

## A comparative study on bond of different grade reinforcing steels in concrete under accelerated corrosion

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**Abstract.** Corrosion is important reason for the deterioration of the bond between reinforcing steel and the surrounding concrete. Corrosion of the steel mainly depends on its microstructure. Smooth S220, ribbed S420 and S500 grade reinforcing steels were used in the experiments. Samples were subjected to accelerated corrosion. Pullout tests were carried out to evaluate the effects of corrosion on bond strength of the specimens. S500 grade steel which has tempered martensite microstructure showed lower corrosion rate in concrete than S220 and S420 steels which have ferrite+perlite microstructure. S500 grade steel showed highest bond strength among the other steel grades in concrete. Bond strength between reinforcing steel and concrete increased with increase in the strength of steel and concrete. It also depends on whether reinforcing bar is ribbed or not.

**Keywords:** Bond strength; corrosion; tempcore steel; accelerated corrosion; concrete

### 1. Introduction

Although developments in the new building methods, steel reinforced concrete is still the most commonly used materials all over the world. Increase in the high rise buildings requires higher strength reinforcing steels. Several steel grades have been developed over the years. The main objective of these developments is raising the strength properties of the steel while keeping the yield properties above certain acceptable values. There are three main approaches for the production of high-strength concrete reinforcing steels. The first one is micro-alloyed low carbon hot rolled steel which is rather expensive (Nikolaou and Papadimitriou 2004, Bakkaloğlu 2002). Work hardening of steel bars by cold working is another method which results in increase in the yield strength with great reduction in ductility. The third and mostly used method consist of heat treatment process which is known as Tempcore, Thermex, etc. The name Tempcore is used to define a new process of producing high yield strength concrete reinforcing steel bars (S500a designation according to Turkish Standarts) (Simon *et al.* 1984, Çetinel *et al.* 2000). This process consists of controlled cooling (quenching) of the hot rolled steel. At the end of the process

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specific microstructure occurs which is very different than ordinary ferrite+pearlite reinforcing steels (S400a, S220a). Martensitic outer shell layer is formed on the ferrite+pearlite core.

Apart from structural design failures, the corrosion of the reinforcing steel is another important cause for the concrete degradation. Reinforcing steel in concrete is normally protected from corrosion by the passive film formed at the steel/concrete interface inside the alkaline cementitious matrix. However, carbonation or by the presence of chloride salts deteriorate the passive film and initiate corrosion of the reinforcing steel and eventually damages the surrounding concrete. After initiation of the corrosion process, the accumulation of corrosion products (iron oxides and hydroxides), occupying a volume several times larger than that of the original iron leads to internal stresses that result in cracking and spalling of the concrete cover. Corrosion of steel bars (rebar) affects the durability of reinforced concrete in two ways: (i) it reduces the cross-section of the rebar, thereby, decreasing its load bearing capacity and (ii) it degrades the integrity of the surrounding concrete (Montemor *et al.* 2003, Jaffer and Hansson 2009). When structures are exposed to aggressive environments and when the concrete protection is deteriorated, corrosion of the reinforcement is initiated. Rust, the corrosion product of iron, is the result of an electrochemical process during which metallic iron is converted to iron oxide, creating volumetric expansion of the steel bars and also causing extremely high-tensile forces within the concrete cover. This results in crack formation from the steel bar to the concrete surface or between bars allowing oxygen and moisture to attack the bars faster and increase the corrosion rate. The rust reduces the bond strength and results in the loss of steel-concrete composite action, which affects the serviceability and performance of structures (Apostolopoulos *et al.* 2007, Fang *et al.* 2004, Capozucca 1995). Rust occurs because of differences in electrical potential between small areas on the steel surface involving anodes, cathodes and an electrolyte. These differences on the steel surface are caused by variations in composition structure, presence of impurities, uneven internal stress and presence of non-uniform environment.

When the Tempcore type reinforcing steel is thought, two different factors become important for the corrosion. Tempcore process is a kind of surface hardening process. Surface hardening process generates compressive residual stress on the hardened steel surface. This internal stress may induce corrosion of the reinforcing steel. On the other hand, residual stress on the surface of the Tempcore processed reinforcing steel was found to be useful for the superior fatigue properties (Zheng and Abel 1999). Ordinary reinforcing steel consist of ferrite and pearlite. Pearlite is a lamellar phase mixture of ferrite ( $\alpha$ -iron) and cementite ( $\text{Fe}_3\text{C}$ ). When two different phases come into contact, galvanic cell is formed. Formation of galvanic cell between two different phases induces corrosion. On the other hand, Tempcore type reinforcing steel has more uniform phase structure than the ordinary reinforcing steel. Outer part of the Tempcore steel is covered by tempered martensite phase. Due to the lower risk of galvanic cell formation, one can expect better corrosion resistance of Tempcore type steel compared to the ordinary reinforcing steel. Several authors reported different results on the corrosion behaviour of Tempcore steel and martensite containing dual phase steels. Apostolopoulos *et al.* (2006) drew attention on the subject that S500 grade Tempcore steels shows greater mass loss due to corrosion compared to steel classes S400 and S220. On the other hand Ismail *et al.* (2007) concluded that martensite containing dual-phase steels have better corrosion resistance than conventional steel rebar. They stated that; presence of pearlite phase in the microstructure of conventional steel which contains the eutectoid carbide makes the steel susceptible to pitting corrosion. On the other hand, dual-phase steel rebar is more corrosion resistant than conventional steel because it contains no carbide and most of the carbon atoms are trapped in the martensite structure (Ismail *et al.* 2010 ). Trejo *et al.* (1993) also

stated that the absence of carbide phase ( $\text{Fe}_3\text{C}$ ) in the martensite containing dual phase steels makes it more corrosion resistant than ordinary steel rebar. They claimed that; the conventional steels have ferrite-carbide microstructures and in corrosive environments the carbides are cathodic to ferrite, therefore making galvanic corrosion inevitable. Martensite containing dual-phase steels contain ferrite-martensite structures with no carbides and should be more resistant to corrosion. Ramirez-Arteaga *et al.* (2010) justified that the corrosion rate of martensite containing steel decreases with an increase in the volume fraction of martensite. Completely opposite findings were stated in the studies of Sarkar *et al.* (2005) and Keleştemur *et al.* (2009) for dual phase steels. They found that corrosion rate has increased with increase in the amount of martensite in the steel. Batis *et al.* (2005) compare the corrosion rate of the Tempcore type reinforcing steel with S220 and S400 type steels under open atmosphere and they found that, Tempcore type steel (S500) has the least corrosion resistance. Al-Negheimish *et al.* (2004) stated that, the rapid water cooling, called quenching, causes micro structural changes in the bar enhancing some properties of the product including corrosion resistance. The bars produced by quenching process resulting in faster rusting, however, the long-term mass loss of the quenched bars is less than hot-rolled bars. The studies performed to determine the effect of martensite phase on the corrosion behaviour reinforcing steel in concrete has not been reached to clear decision. It is also reported that, the effectiveness of the reinforcement depends on the bond strength between steel–concrete interfaces. The corrosion product, rust, resides at the interface between steel rebar and concrete, degrading the bond strength. On the other hand, the rougher the steel surface, the better it adheres to concrete. It has been reported that, oxidation treatment (by water immersion and ozone exposure) of rebar increases the bond strength between steel and cement paste to a value higher than that attained by clean rebars (Fu *et al.* 1996). The studies performed to determine the effect of martensite phase on the corrosion behaviour of reinforcing steel in concrete has not been reached to clear decision. Comparative studies are needed for the more clear explanation of corrosion behaviour of martensite containing Tempcore type reinforcing steel in concrete structure and effect of corrosion state on the bond strength of steel under corrosive conditions.

In this work, three different grade reinforcing steel (S220, S420, S500-Tempcore) were selected for the accelerated corrosion test of the steel bars embedded in to the concrete. Corrosion behaviour of the different grade reinforcing steels in concrete have been investigated. Bond strength of different grade steels was compared after the accelerated corrosion test.

## 2. Experimental

### 2.1 Steel grades and microstructures

3 different grade hot rolled reinforcing steels were selected for the experiment. S220a is the non-ribbed reinforcing steel. S420a and S500a are hot rolled ribbed reinforcing steels. S500a is a Tempcore type steel. Chemical compositions of the steels are given in Table 1. S220a and S500a have nearly the same carbon content. However, S420a steel contains higher carbon content than the others. S220a steel was produced in Karabük Iron and Steel Plant, S420a and S500a steels were produced in Iskenderun Iron and Steel Plant in Turkey. 16 mm diameter bars were selected for the experiments.

Table 1 Chemical composition of different grade reinforcing steels

| Steel Grade | C    | Si   | Mn   | P    | S    | Cr   | Cu   | Ni   | N    | Fe      |
|-------------|------|------|------|------|------|------|------|------|------|---------|
| S220a       | 0,16 | 0,40 | 0,50 | 0,02 | 0,04 | 0,10 | 0,21 | 0,13 | 0,01 | balance |
| S420a       | 0,27 | 0,30 | 0,80 | 0,03 | 0,05 | 0,07 | 0,29 | 0,14 | 0,01 | balance |
| S500a       | 0,17 | 0,20 | 0,69 | 0,01 | 0,04 | 0,13 | 0,40 | 0,13 | 0,01 | balance |

Fig. 1 shows the microstructure of different grade steels. S220a steel contains ferrite and pearlite. S420a steel also contains ferrite and pearlite. However, the amount of pearlite phase is higher than S220a steel. S500a steel's microstructure is different than the others. 3 different region of the sample were combined in one picture which shows inner, transition and outer section of the sample. The cross section of Tempcore bars consist of 3 main zone; a fine ferrite-pearlite, an intermediate layer with mixture of bainite and ferrite and a tempered martensite at the outer surface.

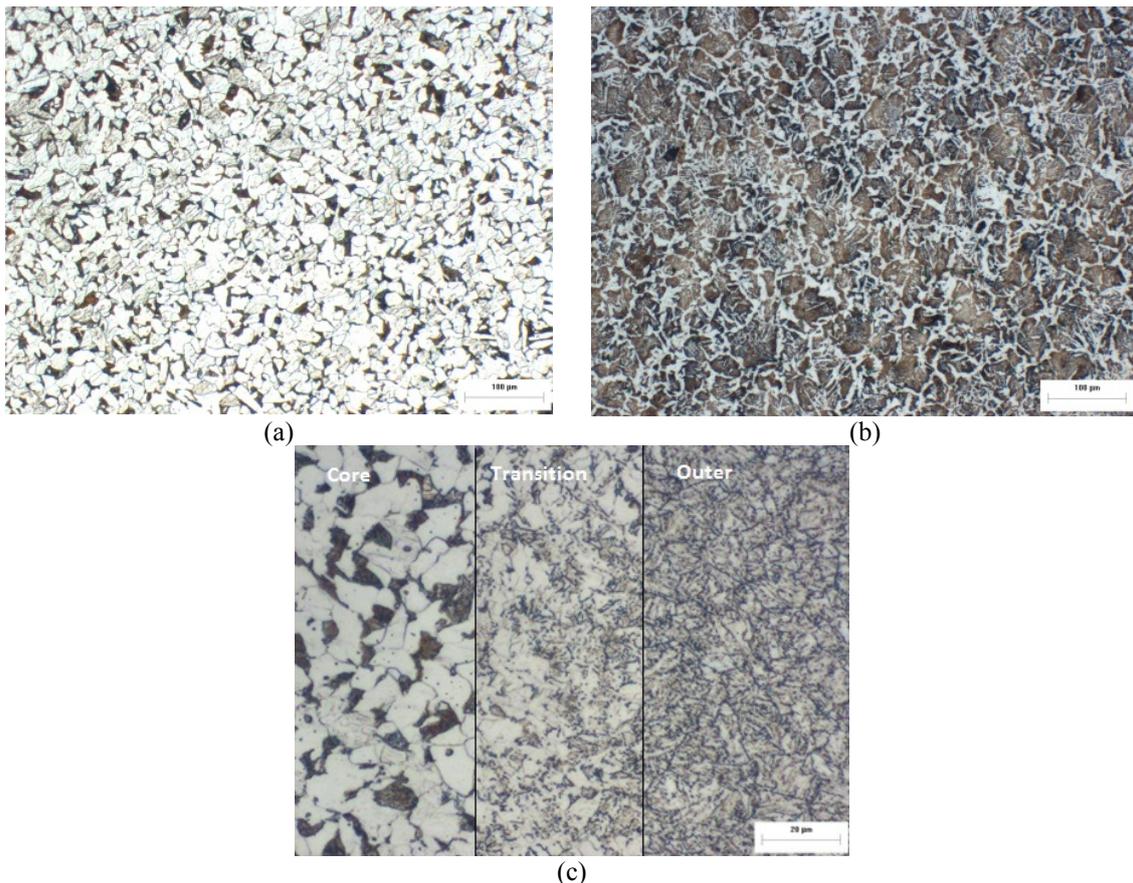


Fig. 1 Microstructure of the different grade steels ((a): S220a, (b): S420a, (c): S500a)

## 2.2 Sample preparation

Three different class of concrete were prepared in order to investigate the effect of concrete quality on the bond strength of reinforcing steel embedded in concrete. Properties of the concretes are given on Table 2. CEM I 42.5 R type cement was used for the concrete samples. Calcite based coarse aggregates and silicate based fine aggregates were used for the production of concrete samples. Compressive and bending strength were defined based on the TS EN 12390-3 and TS EN 12390-5, respectively.

Table 2 Mechanical and physical properties of the concrete

| Concrete Type | Water/cement | Compressive strength (MPa) | Bending strength (MPa) | Apparent Porosity % | Water absorption % |
|---------------|--------------|----------------------------|------------------------|---------------------|--------------------|
| A             | 0.728        | 21.4                       | 3.0                    | 14.5                | 6.7                |
| B             | 0.600        | 34.6                       | 4.2                    | 11.9                | 5.5                |
| C             | 0.481        | 44.3                       | 4.6                    | 9.7                 | 4.4                |

150x150x150 mm cube specimens were used for compressive strength test and water absorption tests. Bending strength test was made on the prism (100x100x300 mm) specimens. Five Specimens from each mixture were tested. 45 concrete sample were used for these tests. The reinforced concrete specimens for the accelerated corrosion tests were Ø150x300 mm cylinder specimens in which a Ø16 mm diameter steel reinforcement was centrally embedded. 450 mm long steel bars were embedded standard depth of 250 mm into the concrete (Fig. 2).

Five specimens for three concrete mixes (A, B, C), three steel reinforcement types (S220, S420, S500) and three corrosion levels (Normal Condition-NC, Fixed Term Corrosion-FTC, Unit Cracks Corrosion-UCC) were used (Fig. 2). 135 reinforced concrete specimens were used for these tests.



Fig. 2 Amount of lollipop shape test samples prepared for each concrete type

### 2.3 Corrosion acceleration and corrosion evaluation

In order to evaluate the corrosion behaviour of the different grade steel samples 3 different approach have been used; corrosion current monitoring in accelerated corrosion setup, half cell potential measurements (ASTM C876) and corrosion rate calculation (ASTM G1 2003).

In the first approach, electrolytic corrosion method was used to accelerate the corrosion of the reinforcement in concrete. To accelerate the reinforcement corrosion, direct electric current was passes on the steel bar embedded in the concrete. Fig. 3 shows schematically the electrochemical system used. Direct current power supply was used for the electrolyte corrosion process. After 90 day curing, the specimens were immersed into the electrolyte which contains 5% NaCl solution. The positive terminal was connected to the steel bar (anode) and the negative terminal was connected to the stainless steel plates (cathode) immersed in the electrolyte. Corrosion current was recorded with time by data acquisition system. Two different corrosion monitoring were applied to the specimens. First, corrosion current was monitored for 100 hour constant time for each sample series (Fixed Term Corrosion-FTC). Second, corrosion current was recorded until the first cracks observed on the sample (Unit Cracks Corrosion-UCC).

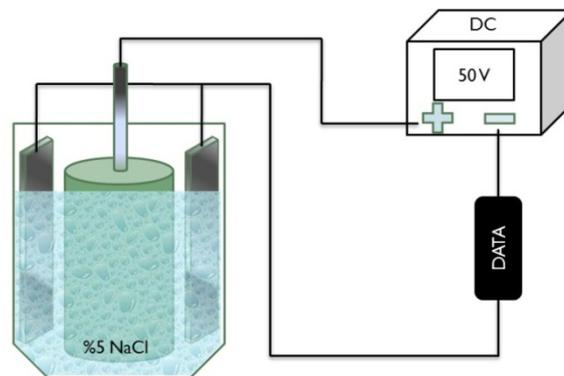


Fig. 3 Schematic representation of the accelerated corrosion setup

In the second approach, halfcell potential measurements ( $\text{Cu}/\text{CuSO}_4$  electrode) were done on samples which were exposed to different corrosion monitoring levels such as FTC and UCC. According to the measured potential readings, corrosion probability is decided. If the potential is less negative than  $-0.200$  V than 90% probability of no corrosion, more negative than  $-0.35$  V than 90% probability of corrosion and between  $-0.200$  V and  $-0.350$  V than there is an increasing probability for corrosion.

In the third approach, corrosion rate of the samples which were subjected to accelerated corrosion test were measured according to ASTM G1 2003 procedure. ASTM G1 is a standard used in determining the rate of corrosion depending on loss of weight. Corrosion rate was given in mils per year (milli-inch per year,  $1\text{mpy}=0,0254$  mm/year) according to reference procedure. After the pullout test, different grade reinforcing steels were taken from the concrete samples and used for the corrosion rate measurements.

## 2.4 Measurement of bond strength-pullout testing

The simplest and widely used way to determine the bond strength of the reinforcement is pull-out testing. Concentric lollipop shape samples were used in the pullout tests. 100 kN capacity tensile testing machine was used for the pullout testing. A specially designed loading rigid frame was used for the tests under pullout loading (Fig. 4). Standard loading speed of 0.5 mm/s was used for all samples. The load and displacement readings were recorded automatically by the computer. Maximum load level at the force-displacement curve was taken into account for the calculation of pullout strength. 5 samples were used for each series and average values were presented. Yielding of the steel bars was not observed. Bond strength was calculated according to Eq. (1) [19] where  $T_{\max}$ , bond strength (MPa);  $d$ , diameter of the steel bar (16 mm);  $l$ , embedment length (250 mm).

$$T_{\max} = \frac{P}{\pi dl} \quad (1)$$

Samples were designed according to splitting failure mode. Splitting failure mode was observed in ribbed bars but it was not observed in smooth uncorroded bars. Pull-out failure mode has been observed for smooth uncorroded bars. Length of the embedment ( $l$ ) was around 15 Db where Db is the diameter of the reinforcing steel bar. According to ACI 318 2000 and EC2, embedment length is respectively min 12 Db and min 15 Db. 250 mm embedment length was used to ensure the anchorage condition instead of 240 mm calculated from min 15 Db anchorage condition. All specimens considered, a constant C/Db ration of about 8.9 was used aiming to encourage splitting failure (C is the concrete cover: 142 mm and Db the bar diameter: 16 mm).

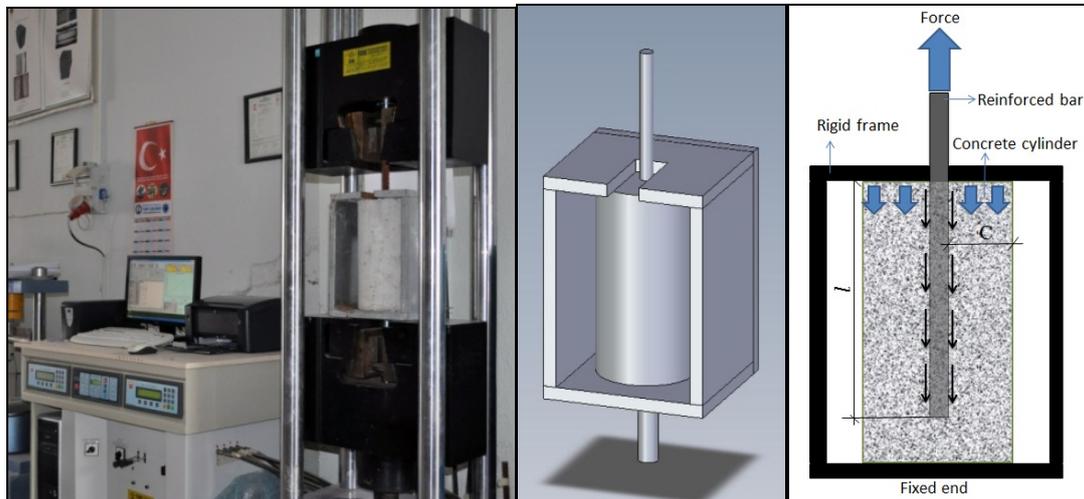
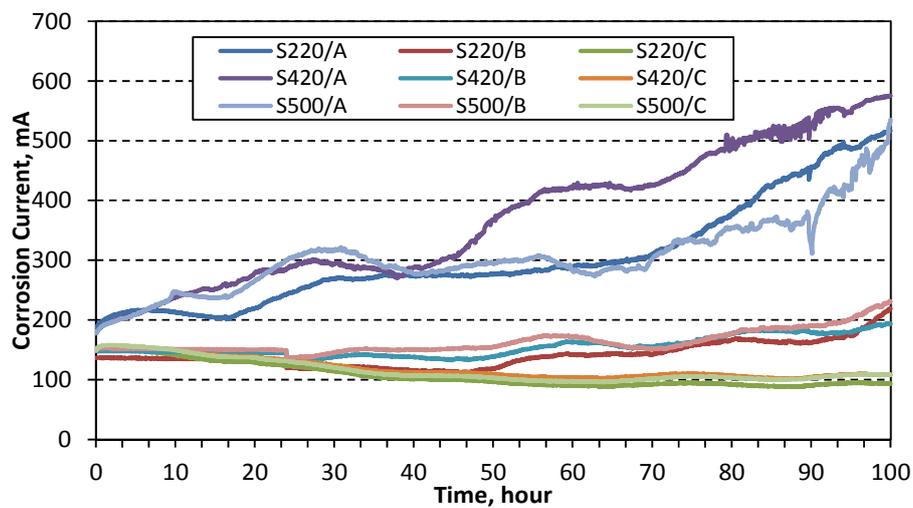


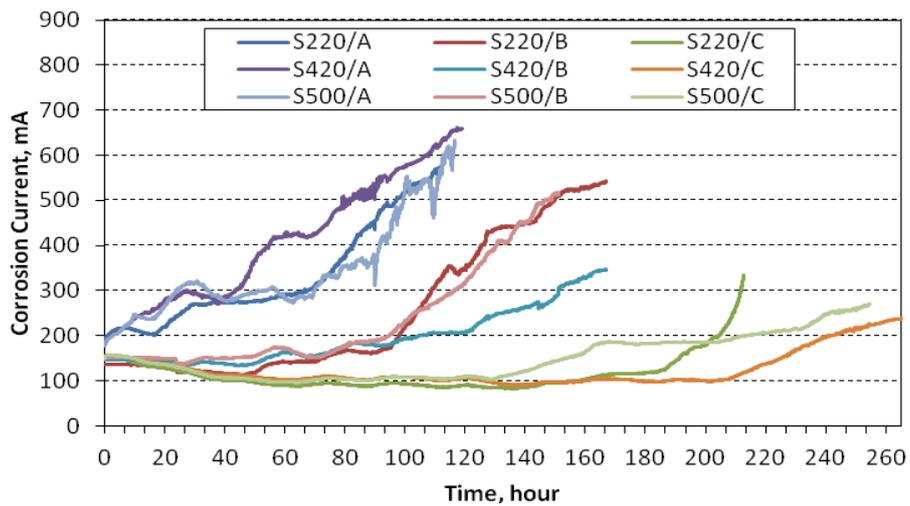
Fig. 4 Pullout test system and rigid frame

Bond strength of the samples was measured at three different corrosion states; at Normal Condition (before the accelerated corrosion test), after Unit Cracks Corrosion-UCC and after Fixed Term Corrosion-FTC. There is no corrosion at the normal condition. When the first crack or rust

line observed on the sample surface, the accelerated corrosion test was stopped. Then the samples were tested for bond testing (UCC condition). Corresponding corrosion time which can be read from the end of the corrosion current graphs are the elapsed corrosion time for the samples (Figure 5b). Because of the difficulties in taking a corrosion time reference (difficulties in observing the first crack formation) in UCC samples, fixed term corrosion state was used to fix the corrosion time. Accelerated corrosion test was stopped after 100 hour. Then samples were tested for the bond strength (FTC condition).



(a)



(b)

Fig. 5 Corrosion current-time graphics obtained from accelerated corrosion setup (a: Fixed Term Corrosion-FTC, b: Unit Cracks Corrosion-UCC)

### 3. Result and Discussion

#### 3.1 Evaluation of the Corrosion Test Results

Fig. 5 shows the measured corrosion current vs time graphics which obtained from accelerated corrosion setup for two different monitoring type; Fixed Term Corrosion-FTC (Fig. 5a) and Unit Cracks Corrosion-UCC (Fig. 5b).

It is very difficult to conclude which grade steel reinforcement corrode much faster from the monitoring graphics of corrosion current at accelerated corrosion test (Fig.5). However, there is a clear relation between concrete quality and measured corrosion currents. When the porosity of the concrete increased, permeability of the concrete increased. This allowed more Cl<sup>-</sup> ions existence between the steel-concrete interface. Increase in the chloride ions accelerates the dissolution of Fe<sup>+2</sup> ions at the anodic regions. Therefore, when the quality of the concrete decreased, higher corrosion currents were measured in the accelerated corrosion setup. Higher corrosion currents were measured at more porous A type concrete samples when compared to B and C type concrete samples (Fig. 5a). When the corrosion rate increases, corrosion products also increase at the steel-concrete interface which creates expansive forces and cracks. When the porosity of the concrete decreased, cracks formed at later times (Fig. 5b).

Results of the half cell potential measurements are given in Fig. 6. Much higher negative potential values were measured when the concrete samples were more porous. More porous concrete samples resulted in more corrosion of the reinforcing steel. Potential values decreased gradually from A series to C series concrete samples for both type of monitoring.

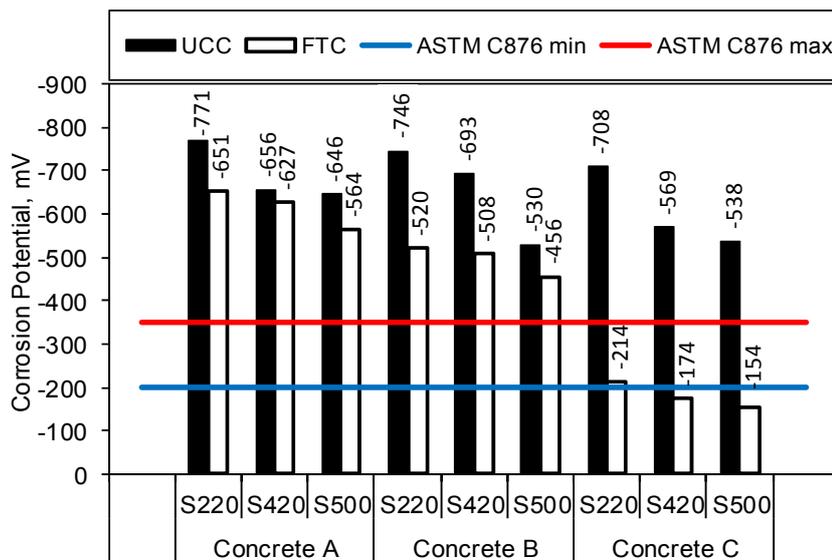


Fig. 6 Half cell potential graphics

Lowest negative half cell potential were measured for the Tempcore grade (S500) steel reinforcement with C type concrete. Half cell potential values lower than the -200 V mean that there is 90% probability of no corrosion. S500 grade reinforcing steel samples showed lowest half cell potential values for all type concrete samples. S220 grade steel containing samples showed highest negative potential values.

It very clear from the half cell potential measurements that (Fig.6), S500 grade steel containing samples resulted in lower corrosion probability than the S200 and S420 grade steels.

Fig. 7 shows the results of the corrosion rate measurements according to ASTM G1 2003 procedure for steel samples which were taken after the accelerated corrosion testing.

When the required conditions were supplied to start the corrosion process, the natural corrosion rate in dry concrete is negligible and at the level of 0.0456 mpy and when the humidity goes up maximum values of around 45.6 mpy (in sea water) (Andrade *et al.* 2002).

S500 grade steel showed lowest corrosion rate for both type of monitoring and for all type of concrete. S220 grade reinforcing steel showed highest corrosion rate in the concrete samples. Average values of the experiments were presented. Scatter (standarts deviations) were in the range of  $\pm 0,19$  to  $\pm 0,62$ .

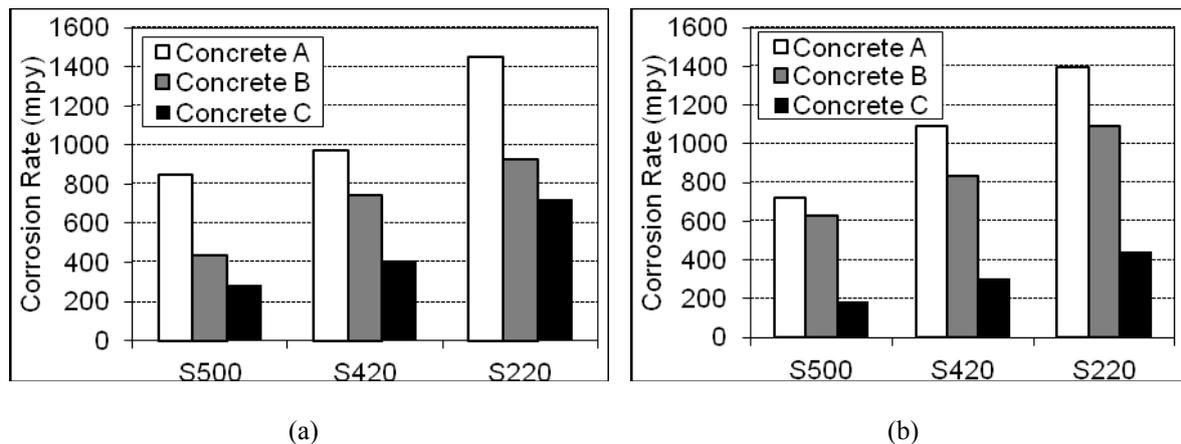


Fig. 7 Corrosion rates in milli-inch per year (mpy). (a: Unit Cracks Corrosion-UCC, b: Fixed Term Corrosion-FTC)

Apart from the first corrosion evaluation method that is monitoring of the corrosion current during accelerated corrosion setup, other two corrosion evaluation method indicated that S500 grade reinforcing steel has the lowest corrosion potential than the S220 and S420 grade steels.

### 3.2 Evaluation of the Pull-out Test Results

Bond strength of the samples was measured at three different states; at Normal Condition (before the accelerated corrosion test), after Fixed Term Corrosion-FTC and after Unit Cracks Corrosion-UCC. S220 type reinforcing steel showed the lowest bond strength in all type of steels and monitoring types. Since S220 steel is the non-ribbed reinforcing steel, it showed the lowest

adhesion. S420 and S500 steel have similar bond strength in A type concrete but S500 has higher bond strength than S420 steel in B and C type steel. Bond strength of the ribbed reinforcing steels (S420 and S500) decreased with increased corrosion state. If the bars are smooth, the main contributions to bond strength come from the chemical adhesion and the friction resistance occurring between the bar and the concrete. If, however, the bars are fibbed, two additional sources of bond strength become more significant. These are the bearing capacity of the concrete between the lugs and the shear strength of the concrete cylindrical surface located between the lugs. When the steel surfaces corrode, the ribs are disappeared due to the new corrosion products on the steel surface. Therefore, anchorage action of the ribs is disappeared and the bond strength decreased. Bond strength reduction by increased corrosion state can be seen in Fig. 8. Tempcore grade steel (S500) has the highest bond strength than the others after accelerated corrosion test. Unlike the situation for S420 and S500 steels, the bond strength of the S220 steel increased with increased corrosion state. The main reason for this behaviour is the chemical binding action of corrosion products between the non-ribbed steel surface and concrete. This chemical binding effect is more evident in the SEM examination of the steel-concrete interface for S220 steel (Fig. 9). Deformed bars, the shear mechanism due to the ribs bearing on the concrete played a major role in the bond resistance. This mechanism disrupted by corrosion.

Iron rich corrosion layer (red region) between steel and concrete interface can be seen in Fig. 9(b). Penetration of the iron rich corrosion products into the concrete shown on Fig. 9(b). and Fig. 9(c).

Concrete strength was found to be a factor which influencing the bond strength of the especially ribbed steels under normal conditions. On the other hand, S500 grade steel showed higher bond strength than S420 grade steel already under uncorroded state. S500 grade steel has exclusive material properties due to heat treatment processing during production. Comparing to other two grade steel, S500 grade steel has initially higher potential for corrosion. Residual stresses due to heat treatment and non equilibrium martensitic phase makes the S500 grade steel more active for the corrosion compared to other grade steels. Therefore, faster formation of corrosion products on the S500 grade steels resulted in better bond strength by the increase in the chemical bonding action between steel and concrete interface.

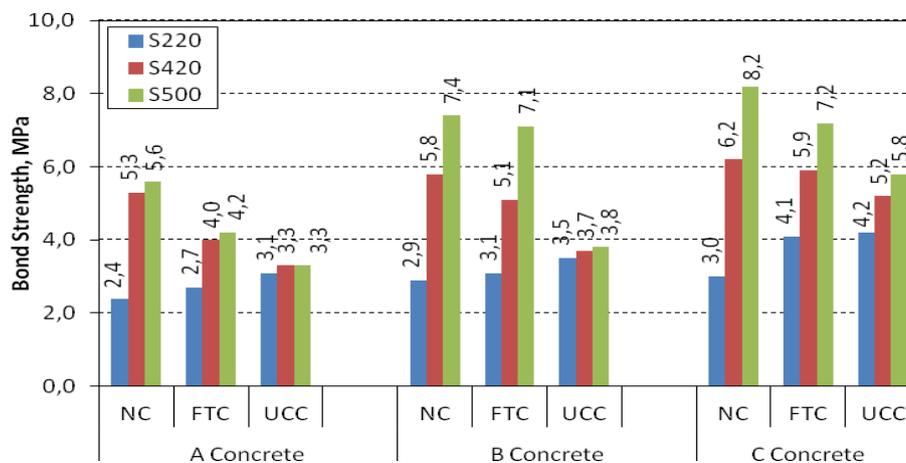


Fig. 8 Bond strength of the samples

On the other hand, further corrosion of the Tempcore grade S500 steel is potentially lower than other grade steels. Because, ferrite and finely dispersed Fe<sub>3</sub>C microstructure after Tempcore process has lower corrosion potential than ordinary ferrite and pearlite microstructure which is the main microstructure in S220 and S420 grade steel (Revie and Uhlig 2008)

Fang *et al.* (2004) also found that the bond strength increased as the corrosion level increased for smooth reinforcing bar specimen at low and medium corrosion levels. For ribbed reinforcing bar samples with higher corrosion levels, bond strength decreased. Similarly the improvement of the bond strength was reported for smooth reinforcing bar samples which can be attributed to the increasing friction resulting from increased roughness due to the rusting (Al-Negheimish *et al.* 2004). Cheng *et al.* 2005 found that adherence between steel and concrete decreased when the corrosion level increased. Similar to the present results, many author also found that when the strength of the concrete increased, bond strength increased (Lee *et al.* 2002, Larrard *et al.* 1993).

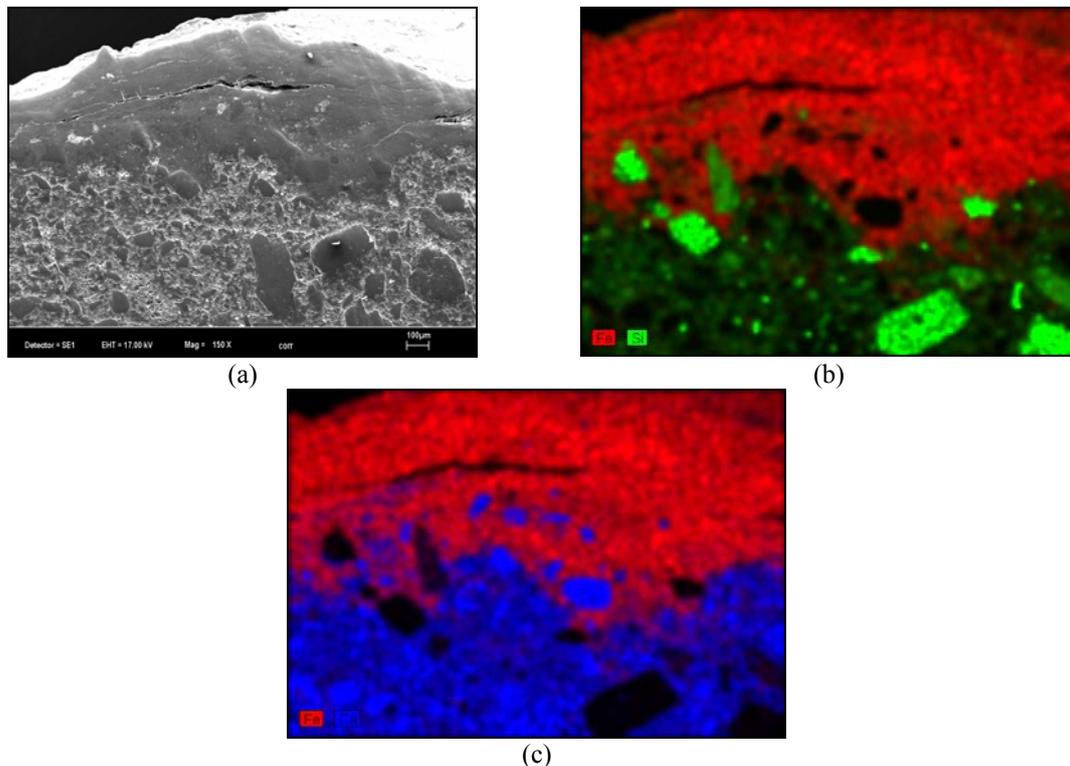


Fig. 9 SEM image at steel-concrete interface and mapping results for smooth S220 steel

#### 4. Conclusions

The main objective of this study was to understand the corrosion behaviour of S220, S420 and S500 (Tempcore) grade reinforcing steels in different concrete type and making comparison of the resulting adherence. Following conclusions were derived from the study;

- Tempered martensite layer at the outer part of the S500 grade steel showed better corrosion resistance than the ferrite+pearlite structure which is the main phase composition in S220 and S420 steels. Therefore, highest bond strength was measured for S500 grade steel.
- Corrosion current which was measured during the accelerated corrosion test is mainly dependent on the concrete properties rather than the steel properties. Corrosion current decreased, corrosion time increased with increase in the concrete strength.
- When the steel and concrete strength increased probability for the corrosion decreased. Tempcore steel (S500) in C type concrete was found to be lowest corrosion potential than the other steel grades.
- S500 grade steel showed lowest corrosion rate among the other steel grades in concrete. When the steel and concrete strength increased corrosion rate decreased.
- Bond strength of the ribbed steels decreased with increased corrosion level. On the other hand, bond strength of the non-ribbed steel increased with increased corrosion level. It was concluded that corrosion products between the steel and concrete surface decreased the mechanical bond in ribbed steel and increased in non-ribbed steels. However, increase in the bond strength values for non-ribbed steel was still lower than the values for the ribbed steels.

## References

- Al-Negheimish, A.I. and Al-Zaid, R. Z. (2004), "Effect of manufacturing process and rusting on the bond behaviour of deformed bars in concrete", *Cement Concrete Comp*, **26**(6), 735–742.
- Andrade, C., Alonco, C., Sarria, J. (2002), "Corrosion rate evolution in concrete structures exposed to the atmosphere", *Cement Concrete Comp*, **24**(1), 55-64.
- Apostolopoulos, C. A. and Michalopoulos, D. (2007), "Mechanical properties of reinforcing steel and fatigue behavior in corrosive environment", *J. Mater. Eng. Perform*, **16**(5), 559-566.
- Apostolopoulos, C. A., Papadopoulos, M.P. and Pantelakis, S.G. (2006), "Tensile behavior of corroded reinforcing steel bars BSt 500s", *Constr. Build. Mater*, **20**(9), 782–789.
- Bakkaloğlu, A. (2002), "Effect of processing parameters on the microstructure and properties of an Nb microalloyed steel", *Mater Lett*, **56**(3), 263-272.
- Batis, G. and Rakanta, E. (2005), "Corrosion of steel reinforcement due to atmospheric pollution", *Cement Concrete Comp*, **27**(2), 269–275.
- Capozucca, R. (1995), "Damage to reinforced concrete due to reinforcement corrosion", *Constr. Build. Mater*, **9**(5), 295–303.
- Çetinel, H., Toparlı, M. and Özsoyeller, L. (2000), "A finite element based prediction of the microstructural evolution of steels subjected to the Tempcore process", *Mech. Mater*, **32**(6), 339-347.
- Cheng, A, Huang, R., Wu, J.K. and Chen, C.H. (2005), "Effect of rebar coating on corrosion resistance and bond strength of reinforced concrete", *Constr Build Mater*, **19**(5), 404-412.
- Fang C., Lundgren, K., Chen, L. and Zhu, C. (2004), "Corrosion influence on bond in reinforced concrete", *Cement Concrete Res*, **34**(11), 2159–2167.
- Fu, X. and Chung D.D.L. (1996), "Improving the bond strength between steel rebar and concrete by oxidation treatments of the rebar", *Cement Concrete Res*, **26**(10), 1499–503.
- Ismail, M., Hamzah, E., Guan, G.C. and Rahman, I.A. (2010), "Corrosion performance of dual-phase steel embedded in concrete", *The Arabian Journal for Science and Eng.*, **35**, 81-89.

- Jaffer, S. J. and Hansson, C. M. (2009), "Chloride-induced corrosion products of steel in cracked-concrete subjected to different loading conditions", *Cement Concrete Res*, **39**(2), 116–125.
- Keleştemur, O. and Yıldız, S. (2009), "Effect of various dual-phase heat treatments on the corrosion behaviour of reinforcing steel used in the reinforced concrete structures", *Constr Build Mater*, **23**(1), 78–84.
- Keleştemur, O., Aksoy, M. and Yıldız S. (2009), "Corrosion behaviour of tempered dual-phase steel embedded in concrete", *Int. J. Min Met Mater*, **16**(1), 43–50.
- Larrard, F., Schaller, I. and Fuchs, J. (1993), "Effect of bar diameter on the bond strength of passive reinforcement in high performance concrete", *ACI Material Journal*, **90**, 333-339.
- Lee, H., Noguchi, T. and Tomosawa, F. (2002), "Evaluation of the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion", *Cement Concrete Res*, **32**(8), 1313-1318.
- Montemor, M.F., Simoes, A.M.P. and Ferreira, M.G.S. (2003), "Chloride-induced corrosion on reinforcing steel: from the fundamentals to the monitoring techniques", *Cement Concrete Comp*, **25**(4-5), 491–502.
- Nikolaou, J. and Papadimitriou, G.D. (2004), "Microstructures and mechanical properties after heating of reinforcing 500 MPa class weldable steels produced by various processes (Tempcore, microalloyed with vanadium and work-hardened)", *Constr Build Mater*, **18**(4), 243–254.
- Ramirez-Arteaga, A.M., Gonzalez-Rodrigue, J.G., Campillo, B., Gaona-Tiburcio, C., Dominguez-Patiño, G., Leduc Lezama L., Chacon-Nava, J.G., Neri-Flores, M.A., Martinez-Villafañe, A. (2010), "An electrochemical study of the corrosion behavior of a dual phase steel in 0.5m H<sub>2</sub>SO<sub>4</sub>", *Int J Electrochem Sci*, **5**, 1786–1798.
- Revie, R.W. and Uhlig, H.H. (2008), *Corrosion and Corrosion Control; An Introduction to Corrosion Science and Engineering*, John Wiley & Sons, 4<sup>th</sup> edition, p142-143.
- Sarkar, P.P., Kumar, P., Mana, K.M. and Chakraborti P.C. (2005), "Microstructural influence on the electrochemical corrosion behaviour of dual-phase steels in 3.5% NaCl solution", *Mater Lett*, **59**(19-20), 2488–2491.
- Simon, P., Economopoulos, M. and Nilles, P. (1984), "Tempcore: a new process for the production of high quality reinforcing bars", *Iron Steel Eng*, 55–57.
- Trejo, D., Monteiro, P., Thomas, G. and Wang, X. (1994), "Mechanical properties and corrosion susceptibility of dual-phase steel in concrete", *Cement Concrete Res*, **24**(7), 1245-1254.
- TS EN 12390-3, (2010), Testing hardened concrete-Part 3: Compressive strength of test specimens
- TS EN 12390-5, (2010), Testing hardened concrete-Part 5: Flexural strength of test specimens
- Zheng, H. and Abel, A. A. (1999), "Fatigue properties of reinforcing steel produced by tempcore process", *J. Mater. Civil Eng*, **11**(2), 158-165.