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Comparative Assessment of Corrosion Behaviour of Two Different Grades of Thermo-Mechanically Treated Reinforcing Bars in 3.5% by Weight NaCl Solution

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***Abstract*: The immense use of thermo-mechanically treated reinforcing steel bars in structural applications compels human beings to study the corrosion behaviour of these re-bars and their mechanical properties in great depth and detail. However it is extremely difficult to propose a mechanism and the corresponding governing equations that would encapsulate all the corrosive environmental conditions and their interdependence without introducing some serious mathematical and chemical complexity. So, this paper is largely aimed at studying and analyzing corrosion instigated by marine (3.5 wt% NaCl) environment. Potentio dynamic polarization test and immersion test methods were adopted to determine the corrosion rate of TMT re-bars of Fe-600 EQR and Fe-550D grades. The presence of copper, chromium and nickel indicated that the steel becomes more corrosion resistant with increase in their percentage. Scanning Electron Microscopy was used to identify that pitting was the main cause of corrosion. Hence uniform corrosion approach can be discarded ad the entire focus can be shifted to localized corrosion. Optical Microscopy was done for microstructural observation. Tension and hardness tests were conducted to evaluate mechanical properties and finally a comparative assessment was made for these two different grades of steels.**

Keywords: Corrosion rate, thermo-mechanical treatment, Potentio dynamic polarization curves.

I. INTRODUCTION

Reinforced concrete structures are subjected to the concurrent actions physical, chemical and electrochemical processes which are detrimental to the structural integrity of the reinforcing bars when exposed to the marine environment with significant chloride content It has long been recognized that reinforcing bars have a low resistance to corrosion in chloride environments, resulting in marine structures having been severely injured and damaged by corrosion of the reinforcement. Corrosion of reinforcing steel bars may cause the bars to fail locally due to the presence of stress raisers and thus leading to a decrease in yield strength, load carrying capacity ad deterioration of other mechanical properties. [1-4].Although concrete provides protection for embedded steel, the penetration of oxygen, water and chloride to the carbon steel allows rapid deterioration of the entire structure (Castro, 2003).

. High percentage of carbon was added in steels to optimize strength. However, it was realized that higher content of carbon resulted in brittleness and accelerated rate of corrosion due to the presence of cementite phases in steels which are brittle and also very potent cathode for oxygen reduction reactions during the process of corrosion. This problem was partly controlled by lowering carbon content to less than 0.3 wt. % and twisting re-bars (cold working which hardened steels and enhanced their yield strength.). Such treatment however was quite extortionate and also deformed the crystal structures of iron resulting in increased susceptibility to uniform and localized corrosion. A further improvement took place where during process of rolling, quenching and tempering treatments are provided. This treatment yields composite micro-structure of steels. The process popularly known as thermo-mechanical treatment (TMT) transforms about 6–10% of outer diameter of re-bars in to hard tempered martensitic structure (rapid quenching and gradual tempering of surface as a result of heat flow from core of the bars) whereas the core remains in the form of soft pearlite-ferrite. This combination of structure provides ductility as well as strength to TMT re-bars.. Also elements such as copper, vanadium and some other d-block elements are added to improve the properties of steels by grain refinement and precipitations hardening due to formation of carbides and nitrides. Chromium, nickel and copper help in the formation of highly adherent and chemically stable protective oxide layer which inhibits the corrosion. The process of corrosion gets aggravated due to low pH, high electrode potential, high humidity, pressure and temperature. [5-10].The primary objective of the project work is to study the mechanical properties and corrosion behaviour of high strength TMT steel bars of 550D (steel 1) and 600 EQR(steel 2) grades in tap water and 3.5wt % NaCl in water.

II. EXPERIMENTAL PROCEDURE

A. Optical Emission Spectroscopy

In this experiment samples used are high strength TMT steels of grade 550D and 600 EQR of 10mm diameter. The chemical composition of the steels is found from optical emission spectroscopy and it is listed below in Table-1.

B. Optical Emission Microscopy

The samples were polished mechanically to a mirror finish using successive grades of emery papers followed by polishing with alumina powder. : For the microstructure the etchant used was 2% metal solution which was a composition of 2ml nitric acid and 98ml ethanol or methanol.

Etching was done by rubbing the polished surface gently with the cotton swab wetted with the etching reagent. Finally the sample was examined under the microscope.

TABLE I
CHEMICAL COMPOSITION OF STEELS OBTAINED (IN WT. %)

Steel variation	TMT Steel-1	TMT Steel-2
Fe	98.50	98.90
C	0.23	0.25
Si	0.17	0.13
Mn	0.70	0.51
S	0.03	0.035
P	0.03	0.035
Cu	0.20	0.09
Cr	0.16	0.05

C. Tensile Testing

Tensile tests were performed on reinforcing steel bars using universal testing machine. The impact of corrosion on tensile properties was noticed and it was established that the formation of pits caused the stress raisers to operate with different stress distribution.

D. Hardness Testing

Vicker hardness test was conducted to make a comparison of resistance to indentation and localized plastic deformation between two different grades of steel.

E. Corrosion Test

To quantify the corrosion behaviour, corrosion rates were measured by adopting immersion test (weight loss) method and electrochemical test method in the form of potentio dynamic polarization based on Tafel equation. The corrosion rates were compared for two different reinforcing bars in chloride and tap water environment. The corrosion test which was carried out using weight loss method involved immersing the test samples in two different corrosive media for 70 days and measuring the weight loss after every 7 days. The corrosion rates were also determined by employing potentio dynamic polarization method. PDP measurement technique involves plotting the potential against logarithm of current density by scanning the sample potential through a certain range with appropriate scan rate. In a PDP measurement, the electrochemical reactions that occur on the sample surface can be controlled, i.e. to cause it to act independently as either an anode or a cathode. Thus, by studying the anodic and the cathodic processes separately, the corrosion behaviour of the sample can often be further understood.

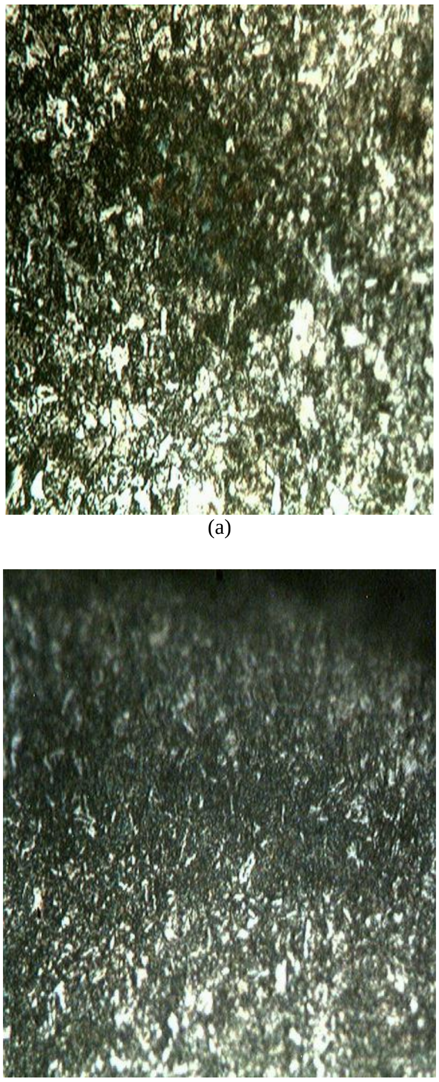
$$CR(mm/yr) = \frac{3270 \times M \times i_{corr}}{\rho \times Z} \quad (1)$$

F. Scanning Electron Microscopy

Scanning electron microscopy is used to examine the surface morphology of the corroding reinforcing bars and to ascertain the mechanism of corrosion. Accelerated electrons in an SEM carry significant amounts of kinetic energy, and this energy is dissipated as a variety of signals produced by electron-sample interactions when the incident electrons are decelerated in the solid sample and finally the image is produced.

III. RESULTS AND DISCUSSION

The microstructure of TMT reinforcing bars was perceived under an optical microscope. The microstructure of different zones (case and core) of rebars under specific magnification unveiled that case portion of both TMT bars are comprised of tempered martensitic formation. However, in core region, the microstructures were remarkably disparate. For a correctly heat treated reinforcing bars, the core microstructure should consist of highly evolved pearlite (dark grains) and ferrite (bright grains) and the result was consistent for steel 1, Fig.1. On the other hand the grains of ferrite and pearlite showed a pronounced digression from typical microstructure in case of steel 2, Fig. 2.



(a)

(b)

Fig. 1. (a) Optical image depicting microstructure of core (b) case of reinforcing bar 1 at 200X

This type of departure from typical microstructure suggests the involvement of residual stress in it. This residual stress is accountable for higher hardness values in the reinforcing bars. From Table-2, it is confirmed that the hardness of case and core of steel 2 is notably higher than that of steel 1.

The results of Vicker hardness testing (load 10 kg) are shown in Table-2.

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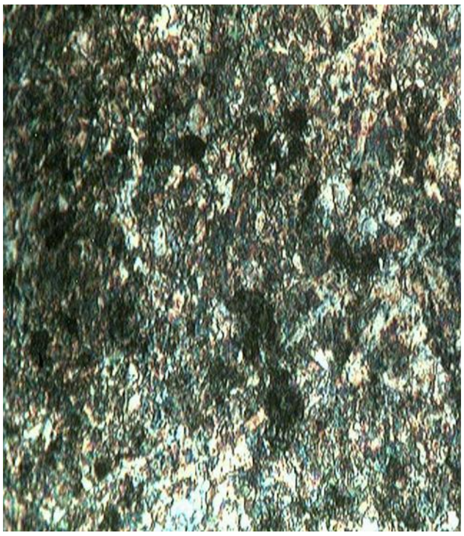
From Table-3, it is very obvious that the properties like yield and ultimate tensile strength of steel 2 is considerably higher than that of steel 1, which can also be anticipated from its hardness numbers. However the ductility, which is a measure of percentage elongation, of steel 2 is significantly lower than that of steel 1. Hence the results signify that these thermo-mechanically treated reinforcing bars have good amalgamation of strength and ductility. Corrosion of these reinforcing bars assist in significant reduction of strength. These steels exhibit untimely and abrupt failure in regions significantly below design values of strength when put to applications in hostile corrosive media. This aberration can be attributed to the fact that stress concentration factor comes into the picture as a result of localized corrosion.



(a)

(b)

Fig. 2. (a) Optical image depicting microstructure of core and (b) case of reinforcing bar 2 at 200X

The study of the fracture modes of these two reinforcing bars revealed that steel 1 exhibited ductile fracture (cup and cone) while fractured surface of steel 2 exhibited somewhat flat facets indicating comparatively brittle fracture.

The investigation of corrosion behaviour of thermo-mechanically processed reinforcing bars was done by computation and measurement of weight loss suffered by the steel samples. The study of response to corrosion by steel bars was done for 70 days. The fluctuation of corrosion rate (mpy) with exposure time (days) of reinforcing bars in 3.5% NaCl and fresh water was plotted as shown in Fig.3 and Fig.4 respectively. It was found that the corrosion rates of reinforcing bars in the corrosive media first decreased with an increase in immersion time. However for steel 1 (Fe-550 D) corrosion rate in NaCl solution first decreased, then gradually increased and then finally increased.

TABLE II
MEASUREMENT OF HARDNESS AT DIFFERENT SECTIONS OF CASE AND CORE

TMT steel 1					
Sample	**Surface area**	**d_1**	**d_2**	**d_{avg}**	**HV**
1	CASE	218	226	222	376
	CORE	258	281	270	254
2	CASE	221	227	224	370
	CORE	272	292	282	233
3	CASE	223	237	230	351
	CORE	276	285	281	235
TMT steel 2					
Sample	**Surface area**	**d_1**	**d_2**	**d_{avg}**	**HV**
1	CASE	202	212	207	433
	CORE	248	270	259	276
2	CASE	204	215	210	420
	CORE	260	278	269	256
3	CASE	210	224	217	394
	CORE	268	276	272	251

TABLE III
TENSILE PROPERTIES OF TMT STEEL BARS USED

Sample	Nominal Dia. (mm)	Area (mm^2)	Gauge length (mm)	σ_y (MPa)	σ_u (MPa)	σ_f (MPa)	% El	% RA
TMT steel 1	10	78.53	50	584.851	626.090	436.138	19	59.29
TMT steel 2	10	78.53	50	594.84	658.58	467.381	14	54.3

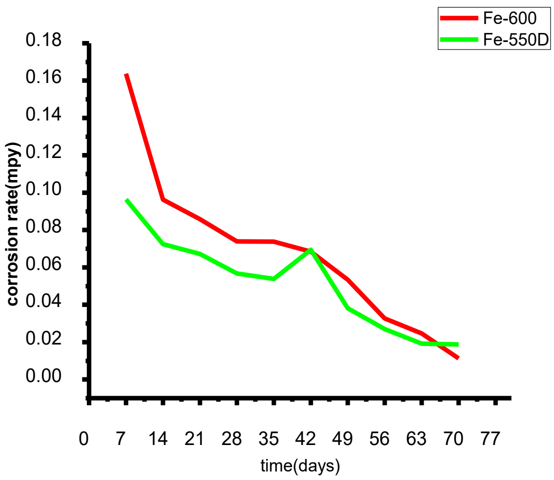


Fig. 3. Variation of corrosion rate (mpy) with exposure time (days) of TMT steels in 3.5%NaCl

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TABLE IV
CUMULATIVE WEIGHT LOSS AND CORROSION RATE OF TMT STEEL BARS

3.5%NaCl				
	TMT steel 2		TMT steel 1	
No. of days	Weight loss (gms)	Corrosion rate (mpy)	Weight loss (gms)	Corrosion rate (mpy)
1 - 7	0.3345	0.16374	0.1969	0.09637
8 -14	0.1967	0.09628	0.1481	0.07246
15 - 21	0.1754	0.08583	0.1374	0.06725
22 - 28	0.1510	0.07391	0.1160	0.05677
29 - 35	0.1509	0.07384	0.1101	0.05389
36 - 42	0.1398	0.06841	0.1419	0.06943
43 - 49	0.1090	0.05336	0.0779	0.03817
50 - 56	0.0667	0.03265	0.0551	0.02695
57 - 63	0.0498	0.02468	0.0392	0.01917
64 -70	0.0229	0.01124	0.0383	0.01876
Fresh water				
	TMT steel 1		TMT steel 2	
No. of days	Weight loss (gms)	Corrosion rate (mpy)	Weight loss (gms)	Corrosion rate (mpy)
1 - 7	0.1258	0.06155	0.1294	0.06335
8 -14	0.1089	0.05334	0.1210	0.05922
15 - 21	0.1015	0.04968	0.1109	0.05431
22 - 28	0.0934	0.04572	0.0978	0.04786
29 - 35	0.0814	0.03981	0.0854	0.04178
36 - 42	0.0673	0.03293	0.0699	0.03423
43 - 49	0.0602	0.02946	0.0810	0.03965
50 - 56	0.0520	0.02545	0.0535	0.02618
57 - 63	0.0404	0.01979	0.0394	0.01927
64 -70	0.0259	0.01267	0.0254	0.01244

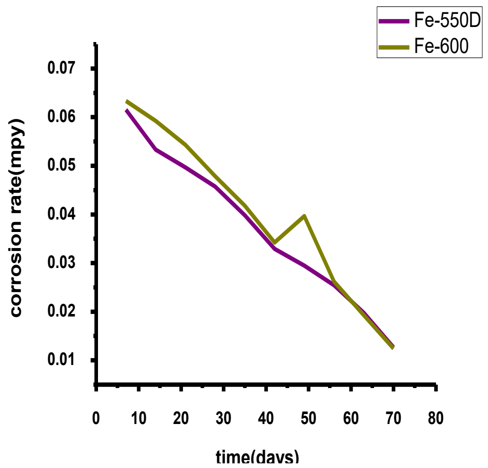


Fig. 4. Variation of corrosion rate (mpy) with exposure time of TMT steels in fresh water

The possible explanation for decrease in corrosion rates with increase in immersion time can be derived from Pourbaix diagram. It suggests that there can be formation of passivating oxide layer which will inhibit the corrosion process. This layer can also break resulting in further increase in corrosion process. The different zones of corrosion, immunity and passivation in the Pourbaix diagram for different values of E and pH help in investigating the corrosion phenomena with high accuracy.

. The Potentiodynamic polarization curve for corrosion of thermo-mechanically treated reinforcing bars in 3.5% NaCl and fresh water are presented in Fig.6 and Fig.7.The results obtained from PDP tests were consistent with the results of immersion test. Tafel equations were employed to calculate the corrosion current. The variation of electrode potential was plotted against logarithm of current density.It was found that higher contents of chromium, nickel and copper in steel 1 together with high residual stresses in steel 2 contributed significantly in comparatively faster corrosion of steel 2.

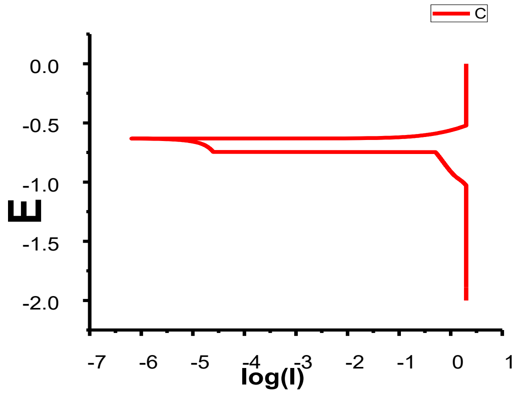


Fig. 5. Tafel polarization curve of TMT Fe 600 EQR steel in 3.5% NaCl

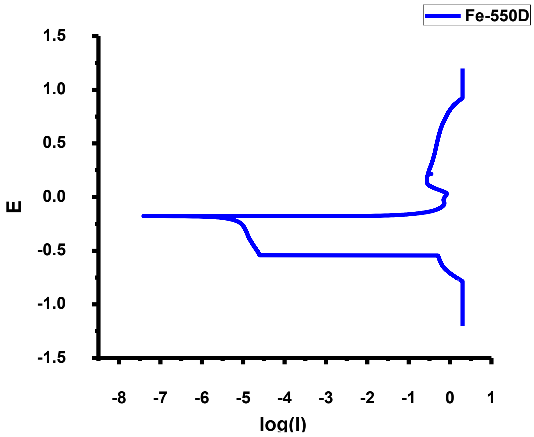
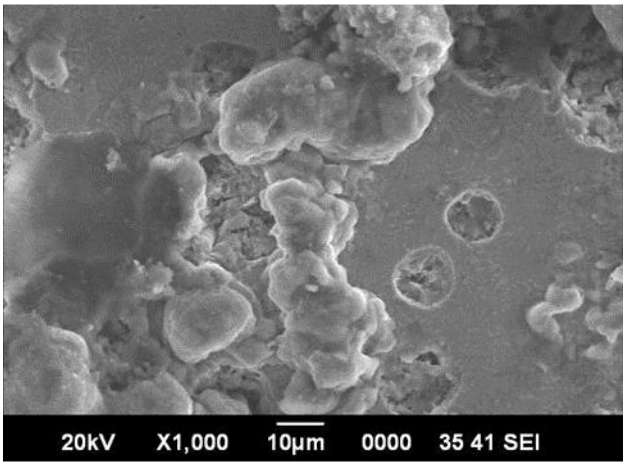
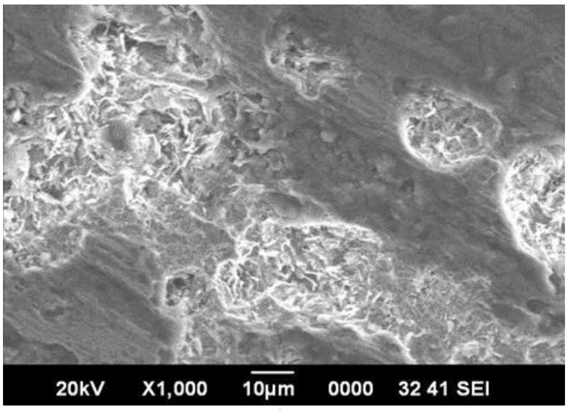


Fig. 6. Tafel polarization curve of TMT Fe 550D steel in 3.5% NaCl



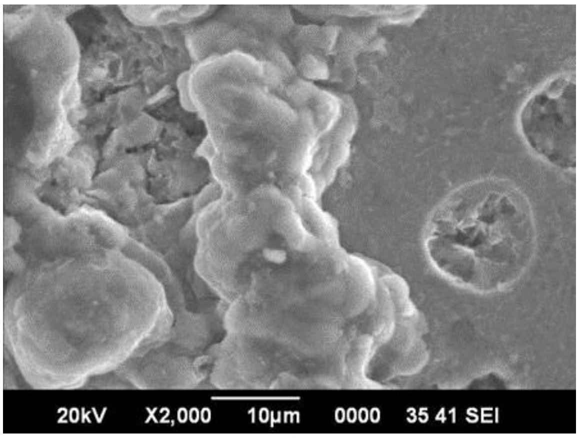
(a)

The surface morphology obtained from scanning electron microscope (shown in Fig. 7 and 8) indicated that both of these reinforcing steel bars suffered from pitting corrosion, since the formation of pits were seen very clearly from surface analysis.

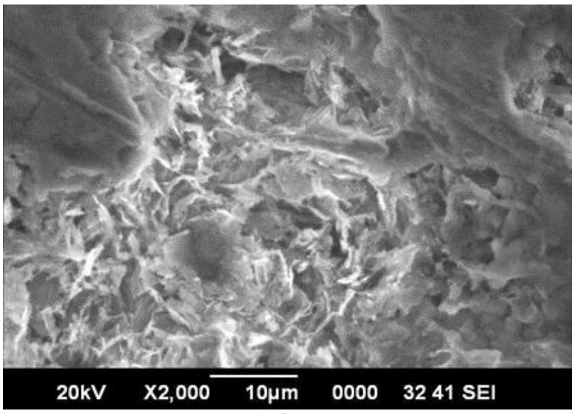


(b)

Fig. 7. SEM photomicrographs of surfaces of re-bar 1 (a) and re-bar 2 (b) at 1000X after corrosion



(a)



(b)

Fig. 8. SEM photomicrographs of surfaces of re-bar 1(a) and re-bar 2(b) at 2000X after corrosion

IV. Conclusion

The corrosion behaviour displayed by the two different grades of steel was investigated and the following conclusions were made.

1. The results obtained from immersion test method showed that steel 2 corroded at a faster rate than steel 1 in 3.5% NaCl solution as well as in tap water environment.
2. Steel 1 which had lower corrosion rate was composed of higher percentage of nickel, copper and chromium. Their presence helped in forming a highly adherent and chemically stable protective oxide layer.
3. The results obtained from potentiodynamic polarization tests were consistent with that of the immersion test and the corrosion rate of steel 2 was more than steel 1. Higher energy of the stress field due to the presence of residual stresses in steel 2 provided the favourable condition for corrosion.
4. The surface of the reinforcing steel bars was investigated and it was found that pits were forming on the surface. Hence bars were subjected to pitting corrosion.
5. The presence of the stress distribution due to stress concentration as a result of pitting caused the steel bars to weaken in a localized manner.

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