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Mitigation of Salt-Induced Corrosion of Reinforcing Steel in Concrete using Rebar-Coating Technique

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Abstract:** The article aims to render the study results on mitigation of salt-induced corrosion of reinforcing steel in concrete using rebar-coating technique prior to concreting. Regarding the characteristics of the tested type of salt-contaminated concrete, it had chloride ion content of 0.6, 1.2, 1.8 and 2.4 kg per m^3 of concrete (with M300grade, B10 waterproof level and concrete cover thickness of 30mm) which evidently passed the destructive accelerated corrosion tests for concrete samples. M30.3.0.6 concrete sample (i.e.,M300 grade reinforced concrete with uncoated rebar, cover thickness of 30mm and chloride ion content of 0.6kg/m^3 of concrete) served as the reference sample. From the perspective of the accelerated corrosion test, the sample with polymer cement-coated rebar, in case of salinity of 1.8kg/m^3, suffered from the reinforcing steel corrosion level lower than that of the reference sample. Along with that, the samples with polyurethane- or epoxy-coated rebars suffered from the rebar corrosion level lower than that of the reference sample in case of salinity of 2.4 kg/m^3. It became evident that the different protective coatings were characterized by the different corrosion resistance levels in the following order: polymer cement with the highest level, followed by polyurethane and epoxy.

***Keyword:** reinforcing; coating technique; polymer cement; Concrete*

I. INTRODUCTION

With regard to reinforced concrete structures suffering from the salinity of less than 0.6 kg/m^3 of concrete, which is difficult for setting the required rebar cover thickness as required in Table 1 [1], the smaller cover thickness in combination with one of secondary protection measures including corrosion-resistant coatings for rebar is preferred. In spite of the fact that amongst the concrete structures suffering from the salinity of more than 0.6 kg/m^3 of concrete (from 0.6 to 2.4 kg/m^3), those involved in the salinity of 2.4 kg/m^3 are treated with improved waterproofing level (concrete grade) combined with the improved cover thickness to reduce the rebar corrosion level, thin structures such as slabs, overhangs, etc., cannot bear the greater thickness of cover. For the purpose of tackling the unavoidable challenges, three types of coatings, namely, epoxy, polyurethane and polymer cement as commercial products, were examined in the study. Rebars were coated before pouring of concrete having B10 waterproof level (M300 grade) and concrete cover thickness of 30mm and suffering from salinity of 0.6, 1.2, 1.8 and 2.4kg/m^3. M30.3.0.6 concrete sample (with B10 waterproof level and M300 grade) served as reference sample to compare the rebar corrosion level through observing the times to crack initiation in the concrete samples. The method adopted in the study followed the NT Build 356[2]. A number of required properties of the rebar coatings, such as adhesion between concrete and rebar, flexural strength, impact resistance and alkaline resistance, were tested before the study was in effect carried out.

II. MATERIAL AND METHOD

A. Material

1) *Cement:* But Son PCB40 Cement, whose technical specifications meet the technical requirements as shown in TCVN 2682: 2009, was used for the study.
2) *Sand:* Nha Trang beach sand with the fineness modulus M_n = 2.1 was examined. The content of chloride ion in the kind of sand is 0.33 %, greater than the limited value of 0.05% as shown in TCVN 7570: 2006 and TCVN 9346: 2012.
3) *Stone*: Crushed stone in Hoa Binh, whose technical specifications meet the technical requirements as shown in TCVN 7570:2006, was used.
4) *Mixing water for concrete*: Mixing water was supplied from tap water whose technical specifications meet the technical requirements as shown in TCVN 4506 : 2012.

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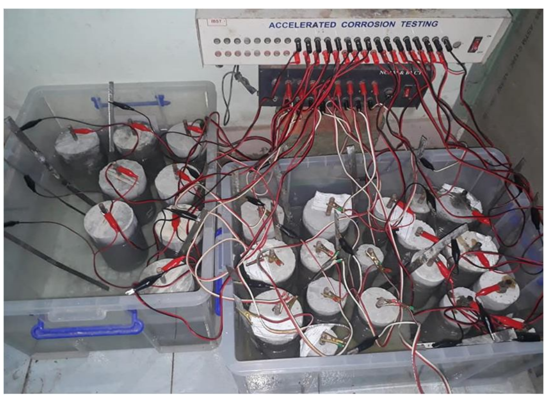
5) *Superplasticizer*: BIFI HV252 was used. This kind of admixture has been declared conform to the technical requirements TCVN 8826 :2011 by the relevant manufacturers.
6) *Rebar*: The rebar, used in the study, was Φ14 CT3 deformed rebar of Hoa Phat, lathed into Φ10 plain bar.
7) *Coating*: The above-mentioned types of coatings, which are all highly resistant to corrosion, was used. Film thickness examined in the study was as follows:

a) *For Epoxy:* film thickness of 175±18µm;
b) *For 3000 Polyurethane:* film thickness of 150±15µm;
c) *For AC-05 Polymer Cement:* film thickness of 1500±150µm.

B. Method

The technique of accelerated corrosion of reinforcing steel in concrete was adopted in the study. The reinforced concrete samples was cured for 28 days, then, put into the accelerated corrosion test. The samples were immersed in 3% NaCl solution so that water level was always 3cm away from the top of each sample. A rebar was connected to the anode of a 5V DC power supply while the cathode was connected to another stainless steel electrode immersed in a solution. Under the influence of the current, the diffusion rate of Cl^- ion into concrete increased sharply whilst the rebar corrosion accelerated; as a result, rust appeared and initiated the cracks in each sample. The amperage was measured regularly every 24 hours; at the same time, the surface state of the samples was observed. At the time of a surge in amperage, cracks together with rust appeared on the surface along the length of the rebar. The stronger the corrosion was, the less time it took from the starting time of the test to the time of current surge. The data of time served as a basis to clarify the difference in the corrosion levels of reinforcing steel in different types of concrete affected by different salinity levels and having the various types of rebar coatings. The testing diagram and samples are shown in Figure 1. Concrete aggregates used in the study are shown in Table 1.



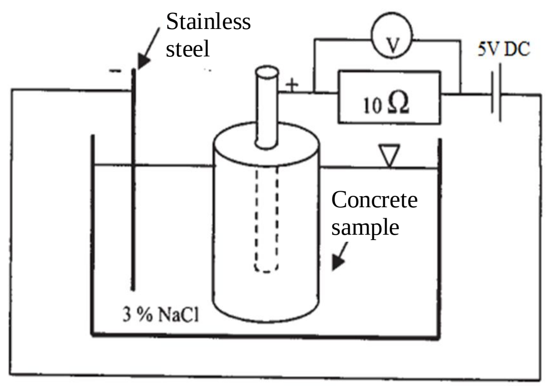


Figure 1. Sample composition and testing diagram

Table 1. Concrete aggregates M300(B10) used in the study

TT	Sample notation	Material composition in 1m3 of concrete						R_{28}, MPa	Degrees waterproof	Note
		Cement, kg	Sand, kg	Stone, kg	Water, liters	Additives, liters	Cl^-, kg/m^3 of concrete			
1	M30.3.0.6	348	725	1165	185	3,83	0,6	33,2	B10	Steel reinforcement is painted with epoxy, polyurethane and polymer cement
2	M30.3.1.2	348	725	1165	185	3,83	1,2	33,9	B10	
3	M30.3.1.8	348	725	1165	185	3,83	1,8	34,4	B10	
4	M30.3.2.4	348	725	1165	185	3,83	2,4	34,8	B10	

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III. FINDINGS AND ARGUMENTS

A. *Findings*

The testing results are shown in Figures 2 to 6 and Tables 2 to 4 as well.

Table 2. Amperage of concrete samples having B10 waterproofing level and epoxy- and polyurethane-coated rebars and suffering from different salinity levels

Test day	Amperage, mA								
	M30.3.0. 6	M30.3.0. 6.P	M30.3.1. 2.P	M30.3.1. 8.P	M30.3.2. 4.P	M30.3.0. 6.E	M30.3.1. 2.E	M30.3.1. 8.E	M30.3.2. 4.E
1	2.4	0.02	0.03	0.04	0.06	0.01	0.02	0.03	0.05
2	2.2	0.22	0.31	0.35	0.48	0.18	0.23	0.34	0.45
3	2.3	0.49	0.52	0.58	0.89	0.32	0.35	0.56	0.87
4	2.7	0.72	0.79	0.81	1.2	0.68	0.69	0.69	1.1
5	3.8	0.9	1.3	1.5	1.8	0.83	0.84	1.2	1.3
6	4.7	1.1	1.4	1.7	2.3	0.91	0.98	1.4	1.4
7	5.2	1.3	1.5	1.9	2.6	1.1	1.2	1.6	1.7
8	6.4	1.8	2.2	2.7	3.1	1.4	2.1	2.5	2.8
9	16.5*	1.9	2.4	3	3.2	1.5	2.3	2.6	2.9
10		2.1	2.6	3.1	3.2	1.7	2.4	2.7	3.1
11		2.2	2.8	3.3	3.3	1.8	2.6	2.8	3.2
12		2.3	3	3.5	3.6	1.9	2.7	2.9	3.4
13		2.5	3.4	3.6	3.7	2.2	3.2	3.3	3.6
14		2.6	3.8	3.8	3.9	2.3	3.7	3.8	3.8
15		2.7	3.9	3.9	4.1	2.5	3.8	3.8	3.9
16		2.8	4.1	4.1	4.3	2.7	4	4.1	4.2
17		3	4.3	4.4	4.6	2.9	4.1	4.3	4.5
18		3.2	4.5	4.7	4.8	3	4.3	4.5	4.6
19		3.3	4.6	4.8	5	3.2	4.4	4.7	4.7
20		3.5	4.7	4.9	5	3.4	4.5	4.8	4.9
21		3.6	4.8	5	5.1	3.5	4.6	4.9	5
22		3.8	4.9	5.2	5.2	3.6	4.8	5.1	5.1
23		3.9	5	5.3	5.4	3.7	4.9	5.2	5.3
24		4.1	5.2	5.5	5.6	3.9	5.1	5.3	5.4
25		4.2	5.3	5.6	5.7	4.1	5.2	5.4	5.6
26		4.3	5.5	5.7	5.8	4.2	5.4	5.5	5.7
27		4.5	5.7	5.9	6.1	4.4	5.7	5.7	5.9

Test day	Amperage, mA								
	M30.3.0.6	M30.3.0.6.P	M30.3.1.2.P	M30.3.1.8.P	M30.3.2.4.P	M30.3.0.6.E	M30.3.1.2.E	M30.3.1.8.E	M30.3.2.4.E
28		4.7	5.9	6	6.3	4.6	5.8	5.8	6.1
29		5	6	6.1	6.4	4.8	5.9	5.9	6.2
30		5.2	6.2	6.3	6.5	4.9	6	6.1	6.4
31		5.3	6.3	6.3	6.6	5.1	6.2	6.3	6.5
32		5.5	6.5	6.4	6.7	5.2	6.3	6.4	6.6
33		5.6	6.6	6.7	6.9	5.4	6.4	6.5	6.7
34		5.7	6.7	6.8	6.9	5.6	6.5	6.7	6.8
35		5.9	6.9	7	7	5.8	6.7	6.7	6.9
36		6.1	7.1	7.1	7.2	5.9	6.8	6.8	6.9
37		6.3	7.2	7.3	7.3	6.1	7.2	7.3	7.5
38		6.4	7.4	7.4	7.5	6.2	7.3	7.4	7.6
39		6.6	7.5	7.6	7.6	6.4	7.4	7.6	7.7
40		6.7	7.5	7.7	7.8	6.5	7.5	7.6	7.8
41		6.9	7.6	7.7	7.8	6.7	7.6	7.7	7.9
42		7.1	7.6	7.8	17.5*	6.9	7.6	7.7	8
43		7.2	7.7	7.8		7	7.7	7.8	8.2
44		7.3	7.8	7.9		7.2	7.7	7.8	8.3
45		7.3	7.8	15.6*		7.3	7.8	7.9	8.3
46		7.4	7.9			7.3	7.8	8	8.4
47		7.5	14.8*			7.4	7.9	8.2	8.5
48		7.5				7.5	7.9	8.2	8.6
49		7.6				7.6	8	8.3	8.6
50		14.4*				7.6	8.1	8.4	8.7
51						7.7	8.2	8.4	8.8
52						7.8	8.2	8.5	16.7*
53						7.8	8.3	8.5	
54						7.9	8.3	15.2*	
55						8	8.4		
56						8	8.4		
57						8.1	8.5		
58						8.2	13.7*		

Test day	Amperage, mA								
	M30.3.0.6	M30.3.0.6.P	M30.3.1.2.P	M30.3.1.8.P	M30.3.2.4.P	M30.3.0.6.E	M30.3.1.2.E	M30.3.1.8.E	M30.3.2.4.E
59						8.2			
60						8.3			
61						12.9*			

Table 3. Current intensity of concrete sample, waterproofing strength B10, different salinity, reinforced with cement-polymer paint

Test day	Amperage, mA				
	M30.3.0.6	M30.3.0.6.X	M30.3.1.2.X	M30.3.1.8.X	M30.3.2.4.X
1	2.4	0.1	0.6	0.8	0.9
2	2.2	0.3	0.9	1.1	1.2
3	2.3	0.7	1.3	1.5	1.6
4	2.7	0.8	1.5	1.6	1.8
5	3.8	1.1	1.6	1.7	2.1
6	4.7	1.4	1.7	1.9	2.2
7	5.2	1.7	1.9	2.1	2.9
8	6.4	1.8	2.3	2.9	18.1*
9	16.5*	2.2	2.5	3.2	
10		2.4	2.7	3.3	
11		2.6	2.9	17.3*	
12		2.9	3.2		
13		3	3.5		
14		3.2	3.9		
15		3.4	15.7*		
16		3.5			
17		15.1*			

Note: * Electric current at the time of sample cracking

Figure 2. Effect of coating of rebar in concrete with Cl^{-}=0.6 kg/m^3 on time to crack initiation in sample

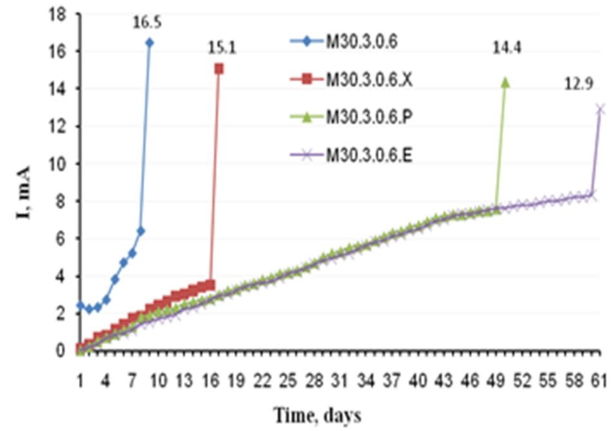

Figure 3. Effect of coating of rebar in concrete with Cl^{-} =1.2 kg/m^3 on time to crack initiation in sample

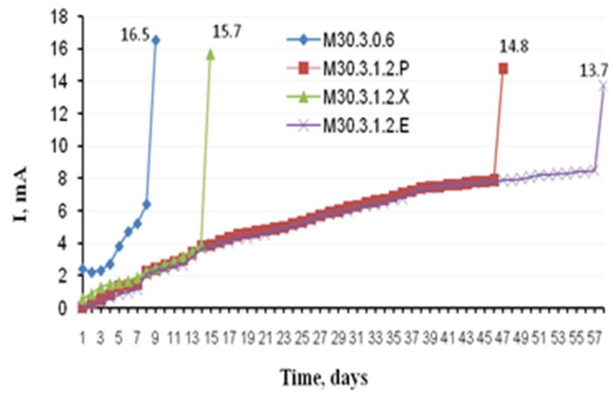

Figure 4. Effect of coating of rebar in concrete with Cl^{-}=1.8 kg/m^3 on time to crack initiation in sample

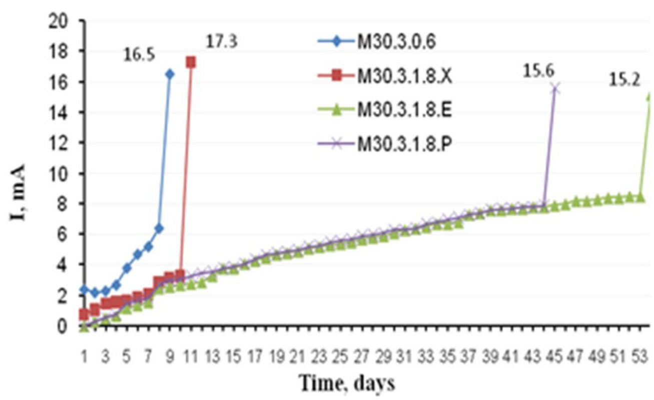

Figure 5. Effect of coating of rebar in concrete with Cl^{-} =2.4 kg/m^3 on time to crack initiation in sample

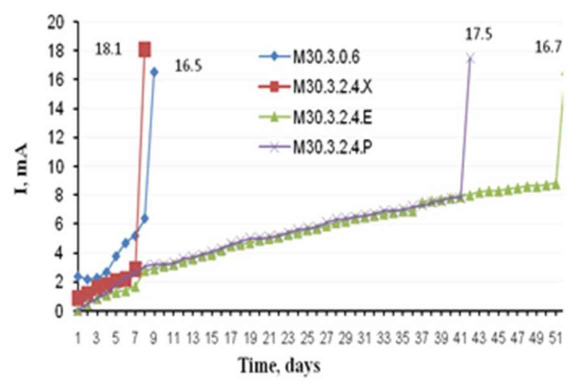

Table 4. Summarized testing results of times to crack initiation, amperage before and after times to crack initiation of concrete types having B10 (M300) waterproofing level and epoxy- and polyurethane- and polymer cement-coated rebars and suffering from different salinity levels

STT	Types of coatings	Sample Notation	Date of time to crack initiation	Average, Amperage, mA	Amperage at the time to crack initiation, mA
1	Non- Coated	M30.3.0.6	9	3,71	16,5
2	Polyurethane	M30.3.0.6.P	50	4,24	14,4
3		M30.3.1.2.P	47	4,84	14,8
4		M30.3.1.8.P	45	4,88	15,6
5		M30.3.2.4.P	42	4,84	17,5
6	Epoxy	M30.3.0.6.E	61	4,78	12,9
7		M30.3.1.2.E	58	5,38	13,7
8		M30.3.1.8.E	54	5,32	15,2

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STT	Types of coatings	Sample Notation	Date of time to crack initiation	Average, Amperage, mA	Amperage at the time to crack initiation, mA
9		M30.3.2.4.E	52	5,42	16,7
10	Polymer- Cement	M30.3.0.6.X	17	1,94	15,1
11		M30.3.1.2.X	15	2,18	15,7
12		M30.3.1.8.X	11	2,01	17,3
13		M30.3.2.4.X	8	1,81	18,1

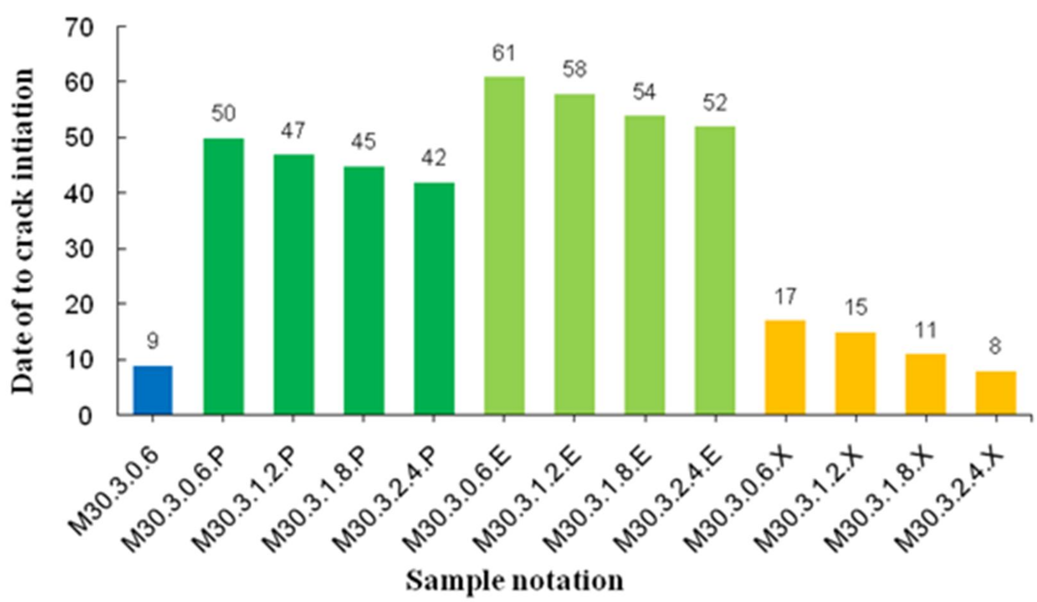

Figure 6Comparison of cracking time of concrete with waterproofing B10 (M300), steel reinforcement paint with different salinity levels

B. Arguments About the Findings

The data in both Tables 2 to 4 and Figures 2 to 6 showed the states of samples with differently coated rebars as follows:

At the initial time of measurement, the amperage appeared in all of concrete samples, which, however, was relatively low and different in the samples with differently coated rebars. When the salinity levels increased to 0.6; 1.2; 1.8 and 2.4kg/m^3, the amperage for polyurethane-, epoxy-, polymer cement-coated rebars, respectively, was 0.02, 0.03, 0.04, 0.06 mA, 0.01, 0.02, 0.03, 0.05mA and 0.1, 0.6, 0.8, 0.9mA, respectively, which were considerably lower than 2.4mA amperage of M30.3.0.6 reference sample with uncoated rebars. Thus, in the first place, the coatings isolated the rebars from corrosive environment, leading to the negligible corrosion level which was insignificantly different on the type-to-type basis.

From day 2 to the times to crack initiation in the concrete covers of the samples, the amperage rose at different rates for the samples suffering from different salinity levels. The assessment of the coatings' effect on corrosion mitigation for rebar based on both amperage values measured at testing time-points and salinity levels showed a general rule that at the same time of measurement, the different types of rebar coatings gave inconsistent amperage values which were always smaller than those of uncoated rebars and lowered gradually depending on whether polymer cement, polyurethane or epoxy was applied. For example, at the time of day-5 measurement, with salinity level of 1.8 kg/m^3, the amperage measured at the polymer cement-, polyurethane-, epoxy-coated rebars decreased from 1.7 and 1.5, respectively to 1.2 mA. This rule demonstrated that the coated rebars were more highly resistant to corrosion than the uncoated ones; generally, the corrosion resistance of polymer cement was lower than that of the two others.

At the times to crack initiation, on a type-by-type basis, the surge in amperage decreased along with the increased salinity in concrete. This proves that the rebar corrosion level was proportional to salinity level. The epoxy-coated rebars involved the increase in amperage from 12.9 to 16.7mA together with the decrease in time to crack initiation from 61 days to 52 days. Such increase and decrease of polyurethane-coated rebars were from 14.4 to 17.5mA and from 50 days to 42 days, respectively while those of polymer cement-coated rebars were from 15.1 to 18.1mA and from 17 to 8 days, respectively.

In terms of the effect on corrosion mitigation for rebar at the times to crack initiation, at the given salinity levels, the surge in amperage values tended to increase while the times to crack initiation decreased. Therefore, the rebar corrosion level was reduced when rebars were coated in turn with epoxy, polyurethane and polymer cement. The epoxy, polyurethane and polymer cement were rated in descending order of film effect on corrosion mitigation for rebar. Specifically, at salinity level of 0.6 kg/m^3, the times to crack initiation were 61, 50 and 17 days, respectively while amperage values at the times to crack initiation were 12.9, 14.4 and 15.1mA, respectively. At salinity level of 1.2 kg/m^3, the times to crack initiation were 58, 47 and 15 days, respectively while amperage values at the times to crack initiation were 13.7, 14.8 and 15.7mA, respectively. At salinity level of 1.8 kg/m^3, the times to crack initiation were 54, 45 and 11 days, respectively while amperage values at the times to crack initiation were 15.2, 14.8, 17.3mA, respectively. At salinity level of 2.4 kg/m^3, the times to crack initiation were 52, 42 and 8 days, respectively while amperage values at the times to crack initiation were 16.7, 17.5, 18.1mA, respectively.

To assess the rebar corrosion resistance on a type-to-type basis, M30.3.0.6 concrete with salinity of 0.6 kg/m^3, cover thickness of 30mm and 9-day time to crack initiation was taken as reference sample. The reinforced concrete samples, suffering from the salinity of 1.2, 1.8 and 2.4 kg/m^3 and having differently coated rebars, were compared with the reference sample in terms of times to crack initiation. The comparison results was as follows:

1) *Concrete with salinity of 0.6kg/m^3:* M30.3.0.6.P, M30.3.0.6.E, M30.3.0.6.X samples had times to crack initiation of 50, 61 and 17 days, equal to 556%, 678% and 189%, respectively of that of M30.3.0.6 reference sample.
2) *Concrete with salinity of 1.2kg/m^3:* M30.3.1.2.P, M30.3.1.2.E, M30.3.1.2.X samples had times to crack initiation of 47, 58 and 15 days, equal to 522%, 644% and 167%, respectively of that of M30.3.0.6 reference sample.
3) *Concrete with salinity of 1.8kg/m^3:* M30.3.1.8.P, M30.3.1.8.E, M30.3.1.8.X samples had times to crack initiation of 45, 54 and 11 days, equal to 500%, 600% and 122%, respectively of that of M30.3.0.6 reference sample.
4) *Concrete with salinity of 2.4kg/m^3:* M30.3.2.4.P, M30.3.2.4.E, M30.3.2.4.X samples had times to crack initiation of 42, 52 and 8 days, equal to 467%; 578% and 89%, respectively of that of M30.3.0.6 reference sample.

For this reason, it is said that rebar coating with Polyurethane and epoxy reduced corrosion level of rebar in concrete suffering from salinity from 0.6 to 2.4 kg/m^3 in comparison with that of the reference sample. On the contrary, the coating of polymer cement, in spite of its assured effect on mitigation of rebar corrosion level in case of salinity from 0.6 to 1.8kg/m^3, were incapable to reduce the rebar corrosion level in case of salinity of 2.4 kg/m^3, both in comparison with that of the reference sample.

IV. CONCLUSION

Using accelerated corrosion tests according to NT Build 356 and taking M30.3.0.6 as the reference sample, preliminarily, the corrosion mitigation for rebars coated with polyurethane, epoxy and polymer cement prior to concreting is assessed as follows, corresponding to the salinity of sand:

Polyurethane and epoxy coating reduces the corrosion level of rebar in concrete suffering from salinity of up to 2.4kg/m^3 compared to that of reference sample (the time to crack initiation of samples decreases by 556% ÷ 467% and 678% ÷ 578% of that of reference sample).

Polymer cement coating reduces the corrosion level of rebar in concrete suffering from salinity of up to 1.8kg/m^3 compared to that of reference sample (the time to crack initiation of samples decreases by 189% ÷ 122% of that of reference sample).

In terms of corrosion resistance, epoxy is the most highly resistant, followed by polyurethane and polymer cement.

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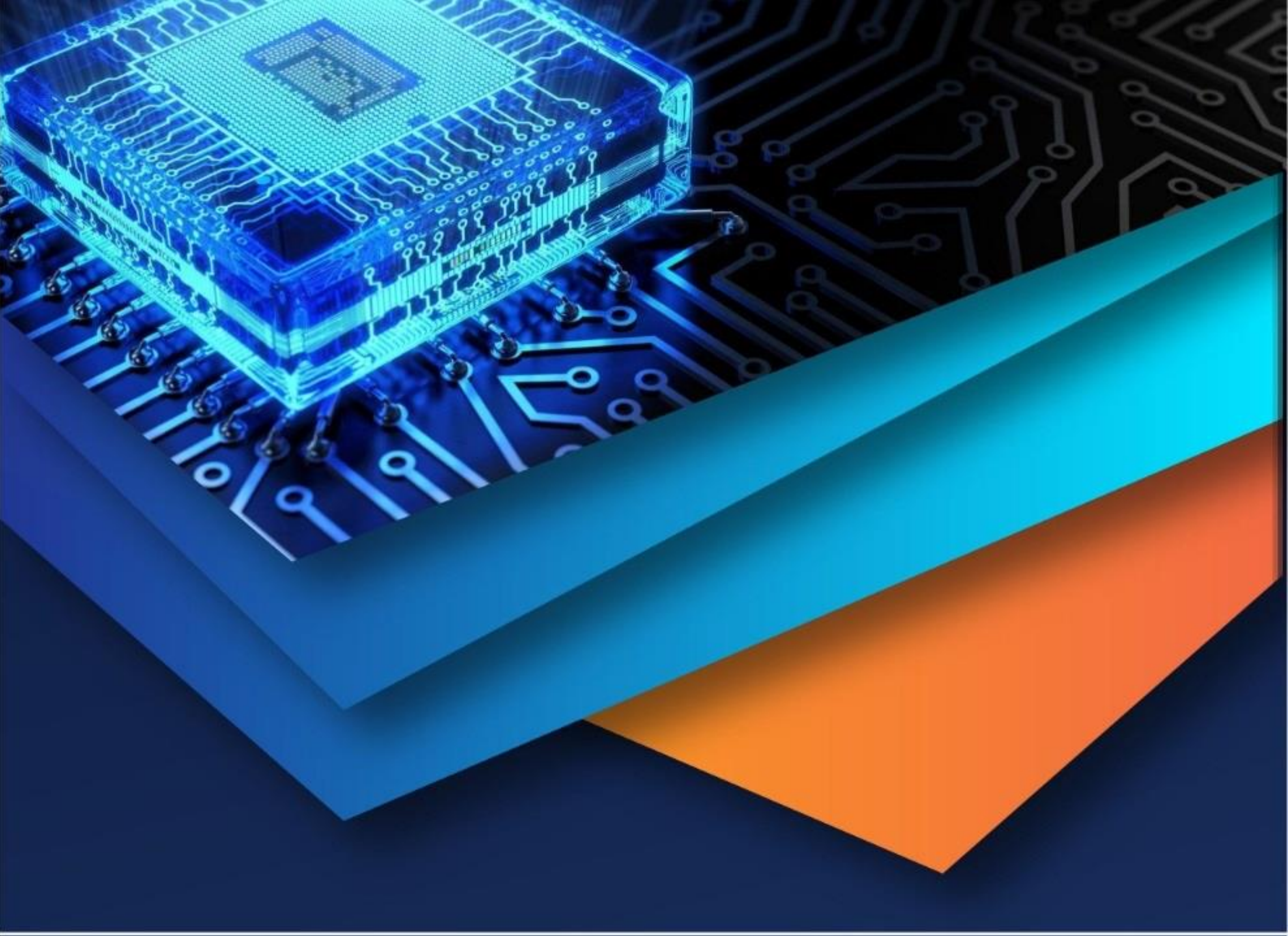

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IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

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