

Research Article

An Experimental Study for Quantitative Estimation of Rebar Corrosion in Concrete Using Ground Penetrating Radar

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Corrosion of steel rebar in reinforced concrete is one of the most important durability issues in the service life of a structure. In this paper, an investigation is conducted to find out the relationship between the amount of reinforced concrete corrosion and GPR maximum positive amplitude. Accelerated corrosion was simulated in the lab by impressing direct current into steel rebar that was submerged in a 5% salt water solution. The amount of corrosion was varied in the rebars with different levels of mass loss ranging from 0% to 45%. The corroded rebars were then placed into three different oil emulsion tanks having different dielectric properties similar to concrete. The maximum amplitudes from the corroded bars were recorded. A linear relationship between the maximum positive amplitudes and the amount of corrosion in terms of percentage loss of area was observed. It was proposed that the relationship between the GPR maximum amplitude and the amount of corrosion can be used as a basis of a NDE technique of quantitative estimation of corrosion.

1. Introduction

Ground Penetrating Radar (GPR) has been widely used in several types of nondestructive evaluation of concrete, such as detecting and locating rebar, finding concrete thickness, and detecting voids and cracks. GPR has also been used with great success to map deterioration in bridge decks [1–3]. Rebar corrosion is one of the main reasons for the deterioration of reinforced concrete. During corrosion, the resulting products accumulate over the anodic steel rebar. If there is crack or the concrete is very porous, the corrosion material dissipates around the rebar. So, the property of concrete around the rebar changes and the effective diameter of the rebar is reduced. When concrete is very dense around the rebar, the corrosion product accumulates around the rebar but it cannot disperse around the rebar into the concrete. The reason is that high strength concrete is very dense; therefore, the permeability is very low. Because the corrosion material cannot be dispersed around the rebar into the aggregate, it stays on the surface of the rebar. This cumulative accumulation of corrosion product creates a high pressure. This pressure is

higher in high strength concrete than low strength concrete. So high strength concrete cracks earlier than low strength concrete. ASTM C876 Half Cell Potential is a widely used method for a qualitative estimation of corrosion activity [4]. In the past, GPR data was used to predict the deterioration due to rebar corrosion [5]. Experimental methods involving GPR to detect the presence of rebar corrosion have also been reported, where an accelerated corrosion test was performed on a rebar embedded in concrete in a laboratory environment [6]. The response of GPR waves at three different levels of corrosion, NaCl contamination of concrete, depassivation of rebar, and starting of rebar corrosion, was monitored. Another study was performed on accelerated corrosion where the peak to peak amplitudes of the direct wave (DW) and the reflected wave (RW) were taken as GPR parameters [7]. These existing studies on GPR use for rebar corrosion investigation addressed either detection or qualitative evaluation of corrosion. A quantitative nondestructive approach to estimate the rebar corrosion in existing concrete will be very useful, especially in forensic investigation. This will allow the determination of the extent of rebar corrosion in

existing concrete structures, thereby estimating the impact of the reduced rebar sizes on member strength, ductility, and serviceability. If needed and feasible, rehabilitation and strengthening of the deteriorated structures could be undertaken. GPR can nondestructively scan existing concrete structures, especially flat extended surfaces (such as slabs, decks, and pavements), at a very fast rate. Coupling this fast scanning method with a quantitative rebar corrosion detection technique will be a groundbreaking effort of significant benefit to various relevant parties. The existing research on corrosion monitoring with GPR did not address the effect of changing electromagnetic property of concrete at different level of corrosion. The change is that concrete property at different corrosion level is a result of changing permittivity and conductivity of the concrete due to the presence of the corrosion agents and corrosion products in the microstructure of concrete surrounding the rebar. In the study reported herein, an approach of simulating corroded steel rebars in concrete in an experimental setting was undertaken. From the GPR response of the laboratory simulated corroded steel rebars, a basis to estimate the quantitative amount of rebar corrosion was developed. The existing methods discussed above focused on determining the qualitative stages of corrosion. In the study, it is shown that the physical loss of rebar area due to corrosion can be quantitatively correlated with the changes of GPR response.

2. Experimental Setup

A corrosion tank was prepared to perform the accelerated corrosion of three rebars 16 mm in diameter. The tank was filled with 5% sodium chloride solution, made of regular table salt and tap water. The 300 mm long rebars were submerged in the solution to act as anode of an electrochemical cell. A few extra rebars were also submerged in the salt water solution to act as a cathode. The three rebars were connected in series, ensuring that the first of the three rebars would attract the most electrical current. This was expected to cause most amount of mass loss in the first rebar. The other two rebars, as they were connected in the series connection, would receive less electrical current, resulting in lesser amounts of corrosion. This approach resulted in the varying amounts of corrosion in the three rebars as needed for the experiment. A 15-volt DC current source was used to supply electrical current to the electrochemical cell through the anodes and the cathodes. The experimental setup of the accelerated corrosion of the rebars is shown in Figure 1. The resulting corrosion products can be seen floating on the salt water solution.

After three days of continuous electrical current through the electrochemical cell, the process was stopped and the anode rebars were taken out of the solution and thoroughly cleaned. The rebars were weighed to determine the amount of weight loss due to corrosion. Some parts of the rebars were outside of the solution tank and did not experience any corrosion, and they were excluded in the calculation of weight loss. It was assumed that the weight loss due to corrosion occurred uniformly along the corroded length of the rebar. Figure 2 shows the three rebars with varying amounts of



FIGURE 1: Tank for accelerated corrosion.



FIGURE 2: Rebars with different degrees of corrosion.

corrosion. An uncorroded rebar is shown on the extreme left for comparison. Table 1 presents weight losses for each rebar and the associated rebar cross-sectional area losses. The corrosion loss for rebar areas ranged between 0 and 45%. Active corrosion can reduce the rebar diameter by as much as 0.0039 in (0.1 mm) per year [8]. Therefore, the range of rebar corruptions studied herein is practical for concrete structures.

3. Underlying Theory and Assumptions

In the electrochemical corrosion process of embedded steel rebars in concrete, the iron ions from the rebar are converted to iron oxide or rust through the presence of chloride ions, which is a very strong oxidizing agent. These corrosion products accumulate around the rebar and the effective core area of the rebar gets smaller as the corrosion process continues. The corrosion products contaminate the concrete in the vicinity of the rebar. This contamination increases the dielectric permittivity as well as the electrical conductivity of concrete. During the GPR scanning of a corroded rebar, the GPR electromagnetic wave travels through the rust contaminated concrete towards the rebar. But the radar wave has to penetrate through the corrosion product to hit the surface of the noncorroded core of the rebar and then reflected back towards the receiver of the GPR antenna. The dielectric constant of iron oxide is higher than that of concrete [9]. Steel is a very good conductor and almost totally

TABLE 1: Weight and area loss in corroded rebars.

Rebar #	Initial weight (g)	Weight after corrosion (g)	Weight loss (g)	Length of corroded part of rebar (mm)	Average area loss, %
1	472	472	0	0	0
2	472	394	78	175	22
3	472	363	109	150	31
4	472	310	162	150	45

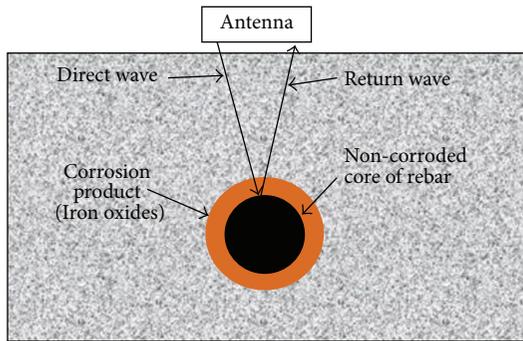


FIGURE 3: GPR scanning of corroded rebar in concrete.

reflects the incident GPR wave. The power of the reflection wave from the interface of two different materials depends on the contrast of the dielectric constants of the two media [10]. If the contrast is high, most of the incident wave gets reflected and a small part of the wave goes through the interface. If the dielectric contrast is low, a small part of the incident wave gets reflected and most of it travels through the interface into the second medium. In this study we assume that the concrete is very severely corroded and the corrosion products got dispersed around the rebar through cracks and interstitial pores. The dielectric constant of iron oxide is 14 [9] which is a little higher than the dielectric constant of concrete. This close difference indicates that a radar wave can penetrate through the corrosion contaminated concrete and the rust and eventually reflect back from the surface of the noncorroded rebar core. Therefore, it is assumed that GPR wave can travel through the corrosion products. The changed environment in the vicinity of a corroded rebar can be monitored with a GPR. The schematic diagram of GPR scanning of a corroded rebar in concrete is shown in Figure 3. The dielectric constant of the concrete between the GPR antenna and the noncorroded core of the rebar increases due to the contamination of the concrete by external corrosion agents and the internal development of corrosion products. The reduction of the rebar area and the increase of the dielectric constant of rust contaminated concrete are the two major factors that can differentiate the GPR response from a corroded rebar and that from a noncorroded rebar. It was expected in the study reported herein that the increase of dielectric constant and decrease of the rebar size would result in a decrease in the maximum amplitude of the returning radar wave from the rebar. It is worth mentioning that the

corrosion products and agents not only increase the overall dielectric constant of the concrete but also increase the electrical conductivity of the concrete which is an important factor for GPR signal attenuation. In this study, only the effect of changing dielectric constant is addressed. The corrosion product is mainly iron oxide and it may affect the magnetic part of the electromagnetic wave. This effect is also not considered in this study.

4. GPR Scanning

According to existing research knowledge, water oil emulsions can be used as a substitute of concrete in geophysical investigation using GPR [11]. This emulsion can be made with appropriate proportioning of water and oil to match the dielectric constant of concrete. In this study, three different water oil emulsion tanks were prepared to simulate concrete dielectric constants for embedding the corroded rebars in these solutions. Sodium lauryl sulphate was used as an emulsifying agent to assure proper mixture of oil and water in the emulsions. The simulated dielectric constants of the three tanks were measured as 2.73, 5.47, and 9.3 using the two-way travel time (TWTT) of a GPR scan by placing a steel plate under the tank. These values fall within the range of dielectric constants of most concrete. GPR is very sensitive to presence of moisture because of the very high dielectric constant of water. The dielectric constant of concrete mainly depends on the presence of moisture in the interstitial spaces in concrete. Very dry concrete has a low dielectric constant and fresh concrete or concrete with a high moisture content shows higher value of dielectric constant. A system was designed and made to hang the rebars at particular depth in the oil water emulsion tanks. The rebar hanging arrangement was supporting the Plexiglas cover over the emulsion as shown in Figure 4. A thin Plexiglas cover was placed over the emulsion tank to facilitate the movement of the antenna over the liquid surface. The dielectric property of Plexiglas is similar to the oil used in the emulsion. So the GPR wave is assumed to be unaffected by the layer of Plexiglas at the top of the emulsion. Figure 5 shows comparison between GPR data collected from the oil emulsion tank and a real concrete beam. It is obvious from Figure 5 that the B-Scan and A-Scan from both the sources are compatible.

Each corroded rebar was placed in each emulsion tank at three different depths of 1 in (25 mm), 2 in (50 mm), and 3 in (75 mm). The placement of the corroded rebar in the emulsion tanks with known dielectric constants was similar to a real corroded rebar embedded in concrete. The GPR



(a) Antenna supported by Plexiglas cover (b) Rebar supporting arrangement

FIGURE 4: Rebar and antenna supporting system in the emulsion tank.

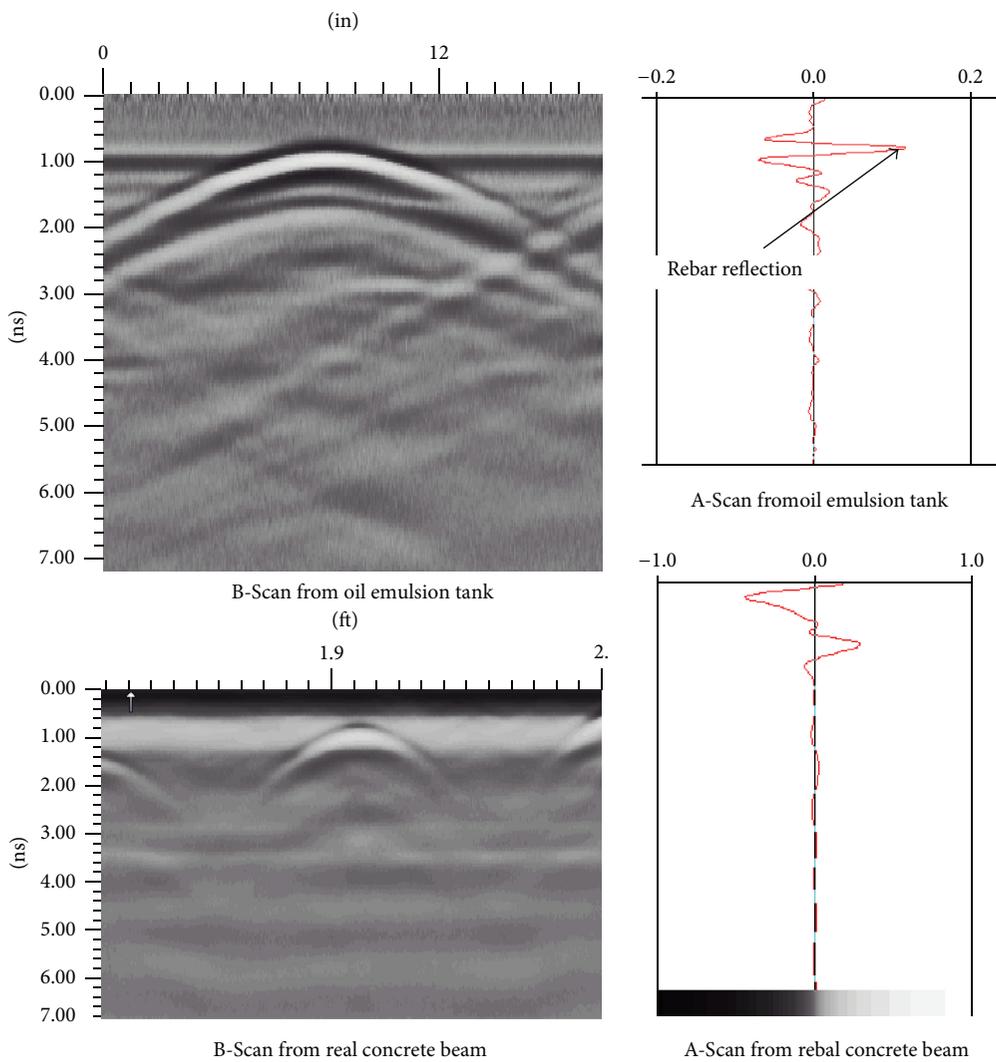


FIGURE 5: Comparison between the emulsion tank and a real concrete beam.

equipment consists of a mainframe radar wave generator, a hand cart with antenna mount and calibrated wheels, and a high frequency antenna. The GPR scan can be performed and the scan results can be seen in real time. The GPR antenna

was of a ground coupled 2.6 GHz type, which has one of the highest frequencies among the commercially available GPR antennas. The wavelength of the antenna is 1.8 in (46 mm) in free space. The B-Scans (two-dimensional GPR scans)

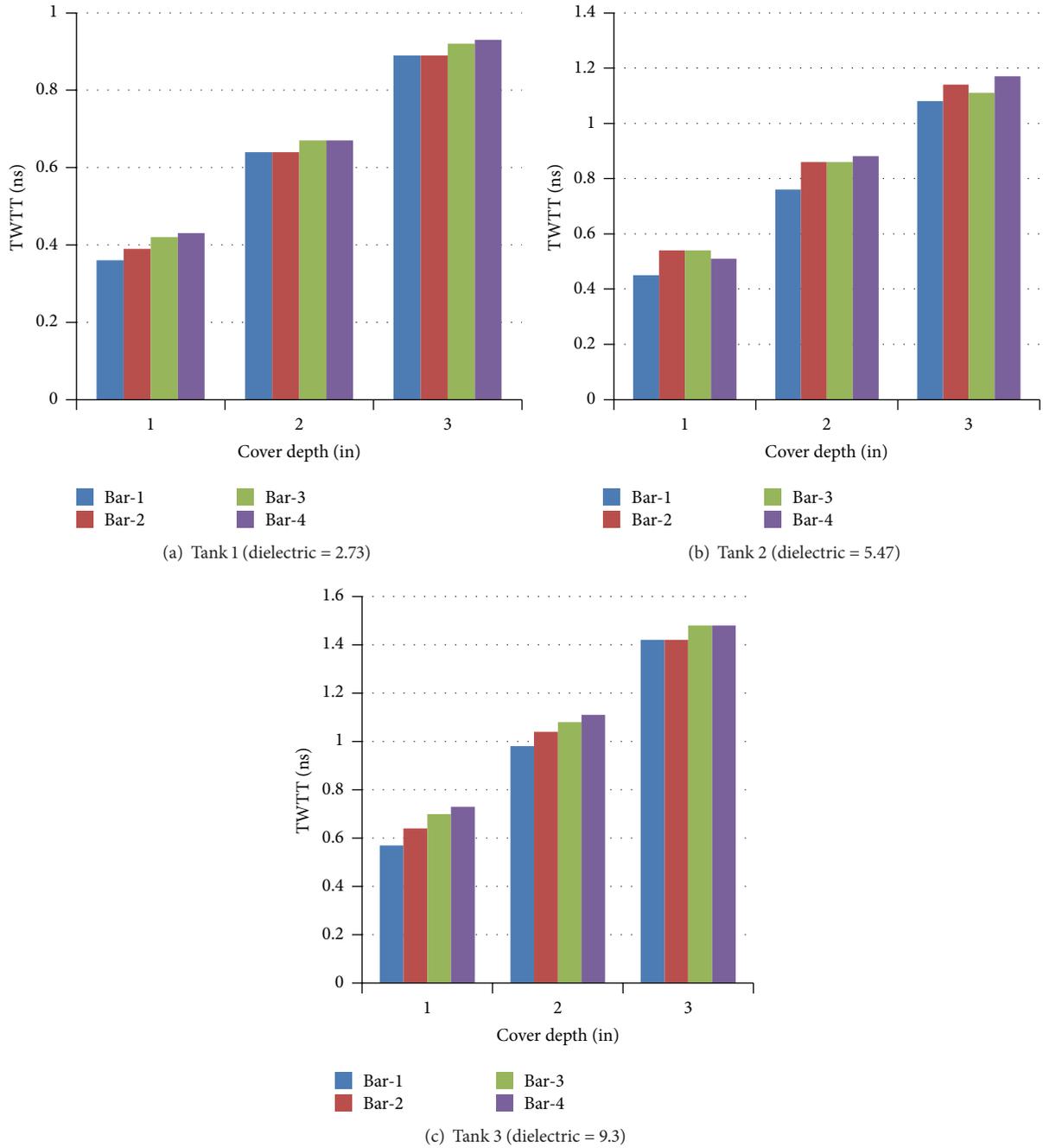


FIGURE 6: Change of TWTT with cover depth for varying corrosion levels. Note: 1 in = 25 mm.

or radargrams for each rebar were recorded for different tanks and different depths in each tank. For each rebar, nine sets of data were collected where 3 sets were collected from each tank at three different cover depths. Data was also collected for the noncorroded rebar to compare with the corroded rebars. The B-Scans were transferred to the GPR postprocessing software for refinement. During the postprocessing, background removal filter was applied and the maximum amplitudes from the rebars and the TWTT were recorded.

5. Results and Discussion

Two GPR parameters were chosen to relate with the extent of rebar corrosion. They are two-way travel time (TWTT) from the rebar and the maximum positive reflective amplitude from the rebar. Two-way travel times were plotted against the rebar depth in the corrosion tanks, as seen in Figure 6. It may be observed that the TWTT is increasing with the increase of the corrosion rate. The reduced rebar diameter due to corrosion created a longer travel path for the GPR

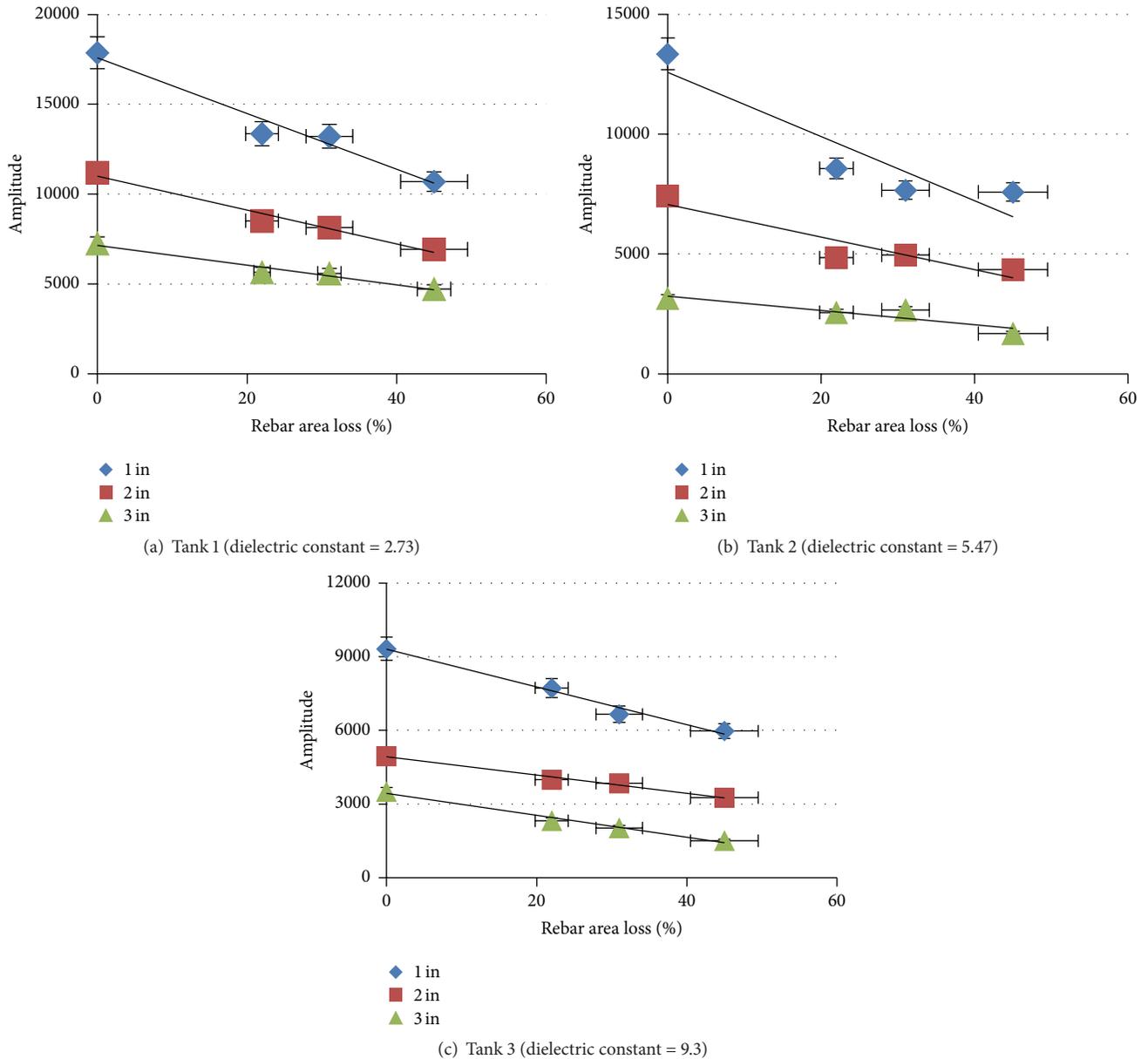


FIGURE 7: Maximum amplitude versus rebar area loss.

signal and the extra distance traveled was reflected in the increase of TWTT. Figure 6 shows that the TWTT increased with increasing cover depths. Similar behavior was observed in all three tanks. However, the TWTT for a particular cover depth and rebar corrosion is increasing with the increase of the dielectric constant.

Figure 7 shows the plot of maximum amplitudes versus cover depths for the three tanks having three different dielectric constants. It is observed that the maximum amplitude decreased with the increase of rebar area loss due to corrosion in all three tanks with varying dielectric constants and for all cover depths. In order to develop predictive models for rebar corrosion estimation, regression equations for the best fit trend lines (shown in Figure 6) were

generated herein. The best fit equations and the corresponding correlation coefficients are presented in Table 2. The correlations coefficients are very high, ranging from 0.85 to 0.99, indicating high levels of accuracy of the corrosion models. It is also observed that the relationship between the GPR maximum amplitude from the corroded rebars and the amount of corrosion is almost linear. Figure 6 shows that the rate of change in GPR amplitudes is greater at lower cover depths which means that the changes in GPR signal due to corrosion at lower depths are more prominent. The models from Table 2 show that a relationship exists between the maximum positive amplitude and the amount of corrosion if the dielectric constant and the concrete cover are known.

TABLE 2: Amplitude corrosion relationships for 16 mm rebar.

Dielectric constant	Cover depth (mm)	Rebar corrosion area loss, y (%), $x =$ maximum amplitude	Correlation coefficient	Measured mass loss %	Predicted mass loss %	% error
2.73	25	$y = \frac{x - 17584}{-155.13}$	0.97	22	27	23
				31	28	-10
				45	44	-2
	50	$y = \frac{x - 11000}{-94.29}$	0.98	22	26	18
				31	30	-3
				45	43	-4
	75	$y = \frac{x - 7146}{-55.01}$	0.96	22	27	23
				31	29	-6
				45	44	-2
5.47	25	$y = \frac{x - 12568}{-133.78}$	0.85	22	29	32
				31	36	16
				45	37	-18
	50	$y = \frac{x - 7058}{-69.99}$	0.87	22	31	41
				31	30	-3
				45	39	-13
	75	$y = \frac{x - 3244}{-29.73}$	0.84	22	23	5
				31	20	-35
				45	52	16
9.3	25	$y = \frac{x - 9302}{-76.83}$	0.98	22	21	-5
				31	34	10
				45	43	-4
	50	$y = \frac{x - 4923}{-37.04}$	0.99	22	25	14
				31	29	-6
				45	45	0
	75	$y = \frac{x - 3432}{-44.62}$	0.99	22	25	14
				31	31	0
				45	43	-4

6. Conclusions

In this study, the variation of GPR response over a range of corrosion states of steel rebar embedded in concrete was investigated. The effect of concrete dielectric constant on GPR response was also investigated. Rebars were corroded in an accelerated environment and a method of simulating the corrosion in laboratory using oil water emulsion tank was used. The corroded rebars were scanned with a 2.6 GHz ground coupled antenna. It is assumed that the corrosion process reduces the diameter of the rebar and increases the dielectric constant of concrete. It is also assumed that the GPR wave penetrates through the corrosion products around the rebar and reflects from the uncorroded core of steel rebar. The following conclusions may be made based on the results reported herein:

- (i) The issue of quantitative nondestructive corrosion estimation of steel rebar in concrete structures has been addressed herein. The method is based on GPR scanning of severely corroded existing concrete surfaces with embedded steel rebars. GPR scanning is a speedy and labor friendly technique that may be conveniently and economically used to estimate the corrosion levels in rebars without any concrete damage. This study involved only the evaluation of

16 mm embedded rebars. However, the study can be extended to other rebar sizes as well through the development of appropriate corrosion models.

- (ii) The dielectric constants employed herein (2.73 to 9.3) using emulsion tanks represent most practical concrete mixes. The dielectric constant of concrete for a specific case should be known for using the correlations for estimating rebar corrosion. The constant may be conveniently found through GPR scanning in combination with some investigative drilling. Here the relationships between amplitudes and corrosion are different for different dielectric constants and different concrete covers. For practical use, where the dielectric constant and concrete cover can change spatially over the concrete surface, a unique model has to be developed which is independent of dielectric constant and the concrete cover. To make the model more useful, the effect of changing electrical conductivity must be included in the amplitude versus corrosion loss model.
- (iii) The two-way travel time of GPR waves increases with the increase of rebar corrosion. The rate of change of two-way travel time of GPR waves is higher at smaller concrete cover depths. At smaller concrete cover,

the loss of energy in the radar wave is less. Therefore, when the radar wave is reflecting from the surface of the corroded rebar, there is a small amount of loss of energy. This is evident by high magnitude of amplitudes from the rebar at 25 mm cover depth level. When the cover depth is higher, the radar wave has to travel a longer path to and from the rebar towards the antenna. In the process, the loss of energy in the radar wave is high. This is evident by the low magnitude of amplitude at 75 mm cover depth.

- (iv) The relationship between the maximum GPR amplitudes from corroded rebars and the corrosion loss of the rebar is observed as linear. However, this study is done with only four different levels of corrosion. More points need to be considered to confirm the linearity of the amplitude versus mass loss relationship. Maximum amplitudes decrease with the increase of corrosion. The rate of decrease of amplitude is higher at lower concrete covers.
- (v) The maximum amplitude from a rebar for a particular stage of corrosion was decreasing with the increase of dielectric constant.
- (vi) This experimental study can be used as a basis for quantitative estimation of concrete rebar corrosion extent in the field using GPR. Extensive experimental study on real concrete samples with corroded rebars needs to be done to verify the method of estimating corrosion.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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