Quantitative Sensing of Corroded Steel Rebar Embedded in Cement Mortar Specimens using Ultrasonic Testing

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ABSTRACT

Corrosion of steel reinforcing bars (rebars) is the primary cause for the deterioration of reinforced concrete structures. Traditional corrosion monitoring methods such as half-cell potential and linear polarization resistance can only detect the presence of corrosion but cannot quantify it. This study presents an experimental investigation of quantifying degree of corrosion of steel rebar inside cement mortar specimens using ultrasonic testing (UT). A UT device with two 54 kHz transducers was used to measure ultrasonic pulse velocity (UPV) of cement mortar, uncorroded and corroded reinforced cement mortar specimens, utilizing the direct transmission method. The results obtained from the study show that UPV decreases linearly with increase in degree of corrosion and corrosion-induced cracks (surface cracks). With respect to quantifying the degree of corrosion, a model was developed by simultaneously fitting UPV and surface crack width measurements to a two-parameter linear model. The proposed model can be used for predicting the degree of corrosion of steel rebar embedded in cement mortar under similar conditions used in this study up to 3.03%. Furthermore, the modeling approach can be applied to corroded reinforced concrete specimens with additional modification. The findings from this study show that UT has the potential of quantifying the degree of corrosion inside reinforced cement mortar specimens.

Keywords: Steel reinforcing bar corrosion, cement mortar, ultrasonic testing, ultrasonic pulse velocity, corrosion-induced cracks

1. INTRODUCTION

Premature failure of reinforced concrete (RC) structures due to corrosion of steel reinforcing bar (rebar) is a global problem. Several nondestructive evaluation (NDE) methods have been developed for corrosion sensing in RC structures. These methods have proved to be promising for prolonging the service life of RC structures by providing information useful for their timely maintenance. Among NDE methods, electrochemical methods (e.g., half-cell potential) are very popular for corrosion sensing because they provide reliable information on the probability of corrosion and are easy to use.[1–6] However, they cannot quantify the degree of corrosion, which is useful in predicting the level of deterioration of corroded RC structures. Elastic wave methods such as acoustic emission[7,8] and impact-echo[9] have been used to detect and quantify corrosion damage of steel rebar inside concrete. Another elastic wave method for evaluating the quality of in-situ RC structures is the ultrasonic method . In the ultrasonic test (UT) method, amplitude and velocity of ultrasonic waves (pulses) are usually used for evaluating the quality of concrete.[10–12]

Research work on detecting corrosion of steel rebar inside concrete using UT method was reported in literature. Liang *et al.*[13] used ultrasonic pulse velocity (UPV) and amplitude to detect the corrosion damage of RC specimens. Yeih and Huang[14] combined ultrasonic pulse amplitude (UPA) attenuation method and open circuit potential (OCP) to evaluate corrosion damage in RC blocks. They found that the UPA decreases linearly with an increase in the probability of corrosion. Watanabe *et al.*[15] evaluated RC prisms with corrosion induced cracks using UT method. The presence of corrosion-induced cracks was reported to cause attenuation of ultrasonic waves and subsequent reduction in UPV of the RC prisms.

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Although there have been several attempts to detect the degree of corrosion in RC structures by UT methods, quantitative evaluation of the degree of corrosion using UT parameters such as amplitude and pulse velocity is scarce in literature. One recent effort to quantify the degree of corrosion of steel rebar in RC specimens was based on the linear relationship between OCP and UPA values.[14] Yeih and Huang found that UPA and OCP values are linearly related. Since OCP values only provide information about the probability of corrosion, their model cannot be used to quantify the degree of corrosion.

In this study, UPV is utilized for the quantitative sensing of corroded steel rebar inside cement mortar. Cement mortar was used because it is a fairly homogeneous medium to investigate the effect of corrosion on the UPV in cementitious composites (e.g, cement mortar). The objective of this paper is to establish relationships among UPV, surface crack width and degree of steel rebar corrosion inside cement mortar specimens.

2. THEORETICAL BACKGROUND

2.1 Accelerated corrosion

In this research, accelerated corrosion of steel rebar inside cement mortar is achieved by using impressed current technique governed by anodic and cathodic reactions:[16]

$$2Fe^0 - 4e^- \rightarrow 2Fe^{2+} \text{(Anodic reaction)} \tag{1}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH^-) \text{(Cathodic reaction)} \tag{2}$$

where Fe^0 is iron atoms on steel surface, Fe^{2+} dissolved iron ions, O_2 dissolved oxygen molecules, and OH^- dissolved hydroxide ions in pore solution of cement mortar. In this technique, an external current is applied to steel rebar to accelerate corrosion by providing more electrons to speed up the anodic (Eq. (1)) and cathodic (Eq. (2)) reaction rates. Mass loss of steel rebar involved in the accelerated corrosion process occurs at the anode site. In anodic reactions, iron atoms (Fe) are ionized to ferrous (Fe^{2+}) ions that dissolves in the pore solution of cement mortar. This process leads to the rise of electric potential on the steel rebar surface which causes electrons to flow to the lower potential (cathodic) site. The accelerated corrosion process leading to mass loss of the steel rebar inside cement mortar continues as long as the number of electrons deposited at the anode site is accepted at the cathode site.

2.2 Ultrasonic Pulse Velocity

When ultrasonic pulses are introduced into an elastic medium, three types of mechanical/stress waves (compressive, shear and surface waves) are created. The propagation of the compressive waves through the medium is similar to the propagation of sound waves through air. For elastic, homogeneous solid media, the compressive wave velocity is a function of the elastic properties and density of the medium (Eq. (3)),[17]

$$v = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{3}$$

where v is the compressive wave velocity (m/s), E the dynamic modulus of elasticity (MPa), ρ the density (kg/m^3) and ν the dynamic Poisson's ratio of the material under investigation.

By rearranging Eq. (3), the dynamic moduli of elasticity of cement mortar (CM) and reinforced cement mortar (RM) can be determined by Eq. (4).

$$E = \frac{v^2\rho(1+\nu)(1-2\nu)}{(1-\nu)} \tag{4}$$

3. EXPERIMENTAL PROGRAM

3.1 Specimen Description

Six cement mortar specimens with dimensions of 100 mm by 100 mm by 200 mm (Figure 1) were manufactured using TypeI/II ordinary Portland cement and regular sand in a cement-to-sand ratio of 0.33 and a water-to-cement ratio of 0.50. Five cement mortar specimens were reinforced with a 300-mm long steel rebar with a nominal diameter of 12.7 mm. The steel rebars were cleaned and weighed to obtain their initial mass. Their ends, 65 mm long, were tapped with electrical insulation tape to prevent corrosion at the interface between the protruded steel rebar and cement mortar, leaving only 170 mm portion inside the cement mortar exposed to corrossion agents (e.g., chloride ions, moisture and oxygen). The steel rebars were then placed at the center of the wooden mold at the time of casting leaving a cover of 43.5 mm ± 0.5 mm. The specimens were moist cured for 28 days after 24 hours of casting. They were labeled as CM, RM1, RM2, RM3, RM4 and RM5. CM has no steel rebar and was used to obtain UPV of cement mortar. RM1 was reinforced with a steel rebar and was used to study the effect of steel rebar on UPV of cement mortar. The remaining specimens (RM2 $\sim$ RM5) were corroded to investigate the effect of corrosion level (degree of corrosion) and corrosion-induced cracks (surface cracks width) on the UPV of reinforced cement mortar. The specimens were stored in room condition for more than a month before the accelerated corrosion test (ACT) took place.

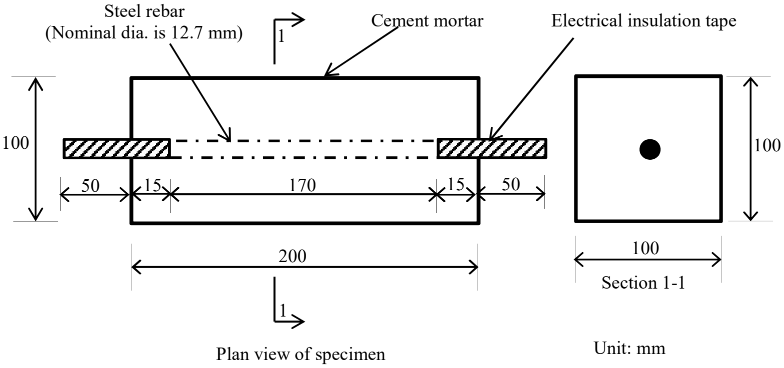


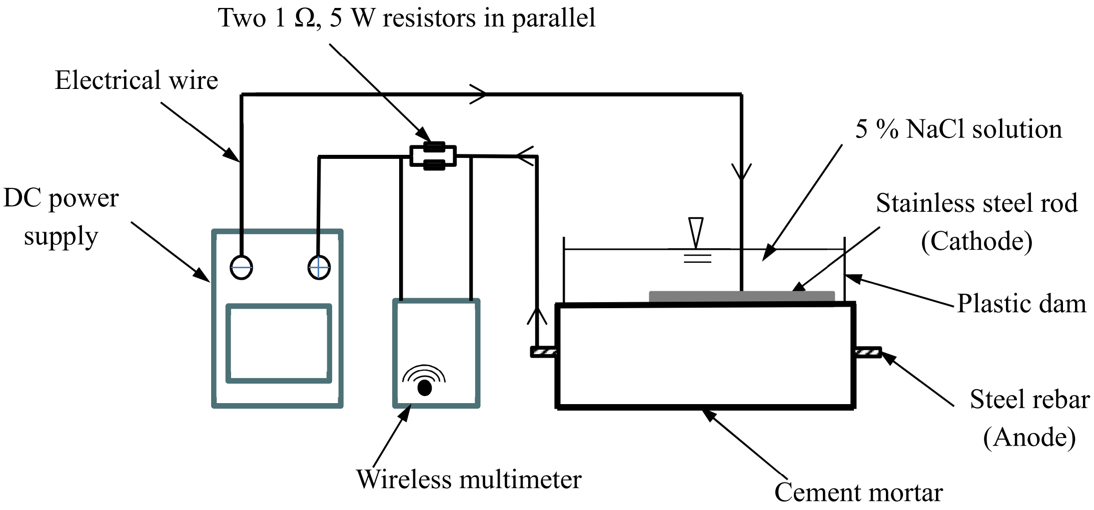
Figure 1: Schematic diagram of specimen (Plan view)

3.2 Accelerated Corrosion Test

To induce corrosion within a short period of time, an impressed current ACT technique was used. Figure 2 shows the experimental configuration of this technique. In Figure 2, direct current was impressed on the steel rebar inside cement mortar using a power supply (Tekpower ®, HY1803D, 0 $\sim$ 18 V, 0 $\sim$ 3 A), together with a wireless multimeter for monitoring the time-dependent current fluctuation. The surface of reinforced cement mortar specimens was ponded with 5% sodium chloride (NaCl) solution using a plastic dam for 7 days before the direct current was applied. A stainless steel rod with a diameter of 12.7 mm was placed inside the NaCl solution to act as the cathode while the steel rebar serves as the anode. The power supply was set to a constant voltage of 16 V± 0.5V, and the current was allowed to vary over time.

At the end of the ACT, the specimens were dried in an air-conditioned laboratory before UPV test was performed. It was assumed that no further corrosion will take place during this drying period. The moisture distribution inside all specimens at the time of UPV measurement was assumed to be constant.

(a) Picture of ACT setup



(b) Schematic diagram of ACT setup

Figure 2: Accelerated corrosion test (ACT) setup

3.3 Ultrasonic Pulse Velocity Measurement

After the ACT was completed, UPV test was conducted on the specimens using an ultrasonic pulse generator instrument (Proceq Pundit Lab ®) with two 50-mm diameter transducers at an operational frequency of 54 kHz (Figure 3). Direct transmission method (Figure 4) was used to measure the UPV of each specimen. The direct transmission method was chosen over the semi-direct and indirect transmission methods because maximum pulse energy is transmitted at right angles to the face of the specimen.[18] Also, the path length is clearly defined and can be accurately measured in the direct transmission method. The UPV of each specimen was measured at three points (A, B and C) which were equally spaced at 50 mm. UPV values measured at these points were averaged. Before the UPV measurement, the measurement locations were greased with coupling gel to provide good contact between the transducer and the surface of specimens. Table 1 shows a summary of the UPV measurement results. At the end of each UPV measurement, mass loss of steel rebars was measured and the degree of corrosion was calculated by Eq. (5)

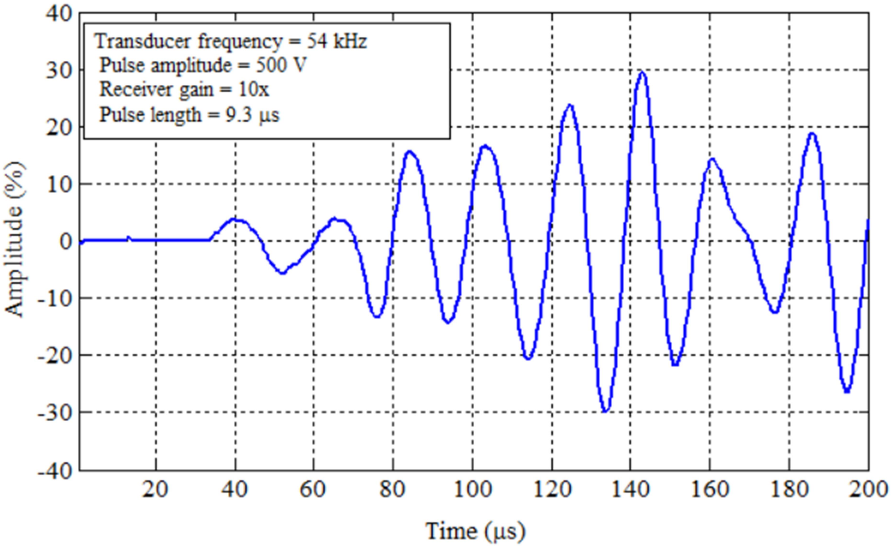
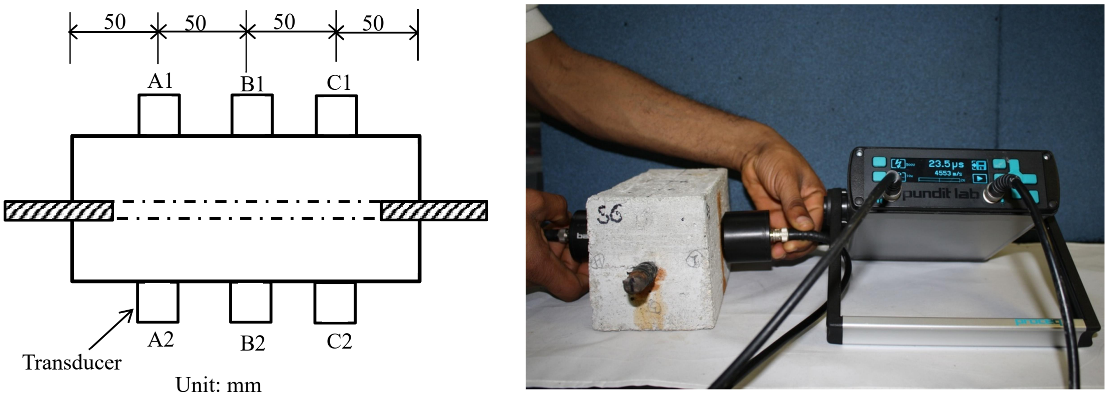


Figure 3: Waveform of Proceq Pundit Lab ® UT system



(a) Direct transmission measurement spots (Plan view)

(b) Picture of UPV test on corroded reinforced cement mortar

Figure 4: Ultrasonic pulse velocity measurement setup

Table 1: Ultrasonic pulse velocity (UPV)

Specimen	UPV (m/s)			
	Point A	Point B	Point C	Average
CM	4,310	4,310	4,310	4,310
RM1	4,241	4,241	4,241	4,241
RM2	4,173	4,173	4,173	4,173
RM3	3,978	4,053	3,905	3,978
RM4	3,835	4,053	3,768	3,885
RM5	3,605	3,732	3,605	3,647

3.4 Degree of corrosion

At the end of the UPV measurement, the reinforced cement mortar specimens were broken apart to take the corroded steel rebars (Figure 5). Acetone (Klean Strip®) was used to remove the corrosion products according to the chemical cleaning procedure described in ASTM G1-03.[19] Mass of the corroded steel rebars was measured using an electronic scale with an accuracy of 0.05 g. The degree of corrosion (δ) was calculated using Eq. (5) with the result summarized in Table 2.

$$\delta = \frac{m_1 - m_2}{l_c m_{pl}} \times 100(\%) \tag{5}$$

where δ is the degree of corrosion (%), m_1 and m_2 the mass values (g) of steel rebar before and after corrosion, respectively, l_c (170 mm) the length of the exposed section of the steel rebar (mm) and m_{pl} the mass per unit length of the steel rebar (g/mm) obtained by dividing the mass of steel rebar before corrosion by the length of the steel rebar (300 mm).

Table 2: Experimentally measured mass loss values and surface crack widths

Specimen	m_1 (g)	m_{pl} (g/mm)	m_2 (g)	δ (%)	surface crack width,w_b (mm)
RM1	277.65	0.9255	277.65	0.0000	0.000
RM2	283.75	0.9458	283.65	0.0622	0.000
RM3	281.25	0.9375	277.05	2.6353	0.367
RM4	282.80	0.9427	278.50	2.6832	0.786
RM5	283.10	0.9437	278.25	3.023	0.900

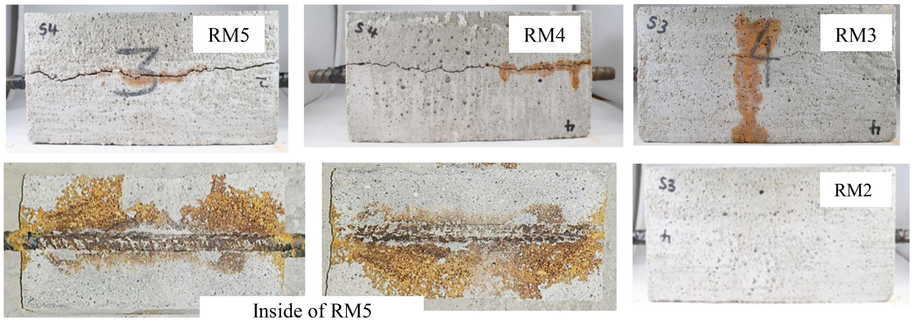


Figure 5: Condition of reinforced cement mortar after corrosion

4. RESULTS AND ANALYSIS

4.1 Effect of steel rebar on the UPV of cement mortar

The UPVs in the cement mortar (CM) and uncorroded reinforced cement mortar (RM1) specimens were 4,310 m/s and 4,241 m/s (Table 1), respectively. This suggested that the presence of steel rebar decreases the UPV of cement mortar by 1.6% in the direct transmission method. The decrease in the UPV was a result of ultrasonic wave scattering at the interface between cement mortar and steel rebar due to differences in their acoustic impedance and the geometry of steel rebar. Lencis *et al.*[20] reported that when the direct transmission method is used, the UPV of concrete in the region above steel rebars is lower than the one in the region without steel rebars. In their study, the presence of steel rebar reduced the UPV of concrete between 2.4% to 4.7% for a steel rebar diameter ranging from 6 mm to 16 mm. Although they used reinforced concrete specimens in their study, our measurement result is qualitatively in good agreement with their result.

Furthermore, the feasibility of using UPV to estimate the dynamic moduli of elasticity of cement mortar and reinforced cement mortar was explored by utilizing Eq. (4). With dynamic Poisson's ratio of 0.195,[21] the estimated dynamic moduli of elasticity were found to be 34.16 GPa and 36.27 GPa for cement mortar (CM) and reinforced cement mortar (RM1), respectively. This suggested that, the presence of a steel rebar increases the dynamic modulus of elasticity of cement mortar by 6.2%.

4.2 Effect of steel rebar corrosion on the UPV of reinforced cement mortar

Figure 6 illustrates the UPV values of the reinforced cement mortar specimens with degree of corrosion ranging from 0% to 3.03% (Table 2). It can be observed that RM1 with 0% degree of corrosion has the highest UPV value whereas RM5 has the lowest UPV value with 3.03% degree of corrosion. During the early stage of corrosion (no visible corrosion products and surface cracks, Figure 5-RM2), there is 1.6% decrease in UPV value which could be due to ultrasonic wave diffraction at the interface between cement mortar and corroded steel rebar caused by micro-cracks and surface roughness of the steel rebar in the wave path. As the corrosion process continued, the micro-cracks connected to form a major crack which propagated to the surface of the specimen (Figure 5-RM3, RM4 and RM5). By comparing RM1 to RM3, RM4 and RM5, it was calculated that, UPV values decrease by 6.20%, 8.39% and 14%, respectively. This was due to the formation of the major cracks in cement mortar and the production of corrosion products on the surface of steel rebar. The major cracks and the corrosion products in the propagating path of the ultrasonic wave caused diffraction that increases total flight time and subsequently decreases the measured UPV value. Wantanabe *et al.*[15] also reported that corrosion induced cracks cause UPV to decrease in corroded reinforced concrete specimens, while no direct correlation between UPV and the degree of corrosion was reported in their work.

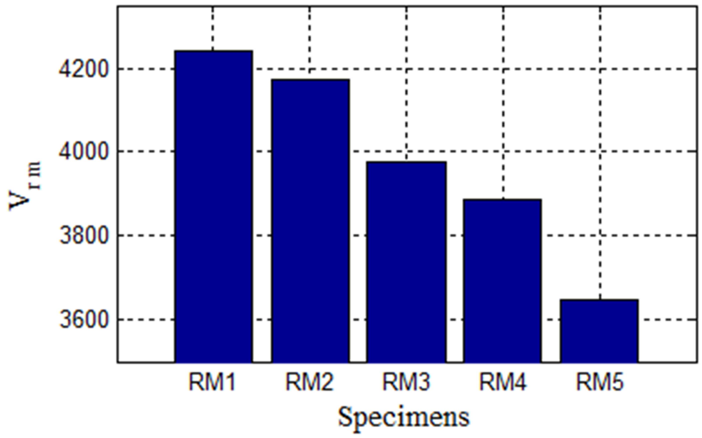
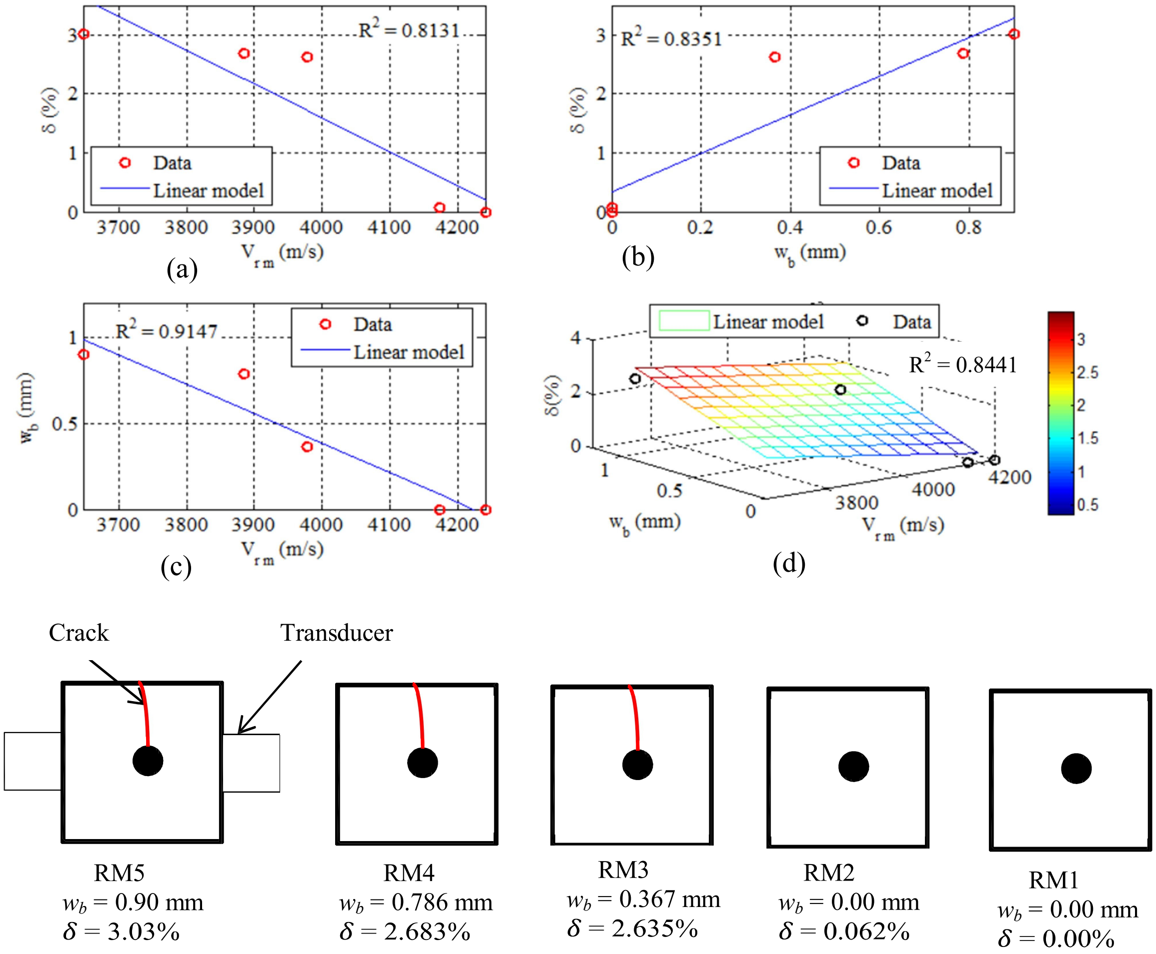


Figure 6: UPV of uncorroded and corroded specimens

4.3 Modeling degree of corrosion as a function of UPV and surface crack width

The relationships among degree of corrosion, UPV and surface crack width of the corroded specimens were developed by fitting the UPV and surface crack width measurements at different degrees of corrosion using a linear model as shown in Figures (7a) and 7(b) and described by Eqs. (6) and (7), respectively . By using coefficient of determination (R^2) as a measure of the model performance, it was observed that the surface crack width fits the linear model better ($R^2 = 0.9147$) than with the degree of corrosion ($R^2 = 0.8131$), suggesting that UPV is more sensitive to surface crack width than to the degree of corrosion. In order to improve the performance of the linear model, surface crack width was introduced to Eq. (6) by fitting both the UPV and the surface crack width measurements to a two-variable linear model (Figure 7(d)). This was because surface crack width correlate fairly well with both parameters (Figures 7(b) and 7(c)). Eq. (8) shows the mathematical expression of this two-variable linear model. By introducing surface crack width into Eq. (6), the R^2 value increased from 0.8131 (Figure 7(a)) to 0.8441 (Figure 7(d)), showing an improvement in the model performance.



(a) (b) (c) (d)

(e) Cross-sections of specimen showing the UPV measurement scheme (direct transmission method)

Figure 7: Relationship among degree of corrosion, surface crack width and ultrasonic pulse velocity

$$\delta(v_{rm}) = 22.84 - 0.0052v_{rm} \tag{6}$$

$$\delta(w_b) = 2.916w_b + 0.604 \tag{7}$$

$$\delta(v_{rm}, w_b) = 5.016 - 0.001056v_{rm} + 2.39w_b \tag{8}$$

where δ is the degree of corrosion (%), v_{rm} the ultrasonic pulse velocity (m/s) of reinforced cement mortar and w_b the surface crack width (mm).

5. SUMMARY

In this paper, our research work on the quantitative sensing of corroded steel rebar embedded in cement mortar using ultrasonic testing (UT) is reported. Research findings are summarized in the following.

- Effect of steel rebar on the UPV of cement mortar: The presence of steel rebar decreases the UPV of cement mortar when the direct transmission method is used. In this study, a steel rebar with a nominal diameter of 12.7 mm decreased the UPV of cement mortar by 1.6%.

- Dynamic modulus of elasticity: Feasibility of using UPV to estimate the dynamic modulus of elasticity of cement mortar and reinforced cement mortar was explored in this study by using Eq. (4). The result indicates that, by reinforcing cement mortar with a single steel rebar of nominal diameter 12.7 mm, the dynamic modulus of elasticity of the specimen can be increased by 6.3% when experimental conditions are similar to the one in this study.

- Effect of steel rebar corrosion on the UPV of cement mortar: In general, the UPV of reinforced cement mortar decreases linearly with the linear increase in the degree of corrossion (Figure 7(a)) and surface crack width (Figure 7(c)). In this study, the relationships among degree of corrosion, UPV and surface crack width were modeled by Eqs. (6) and (7), respectively.

- Modeling degree of corrosion as a function of UPV and surface crack width: It was found that a two-parameter linear model using UPV and surface crack width as the input parameters predicts the degree of corrosion better than a linear model with only UPV as the input parameter, as shown in (Figure 7(d)) and described by Eq. (8). This also suggest the advantage of using more measurement (information) to improve the accuracy of corrosion level prediction. The advantage of this model is that, both UPV and surface crack width can be measured in the field.

6. CONCLUSION

In this paper, degree of corrosion was found to have relationship with UPV values and surface crack width. Since UT is based on mechanical wave propagation and surface crack width can be used as an index for assessing the level of mechanical deterioration in corroded reinforced concrete structures, this approach of quantifying corrosion level of steel rebar inside cementitious composites (e.g., cement mortar and concrete) performs better when both UPV and surface crack width measurements are available. In general, the proposed model provides fairly good prediction of the degree of corrosion up to 3.03% under the experimental conditions used in this study. It was also found that the use of both UPV and surface crack width for the prediction of degree of corrosion is better than using only UPV. Although we have found that including surface crack width in the degree of corrosion model is an alternative approach for using UT for quantifying corrosion of steel rebar in cement mortar, it should be noted that in corroded RC structures, ultrasonic waves are affected by other parameters such as water-to-cement ratio, size of aggregates, diameter of steel rebar and moisture content. Developing a model which accounts for the influence of these parameters will make UT a promising approach for quantifying the degree of corrosion in RC structures.

7. ACKNOWLEDGMENTS

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