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Corrosion of Steel Bars in Concrete Mixes Designed According to Different Codes Recommendations and Exposed to Variable Environmental Classes

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Abstract - The scope of this research is to study experimentally the effect of mix design method and environmental exposure conditions on corrosion of steel bars. Three codes were chosen to make a full comparison of corrosion of steel bars in reinforced concrete and behavior of concrete due to exposure classes. R.C. Cubes and cylinders specimens were cast and tested experimentally. Cubes have a dimension of 100*100*100 mm were chosen to study compressive strength of concrete, cylinders have a dimension of 100* 200 mm were chosen to study splitting strength of concrete and cylinders have a dimension of 50*100 mm were chosen to study corrosion of steel bars. Among the tested samples, curing in pure water were chosen as reference specimens whereas the other specimens were cured in sea water. The investigated variables in this experimental program, include different codes provision and the exposure classes. The experimental results show a significant enhancement on the performance behavior of concrete and steel bars due to different mix designs and different exposure classes. The corrosion of steel bars in concrete cured in pure water less that cured in sea water for the three design mixes ECP, ACI and BS in addition the corrosion of steel in mix design of ACI generally less than the other two mix designs in pure water and sea water. Also, compressive strength of concrete and splitting strength in pure water less than in sea water in the three design mixes (ECP, ACI and BS).

Key Words: mix design, corrosion, exposure classes, Reinforced concrete.

1. INTRODUCTION

Corrosion of steel bars in concrete is a major and an important cause in the deterioration of concrete structures. In the past years several researches have been conducted on the corrosion of reinforcing steel bars in concrete structures. Some of the main factors studied were: Causes interfered with the corrosion process, the development of methods to control reinforcing steel bars corrosion and the assessment of durability models enabling estimates on the service life of reinforced concrete structures affected by corrosion.

Many factors that influence the reinforcing steel bars corrosion process, among which the influence of chloride ions and concrete carbonation, the mix design and curing Conditions of concrete, the chemical composition of the pore solution and the properties of the concrete cover are some of the most important. In addition, there are several local variables, as the mineralogy of raw materials, the influence of local exposure conditions and traditional construction practices, which may influence the reinforcing steel bars corrosion process. All these factors should be taken into account when attempting to assess the extent of reinforcing steel bars corrosion on a reinforced concrete structure [1-6]. Roberge [7], mentioned that Chloride attack is a major concern in reinforced concrete. The chloride may originate from the constituents of the concrete mix itself or from the diffusion of chloride ions from the surrounding environment. Broomfield, [8], investigated that the chlorine in pore solution causes the adjacent metal to go into dissolution at a local site. Sag⍰⍰s et al [9], indicated that with time progresses, chloride from the seawater diffuses through the concrete cover and builds up near the steel-concrete interface. Ai Hongmei, Bai Junying [10], indicated that the Corrosion of steel in concrete is an electrochemical process; the two most common conditions inducing rebar corrosion and breakdown of passive film in reinforced concrete are carbonation and chloride erosion. Elsener, B., [11], Corrosion of steel in concrete occurs either due to the formation of microcells, or macro cells. Ann and Song [12], Investigated the two main phenomena such as carbonation and chloride attack may lead to a breakdown in the surface layer of ferrous hydroxide that covers the steel in the alkaline concrete environment. Bob [13], investigated that the mechanism of ingress of aggressive agents depends on the exposure conditions of the concrete, but all three processes can occur simultaneously. All of the transport mechanisms rely heavily on the quality of the concrete microstructure, which is a function of its total porosity, the size and distribution of pores and capillary tubes of the cement stone and the aggregates that make up the concrete, and the degree to which the coarser pores are interconnected.

Numerous factors influence the microstructure inc1uding the quantity and type of cement, the water-cement ratio (w/c), the grading and the maximum size of aggregate, the use of admixtures, and the compaction and the curing process. Fazio [14], indicated that Chloride ions may be present in concrete during manufacturing, or they may penetrate into the concrete from some source. Specific sources of chloride ions include accelerating admixtures that contain calcium chloride, salt-contaminated aggregates, seawater, salt spray, and most importantly, deliberately applied de-icing salts. The researcher Jones [15], studied experimentally that after hardening, the pore solution in a hydrated Portland cement matrix remains alkaline with a pH value of around 13. In this environment, steel is protected by a thin but dense layer of protective oxides. This layer is known as "passive layer" which is formed spontaneously. In these conditions, the passive layer is produced on the surface of reinforcing steel acting as a barrier for the anodic reaction. L. Xuean and W. Jun [16,17] When chloride ions coexist in concrete with other anions (OH⍰, chloride ions are Easier to be absorbed than OH⍰ resulting in a much lower OH⍰ concentration near passive film than that in micro pores. This local reduction of pH value may initiate Localized breakdown of the film. Lydon (1995) [18], Investigated the effect of w/c ratio on the intrinsic permeability of two types of concrete. It was found that the permeability increased with w/c ratio, with specimens whose ratio was 0.5 exhibiting a higher intrinsic permeability than those with a w/c ratio of 0.4.In another study by Ahmad et al. Ahmad, S., Azad, A. K. and Loughlin, K. F [19], indicated that the w/c ratio has a significant influence on permeability of concrete. It was shown that the permeability increased considerably with an increase in w/c ratio. They also reported, in accordance that the permeability increased more rapidly when the w/c ratio approached 0.6. Yingshu [20], investigated the quality of the concrete cover is involved in the physical protection of steel from environment, because concrete transport properties control the ingress kinetics of aggressive agents. During this phase, no corrosion occurs and it usually takes many years for aggressive agents to reach steel surface and de passivate steel. Bentur, Berke and Diamond, [21], explained the oxide film that forms on the steel. Normally, the film is either ferrous or ferric in nature. Ferric oxide tends to be more stable and eventually any ferrous oxide is converted to the more stable ferric oxide. When chloride ions penetrate to the steel surface, the ions react with the ferrous atoms forming a soluble complex which dissolves in the pore solution removing a component of the protective oxide film. This occurs at locations on the steel where the ferrous oxide has not yet been converted to ferric Oxide. Since this is only in specific locations, there is a localized loss of passivity and chloride penetration often results in extensive and dangerous pitting corrosion.

2. Research Significance

The main goal of this study is to investigate experimentally the corrosion of steel bars in reinforced concrete. Two main parameters which were: different codes used for mix design, two different environment exposure conditions (pure water and sea water). Three mixes of design (ECP 203 -2017, ACI 318 -2019 and BS 8500-1:2015+A2:2019) [22-24], introduced to achieve a compressive strength, splitting strength and corrosion of steel bars in two different environment exposure conditions (pure water and sea water). In order to achieve this objective, a total of 72 cubes (100 mm*100 mm*100 mm), 72 cylinders (100 mm*200 mm) and 72 cylinders (50 mm*100 mm) were casted and tested.

3. Experimental work

3.1 Material properties

All samples of the three codes were casted according to every code recommendation. The cubes (100 mm *100 mm*100 mm), cylinders (100 mm*200 mm) and cylinders (50 mm*100 mm) for every mixture of the three codes (ECP, ACI and BS) constructed from the same batch of concrete to preserve the same concrete Strength. Target mean cube strength of concrete for ECP, ACI and BS mixes were 50 MPa, 42 MPa and 45 MPa, respectively. The reinforcing steel bars were used Φ12 as longitudinal steel reinforcements. The yield strength of main reinforcement was 360 MPa. The maximum size of aggregate was 12.5 mm.

3.2 Mix design

TABLE -1 shows the contents of $1m^3$ concrete mix for the three codes (ECP, ACI and BS), respectively. Also, every mix content (water cement ratio, fine aggregate (F.A.), coarse aggregate (C.A.), cement and water) is given.

3.3 Test specimens

The experimental program of this study involved testing of 120 cubes (100 mm*100 mm*100 mm) as shown in **Fig- 1.a and 1.b**, 120 cylinders (100 mm*200 mm) as shown in **Fig- 2.a and 2.b** and 120 cylinders (50 mm*100 mm) as shown in **Fig- 3.a and 3.b**.

Fig- 1.a: Cubes (100 mm *100 mm*100mm) during casting

Fig- 2.a: Cylinders (100 mm *200 mm) during casting

TABLE -1 ECP, ACI and BS contents of 1m^3 concrete mix

Type	ECP	ACI	BS
	Kg/m^3	Kg/m^3	Kg/m^3
Coarse aggregate (C.A)	1215.02	912.49	927.58
Fine aggregate (F.A)	607.51	702.51	728.81
Cement content (C.C)	400	500	461.11
Water content (W.C)	180	200	207.5
W/C	0.45	0.40	0.45
A / C	4.56	3.23	3.59
C.A / F.A	2	1.3	1.27

Fi g- 1.b: Cubes (100 mm *100 mm*100mm) after hardening

Fig- 2.b: Cylinders (100 mm *200 mm) after hardening

Fig- 3.a: Cylinders (50 mm *100 mm) during casting

3.4 Test setup

All Cubes (100 mm*100 mm*100 mm), cylinders (100 mm*200 mm) and Cylinders (50 mm*100 mm) were divided into two groups (A and B) according to the environment exposure condition. Group A is kept in pure water during the period of Studying, while group B is kept in sea water during the period of Studying. Both of the two groups were tested to achieve compressive strength, splitting strength and corrosion of steel bars at 28 days, 60 days, 90 days, and 180 days as shown in **Fig - 4 , Fig -5 and Fig -6 .**

Fig- 4: Cube (100 mm *100 mm*100mm) during compressive strength test

Fig- 3.b: Cylinders (50 mm *100 mm) after hardening

Fig- 5: cylinder (100 mm *200 mm) during splitting strength test

Fig- 6: cylinder (100 mm *200 mm) during measuring corrosion.

4. Experimental Results and Discussion

The test results of pure water condition and sea water condition specimens are discussed in the following sections. The compressive strength, splitting strength and corrosion of steel bars were compared to evaluate the difference between (ECP), (ACI) and (BS) codes results.

a. Compressive strength

Table -2 and **3** show the compressive strength values of ECP, ACI and BS according to Environmental Exposure Condition. **Fig-7 and Fig-8** show a Comparison between compressive strength values of samples immersed in pure water and sea water (ECP, ACI and BS mixes). It can be observed that for samples cured in pure water, the compressive strength values of BS and ECP less than that of ACI values and all of them increased with the increase of concrete age (**Fig-7**). While for sea water samples, compressive strength values of BS and ECP were decreasing throughout the duration of the study but the compressive strength values of ACI were increased throughout the first 90 days of the study and then decreased after that (**Fig-8**).

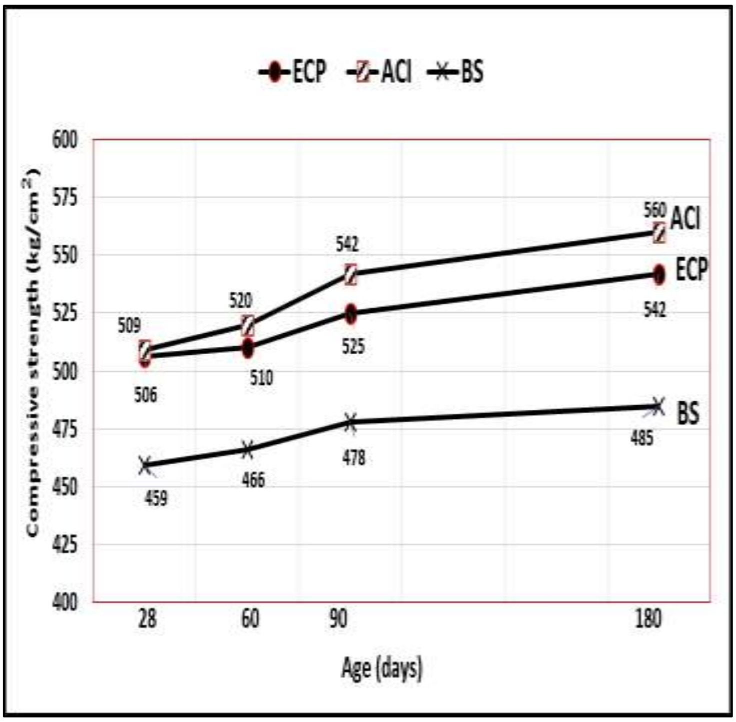

Fig- 7: Comparison between compressive strength values of samples immersed in pure water(ECP, ACI and BS recommendations).

TABLE -2: ECP, ACI and BS compressive strength results in pure water.

Test duration (days)	Average of F_{cu} (Kg/cm^2)		
	ECP	ACI	BS
28	506	509	459
60	510	520	466
90	525	542	478
180	542	560	485

TABLE -3: ECP, ACI and BS compressive strength results in sea water.

Test duration (days)	Average of F_{cu} (Kg/cm^2)		
	ECP	ACI	BS
28	503	490	451
60	498	495	446
90	487	499	430
180	472	445	401

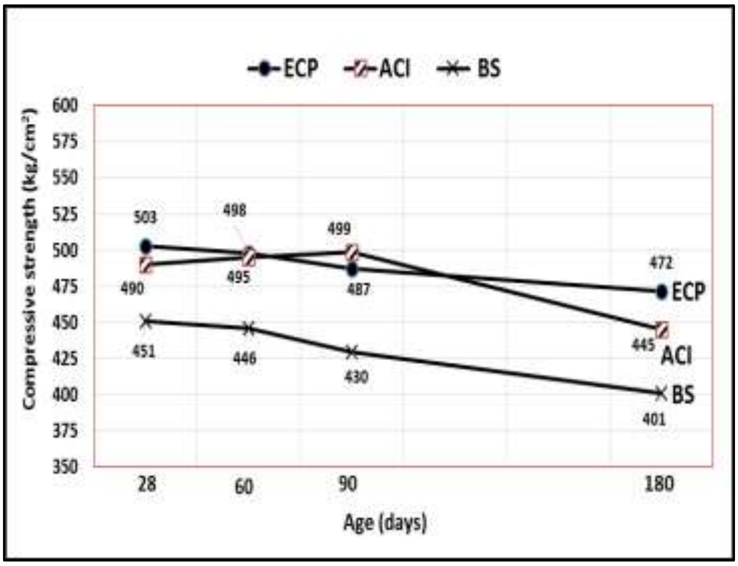

Fig- 8: Comparison between compressive strength values of samples immersed in sea water (ECP, ACI and BS recommendations).

b. Splitting strength

Table -4 and 5 show the splitting strength values of ECP, ACI and BS according to Environmental Exposure Condition. **Fig-9 and Fig-10** shows a comparison of the splitting strength between the three mixtures in pure water and sea water. The results of pure water curing indicated that, the splitting strength values of BS and ECP less than that of ACI values and all of them are increased with the increase of age (Fig-9). While for sea water curing, the splitting strength values of BS and ECP were decreasing throughout the duration of the study but the ACI values were increased throughout the first 90 days of the study and decreased after that (Fig-10). Also, the splitting strength values of BS and ECP are less than that of ACI.

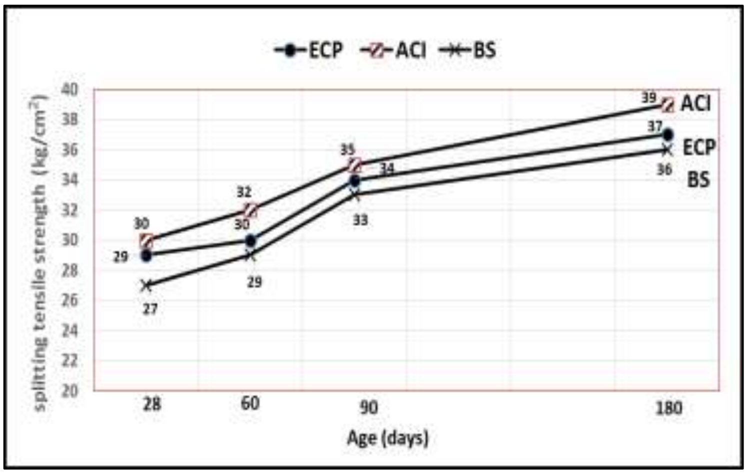

Fig- 9: Comparison between splitting tensile strength values of samples immersed in pure water (ECP, ACI and BS recommendations).

c. Corrosion

Table -6 and 7 shows the corrosion rate values of ECP, ACI and BS according to Environmental Exposure Condition. **Fig-10 and Fig-11** show a comparison of the corrosion between the three mixtures in pure water and sea water, respectively. It can be observed that the corrosion values in pure water less than that in sea water in all of the three mixtures.

TABLE -4: ECP, ACI and BS splitting strength results in pure water.

Test duration (days)	Average of splitting strength (Kg/cm^2)		
	ECP	ACI	BS
28	29	30	27
60	30	32	29
90	34	35	33
180	37	39	36

TABLE -5: ECP, ACI and BS splitting strength results in sea water.

Test duration (days)	Average of splitting strength (Kg/cm^2)		
	ECP	ACI	BS
28	26	28	25
60	25	29	24
90	23	31	22
180	20	25	19

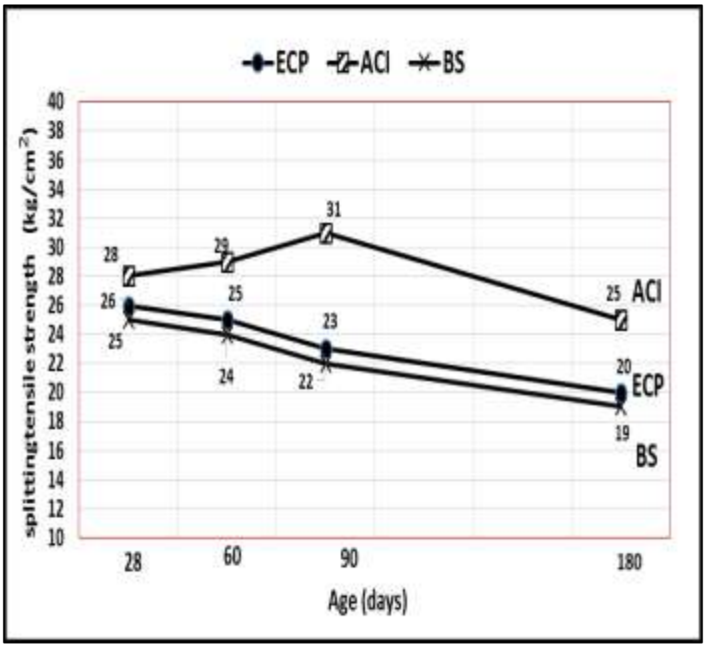

Fig- 10: Comparison between splitting tensile strength values of samples immersed in sea water (ECP, ACI and BS recommendations).

The results indicated that the corrosion values of ECP and ACI less than that BS values. It can be observed that the corrosion values of the three mixtures were increased throughout the duration of the study.

TABLE -6: ECP, ACI and BS corrosion of steel bars results in pure water.

Test duration (days)	Corrosion Rate (μm/ yr.)		
	Code Recommendations		
	ECP	ACI	BS
28	215	118	391
60	258	126	420
90	324	245	450
180	418	318	520

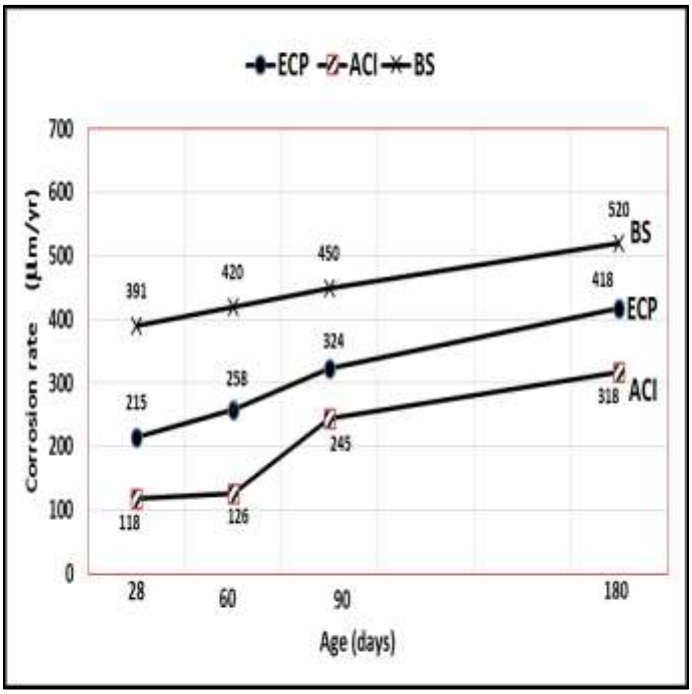

Fig- 10: Comparison between corrosion rate values of samples immersed in pure water (ECP, ACI and BS recommendations).

5. CONCLUSIONS

This study presents an experimental investigation on the Corrosion of steel bars in R.C according to ECP, ACI and BS codes. Three mixtures of concrete casted and tested, the following Conclusion can be summarized.

1. Compressive strength of all mixes immersed in **pure water** increased with the increase of concrete age and Compressive strength of ECP and ACI samples are larger than that of BS samples by average values 10.3% and 12.8 %, respectively.

TABLE -7: ECP, ACI and BS corrosion of steel bars results in sea water.

Test duration (days)	Corrosion Rate (μm/ yr.)		
	Code Recommendations		
	ECP	ACI	BS
28	279	154	699
60	333	173	780
90	471	320	872
180	621	550	986

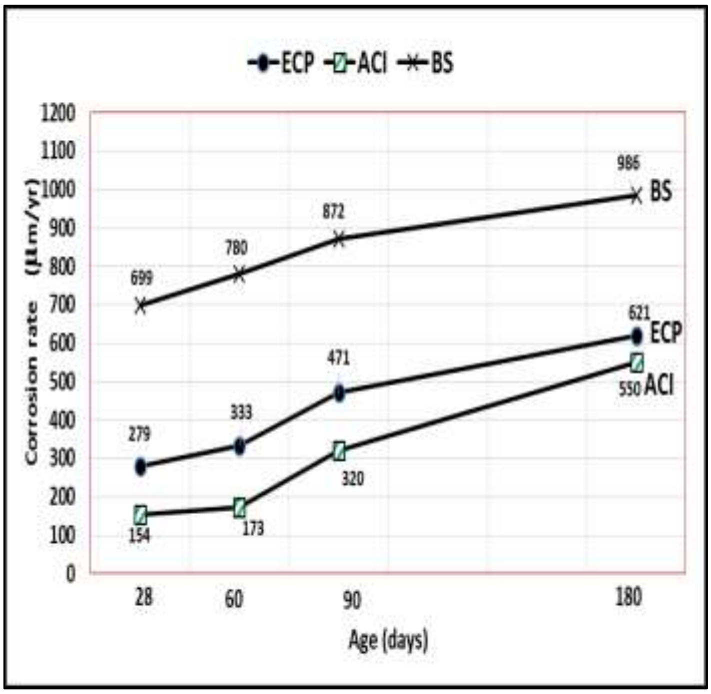

Fig- 11: Comparison between corrosion rate values of samples immersed in sea water (ECP, ACI and BS recommendations).

2. Compressive strength of **ECP 203-2017** samples immersed in pure water at 60, 90 and 180 days increased by 0.8%, 3.75% and 7.11 % of 28 days value, respectively. That of **ACI 318-2019** at 60, 90 and 180 days increased by 2.16%, 6.48% and 10.02 % of 28 days value, respectively. That of **BS 8500-2019** at 60, 90 and 180 days increased by 1.53%, 4.14% and 5.66 % of 28 days value, respectively.
3. Compressive strength of samples immersed in **sea water** of ECP and BS decreased with the increase of concrete age, while that of ACI samples continued in increasing up to 90 days (2%) and started in decreasing after that.
4. Compressive strength of **ECP** and **ACI** samples immersed in **sea water** are larger than that of **BS** samples by average values 13.5% and 8.9 %, respectively.
5. Compressive strength of **ECP** samples immersed in sea water at 60, 90 and 180 days decreased by 1%, 3.18% and 6.16 % of 28 days value, respectively. That of **ACI** samples immersed in sea water at 60, 90 days increased by 1.02% and 1.84% of 28 days value, while at 180 days decreased by 9.18% of 28 days value, respectively. That of **BS** samples immersed in sea water at 60, 90 and 180 days decreased by 1.11%, 4.66% and 11.1 % of 28 days value, respectively.
6. Splitting tensile strength of **ECP** samples immersed in pure water at 60, 90 and 180 days increased by 3.45%, 17.24% and 27.59 % of 28 days value, respectively. That of **ACI** samples immersed in pure water at 60, 90 and 180 days increased by 6.67%, 16.67% and 30% of 28 days value, respectively. That of **BS** samples immersed in pure water at 60, 90 and 180 days increased by 7.41%, 22.22% and 33.33 % of 28 days value, respectively.
7. Splitting tensile strength of **ECP** and **BS** samples immersed in sea water decreased with the increase of concrete age, while that of **ACI** samples immersed in sea water continued in increasing up to 90 days and started in decreasing after that.
8. Splitting tensile strength of **ECP** samples immersed in sea water at 60, 90 and 180 days decreased by 3.85%, 11.54% and 23.08 % of 28 days value, respectively. That of **ACI** samples immersed in sea water at 60, 90 days increased by 3.57% and 10.71% of 28 days value, while at 180 days decreased by 10.71% of 28 days value. That of **BS** samples at 60, 90 and 180 days decreased by 4%, 12% and 24 % of 28 days value, respectively.
9. Corrosion rate of all mixes (ECP, ACI and BS) immersed in pure water and sea water increased with the increase of concrete age.
10. Corrosion rate of **ECP** samples immersed in pure water and sea water are larger than that of **ACI** and smaller than that of **BS**.
11. **ECP 203-2017** mix design is more conservative than **BS 8500-2019**, and **ACI 318-2019** mix design is the most conservative.
12. Average increase of Corrosion rate of **ACI** and **BS** samples immersed in **pure water** are 64 % and 152 % of **ECP** values, respectively. For samples immersed in **sea water**, average increase of Corrosion rate of **ACI** and **BS** are 66 % and 207 % of ECP values, respectively.
13. Corrosion rate at 180 days for samples immersed in **sea water** increased by 48.6%, 73.0%, and 89.6% than that immersed in **pure water** for ECP, ACI and BS samples, respectively.
14. Corrosion rate of **ECP** samples immersed in **pure water** at 60, 90 and 180 days increased by 20%, 50.7% and 94.42 % of 28 days value, respectively. That of samples immersed in **sea water** at 60, 90 and 180 days increased by 19.35%, 68.82% and 122.58 % of 28 days value, respectively.
15. Corrosion rate of **ACI** samples immersed in **pure water** at 60, 90 and 180 days increased by 6.78%, 107.63% and 169.49 % of 28 days value, respectively. That of samples immersed in **sea water** at 60, 90 and 180 days increased by 12.34%, 107.79% and 257.14 % of 28 days value, respectively.

16. Corrosion rate of **BS** samples immersed in **pure water** at 60, 90 and 180 days increased by 7.42%, 15.09% and 32.99 % of 28 days value, respectively. That samples immersed in **sea water** at 60, 90 and 180 days increased by 11.59%, 24.75% and 41.06 % of 28 days value, respectively.

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