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EFFECT OF BENZOTRIAZOLE CORROSION INHIBITOR IN ORDINARY AND HIGH PERFORMANCE CONCRETE

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ABSTRACT

Technological advances have provided new ways of combating corrosion. Corrosion inhibitors are one means of protection for reinforced concrete structures. The effectiveness of commercially available inhibitor for concrete has been investigated. This study focuses on the effects of benzotriazole inhibitor on ordinary concrete and high performance concrete. The strength and durability property of different dosage of specimens without and with inhibitors on ordinary concrete and high performance concrete was compared. Corrosion tests such as Alternative Current (AC) impedance, Open circuit potential, Long term Potential Resistance (LPR) sweep, Custom sweep, and Half-cell potential were also conducted and compared with ordinary and high performance concrete without and with benzotriazole inhibitor. The inhibitor shows better performance strength, durability and good corrosive resistance.

Keywords: Ordinary concrete; high performance concrete; corrosion inhibitor; corrosion resistance tests.

1. INTRODUCTION

Concrete is a composite construction material composed primarily of aggregate, cement and water. There are many formulations, which provide varied properties. The aggregate is generally coarse gravel or crushed rocks such as limestone, or granite, along with a fine aggregate such as sand. The Portland cement is the most commonly used of modern hydraulic cements. In this case, the word hydraulic means that the cement's characteristic of holding aggregate together is caused by water or other low viscosity fluids.

High-performance concrete (HPC) is defined as a concrete meeting special combination of performance and uniformity requirements that cannot always be achieved routinely using

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conventional constituents and normal mixing, placing, and curing practices. High-performance concrete almost always has a higher strength than normal concrete. However, strength is not always the primary required property.

High-performance concrete characteristics are developed for particular applications and environments; some of the properties that may be required include: high strength, high early strength, high modulus of elasticity, high abrasion resistance, high durability and long life in severe environments, low permeability and diffusion, resistance to chemical attack, high resistance to frost and deicer scaling damage, toughness and impact resistance, volume stability, ease of placement, compaction without segregation, inhibition of bacterial and mold growth. In this study, the effect of benzotriazole corrosion inhibitor in high performance concrete with different dosages is compared with that of ordinary concrete.

2. LITERATURE REVIEW

Ababneh et al. [1] investigated the effectiveness of benzotriazole (BTA) as anticorrosion material for steel reinforcement in concrete structures. BTA is used in three different corrosion-protection systems: BTA inhibition, BTA coating, and BTA as a hybrid system. Reinforced concrete beams were cast, exposed to a 3 percent sodium chloride solution, and subjected to drying and wetting cycles to accelerate the corrosion attack. Electrochemical measurement techniques were used to evaluate the corrosion behaviour of reinforcement. Shi [2] investigated the effects of benzotriazole (BTA) on the corrosion behaviour of reinforcing steel in mortar specimens by corrosion potential (E_{corr}), polarization resistance (R_p), and resistivity of mortar cover (ρ_c). Additionally, the corrosion inhibiting efficiencies of BTA and $NaNO_2$ (Sodium Nitrite) were compared after exposure to 3.5 percent (wt) NaCl solution for 360 days. Mennucci et al. [3] investigated that BTA, a well-known corrosion inhibitor for copper, has been evaluated as a possible corrosion inhibitor of a carbon steel (CA-50) used as reinforcement in concrete. BTA was added to a simulated pore solution of an aged concrete with addition of 3.5 percent(wt) NaCl to imitate marine environments. Ayman Ababneh et al. [4] developed a corrosion protection system for reinforced concrete structures under carbonation attack. BTA and BTA derivatives were used as two separate protection systems: inhibition and pickling protection systems. Elliott et al. [5] evaluated the long-term performance potential of sodium nitrite and dinitrobenzoic acid used as the corrosion inhibiting additives in chloride contaminated reinforced concrete. Electrochemical impedance spectroscopy and linear polarization techniques were used to study five-year-old lollipop-like concrete specimens containing sodium nitrite and dinitrobenzoic acid. Anees et al. [6] investigated the migratory corrosion inhibitors (MCI) which have been suggested as the possible chemicals for rehabilitating the damaged reinforced concrete structure. The inhibitor migrates through the concrete to the reinforcing steel and protects it from further corrosion by providing a thin, protective coating of MCI- molecules on steel reinforcement. Studies have been carried out to investigate the performance of MCI- 2000 used as a concrete admixture and MCI-2020 used as a surface coating. Ramazan Kahraman [7] searched for an inhibitor to slow down or prevent atmospheric corrosion/discoloration of the local mild steel during storage in the Arabian Gulf region. Various inhibitors were reported in the literature that can help in protection against atmospheric corrosion.

3. EXPERIMENTAL INVESTIGATION

3.1 Mix proportions

The type of cement used in the study is Ordinary Portland Cement (Zuari) 43 grade, river sand conforming to zone II,as per IS 383- 1970 [8] coarse aggregate 12 mm size, super-plasticizer,and conplast SP430 are also selected. The mix is designed based on as per IS 10262 – 2009 [9] for ordinary concrete. The grade of concrete used for this research work is M 30 of mix ratio 1:1.55:2.29 with water-cement ratio 0.45. The same grade is used for High performance concrete (HPC) by replacing cement with Ground Granulated Blast Furnace Slag (GGBS) by 40 percent and 4 percent addition of silica fume [10], and the Benzotriazole corrosion inhibitor is used in various dosages such as 0.10, 0.20, 0.30 and 0.40 percent by mass of cement. The specific gravity and Fineness modulus of fine and coarse aggregate are presented in Table 1.

Table 1: Mix Proportions for M30 concrete

Sl.No	Material	Specific gravity	Fineness modulus	Zone
1	Cement	3.15	-	-
2	Fine aggregate	2.60	3.07	II
3	Coarse aggregate (12.5mm)	2.71	3.16	-
4	Water	1	-	-

3.2 Details of cast specimens

The details of cast specimens and total number of specimen for strength test are shown in Table 2.

Table 2 Details of cast specimen for strength test

Sl. no	Types of test	Specimens and size (mm)	ONI	OBI (0.1)	OBI (0.2)	OBI (0.3)	OBI (0.4)	HNI	HBI (0.1)	HBI (0.2)	HBI (0.3)	HBI (0.4)	Total No. of Specimens
1	Compression Strength test	Cubes (100)	6	6	6	6	6	6	6	6	6	6	60
		Cylinders (100 × 200)	6	6	6	6	6	6	6	6	6	6	60
2.	Split tensile strength test	Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
3.	E for concrete	Cylinders (150 × 300)	3	3	3	3	3	3	3	3	3	3	30

ONI - Ordinary concrete without Inhibitor

HNI - High performance concrete without Inhibitor

OBI(0.1) - Ordinary concrete with 0.1 percent Benzotriazole Inhibitor

HBI(0.1) - High performance concrete with 0.1 percent Benzotriazole Inhibitor

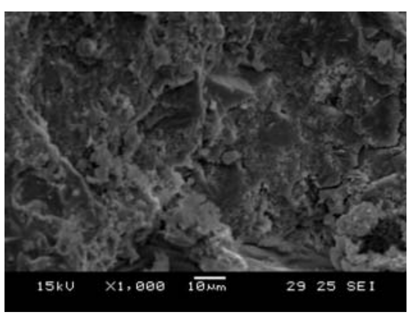
The details of cast specimens and total number of specimen for durability and corrosion tests are shown in Table 3.

Table 3: Details of cast specimen for durability test

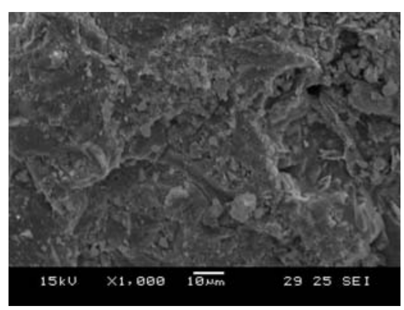
Sl. No.	Types of test	Specimens and size (mm)	ONI	OBI (0.1)	OBI (0.2)	OBI (0.3)	OBI (0.4)	HNI	HBI (0.1)	HBI (0.2)	HBI (0.3)	HBI (0.4)	Total No. of Specimens
1.	Water absorption	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
2.	Acid resistance	Cubes (100)	12	12	12	12	12	12	12	12	12	12	120
3.	RCPT	Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
4.	Open circuit potential	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
		Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
5.	Impedance	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
		Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
6.	LPR sweep	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
		Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
7.	Custom sweep	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
		Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30
8.	Half-cell potential	Cubes (100)	3	3	3	3	3	3	3	3	3	3	30
		Cylinders (100 × 200)	3	3	3	3	3	3	3	3	3	3	30

3.3 Scanning Electron Microscope (SEM) Analysis

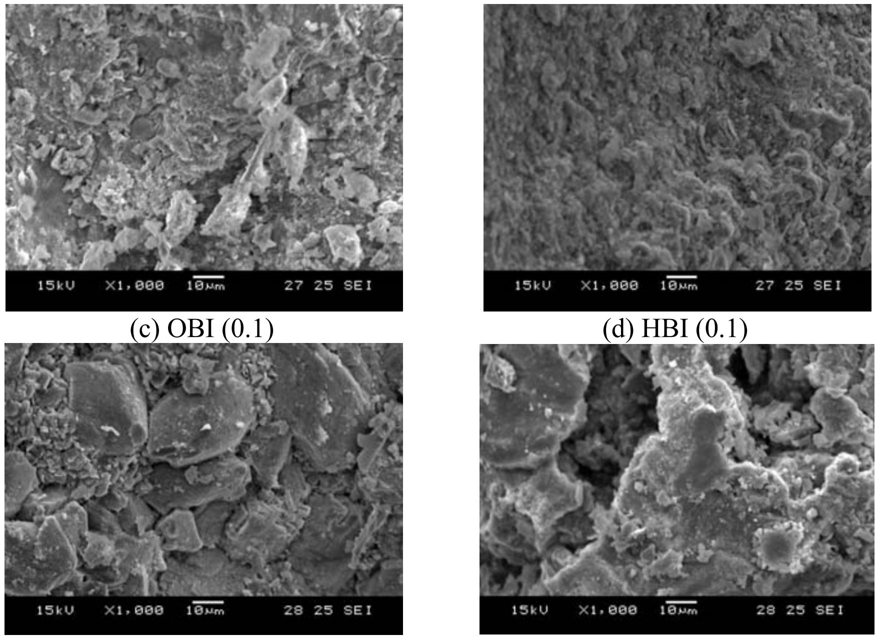
SEM analyses were conducted in ordinary and high performance concrete without and with benzotriazole inhibitor as shown in Figs. 1 (a), (b), (c) (d), (e) and (f).



(a) ONI



(b) HNI



(c) OBI (0.1) (d) HBI (0.1)

(e) OBI (0.4) (f) HBI (0.4)

Figure 1. SEM results of Ordinary and High performance concrete without and with inhibitor

The microstructures and carbonation were analysed. The mineral constituents as well as the textures arrangement for both concretes are largely similar but micro structurally they are quite different.

The scanning electron microscopic study reveals that micro cracks and voids are more in the ordinary concrete without benzotriazole inhibitor than in high performance concrete as shown in Fig. 1(a). The presence of more micro cracks and voids reduces the strength and durability of concrete. On the other hand the sizes of voids are considerably smaller and partially in filled with cementations materials in the samples of ordinary concrete and high performance concrete with benzotriazole.The micro cracks and few in filled with calcium silicates hydrates (C- S - H) gel in the ordinary and high performance concrete mix as shown in Figs. 1 (c), (d), (e), (f). This is due to the addition of benzotriazole in the mix. Further it is also observed that intensive carbonation has taken place more frequently in ordinary concrete without benzotriazole Fig. 1 (a) mix than in high performance concrete mix Fig. 1(b). Clusters of alite and belite have also been observed in interstitial matrix of high performance concrete with benzotriazole which is responsible for strength development of concrete. However, benzotriazole variable to produce good dispersion of filler material in the system is shown in Figs.1(c), (d), (e) and (f). On the basis of present investigation, it is concluded that the use of benzotriazole as admixture can enhance the strength and durability properties of concrete due to better microstructure, formation of additional C-S-H gels and infilling of pores.

4. STRENGTH TEST

4.1 Compressive strength test

The Compressive strength test on concrete cubes of size 100x100 mm and cylinders of size 100x200 mm was conducted in compressive testing machine 2000 kN capacity. The cube and cylinder compressive strength of ordinary concrete without and with inhibitor at 7 days and at 28 days are shown in Fig. 2.

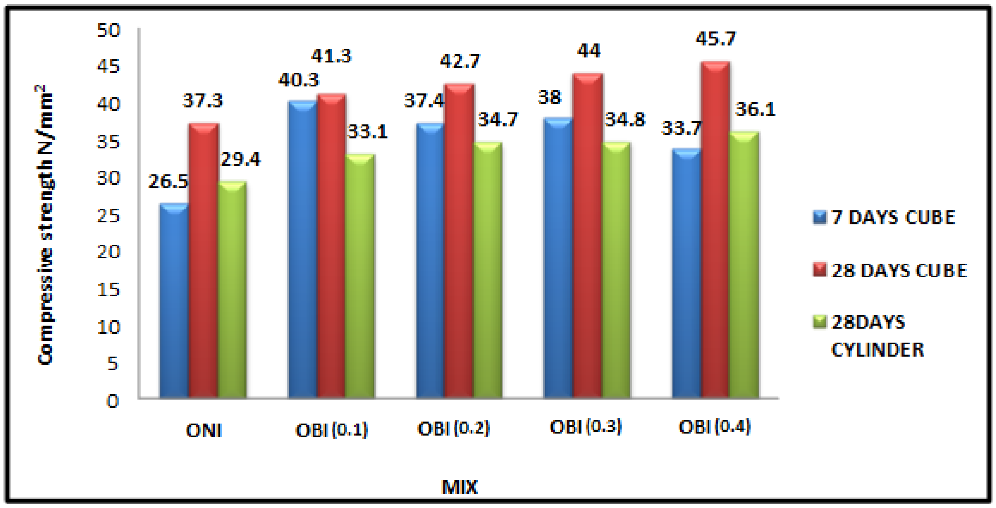


Figure 2. Compressive strength of ordinary concrete without and with inhibitor

The compressive strength of cubes and cylinders of high performance concrete without and with inhibitor at 7 days and at 28 days is shown in Fig. 3.

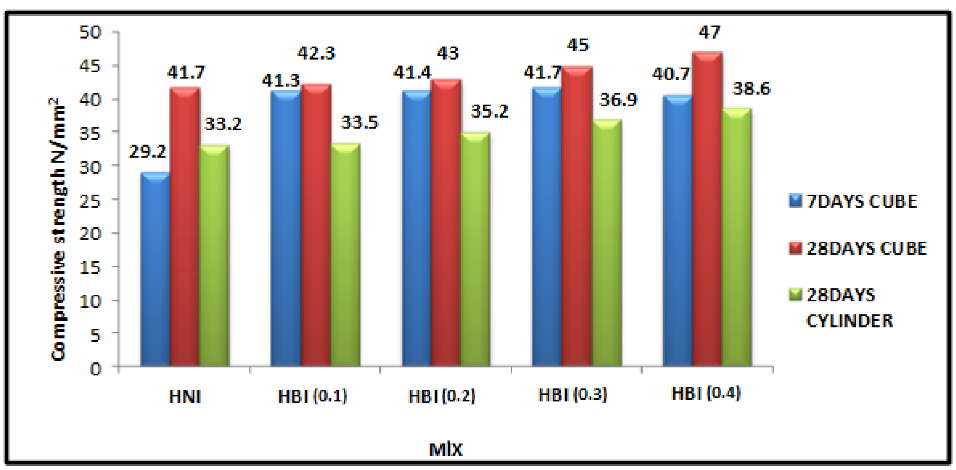


Figure 3. Compressive strength of High performance concrete without and with inhibitor

4.2. Split tensile strength test

The average value of 3 cylinders was recorded as the strength at respective age. The split tensile strength of cylinders of ordinary and high performance concrete without and with inhibitor at 28 days is shown in Fig. 4.

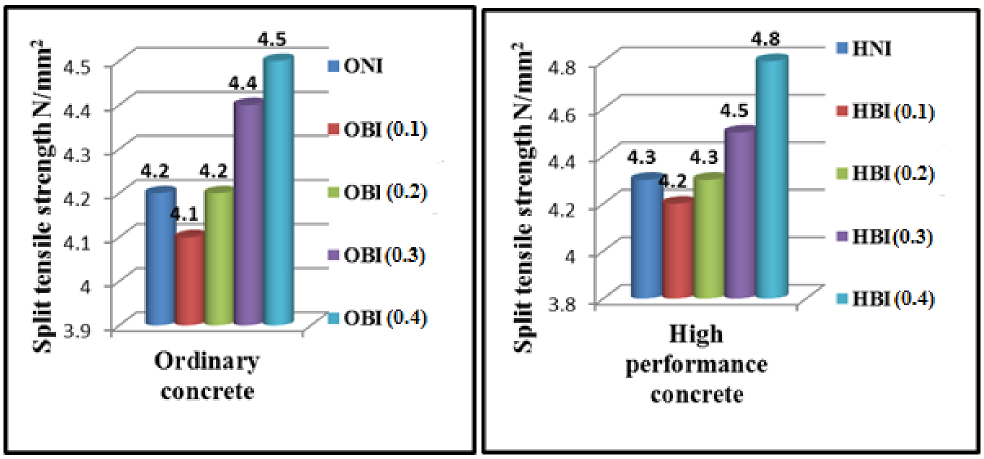


Figure 4. Split tensile strength of concrete specimens

4.3 Modulus of elasticity of concrete

The test specimens shall consist of concrete cylinders 150mm in diameter and 300 mm long. Two extensometers are required each having a gauge length of not less than 102 mm and not more than half the length of the specimen. They shall be capable of measuring strains to an accuracy of 2×10^{-6}. The specimen shall be immediately placed in the testing machine and accurately centred. The load shall be applied continuously without shock. Readings shall be taken at each stage of loading. The stress vs. strain curve for ordinary and high performance concrete without and with inhibitor is shown in Figs. 5 and 6.

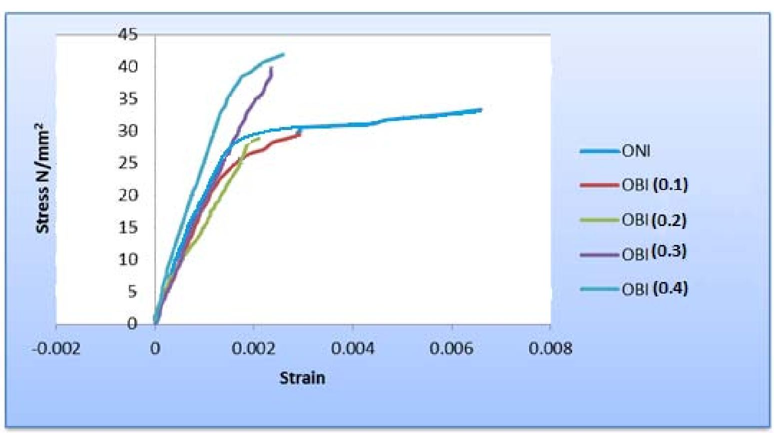


Figure 5. Stress Vs. Strain curve for ordinary concrete without and with inhibitor

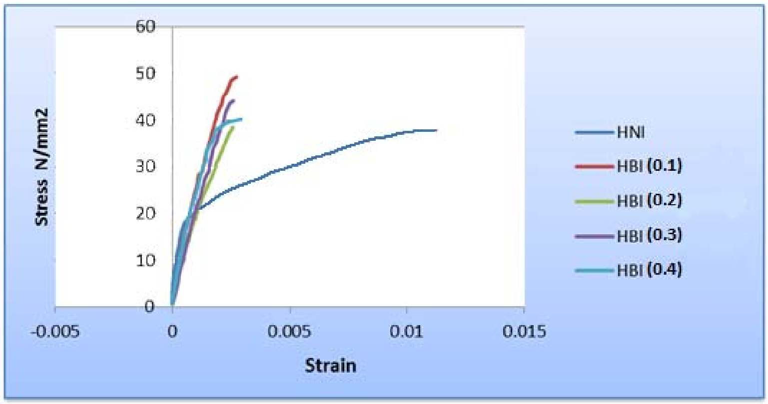


Figure 6. Stress Vs. Strain curve for High performance concrete without and with inhibitor

5. REGRESSION ANALYSIS

SPSS is a Statistical Package for Social Sciences; it is data management software, which is an analysis product. It can carry out a range of important data analysis and management function that includes statistical analyses plus graphical presentation of the data. SPSS is a comprehensive system for analyzing data. SPSS can take data from almost any type of file and use them to generate tabulated reports, charts, and plots of distributions and trends, descriptive statistics, and complex statistical analyses.

For this analysis, minimum three variables are required for each case to form a better equation. In the present research the variables are inhibitor (Benzotriazole) with different dosages say 0.1 to 0.4 percent, different concrete ordinary and high performance concrete mix ratio (Mix= 1,2).

Empirical relationships formulated by adopting the experimental results and simulated data using SPSS are given below:

Compressive strength

7 days

$$fck(Cube) = 28.0 + 3.55\ Dosage + 3.68\ Mix \quad (1)$$

28 days

$$fck(Cube) = 37.3 + 3.28\ Dosage + 1.60\ Mix \quad (2)$$

$$fck(Cylinder) = 28.8 + 2.93\ Dosage + 1.86\ Mix \quad (3)$$

Split tensile strength

$$fck(Cylinder) = 3.92 + 0.220\ Dosage + 0.140\ Mix \quad (4)$$

6. DURABILITY TESTS

6.1 Water absorption test

According to ASTM C 642-06 [11], water absorption test was performed on ordinary and high performance concrete without and with inhibitor. Cubes of size 100×100×100 mm were tested after 28 days of curing. The specimens were taken out and dried in an oven at a temperature of 100 to 110C for not less than 24hours. Each specimen removed from the oven was allowed to cool in dry air to a temperature of 20 to 25C and the dry weight was determined. Then the specimens were immersed in water. The wet weights were recorded for every ½ hour for 2½ hours, every 1 hour for 4 hours, 24 hr, 48 hr and 72 hr. The percentage of water absorption was calculated as follows.

$$percentage\ of\ water\ absorption = \frac{wet\ weight - dry\ weight}{dry\ weight} \times 100 \qquad (5)$$

The results obtained for water absorption test are given in Table 4. It shows that the ordinary concrete without and with inhibitor has higher water absorption capacity than high performance concrete with benzotriazole inhibitor.

Table 4: Percentage of Water absorption of concrete cubes

Sl. No.	**Mix**	**Dry weight**	**Percentage of water absorption**					
			30 min	**120 min**	**210 min**	**330 min**	**1440 min**	**4320 min**
1.	ONI	2.52	0.56	0.60	0.71	0.73	0.83	0.87
2.	HNI	2.49	0.28	0.32	0.36	0.28	0.64	0.68
3.	OBI (0.1)	2.38	0.51	0.63	0.71	0.75	1.09	1.34
4.	OBI (0.2)	2.45	0.20	0.24	0.28	0.32	0.41	0.53
5.	OBI (0.3)	2.42	0.33	0.37	0.41	0.49	0.70	0.91
6.	OBI (0.4)	2.40	0.33	0.33	0.37	0.50	0.66	0.87
7.	HBI (0.1)	2.45	0.12	0.12	0.20	0.28	0.37	0.53
8.	HBI (0.2)	2.47	0.08	0.16	0.24	0.28	0.40	0.60
9.	HBI (0.3)	2.45	0.20	0.24	0.28	0.32	0.45	0.61
10.	HBI (0.4)	2.45	0.20	0.24	0.32	0.36	0.57	1.01

6.2 Acid resistance test

Concrete cubes of size 100×100×100 mm were cast. After 28 days of curing, specimens were dried out and weights (W1) were noted. The solutions were prepared with various concentrations of HCl (1 percent, 4 percent) and H_2SO_4 (1 percent, 4 percent). Then the specimens were immersed in solutions for 30 days.

The high performance concrete with benzotriazole inhibitor has reduced weight loss when compared with ordinary concrete without and with inhibitor as the percentage of dosage increases in HCl acid as shown in Figs. 7 and 8.

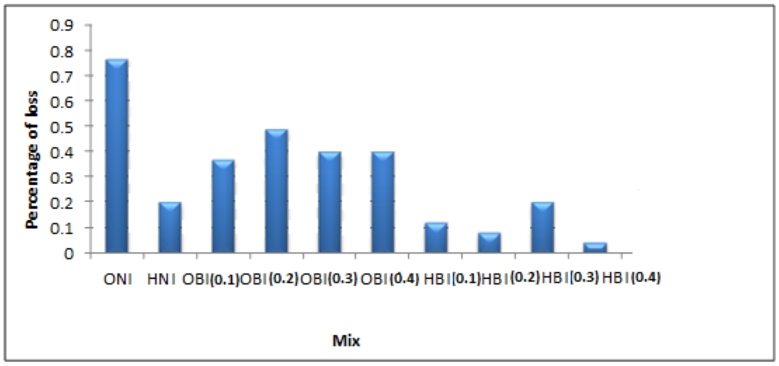


Figure 7. Percentage of Weight Loss by HCl (1 percent) in concrete Specimens

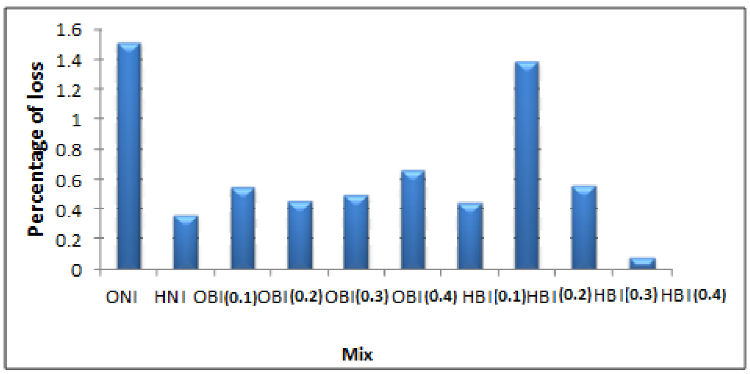


Figure 8. Percentage of Weight Loss by HCl (4 percent) in concrete Specimens

The high performance concrete with benzotriazole inhibitor has reduced weight loss when comparted with ordinary concrete without and with inhibitor as the percentage of dosage increases in H_2SO_4 acid as shown in Figs. 9 and 10.

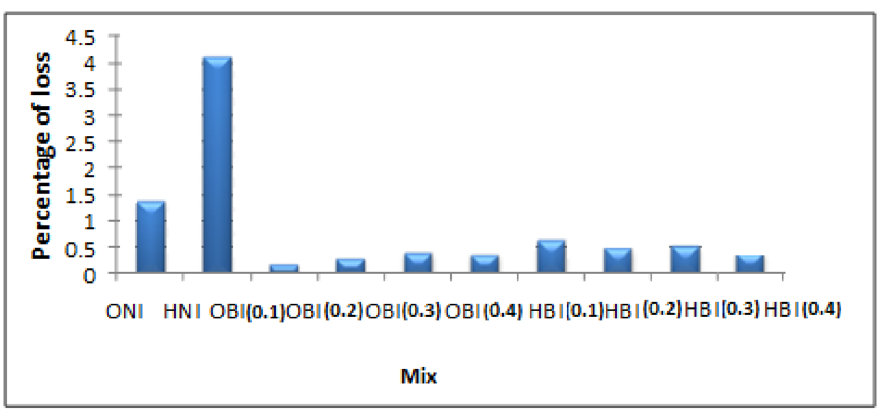


Figure 9. Percentage of Weight Loss by H_2SO_4 (1 percent) in concrete Specimens

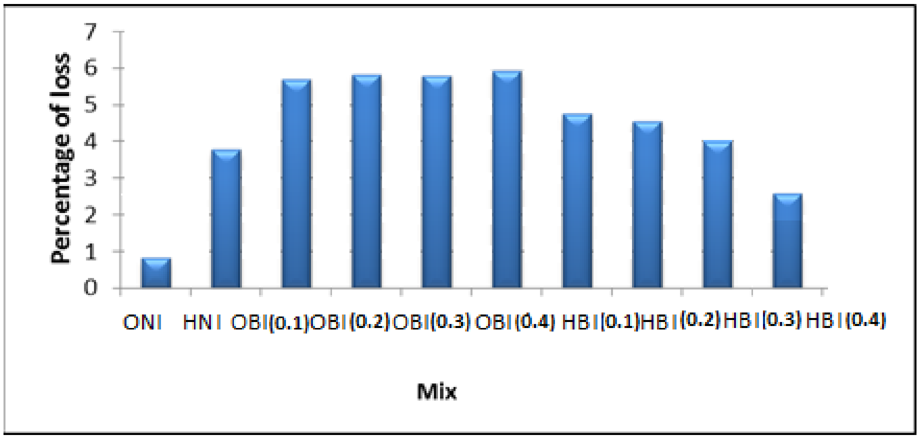


Figure 10. Percentage of Weight Loss by H_2SO_4 (4 percent) in concrete Specimens

6.3 Rapid Chloride Permeability Test

The penetration of chloride ions in terms of coulombs is determined by rapid chloride permeability test according to ASTM C1202 -12 [12]. The presence of chloride ion permeability is very low and negligible as the benzotriazole inhibitor provides better resistance to chloride permeability in concrete. The high performance concrete with benzotriazole inhibitor reduced chloride ion penetration when compared with ordinary concrete with inhibitor as shown in Fig. 11.

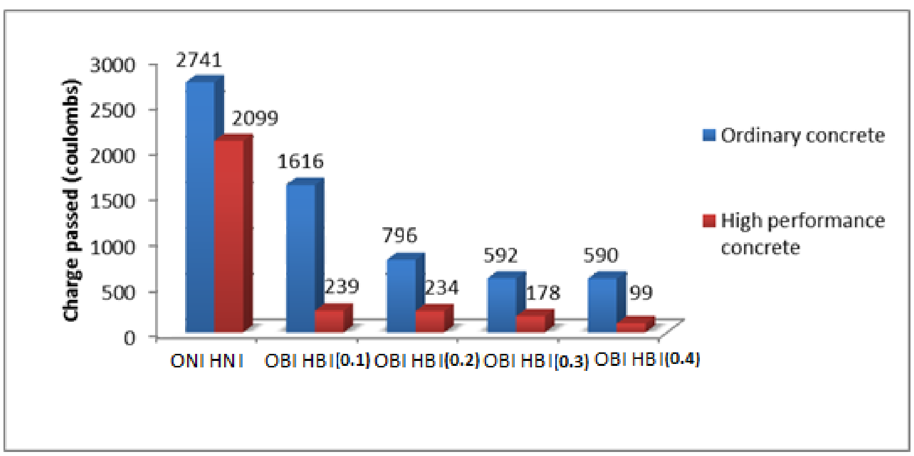


Figure 11. Rapid Chloride Permeability Test results

The ordinary concrete without and with inhibitor shows the corrosion rate from moderate to very low whereas in High Performance Concrete the corrosion rate is very low to negligible as per ASTMC1202 -12 standards as shown in Table 5.

Table 5: Rapid Chloride Permeability Test results

Sl. No.	**Mix**	**Charge passed (coulombs)**	**Chloride permeability as per ASTM C 1202 -12**
1.	ONI	2741	Moderate
2.	HNI	2099	Moderate
3.	OBI (0.1)	1616	Low
4.	OBI (0.2)	796	Very Low
5.	OBI (0.3)	592	Very Low
6.	OBI (0.4)	590	Very Low
7.	HBI (0.1)	239	Very Low
8.	HBI (0.2)	234	Very Low
9.	HBI (0.3)	178	Very Low
10.	HBI (0.4)	99	Negligible

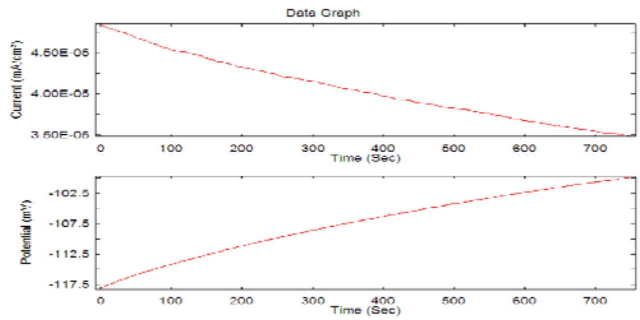
7. CORROSION TESTS

7.1 Open circuit potential Measurements

For conducting open circuit potential test concrete cube specimens of size 100 mm × 100 mm × 100 mm had been cast with 10 mm diameter steel rod inserted at the centre up to a depth of 70 mm, cylinder specimens of size 100 mm × 200 mm had been cast with 10 mm diameter steel rod inserted at the centre up to a depth of 120 mm. Ordinary and high performance concrete with different percentage of inhibitor had been considered along with normal concrete for this test. The concrete specimens were placed in the Electrical analyser, the rebar was connected to working electrode 1 and the reference electrode and also auxiliary electrode directly connected to Guard ring was placed over the specimen. The schematic diagram and the electrode connections of Electrical analyser are shown in Fig. 12.

Figure 12. Electrical analyser setup

The function of Working Electrode (WE-1) is to pass the voltage into the rebar embedded in concrete. The Auxiliary Electrode (AE), converts the passed voltage into the required current and the current spreads the entire specimen. The Reference Electrode using the converted current locates the corrosion/weak points available in the specimen. The output is given as a graph showing time Vs potential, time Vs current (Fig. 13). From the graph voltage ratio has been calculated by the machine.



Delta V (mV) = 5.0487; Average V (mV) = -107.48; Voltage ratio = -0.04

Figure 13. Open circuit potential graph

The corrosion rates of ordinary concrete and high performance concrete without and with inhibitor are shown in Table 6. The corrosion rate of ordinary concrete without and with inhibitor indicates moderate to very low risk corrosion rate whereas high performance concrete without and with inhibitor indicates low to negligible corrosion rate as per ASTM B611-2005 standards [13].

Table 6: Open Circuit Potential Measurements

Sl. No.	Mix	Voltage ratio		Corrosion condition
		Cube	Cylinder	
1.	ONI	-0.10	-0.14	Moderate
2.	HNI	-0.08	-0.09	Low
3.	OBI (0.1)	-0.04	-0.03	Very low
4.	OBI (0.2)	-0.07	-0.06	Low
5.	OBI (0.3)	-0.04	-0.05	Very low
6.	OBI (0.4)	-0.03	-0.02	Very low
7.	HBI (0.1)	-0.0005	-0.0004	Negligible
8.	HBI (0.2)	-0.002	-0.001	Negligible
9.	HBI (0.3)	-0.005	-0.003	Negligible
10.	HBI (0.4)	-0.006	-0.004	Negligible

7.2 AC Impedance test

The Impedance test method measures the corrosion rate using I_{corr} values and also determines the corrosion points available inside the specimens.

Calculation of Corrosion rate

$$I_{corr}=B/R_p \quad (6)$$

$$\text{Corrosion rate} = 0.129 \text{x} I_{corr} \text{ x EW/ dA} \quad (7)$$

B = B is the Stern–Geary constant, Stern–Geary range of 10–30 mV

R_p = Polarization Resistance

E.W=equivalent weight of the corroding species, (g).

A=exposed surface area of the reinforcing steel,

d = the density of the reinforcing steel, in g/cm^3

I_{corr} (mA/cm²) =0.122, Corrosion Rate (mm/year) =1.414, Corrosion rate (mils/yr) = 55.69

The corrosion rates of ordinary concrete and high performance concrete without and with inhibitor are shown in Table 7. The corrosion rate of ordinary concrete without and with inhibitor indicates medium risk to low risk corrosion rate whereas high performance concrete without and with inhibitor indicates medium risk to very low risk corrosion rate as per ASTM CSA / S413 -94 standards [14].

Table 7: AC Impedance test results

Sl. No.	**Mix**	**Corrosion rate (mm/year)**		**Corrosion condition**
		Cube	**Cylinder**	
1.	ONI	9.27	9.1	Moderate risk
2.	HNI	5.73	4.78	Medium risk
3.	OBI (0.1)	3.21	3.10	Medium risk
4.	OBI (0.2)	1.69	1.50	Low risk
5.	OBI (0.3)	1.41	1.30	Low risk
6.	OBI (0.4)	1.33	1.35	Low risk
7.	HBI (0.1)	1.48	1.49	Low risk
8.	HBI (0.2)	2.72	2.50	Low risk
9.	HBI (0.3)	0.92	0.89	Very Low risk
10.	HBI (0.4)	1.32	0.95	Low risk

7.3 Linear Potential Resistance (LPR) Sweep Test

The Linear polarization resistance sweep method measures the instantaneous corrosion rates as compared to other methods on which metal loss is measured over a finite period of time. Instantaneous means that each reading on the instrument can be translated directly into corrosion rate. The experiment can be completed in a matter of minutes and the small polarization from the corrosion potential does not disturb the system. This permits rapid rate measurements (ASTM D2776 & G59 [15]) and can be used to monitor corrosion rate in various process streams. The LPR data enable a more detailed assessment of the structural condition and is a major tool in deciding upon the optimum remedial strategy to be adopted. It is thus imperative that the LPR measurements obtained are accurate. In LPR measurements the reinforcing steel is perturbed by a small amount from its equilibrium potential. This can be accomplished potentiostatically by changing the potential of the reinforcing steel by a fixed amount, ΔE- reinforcing steel and monitoring the current decay ΔI, after a fixed time. Alternatively it can be done galvanostatically by applying a small fixed current, ΔI-to the reinforcing steel and monitoring the potential change, ΔE- after a fixed time period. In each case the conditions are selected such that the change in potential, ΔE falls within the linear

Stern–Geary range of 10–30 mV. The polarization resistance, Rp, of the steel is then calculated from the equation.

$$R_P = \Delta E/\Delta I \quad (8)$$

Where B is the Stern–Geary constant. A value of 25 mV has been adopted for active steel and 50 mV for passive steel.

From which the corrosion rate, Icorr, can then be calculated.

$$I_{corr} = B/R_P \quad (9)$$

The corrosion rates of ordinary concrete and high performance concrete without and with inhibitor are shown in Table 8. The corrosion rate of ordinary concrete without and with inhibitor indicates high risk to very low risk corrosion rate whereas high performance concrete without and with inhibitor indicates moderate risk to very low risk corrosion rate as per ASTM D2776 & G59 standards.

Table 8: LPR Sweep test results

Sl. No.	**Mix**	**Corrosion rate (mm/year)**		**Corrosion condition**
		Cube	**Cylinder**	
1.	ONI	14.294	13.245	High risk
2.	HNI	3.2524	3.8645	Moderate risk
3.	OBI (0.1)	0.0011	0.0015	Very Low risk
4.	OBI (0.2)	0.0008	0.0007	Very Low risk
5.	OBI (0.3)	0.0012	0.0015	Very Low risk
6.	OBI (0.4)	0.0008	0.0007	Very Low risk
7.	HBI (0.1)	0.0003	0.0002	Very Low risk
8.	HBI (0.2)	0.0004	0.0005	Very Low risk
9.	HBI (0.3)	0.0003	0.0004	Very Low risk
10.	HBI (0.4)	0.0005	0.0003	Very Low risk

7.4 Custom sweep test

The Custom sweep method or Tafel Extrapolation Method measures the instantaneous corrosion rates. This technique uses data obtained from cathodic and anodic polarization measurements. Cathodic data are preferred, since these are easier to measure experimentally. In this method, the total anodic and cathodic polarization curves corresponding to hydrogen evolution and metal dissolution are superimposed as dotted lines. It can be seen that at relatively high-applied current densities the applied current density and that corresponding to hydrogen evolution have become virtually identical. To determine the intercept corrosion rate from such polarization measurements, the Tafel region is extrapolated to the corrosion potential.

$$i_{corr} = \frac{\alpha\beta}{2.3(\alpha+\beta)} \frac{\Delta i}{\Delta E}$$

$$i_{corr} = \frac{\alpha\beta}{2.3(\alpha+\beta)} \frac{1}{R_p} \qquad (10)$$

where $\Delta E/\Delta i$=slope of the polarization curve = Polarization Resistance= Rp.

α and β = Cathodic and Anodic Tafel constants.

The corrosion rates of ordinary concrete and high performance concrete without and with inhibitor are shown in Table 9. The corrosion rate of ordinary concrete without and with inhibitor indicates moderate risk to low risk corrosion rate whereas high performance concrete without and with inhibitor indicates medium risk to very low risk corrosion rate as per ASTM C1543 – 10a standards[16].

Table 9: Custom Sweep Test Results

Sl. No.	**Mix**	**Intercept Corrosion rate (mm/year)**		**Corrosion condition**
		Cube	**Cylinder**	
1.	ONI	4.418	3.912	Moderate risk
2.	HNI	2.099	2.565	Medium risk
3.	OBI (0.1)	2.632	2.612	Medium risk
4.	OBI (0.2)	1.050	1.958	Medium risk
5.	OBI (0.3)	0.561	0.658	Low risk
6.	OBI (0.4)	0.357	0.451	Low risk
7.	HBI (0.1)	0.412	0.356	Low risk
8.	HBI (0.2)	0.843	0.536	Low risk
9.	HBI (0.3)	0.038	0.012	Very Low risk
10.	HBI (0.4)	0.093	0.085	Very Low risk

7.5 Half-cell potential measurements

Half-cell potential measurements provide a classification of the corrosion activity of the steel and indicate locations where the steel is potentially corroding. A half-cell potential measurement apparatus consists of a voltmeter with one lead connected to a reference electrode, normally a copper/ copper sulfate ($Cu/CuSO_4$) electrode, placed on the surface of the concrete and a second lead connecting the voltmeter to the reinforcing steel. Current passes from the reference electrode to the concrete surface through a sponge soaked with an electrolytic solution. The objective of the instrumentation is to measure the voltage, or potential difference, between the rebar and the reference electrode. In the half-cell potential setup, the reference electrode behaves as the cathode, as copper is higher in the galvanic series than steel. Through the circuit created, the potential difference is measured. With the reference electrode acting as the cathode and being connected to the positive terminal of the voltmeter, measured half-cell potentials have a negative value. A half-cell potential measurement results from the multiplication of the reinforcement corrosion potential by the ratio of the internal resistance of the voltmeter to the sum of the internal resistance of the voltmeter and the resistance of the concrete. A schematic of the test circuit is shown in Fig. 14.

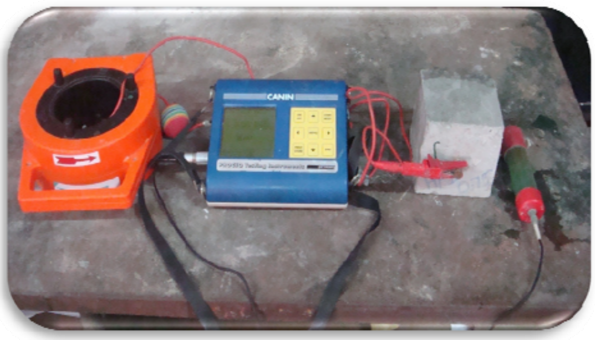


Figure 14. Half-cell potential test setup

The corrosion rates of ordinary concrete and high performance concrete without and with inhibitor are shown in Table 10. The corrosion rate of ordinary concrete without and with inhibitor indicates high risk to very low risk corrosion rate whereas high performance concrete without and with inhibitor indicates moderate risk to negligible risk corrosion rate as per ASTM 876-2009 standards [17].

Table 10: Half-cell potential results

Sl. No.	**Mix**	**Potential (mV) range**		**Corrosion condition**
		Cube	**Cylinder**	
1.	ONI	-301	-310	High
2.	HNI	-250	-270	Moderate
3.	OBI (0.1)	-47	-75	Very low
4.	OBI (0.2)	-37	-45	Very low
5.	OBI (0.3)	-38	-36	Very low
6.	OBI (0.4)	-43	-40	Very low
7.	HBI (0.1)	-33	-35	Very low
8.	HBI (0.2)	-20	-25	Negligible
9.	HBI (0.3)	-19	-23	Negligible
10.	HBI (0.4)	-32	-30	Very low

8. CONCLUSIONS

I. The cube and cylinder compressive strengths of high performance concrete with inhibitor were 2.4 percent – 3 percent higher and 1.2 percent - 6.93 percent higher respectively at 28 days when compared with ordinary concrete with inhibitor as the percentage of dosage increases.

II. The split tensile strength of high performance concrete with inhibitor was 2.3 percent - 6.6 percent higher at 28 days when compared with ordinary concrete with inhibitor as the percentage of dosage increases.

III. The water absorption for high performance concrete with inhibitor reduced by 24 percent when compared to ordinary concrete with inhibitor.

IV. The high performance concrete with inhibitor shows better acid resistance (HCl and H_2SO_4) at 5 percent – 10 percent (measured in weight loss) in 1 percent and 4 percent acid solution comparing with ordinary concrete with inhibitor as the percentage of dosage increases.

V. The presence of chloride ion permeability is very low in high performance concrete with inhibitor (coulombs range: 239-99) when compared with ordinary concrete with inhibitor (coulombs range: 1616-590) as the percentage of dosage increases.

VI. The voltage ratio of open circuit potential in ordinary concrete with inhibitor indicates` very low' rate when compared with high performance concrete which indicates negligible rate' as the percentage of dosage increases.

VII. The corrosion rate of A.C. Impedance in ordinary concrete with inhibitor indicates low risk' when compared with high performance concrete with inhibitor which indicates very low risk' as the percentage of dosage increases.

VIII. The intercept corrosion rate of custom sweep in ordinary concrete with inhibitor indicates `medium risk' when compared with high performance concrete with inhibitor which indicates `very low risk' as the percentage of dosage increases.

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REFERENCES

1. Ababneh A, Sheban M, Abu-Dalo M. Effectiveness of benzotriazole as corrosion protection material for steel reinforcement in concrete, *Journal of Materials in Civil Engineering*, **24**(2012) 141–51.
2. Shi JJSW. Effect of Benzotriazole as Corrosion Inhibitor for Reinforcing Steel in Cement Mortar. Jiangsu Key Laboratory of Construction Materials, *College of Materials Science and Engineering*, Southeast University, Nanjing 211189, P. R. China, 2011.
3. Mennucci MM, Banczek EP, Rodrigues PRP, Costa I. Evaluation of benzotriazole as corrosion inhibitor for carbon steel in simulated pore solution, *Cement & Concrete Composites*, **31**(2009) 418–24.
4. Ababneh A, Sheban M, Abu-Dalo M, Andreescu S. Effect of benzotriazole derivatives on steel corrosion in solution simulated carbonated concrete, *Jordan Journal of Civil Engineering*, **3**(2009) 91-102.
5. Elliott S, Hristova R, Beaudoin JJ, Brousseau RJ, Baldock BA. Study of corrosion inhibitor performance in chloride contaminated concrete by electrochemical impedance spectroscopy, *ACI Materials Journal*, **94**(1997) 385-95.

6. Anees UMIA, Fahd AMGO. Studies on the performance of migratory Corrosion inhibitors (mci) in protection of rebar concrete in gulf seawater environment, Published in *9th Middle East Corrosion Conference and Exhibition in Bahrain* – 12-14 February, 2001.
7. Kahraman R. Effect of sodium benzoate application on atmospheric corrosion of mild steel, *The 6th Saudi Engineering Conference*, KFUPM, Dhahran, 5(2002) pp. 57-70.
8. IS 383-1970 "Specification for coarse and fine aggregates from natural sources for concrete".
9. IS 10262-2009 "Concrete mix proportioning", Bureau of Indian Standards.
10. Palani B. Behaviour of RC beams strengthened with high performance Ferro cement laminates, Ph.D. Thesis, Annamalai University, 2005.
11. ASTM C642 – 06 "Standard test method for Density, Absorption, and voids in Hardened Concrete".
12. ASTM C1202 – 12 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration".
13. ASTM B611 – 2005 "Standard test method for Abrasive wear resistance of cemented carbides".
14. ASTM CSA / S413 – 94 "Durability Guidelines, for the Design Construction, repair maintenance of parking structures".
15. ASTM D2776 & G59 – 97 "Standard test method for conducting polarization resistance measurements".
16. ASTM C 1543 – 10 a "Standard test method for determining the penetration of chloride ion into concrete by ponding".
17. ASTM C876 – 09 "Standard test method for corrosion potentials of uncoated reinforcing steel in concrete".