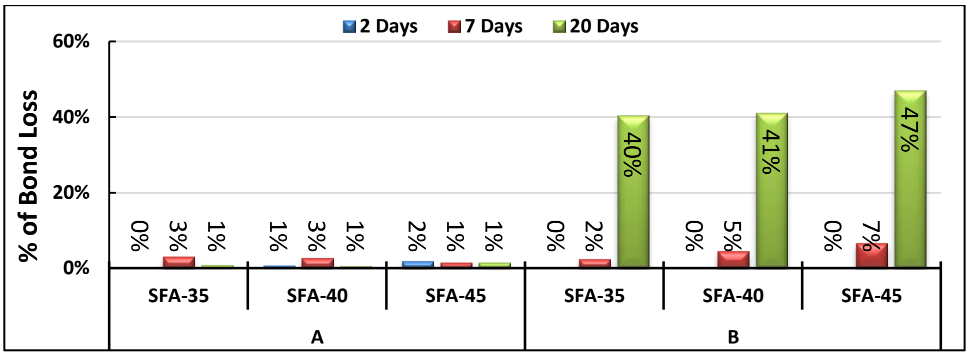
Figure (13) bond loss comparison at 7-days for lollipop specimens (5cm)



(a) (CEM I) Mixtures



(b) (CEM III/A) Mixtures



(c) (CEM III/A + 20% FA) Mixtures

Figure (14) Bond loss due to exposure time for lollipop specimens (10cm)

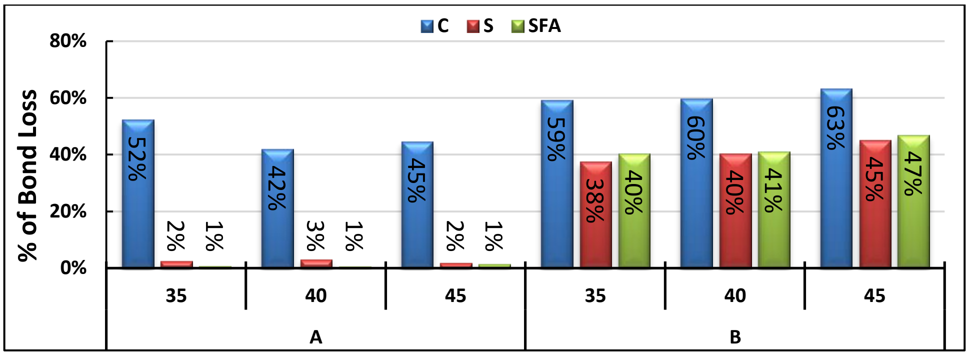
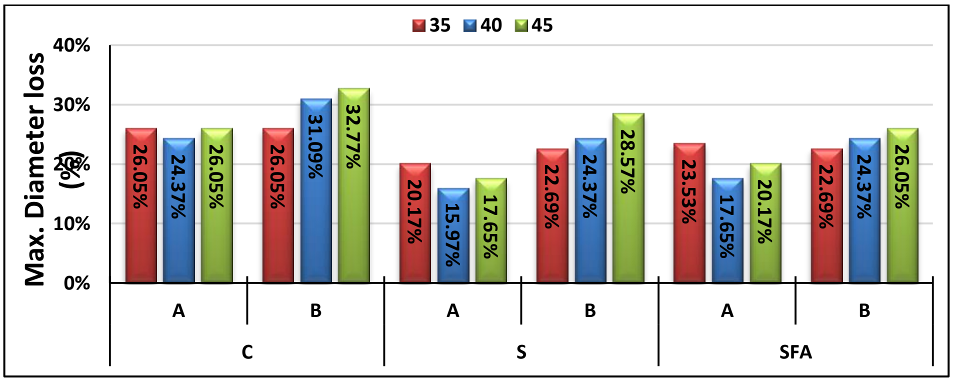


Figure (15) Bond loss comparison at 20-days for lollipop specimens (10cm)

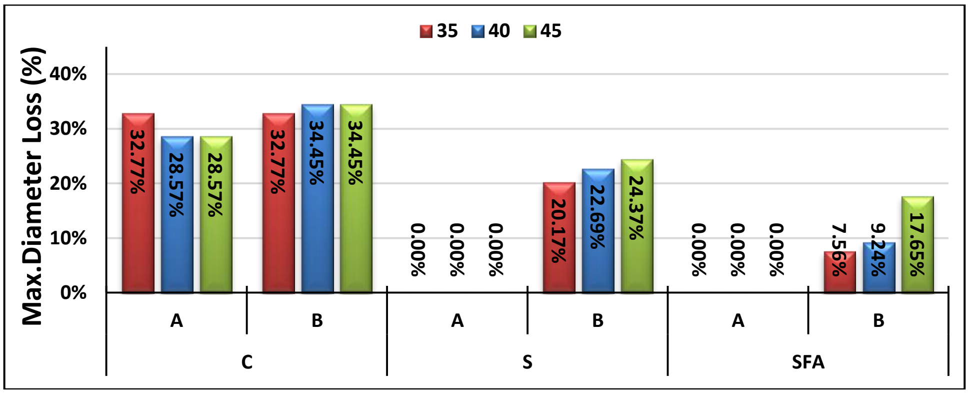
2.4. Determination of maximum rebar diameter loss

Figure (16.a) refer to the percentage of rebar diameter loss results of 5cm lollipop specimens. It showed that using (CEM III/A) and (CEM III/A + 20% FA) lead to a reduction in rebar diameter loss of 40% for w/b ratio 0.45 and 22% for water w/b 0.55 compared with (CEM I).

The percentage of rebar diameter loss results of 10cm lollipop specimens showed in Fig. (16.b). This figure showed that the specimens cast with (CEM III/A) and (CEM III/A + 20% FA) using w/b ratio 0.45 had no effect on its diameter compared with 28% loss in specimens cast with (CEM I). However, the w/b ratio 0.55, results were 33% reduction in rebar diameter loss when the lollipop specimens cast with (CEM III/A), and around (48% to 75%) when the lollipop specimens cast with (CEM III/A + 20% FA) compared with (CEM I)



(a) Lollipop specimens with 5cm-diameter



(b) Lollipop specimens with 10cm-diameter

Figure (16) Maximum diameter loss percentage for lollipop specimens

3. Conclusions

- For 0.45 w/b ratio, increasing the concrete cover from 1.9cm to 4.4cm shows a reduction of the average accelerate corrosion current up to (55%, and 85%) for concrete specimens cast with (CEM I), and (CEM III/A) or (CEM III/A + 20% FA) respectively. On the other hand, the reduction are up to (43%, and 70%) in case of 0.55 w/b ratio.
- For 0.45 w/b ratio, replacing (CEM I) by either (CEM III/A) or (CEM III/A +20% FA) reduced the average measured accelerated corrosion current by 40- 60% for reinforced concrete specimens having small concrete cover (i.e. 1.9cm), whereas such reduction reached 87% for the larger concrete cover (i.e. 4.4cm).
- For 0.55 w/b ratio, using of (CEM III/A) instead of (CEM I) reduced the accelerated corrosion current by only 35% and 65% for the small and large concrete covers (1.9cm, and 4.4cm) respectively. However, the using of (CEM III/A +20% FA) with small cover had no significant corrosion protection. On the other hand, the reduction was up to 55% when 4.4cm concrete cover used.
- For 1.9cm concrete cover and regardless of w/b ratio, the percentage loss of pull-out force up to 7-day of accelerated corrosion between (CEM I), and (CEM III/A) concrete mixtures are close and near to the double for (CEM III/A + 20% FA) mixtures results.
- For 4.4cm concrete cover, the percentage loss of pull-out force up to 20-day of accelerated corrosion was not affected for all binder content used when the concrete mixtures cast with (CEM III/A) or (CEM III/A + 20% FA) comparing with 45% bond loss in (CEM I) mixtures in case of 0.45 w/b ratio. On the other hand, for 0.55 w/b ratio, there is no obvious loss of pull-out force up to 7-day of accelerated corrosion for (CEM III/A) or (CEM III/A + 20% FA) with all binder content used. However at 20-day the loss of pull-out force was around 40% comparing with 60% in (CEM I) mixtures.
- For concrete cover 1.9cm, a saving of 34% in rebar diameter loss is achieved after 7-day of accelerated corrosion for (CEM III/A) or (CEM III/A + 20% FA) instead of (CEM I) in concrete mixtures depending on binder content and w/b ratio.
- For concrete cover 4.4cm, replacing (CEM I) with (CEM III/A) or (CEM III/A + 20% FA) leads to a saving of up to 78% in rebar diameter loss when using w/b ratio 0.55 and depending on binder content after 20-day of accelerated corrosion. On the other hand, almost no corrosion is observed for rebars embedded in mixtures containing (CEM III/A) or (CEM III/A + 20% FA) when 0.45 w/b ratio is used compared with 28% loss in rebras embedded in mixtures containing (CEM I) regardless of binder content.

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