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Assessment of local Binder Type and Content on the Corrosion Behavior of Lollipop Samples

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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 من الرماد المتطاير علي سلوك الصدأ لحديد التسليح داخل الخرسانه المسلحه وذلك بالمقارنه مع الخرسانه التي تحتوي علي 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 لاختبار التيار المؤثر(التعرض للصدأ) . تم دراسه الصدأ من خلال التاكل و نقص القطاع لقضيب حديد التسليح في العينات الاسطوانيه . تم تأكيد و ربط النتائج من خلال اختبارات مقاومه الضغط للخلطات الخرسانيه المستخدمه و النفاذيه بطريقه المياه وايضا اختباراختراق أيونات الكلوريدات المسرعه . تم الوصول الى ان نتائج اختراق و نفاذيه أيونات الكلوريدات ونتائج التيارالكهربي المقاس في اختبار التيارالمؤثر تقل بشكل كبير جدا عند استخدام الخلطات الخرسانيه التي تحتوي علي اسمنت خبث الافران (CEM-III/A) او عند خلطه بالرماد المتطاير و ان الحفاظ على التأكل في حديد التسليح المستخدم يصل الى 75% معتمدا علي نوع الاسمنت و كميته في الخلطه المستخدمه وذلك بالمقارنه بالخلطات الخرسانيه التي تحتوي علي الاسمت البورتلاندي العادي (CEM I).

Abstract
The effect of using local manufactured Egyptian slag cement (CEM-III/A) and a mixture of (CEM-III/A) and fly-ash on the corrosion behavior of reinforced concrete is investigated comparing with the ordinary Portland cement (CEM I) concrete mixture. A total of 432 lollipop specimens were exposed to impressed current to investigate the effects of: different cover thickness, different W/B ratio, binder type and content; and exposure duration. The corrosion is quantified by measuring the rebar diameter loss in the used concrete cylinders. The results were correlated to: compressive strength for the used concrete mixtures, water permeability, and rapid chloride penetration test. Chloride penetrability, permeability and measured current are reduced drastically when using concrete mixtures cast with (CEM-III/A) or (CEM-III/A+FA), and the diameter loss is reduced by up to 75% depending on binder type and content, and W/B compared with (CEM I) concrete mixtures.

1. Introduction
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 [1,2,3]. 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.), [2, 4, and 5], and hardened concrete (reduce permeability and porosity; and increase the long-term strength) [2,6,7].
Five main different groups introduced a total of (27) different cement types are in the new Egyptian standard specification for cement (ESS 4756/2013) [8]. 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) [9] in the way of cement classification.

Corrosion of embedded steel rebars in concrete are one of the main and important causes of reinforced concrete structures deterioration, which leads to structural failure. Corrosion of the embedded steel rebars in concrete plays a vital role in the determination of the durability and life time of the concrete structures [10].

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[11,12,13]. 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 [14, and 15]. 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.[3,10,12,14,15,16].

Most of researches divided the reasons of rebar corrosion into two main parts, the first part contains the external condition such as exposure time, and surrounding environment [10]. Whereas, the second part is concerned with concrete properties themselves such as concrete cover, C_3A content in cement, water/cement ratio, cement content and type; and percentage of mineral additives [2,10,17].

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 [3,16].

The objective of the present work is to assessment of binder type and content of local Egyptian cements on corrosion behavior of lollipop sampls by studying the behavior of concrete with different parameters, which are (different; cement type, and cement content, water binder ratio, compressive strength, concrete cover; and time of exposure) using impressed current technique on lollipop specimens with different sizes. It is also intended to investigate the influence of high binder content in the different concrete mixtures on their corrosion behavior.

2. Experimental Program

2.1. Materials

Three types of local Egyptian cements which are Ordinary Portland cement (CEM I 42.5N), Blast Furnace Slag Cement (CEM III/A 42.5N), and a mixture of Blast Furnace Slag Cement (CEM III/A 42.5N) and locally available Fly ash (FA) Class-F according to ASTM C618 [18] with a mixing ratio of 4:1 were used as different binding materials. The specific surface area and chemical analysis of cementitious materials are showed in table (1), and (2) respectively. Standard aggregate (Coarse and fine) complying with ASTM C33 [19] and ES: 1109/2002 [20] 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 (SSD) condition and complying with ECP 203-2007[21] limits. A modified synthetic dispersion is the technical base of the used admixture as a super-plasticizer (SP) with a specific gravity of 1.19, and pH value 8.3 to achieve the desired fairly constant workability in all concrete mixtures.

Table 1. Specific Surface Area of Different Cementitious Materials

Cement Type	Specific surface area (cm^2/gm)
CEM I 42.5N	3218
CEM III/A 42.5N	4234
Fly Ash	4196
CEM III/A 42.5N + 20 % FA	4215

Table 2. Chemical Analysis of Different Cementitious Materials

Sample	CEM I 42.5N	CEM III/A 42.5N	Fly Ash
SiO_2	20.57	21.96	85.75
CaO	62.13	60.93	0.81
MgO	2.13	1.00	0.11
Fe_2O_3	3.45	3.22	2.66
Al_2O_3	5.02	4.70	6.70
Na_2O	0.4	0.42	0.53
K_2O	0.16	0.17	0.17
Cl	0.09	0.03	0.03
SO_3	3.05	2.69	0.02
L.O.I	1.95	2.74	2.74
Total	99.95	99.96	99.55

2.2. Concrete Mixtures Proportions

A total of eighteen mixtures were designed with two different water binder ratios (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 22cm). Concrete mixtures were cast with the aforementioned different cementitious sources and mixture's proportions are given in Table (3). The abbreviations used in the study for labeling the mixtures were adopted in such a way that they clearly show the main parameters. (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 water binder ratios. The slump test was performed according to ECP 203-2007[21] within 2 minutes after mixing.

Table 3. 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

2.3. 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 figure (1). Cubes with (15*15*15cm) dimensions, cylinders with 10cm diameter and 20cm length were also cast for measuring compressive strength, permeability, and rapid chloride penetration respectively.

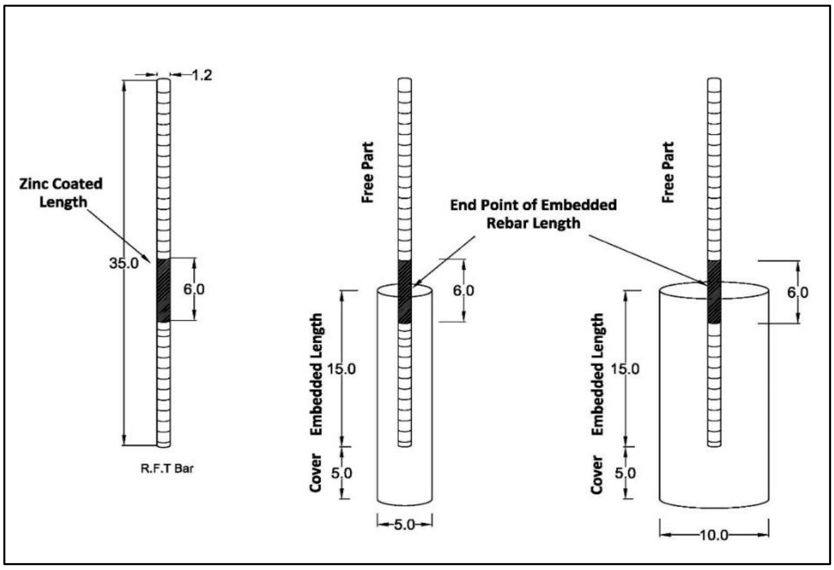


Figure 1. Schematic Diagram of Lollipop Specimens Design (Dimensions are in cm)

2.4. 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. Testing specimens at the ages of (7, and 56 days) is intended to investigate the rate of strength gain of the different binder types especially; (CEM III/A), and (CEM III/A + 20% FA).

2.5. Accelerated Corrosion test (impressed current technique)

The aim of impressed current tests was examining the corrosion performance of reinforced concrete specimens. The impressed current technique (using concrete lollipop specimens showed in figure (2) is an accelerated corrosion testing technique which indirectly gave information about the permeation characteristics of concrete. 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 Figure (3) showed the test arrangement. Specimens of the same size were separated in one plastic container as shown in figure (4). Electric current was read by the ohmmeter board showed schematically in detail (A) of figure (3).

Figure 2. Lollipop Samples after Casting and Curing Process

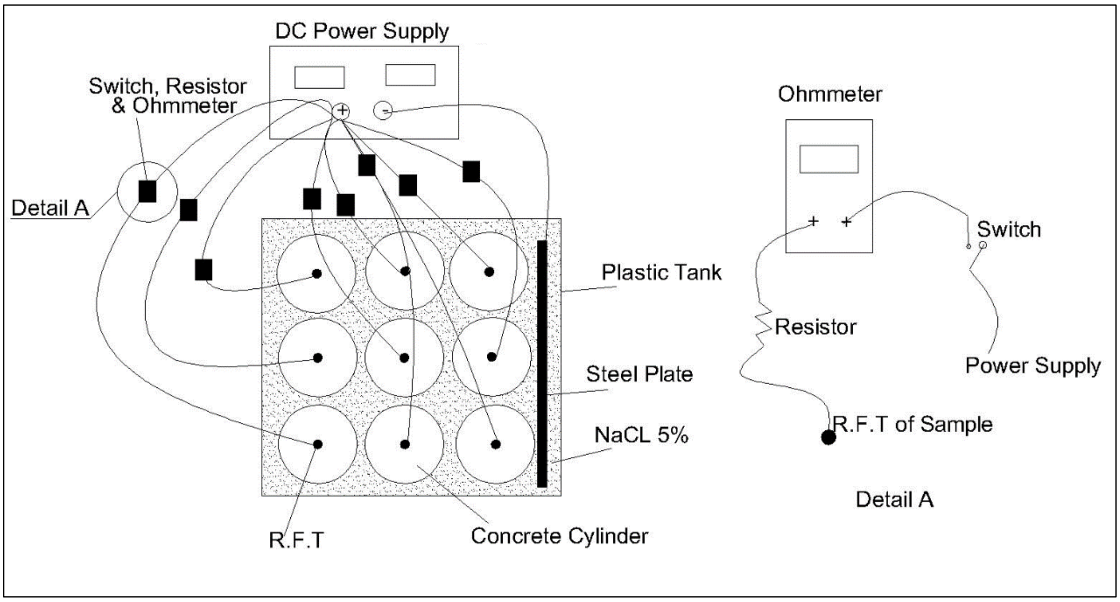


Figure 3. Schematic Diagram of Impressed Current Test Method for Lollipop Samples

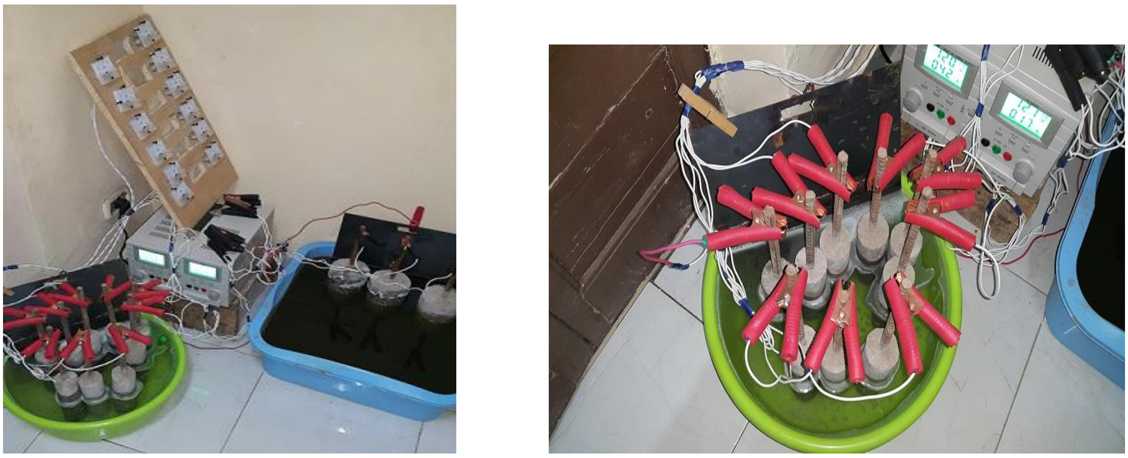


Figure 4. Test Setup Contains (DC Power Supply, 2 Plastic Containers, and Ohmmeter Board)

2.6. Permeability Test

Water Permeability test of concrete was performed according to BS EN 12390-8 [22] *(Depth of penetration of water under pressure)*. Three concrete cube specimens from each mixture shown in table (4) were tested. Concrete mixtures in table (4) were chosen to identify the influence of high binder content, and water binder ratio on their permeability behavior. According to the test procedure, water was applied under pressure of 5-bar to one surface of the concrete cube specimen for 72-hours and the surrounding four sides of the cube were epoxy isolated. The specimens were then split and the maximum depth of penetration of water was measured.

Table 4. Concrete Mixtures for Permeability Test

Mixture ID	CEM I	CEM III/A	FA	Sand	Aggregate	Water	SP (%)	Slump (cm)
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
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
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

2.7. Rapid Chloride Penetration Test (RCPT)

Rapid chloride penetration (RCPT) was performed, according to ASTM C1202-10 [23], and [24,25] *(Electrical indication of concrete's ability to resist chloride ion penetration)*, which were prepared form the same concrete mixtures described in Table (4) and for the same aforementioned reason. This test method was implemented by monitoring the amount of electrical current passing through 51-mm thick slices cut from 102-mm nominal diameter cylinders. The electric current was measured every 30-minutes up to 6-hours. A potential difference of 60V from external direct current (DC) power supply was maintained across the ends of the concrete specimen, one of which was immersed in a 3% (NaCl) sodium chloride solution (this side of the cell was connected to the negative terminal of power supply), while the other was immersed in a 0.3% (NaOH) sodium hydroxide solution (which was connected to the positive terminal of power supply). The total passing charge, in coulombs, was found to be related to the resistance of the concrete to chloride ion penetration and accordingly the corrosion activity of embedded steel rebar in this concrete type.

In preparation for the RCPT; the lateral surfaces of the concrete specimens were insulated using epoxy coating as shown in figure (5). The second step was to place the concrete specimens in the vacuum desiccator with both uncoated faces kept exposed. Then the desiccator was sealed and the vacuum pump had been started to maintain pressure less than 50mm-Hg (6650 Pa) for 3-hours, and then vacuum saturation for a period of 1-houre after submerging the concrete specimens under water. Finally, after those 4-hours, the vacuum pump was stopped and further the concrete specimens soaked under water for a period of 18±2hours. Figure (6) showed full details of preparation and testing phases.

Figure 5. Concrete Specimens Coated and Prepared

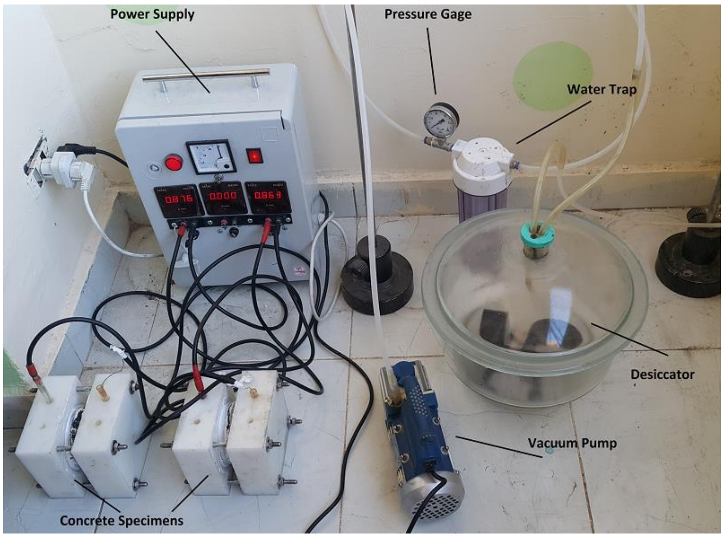


Figure 6. Rapid Chloride Penetration Test and Preparation Phases

2.8. Determination of Maximum Rebar Diameter Loss

After ending of exposure time, the embedded steel rebar in concrete lollipop specimens was extracted as shown in figure (7) 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. Figure (8) showed a set of rebars exposed to corrosion current for different periods after cleaning. The minimum diameter of every rebar was measured by Vernier caliper device and compared with the original size which provided the percentage of maximum rebar diameter loss.

Figure 7. Extracted Rebars from Lollipop Specimens before Cleaning

A: Rebars Extracted from 10cm diameter specimens cast with (CEM I)
B: Rebars Extracted from 5cm diameter specimens cast with (CEM III/A + 20% FA)

Figure 8. Steel Rebars after Cleaning Process Ending

3. Results and Discussions

3.1. Compressive Strength

The compressive strength test for different concrete mixtures carried out at ages of (7, 28, and 56 days). Three specimens were tested for each age and the average result was reported in Table (5). Figure 9 (a, b, and c) showed the compressive strength of different concrete mixtures in different ages.

According to the compressive strength results for concrete mixtures cast with 0.45 water binder 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 water binder 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 water binder ratio lead to decreasing all the compressive strength results for concrete mixtures cast with different cements

Increasing of water binder 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 water binder ratio.

According to the later ages compressive strength results (28, and 56 day); the optimum binder content for the three cement types was 400 kg/m^3. Specimens containing 400 kg/m^3 gave higher or same results as specimens containing 450 kg/m^3 as clearly shown in Table (5), and figure (9.c).

Table 5. Average Compressive Strength Results (kg/cm^2) for All Concrete Mixtures

Mixture ID	CEM I	CEM III/A	FA	7-Days	28-Day	56-Day
C-35-A	350			340.50	454.00	508.50
C-40-A	400			346.50	462.00	516.00
C-45-A	450			351.00	468.00	518.00
C-35-B	350			301.13	401.50	413.00
C-40-B	400			261.50	348.67	384.00
C-45-B	450			248.00	330.67	350.00
S-35-A		350		451.00	458.00	466.00
S-40-A		400		427.00	488.50	519.00
S-45-A		450		363.00	440.33	504.00
S-35-B		350		289.67	375.00	411.00
S-40-B		400		283.33	298.67	356.00
S-45-B		450		234.00	278.00	357.00
SFA-35-A		280	70	307.33	372.67	432.00
SFA-40-A		320	80	302.33	377.00	471.67
SFA-45-A		360	90	249.50	365.50	418.67
SFA-35-B		280	70	206.50	290.67	302.50
SFA-40-B		320	80	184.00	238.67	288.50
SFA-45-B		360	90	169.67	262.67	290.00

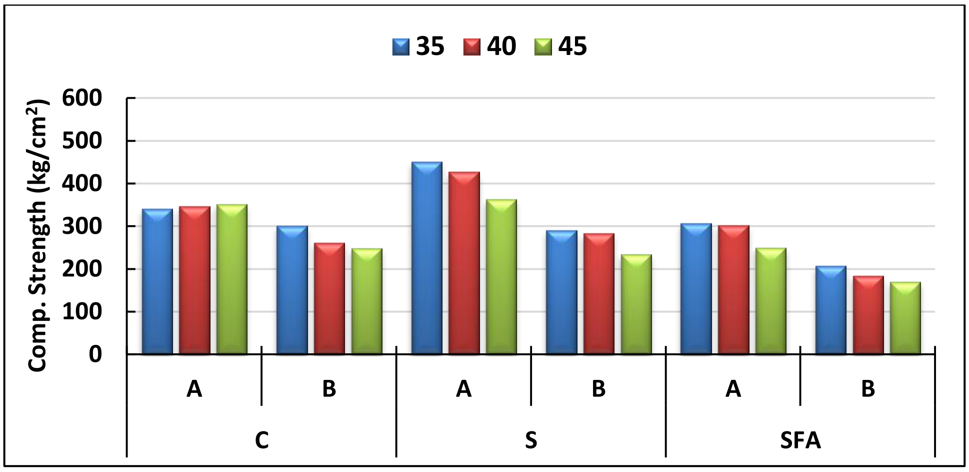


Figure (9.a) Compressive Strength Results at 7-Days

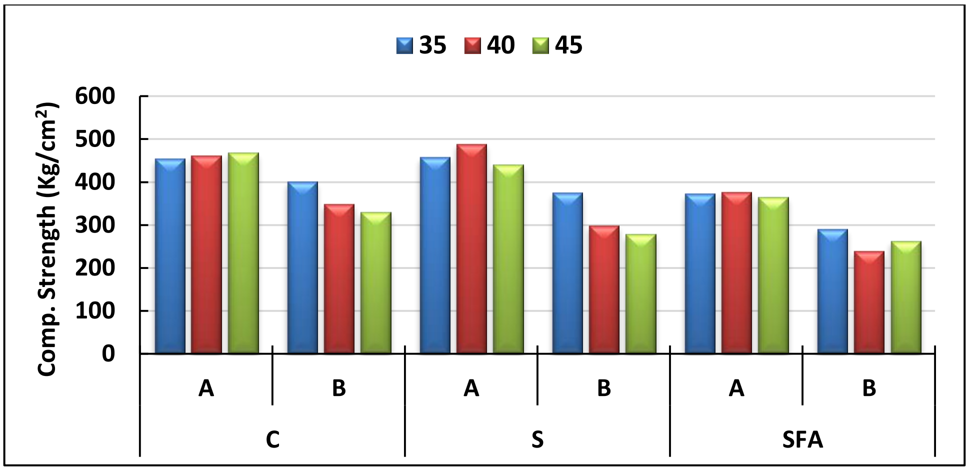


Figure (9.b) Compressive Strength Results at 28-Day

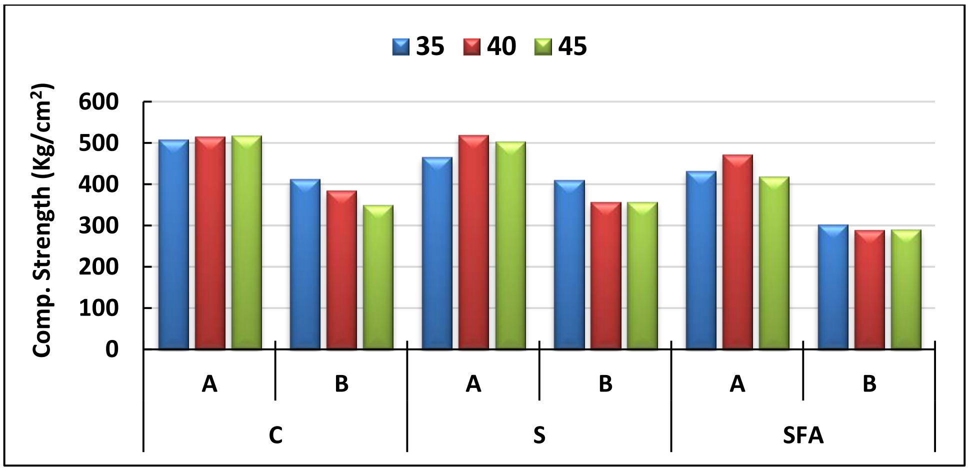


Figure (9.c) Compressive Strength Results at 56-Day

3.2 Impressed Current Readings

For 5cm lollipop concrete specimens cast with (CEM I) there is no significant difference between all current profiles except for the higher water binder ratio 0.55 in the starting measured current only as demonstrated in figure (10.a). On the other hand, 10cm lollipop concrete specimens have more variable measured current depending on water binder ratio and binder content. The current recorded of these specimens gave almost the same values at the end of test figure (12.a)

Lollipop specimens with (5, and 10cm) diameter and cast with (CEM III/A), and (CEM III/A + 20% FA) had the same current profile which had lower measured current values for the mixtures with lower water binder ratio 0.45. There is no significant difference between the measured current values for all concrete mixtures with water binder ratio 0.45 and different binder contents (350, 400, and 450Kg/m^3). However, the difference in the measured current values were more clear in concrete mixtures cast with water binder ratio 0.55, where the measured current values increased with binder content increase. Figures (10.b, 10.c, 12.b, and 12.c) gave a graphical depiction of the results.

By comparison between the electric current profiles in lollipop specimens with 5cm diameter for all mixtures cast with different type of cements, binder contents, and water binder ratios; it found that there is no significant difference between (CEM III/A), and (CEM III/A + 20% FA) current profiles and it was covered by (CEM I) current profile in case of water binder ratio 0.45 as shown in figure (11a, 11b, and 11c), however there is no significant difference between the three types of cement in case of water binder ratio 0.55 as shown in figure (11 d, 11e, and 11f).

In case of lollipop specimens with 10cm diameter the comparison between the electric current profiles for all mixtures cast with different types of cements, binder contents, and water binder ratios; it is found that there is no significant difference between (CEM III/A), and (CEM III/A + 20% FA) current profiles and it was covered by (CEM I) current profile regardless of the water binder ratio as shown in figure 13 (a, b, c, d, e, and f).

Average electric current values were calculated for each mixture as showed in figure (14.a) for 5cm lollipop specimens, and figure (14.b) for lollipop specimens with 10cm diameter. These values emphasized the role of using the modified and blended cements instead of ordinary Portland cement in chloride exposure environments.

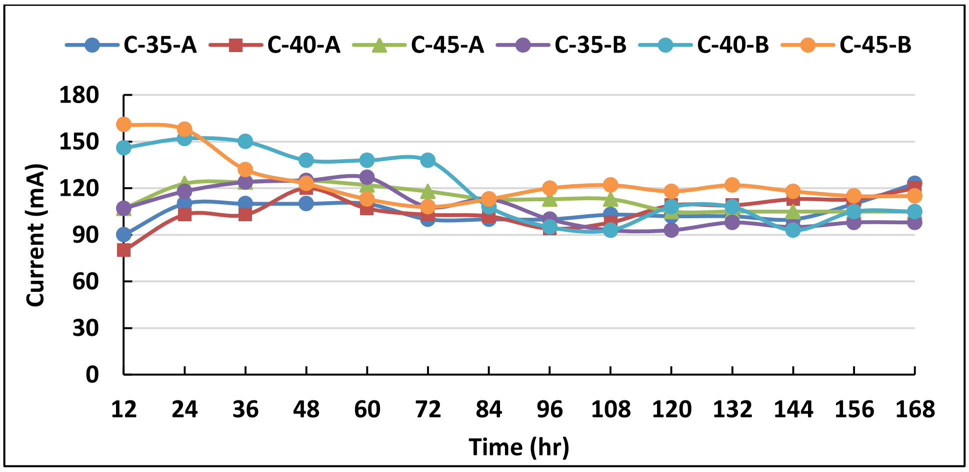


Figure (10.a) Current Values (mA) for (CEM I) Mixtures (5cm diam.)

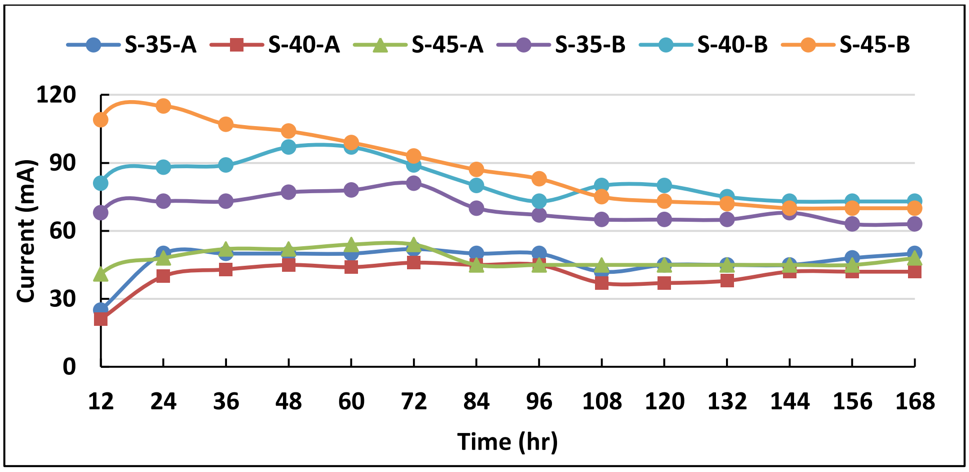


Figure (10.b) Current Values (mA) for (CEM III/A) Mixtures (5cm diam.)

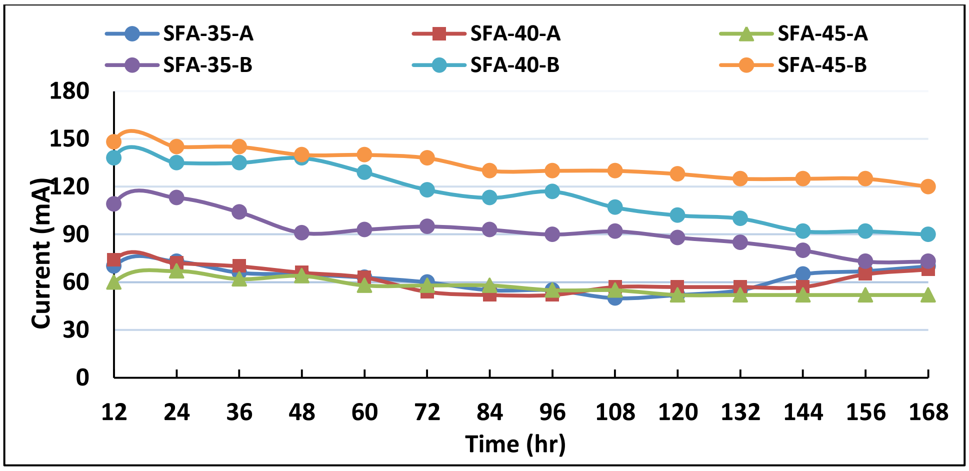
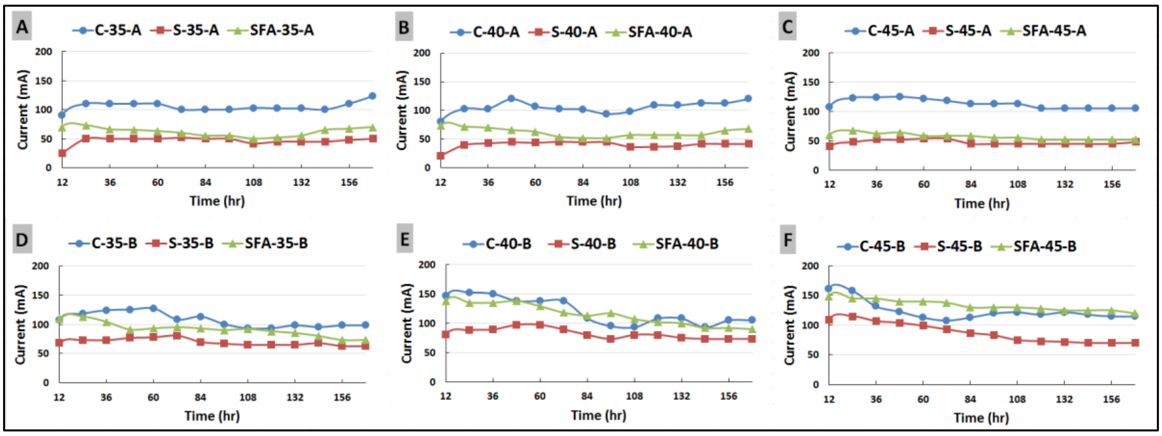


Figure (10.c) Current Values (mA) for (CEM III/A + 20% FA) Mixtures (5cm diam.)



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 11. Current Values (mA) Comparison for the Three Cement Types (5cm diam.)

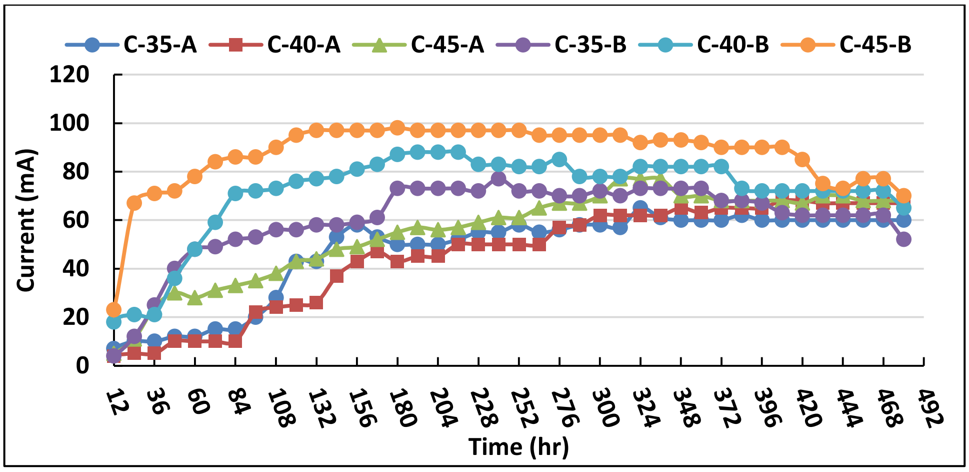


Figure (12.a) Current Values (mA) for (CEM I) Mixtures (10cm diam.)

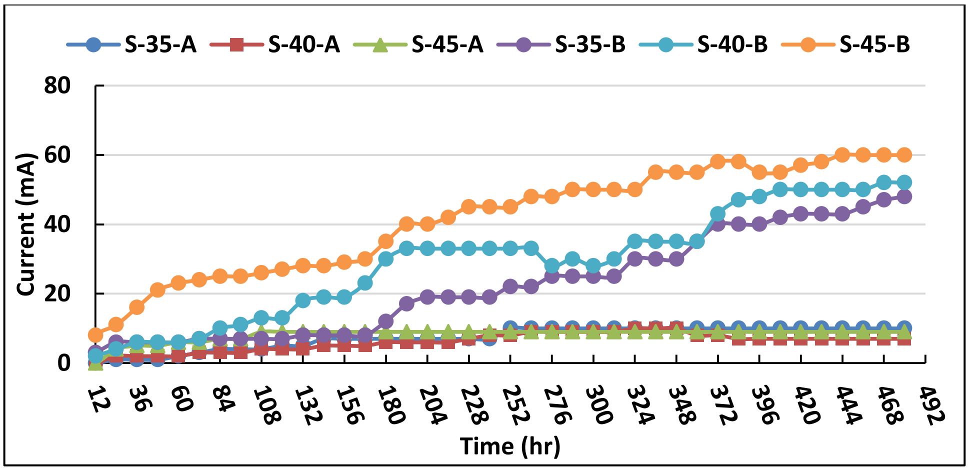


Figure (12.b) Current (mA) for CEM (III/A) Mixtures (10cm diam.)

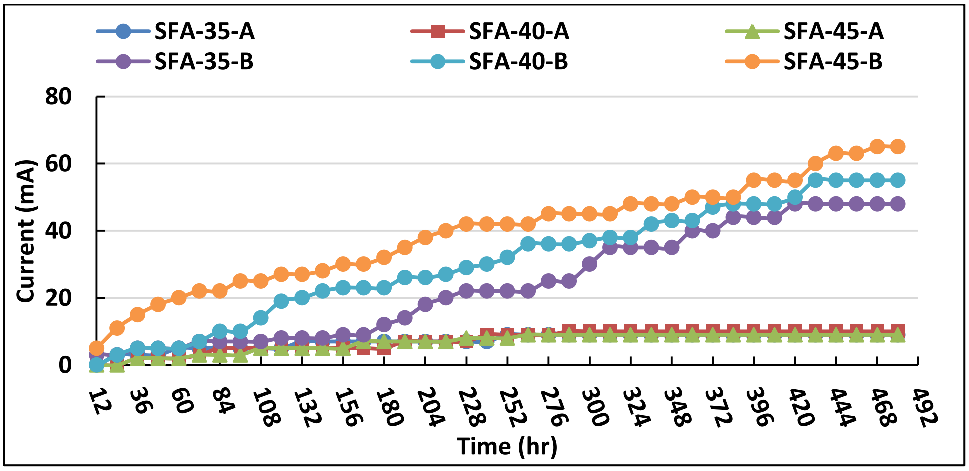
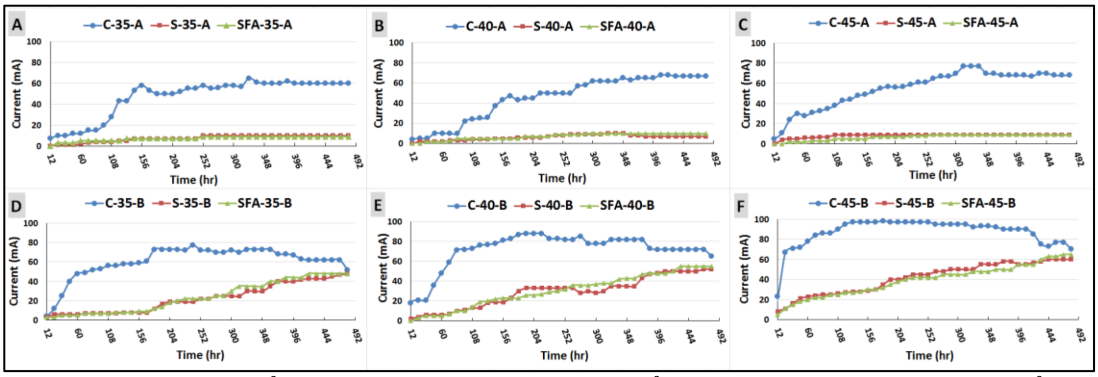


Figure (12.c) Current (mA) for (CEM III/A + 20% FA) Mixtures (10cm diam.)



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 13. Current Values (mA) Comparison for the three Cement Types (10cm diam.)

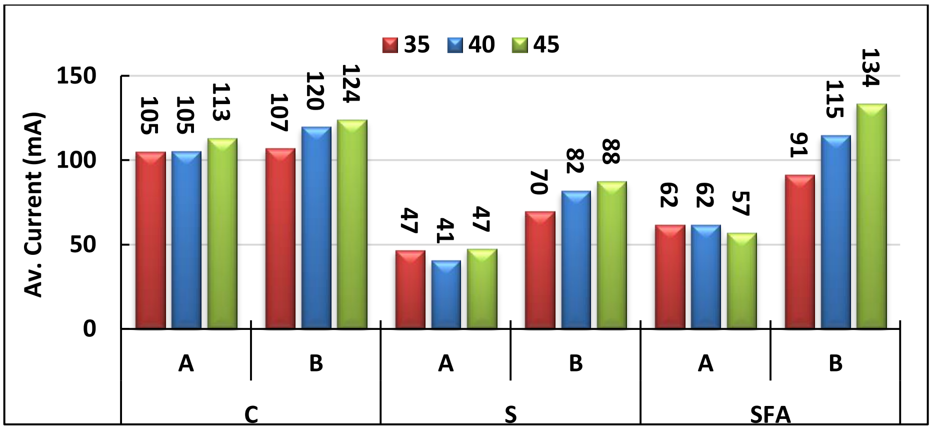


Figure (14.a) Average of Measured Current (mA) for Lollipop Specimens with (5cm diam.)

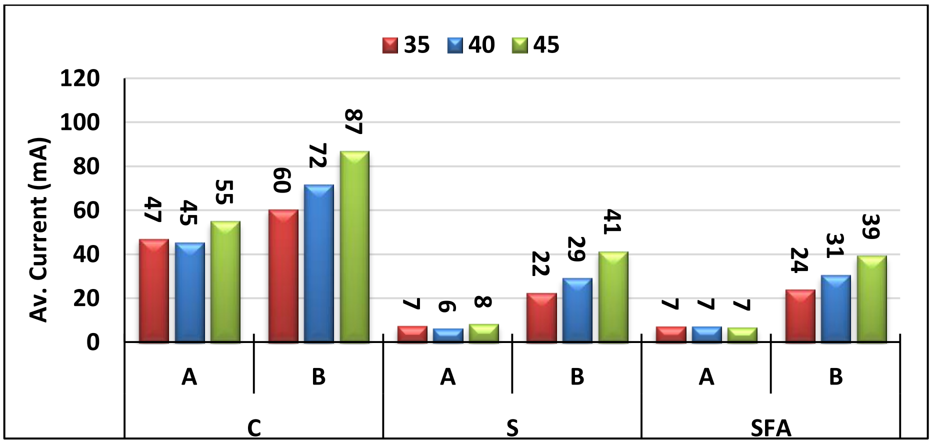


Figure (14.b) Average of Measured Current (mA) for Lollipop Specimens with (10cm diam.)

3.3. Permeability Test Results

Based on the aforementioned compressive strength results, impressed current profiles and values it was clear that the concrete mixtures cast with binder content 350 kg/m^3 gave the lowest permeability in case of water binder ratio 0.55 used, where in water binder ratio 0.45 used the lowest permeability is achieved with 400 kg/m^3 and may be increased or remain the same value with 450 kg/m^3.

Concrete mixtures in table (4) were chosen for permeability test according to the previous expectation and to emphasize the relation between (400, and 450 kg/m^3) binder content and the influence of water binder ratio increase.

It can be inferred from figure (15) that using of (CEM III/A), and (CEM III/A + 20% FA) gave the lowest permeability than (CEM I) which means that changing the type of cement will be effective than increasing binder/cement content. In addition, there is no significant effect on permeability between the concrete mixtures cast with binder content 400kg/m^3 or 450kg/m^3

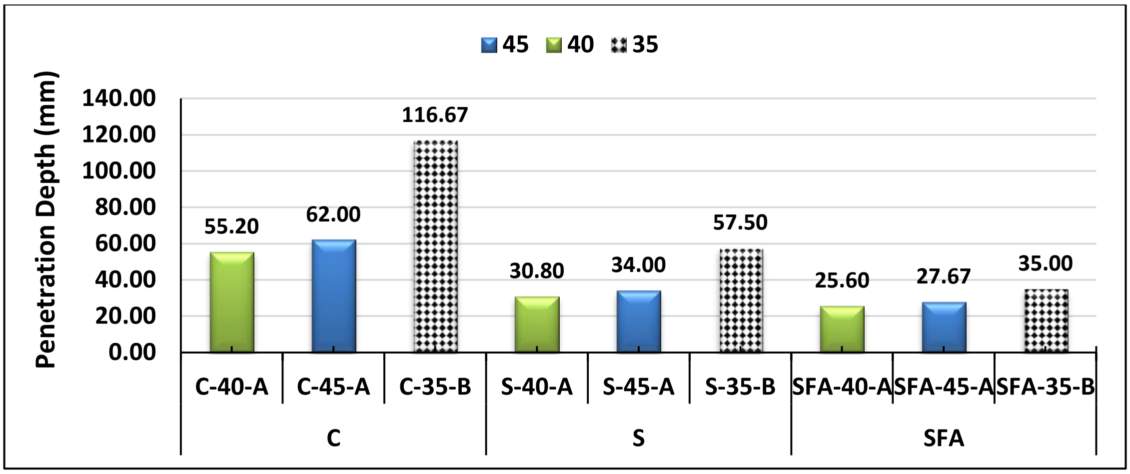


Figure 15. Average Water Depth after Permeability Test

3.4. Rapid chloride penetration test (RCPT)

Figure (16) showed that the current passing through various concrete specimens over the test period. To obtain the result of the test, the area under the current-time curve was calculated in order to obtain the ampere-seconds, or coulombs, of charge passed during the 6-hours test period. Table (6) showed the passed electric charges and the chloride ion penetrability of concrete according to ASTM C1202-10. It can be obtained from the test results that the penetration of chloride ions in hardened concrete is reduced by using (CEM III/A), and (CEM III/A + 20% FA) compared with (CEM I). In addition, there is no significant effect on chloride ions penetrability between the concrete mixtures cast with binder content 400kg/m^3 or 450kg/m^3 specially when (CEM III/A), and (CEM III/A + 20% FA) is used.

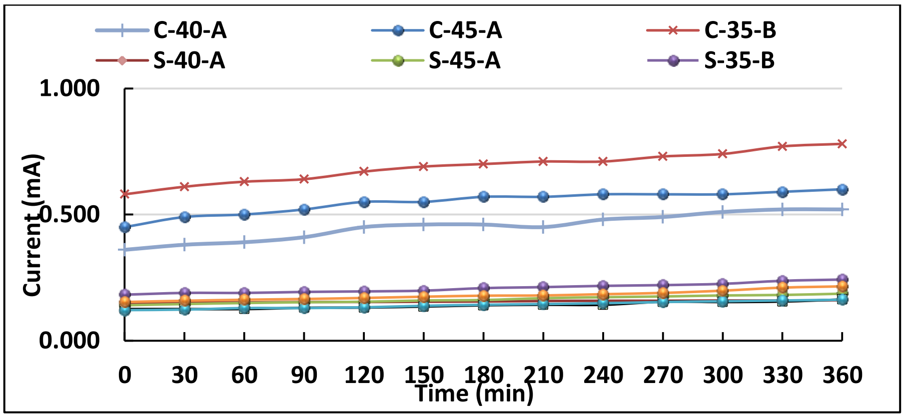


Figure (16.a) Current Passed Through All the Specimens during All 6-Hours

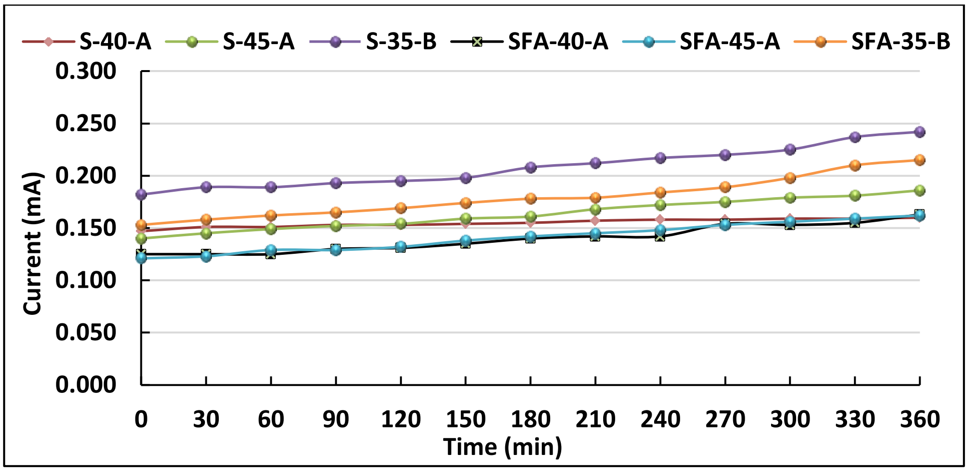


Figure (16.b) Current Passed Through Specimens during All 6-Hours For (CEM III/A, and CEM III/A + 20% FA) only

Table 6. Chloride Ion Penetrability of Concrete Mixtures

Sample ID	Charge passed (coulombs)	Chloride ion penetrability according to ASTM (C1202-10)
C-40-A	9792	High
C-45-A	11889	High
C-35-B	14904	High
S-40-A	3350	Moderate
S-45-A	3524	Moderate
S-35-B	4491	High
SFA-40-A	3016	Moderate
SFA-45-A	3052	Moderate
SFA-35-B	3870	Moderate

3.5. Determination of Maximum Rebar Diameter Loss

After impressed current test; all the embedded steel rebars extracted from lollipop specimens were examined, cleaned and their minimum diameter was measured and compared to the original diameter to obtain the percentage of diameter loss in relation to all different studied parameters.

Figure (17.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 water binder ratio 0.45 and 22% for water binder ratio 0.55 compared with (CEM I).

The percentage of rebar diameter loss results of 10cm lollipop specimens showed in figure (17.b). This figure showed that the specimens cast with (CEM III/A) and (CEM III/A + 20% FA) using water binder ratio 0.45 had no effect on its diameter compared with 28% loss in specimens cast with (CEM I). However, the water binder 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)

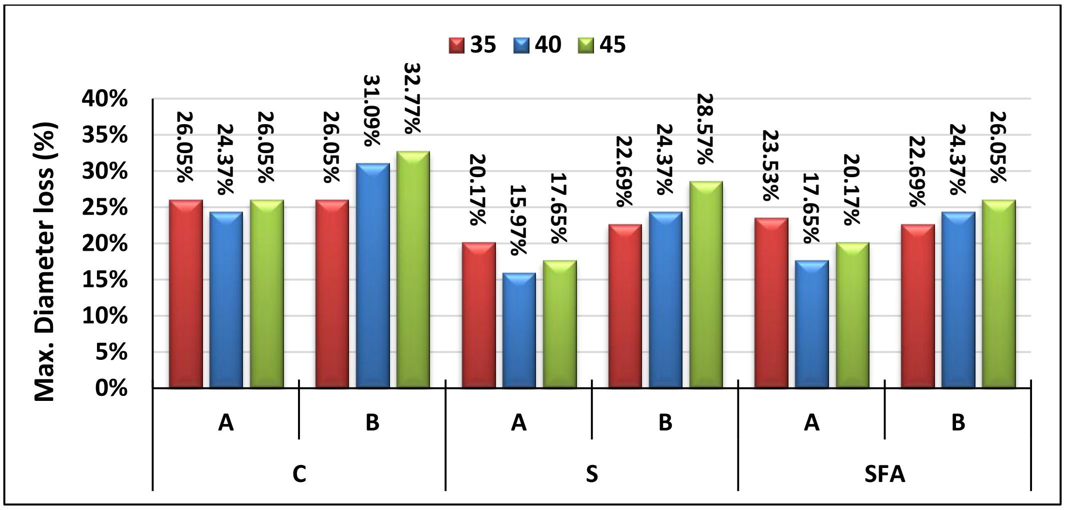


Figure (17.a) Percentage of Max. Diameter Loss for Lollipop Specimens (5cm Diam.)

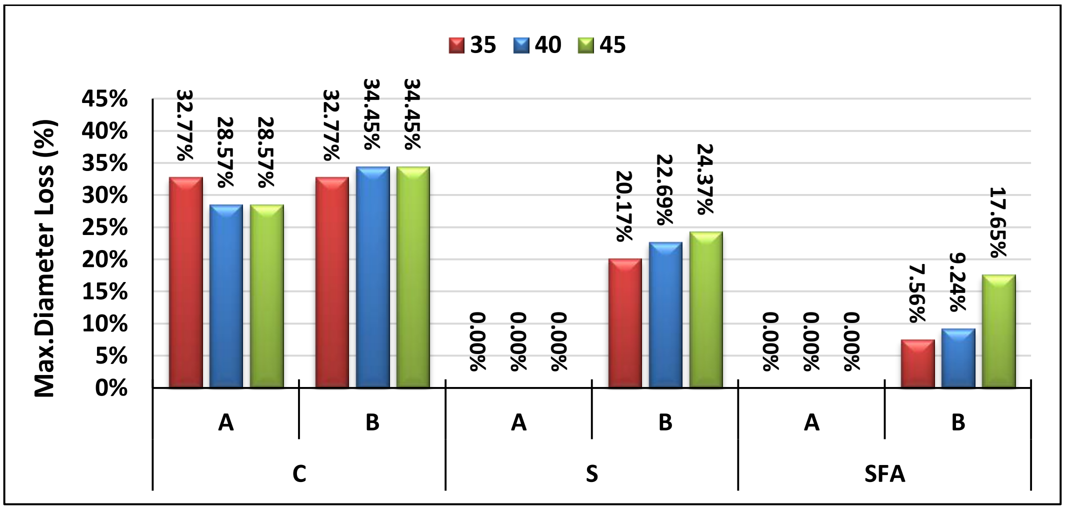


Figure (17.b) Percentage of Max. Diameter Loss for Lollipop Specimens (10cm Diam.)

The showed results suggest that concrete mixtures with lower water binder ratio gave better performance (measured by compressive strength, impressed current, permeability, rapid chloride penetration test, and maximum percentage rebar diameter loss). In the meantime, higher binder content is not effective in enhancing the permeability, chloride penetration resistance of concrete, and embedded rebar diameter loss. Accordingly, it might be advisable to specify concrete mixtures with binder content of not more than 400 kg/m^3 with water binder ratio not more than 0.45 to achieve highest possible corrosion resistance. These recommendations are in agreement with the conclusions of [26,27,28,29,30,31], which described that the electrical charge passed in hardened concrete with a faster and larger content in cement paste volume than aggregate volume because of the lower conductivity of aggregate than cement paste. Thus, increasing of cement paste (binder content) may adversely affect the hardened concrete durability. Optimum binder content for corrosion resistance depends on: cement type, water binder ratio, aggregate grading, aggregate type, and super-plasticizer type and dose.

4. Conclusions

- Increasing the concrete cover from 1.9cm to 4.4cm leads to drastic average impressed current reduction for all concrete mixtures. However, (CEM I) concrete mixtures (no matter how much w/b is) showed a reduction of (40% - 55%) of the average impressed current. For (CEM III/A) and (CEM III/A + 20% FA) concrete mixtures, w/b ratio has stronger effect. A reduction of 85% of impressed current is observed for w/b ratio 0.45. The reduction in impressed current ranges only between 55% and 75% for mixtures with w/b ratio 0.55. This is attributed to the increase in permeability caused by the increase in w/b ratio.
- Concrete mixtures cast with (CEM III/A), and (CEM III/A +20% FA) showed better corrosion resistance than (CEM I) by decreasing the average measured impressed current in lollipop specimens by; (40% - 60%) with small cover (1.9cm), and 85% with large cover (4.4cm) for 0.45 w/b ratio. Whereas in case of 0.55 w/b ratio the measured current decreased by 60% with large cover (4.4cm). In the case of small cover (1.9cm); 30% reduction in measured impressed current is recorded for (CEM III/A) concrete mixtures. For the same small cover specimens, there is no significant effect when concrete mixtures are cast with (CEM III/A +20% FA).
- When considering concrete permeability; binder type is an important factor. For 400,450 kg/m^3 binder content; (CEM III/A), and (CEM III/A +20% FA) show lower permeability than CEM I mixtures. In the case of w/b=0.45; using of concrete mixtures cast with (CEM III/A), and (CEM III/A + 20% FA) led to decrease the permeability by 45%, and 55% respectively. In the case of mixtures cast with cement content of 350 kg/m^3 and w/b = 0.55; the decreasing percentages were 50%, and 70%.
- Low cement content combined with high w/b ratio give higher chloride penetrability. However; for the same cement content and w/b ratio; using CEMIII instead of CEM I leads to 60% reduction in chloride penetrability. Additional reduction of chloride penetrability of 10% is achieved by using CEM III + 20% FA.
- The overall effect of cement content on concrete properties is evaluated. Cement content of 350 kg/m^3 is not recommended due to its high porosity caused by its low paste content. Furthermore, cement content of 450 kg/m^3 would not be beneficial as increasing cement content does not improve strength, impressed current influence, permeability, and rapid chloride penetration.
- The impact of increasing concrete cover is strongly revealed in impressed current values and the percentages of maximum diameter loss of steel rebar, also those results emphasize that using blended cements is more effective than ordinary cement even if cement content is increased.
- Based on these findings, it is possible to reduce the cement content (paste content) without sacrificing the desired workability, compressive strength and durability, for lower water cement ratios.

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