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A study on the Effect of Reinforcement Corrosion Using Ultrasonic Pulse Velocity Test

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Abstract: Reinforcement corrosion in steel is one of the major concrete deteriorations that may induce a reduction of the load-bearing capacity as well as incur underlying safety risks on the durability of the reinforced concrete structure Consequently, a routine inspection of structure that is cost-efficient and timesaving should be carried out to assure that the corrosion does not spread uncontrollably. Experimental work was conducted to study the sensitivity of reinforcement corrosion towards the Ultrasonic Pulse Velocity test (UPV) and to evaluate the presence of corrosion based on the Ultrasonic Pulse Velocity test. Two specimens of cross-section 150 x 165 and length 350 mm were reinforced with two 10 mm bar diameters were used in this study. The impressed current test of 0.08 mA/cm² would be conducted to accelerate the corrosion and Visual Inspection, Half-Cell Potential (HCP) method, and most importantly Ultrasonic Pulse Velocity (UPV) test would be performed for determining the sensitivity and presence of corrosion. The results indicated there is a possibility that the corrosion had taken place when the HCP reading turned down to a negative value. With the increase of corrosion, which was indicated by more negative values of HCL, the UPV values tended to decrease. Besides, the UPV method was effective in the early detection of corrosion through the validation of corrosion by Half-Cell Potential Method and Visual Inspection.

Keywords: Ultrasonic Pulse Velocity, Reinforcement Corrosion, Reinforced concrete

1. Introduction

It is found that corrosion in reinforcement bars may induce a reduction of the load-bearing capacity as well as incur underlying safety risks on the durability of the reinforced concrete structure [1] Hence, it is important to find out efficient and effective ways to monitor reinforcement corrosion in structures

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that can eventually prevent the structure from premature collapse. According to Jason [2], Ultrasonic Pulse Velocity Testing is a non-destructive test (NDT) for the measurement of corrosion of reinforcement embedded in concrete at 8 mm per year or higher. There are some crucial advances in Ultrasonic Pulse Velocity testing, the early detection, and recommendations of corrosion that may arise from propagating a critical condition are effective in preventing any undesirable incident from happening [3]. Thus, a proper monitoring solution can eventually contribute to cost savings over time.

2. Literature Review

2.1 Reinforcement Corrosion

Reinforcement corrosion can be defined as deterioration or degradation of reinforcing steels embedded in concrete due to aging or chemical reaction of reinforced concrete structures with the environment [4]. Reinforcement corrosion has several repercussions, including the loss of steel cross section area, the generation of expansive pressure, which causes concrete cracking, spalling, and delamination of the concrete cover consequently, it weakens the link between the steel reinforcing bar and the concrete, reducing the structure's strength [5] .According to Kim et al.[6], reinforcement corrosion can be divided into three stages, namely, the initiation stage, activation stage, and deterioration stage; the main stage is the initiation of corrosion in which there will have an accumulation of the chloride ingress and penetrate the concrete matrix, the second stage starts when there is a breakdown of the passive layers and the reinforcing bar start to corrode and rust products are deposited, the third stage is deterioration stage at which the cracking and spalling of the concrete cover occurred.

Corrosion of reinforcement is an electrochemical process that happened with the presence of water in the process. When the steel is exposed to water, the iron particles wil undergo oxidation and the become $Fe^{2+}$the oxygen cause the two electrons released to rise up and form hydroxyl ions (OH) and lastly, the hydroxyl ions will then react with Fe^{2+} to form rust. Figure 1 demonstrates the electrochemical process.

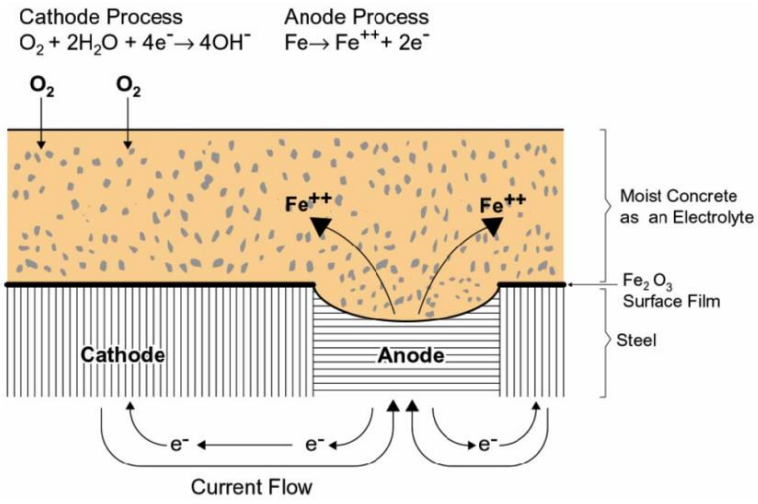


Figure 1: The electrochemical process [7]

2.2 Ultrasonic Pulse Velocity Test (UPV)

According to the standard ASTM C 597-02, the Standard Test Method for Pulse Velocity Method for Pulse Velocity Through Concrete, Ultrasonic Pulse Velocity (UPV) is a non-destructive method that covers the determination of the propagation velocity of the elastic wave pulse passing through a concrete structure [8]. As described by Watanabe et al. [3], the energy of elastic wave generated from the corrosion could acknowledge attenuation of ultrasonic pulse velocity wave due to corrosion, thus, it was relevant for UPV to estimate the corrosion of rebar at the early stage.

2.3 Accelerated Corrosion

Yuan, Ji & Shah [9] state that accelerated corrosion is important for differentiating and comparing the corrosion and structural degradation of the concrete. There are three commonly used accelerated corrosion monitoring, namely Impressed Current techniques, Chloride salt, and wet-dry cycle. Amongst these accelerated corrosion tests, the Impressed Current test was the most widely used [10].

Saifullah and Clark [11] point out that, impressed current values greater than 0.15 mA/cm² result in inconsistent results. Hence, it was recommended to use low current density in order to allow the corrosion to pass through the concrete pores as well as reduce the concrete crack width.

2.4 Visual Inspection

Sossa et al., [12] state that the corrosion can be classified into erosion, galvanic, crevice, pitting, and exfoliation by differentiating via the profile of the structure. the appearance can be used to classify the corrosion rate by monitoring the pattern of attacks of the corrosion

2.5 Half-Cell Potential Method

Half-cell Potential Method was a non -destructive method used to evaluate the corrosion of reinforcement in concrete in accordance to ASTM C876-15. It functioned to provide a fast and accurate evaluation of the probability of corrosion of reinforcement bars in a concrete specimen. Generally, HCP test usually worked as a complementary measure for determining the corrosion rate with other techniques.

2. Methodology

The methodology flowchart was demonstrated in Figure 2.

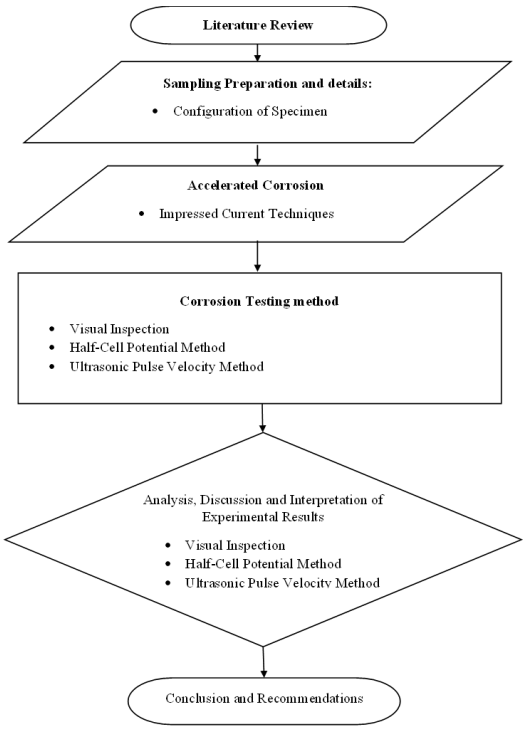


Figure 2: Methodology Flowchart

In this experimental study, two concrete prism specimens, which are labeled Specimen 1 and Specimen 2 were prepared. The mix design of concrete specimens was demonstrated in table1. The cross-section size was 150 x 165 mm, and the length of the specimens was 350 mm for two 10 mm diameter of reinforcing bars embedded with a concrete cover of 20mm. The two bars were located at the corner. The details of specimen specimens are as shown in Figure 3.

Table 1: Mix Design of Concrete Specimens of C25 at 0.5 of water-cement ratio

Specimen	Portland Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	5-10mm aggregates (kg/m^3)	10-20mm aggregates (kg/m^3)	Admixture (kg/m^3)
C25	350	715	175	526	526	1.75

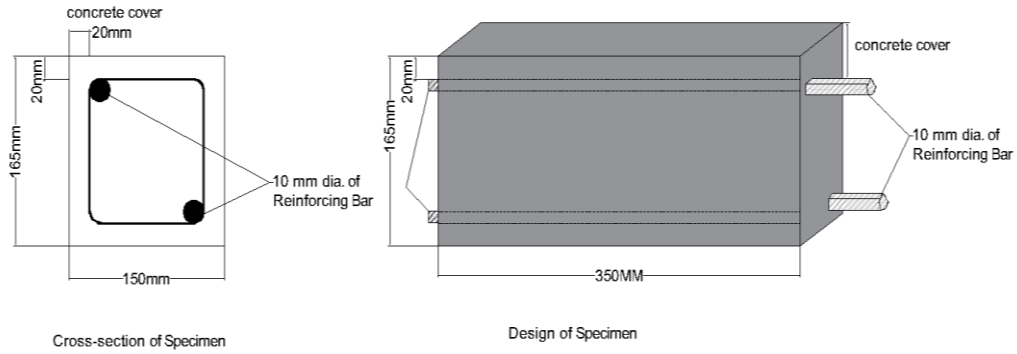


Figure 3: Details of Specimens

Before applying the Impressed current test, Specimen 1 and Specimen 2 were cleaned to remove some rust and soaked in a 3 % of Sodium Chloride Solution (NaCl) for 8 days to ensure full saturation then, the initial Impressed Current values were recorded. Figure 4 below shows the setup of the Impressed Current test for this project. For generating corrosion, the current was set to flow from cathode to anode through the electrical connection yet in the electrolyte, current flow from anode to cathode.

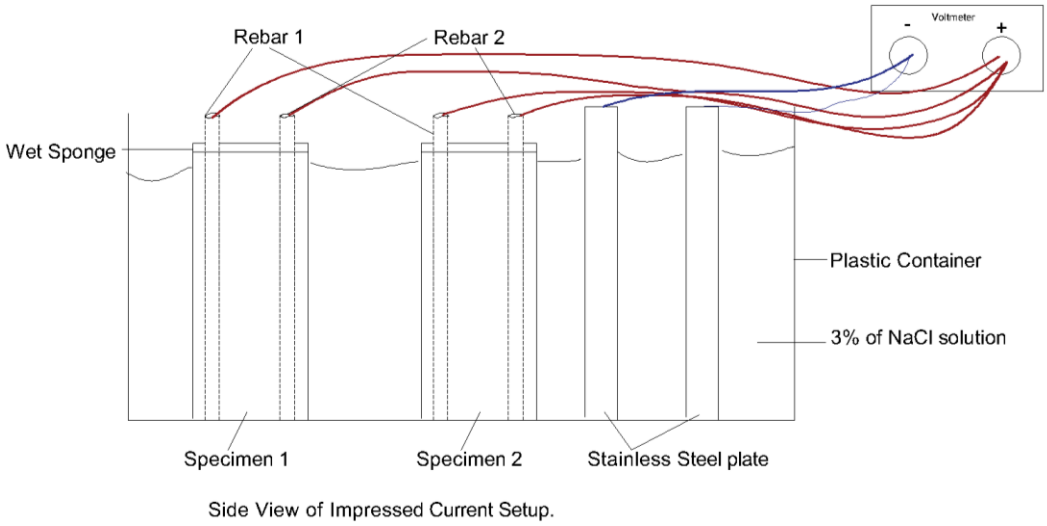


Figure 4: Setup of Impressed Current test for the project

The specimens were set upright and were soaked partial immersion in 3 % of Sodium Chloride Solution which acts as an electrolyte, the reinforcing bar was set to be an anode where the oxidation or corrosion will occur and two stainless steel plates will be served as cathode where reduction occurs. According to the study by Saifullah and Clark [11], the density of current should not be exceeding 0.25 mA/cm². Thus, the current density of 0.08 mA/cm². was selected and monitored within 8 days of Impressed Current test. Sponges act as a counter electrode functioned for current to flow and were placed in contact between rebar and the concrete.

For visual inspection, the initial and final condition of the specimens after undergoing the impressed current test was recorded, and photographs were taken for reference evidence.

The Half-Cell Potential test used was in accordance to ASTM C876-15, during this test, the location of the reinforcing bar was identified and marked out by a grid on the concrete, the point will be parallel

to the rebar location. The measurements will be taken before and after impressed current test using a half-cell electrode probe at the intersection point of the grid and labeled as Points 1, 2, and 3. The arrangement of the transducer will be direct transmission since it was the most reliable configuration. The four side of the prism will be labeled as Side A and Side D for measuring Rebar 1 and Side B and Side C for measuring Rebar 2 as displayed in Figure 5. Figure 6 demonstrates the mark location of the specimen. A water sponge was prepared to wet the location of measurement and facilitate the testing (Figure 7).

The equation used to calculate the change of half-cell measurement before and after the Impressed Current Test (ICT) was calculated as follow:

Potential Difference (mV): | Initial UPV Values before ICT- UPV Values after ICT| Eq.1

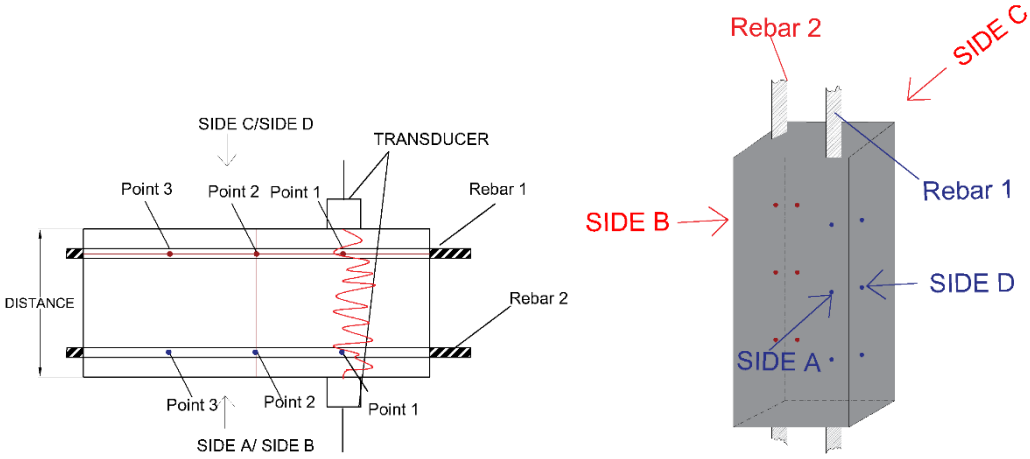


Figure 5: Direct transmission measurement of UPV values of Specimen

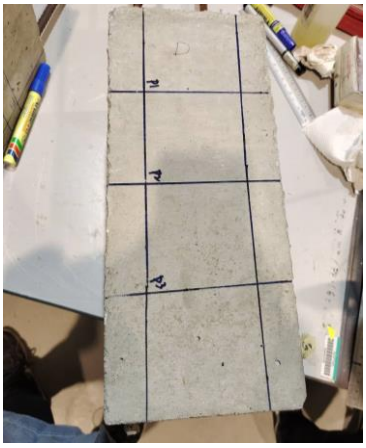


Figure 6: Mark out location of the specimen

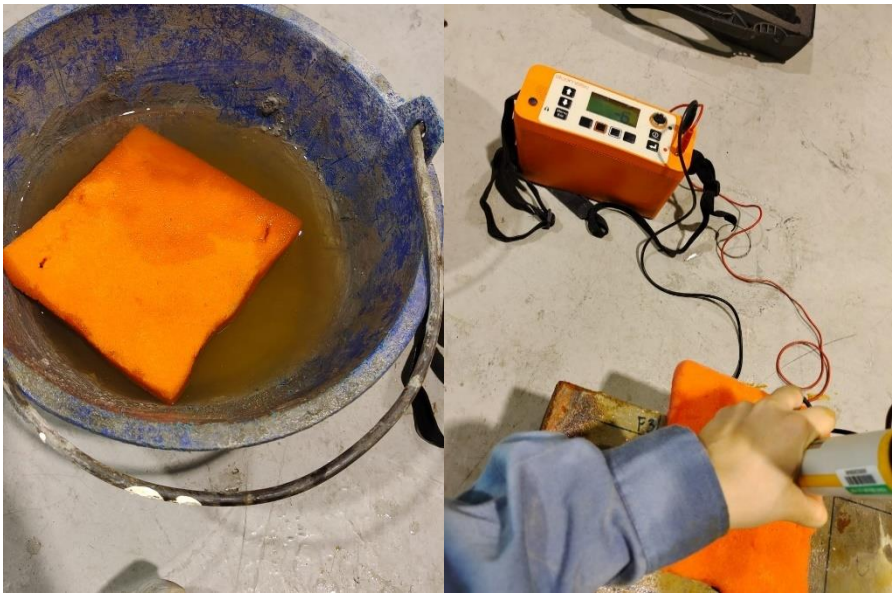


Figure 7: Wet sponges used during testing

On the Ultrasonic Pulse Velocity method, the reading of the specimens before and after Impressed Current test will be recorded via Preceq Tico Ultrasonic Instrument consisting of two transducers of 54kHz, two cables, a calibration rod, couplant, and a carrying case as Figure 8.

Figure 8: Preceq Tico Ultrasonic Instrument used

3. Results and Discussion

Through visual inspection, it was notified that there was clear sign of corrosion spreading outward from the diameter of the rebar, pitting, color progression from metallic colour to reddish-brown rust colour, and the rust also exfoliated. After the Impressed Current test, it can be observed that the bottom side of both specimens corroded the most. Table 2 demonstrates the comparison of specimen profile bottom before and after the 8 days of Impressed Current test in 3% of Sodium Chloride Solution. According to previous findings by Ayop, Mohammad & Ismail [13], the level of concrete corrosion was divided into five different classes by senior engineers and lecturers as shown in Table 3. Generally, from visual inspection, there are major rust stains deposited at the bottom of the rebar, and minor rust stain along the rebar on the concrete. The rebar has exposure of reinforcing ties, the severity level was assumed to be at level 3 that indicates as “Good”.

Table 2: Profile of Specimen 1 and 2 "bottom" before and after Impressed Current test

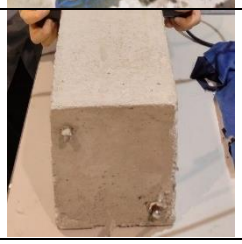
Specimen	Side	Before Impressed Current test	After Impressed Current test
1	Bottom		
2	Bottom		

Table 3: Severity levels of corrosion of reinforcement (Ayop et al., 2018)

Severity Level	Description
1=Excellent	-Dotted stains appeared on the concrete surface
	-There are light rust stains on the concrete surface
2=Very Good	-There have corrosion of wires
	- No exposed rebar
	- There will have exposed rebar with minor corrosion
3=Good	- Rust stain occurred along the rebar on concrete surface.
	- Exposure of the Reinforcing steel ties
	- Major rust stain deposited along the rebar
4=Fair	- Exposed rebar with heavy rusting and localized pitting
	- Loss of bar section at around 10% to 20%
5=Poor	- Loss of section > 20%

For correlating Corrosion level to the Ultrasonic Pulse Velocity values, the correlation corrosion monitoring using ASTM C876-15 via Half-Cell Potential Method will be utilized. Table 4 shows the Interpretation of Half-Cell Potential as per ASTM C876-15. The guidelines proposed by ASTM where the potential measurement for the probability of rebar corrosion are classified into 3 categories, namely low risk, less than 10% of corrosion, uncertain chance of corrosion, and more than 90% probability of corrosion.

According to the results of the Half-Cell Potential test from Tables 5 and 6, there is a clear sign of corrosion since all the half-cell potential measurements displayed becoming more negative after the Impressed Current test or accelerated corrosion. A more negative half-cell reading indicates a greater tendency of corrosion to occur in accordance to standard ASTM C876-15. According to guidelines in Table 4, the negative half-cell potential measurement represents there is a low risk or less than 10% for the probability of rebar corrosion. The most negative value for this half-cell potential measurement was -0.026 V for Specimen rebar 2, hence rebar 2 corroded the most. Overall, the probability of rebar corrosion is directly proportional to the half-cell potential, the more the rebar corroded, the more negative was the half-cell potential. Both the half-cell potential and rebar corrosion were correlated.

Table 4: Interpretation of Half-Cell Potential as per ASTM C876-15 [15]

Half-Cell Potential Measurement	Probability of rebar corrosion
> - 200mV	Low risk, less than 10% of corrosion
-200 to -350 mV	Intermediate corrosion risk, Uncertain
< -0.350 V	High risk, more than 90% of corrosion

Table 5: Results of the Half-Cell Potential (HCP) tests for Specimen 1 before and after Impressed Current tests

Specimen	Rebar	Side	Half-Cell Potential Difference(mV)					
			Point 1		Point 2		Point 3	
			Before	After	Before	After	Before	After
1	1	A	20	-22	12	-9	11	-11
		D	41	-6	36	-1	35	0
	2	B	27	-21	23	-8	23	-1
		C	23	-24	9	-26	12	-20

Table 6: Results of the Half-Cell Potential (HCP) tests for Specimen 2 before and after Impressed Current tests

Specimen	Rebar	Side	Half-Cell Potential Difference(mV)					
			Point 1		Point 2		Point 3	
			Before	After	Before	After	Before	After
2	1	A	33	-10	29	-7	26	-6
		D	13	-11	14	-2	15	-1
	2	B	20	-22	25	-19	27	-20
		C	1	-12	8	-4	6	-5

Four sets of graphs were plotted in Figures 9 to 12 to study the correlation between the UPV values with corrosion rate with regard to the corrosion rate level via a half-cell potential test. From Figures 9 to 12, it can be observed that generally, there is a similar trend shown in the UPV reading that the velocity of the wave had reduced accordingly, thereby, it implies that ultrasonic pulse velocities start to drop when there is a corrosion or defects in the specimens.

The results indicated there is a possibility that the corrosion had taken place when the HCP reading turned down to a negative value. When the UPV values decrease, Half-cell Potential also decreases. The Half-cell potential measurement for both specimens 1 and 2 indicates that the corrosion level of the rebars embedded in the specimens was low, less than 10% of corrosion, hence, it can be deduced that the UPV test was suitable to be employed to detect corrosion in concrete at an early stage.

The results indicated there is a possibility that the corrosion had taken place when the HCP reading turned down to a negative value.

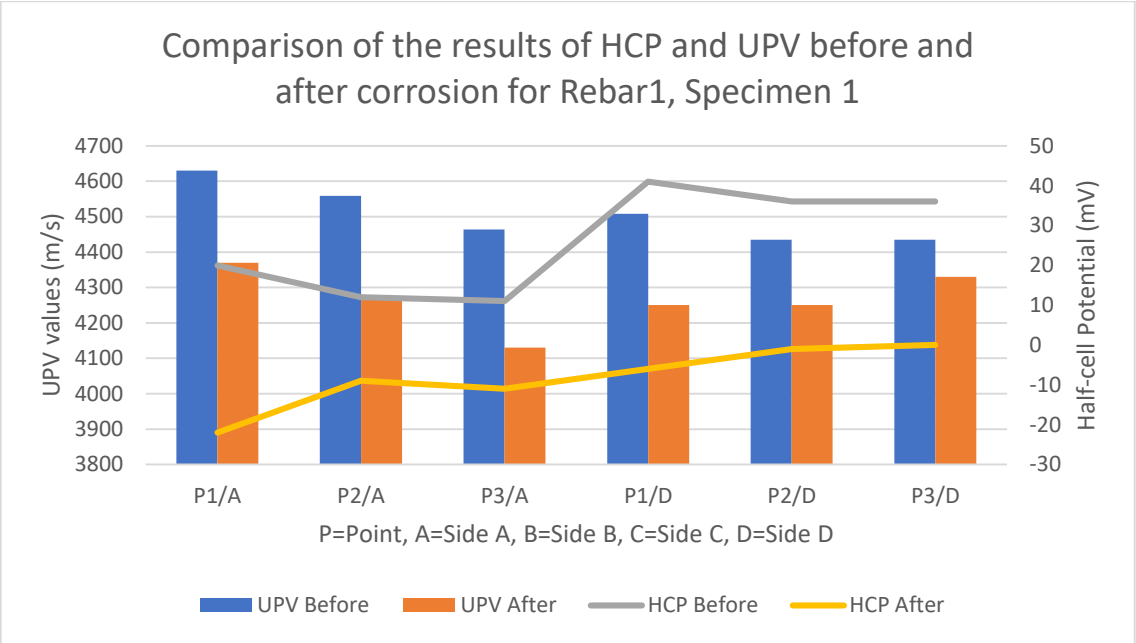


Figure 9: The Comparison of the results of HCP and UPV before and after corrosion for Rebar1, Specimen 1

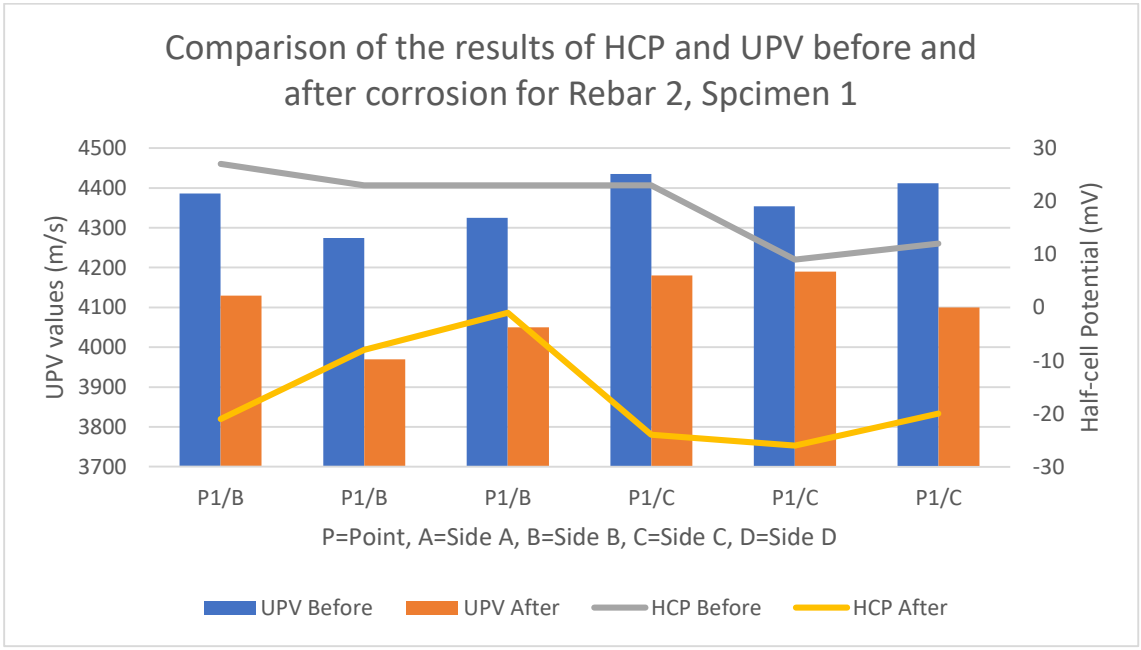


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Figure 10: The Comparison of the results of HCP and UPV before and after corrosion for Rebar2, Specimen 1

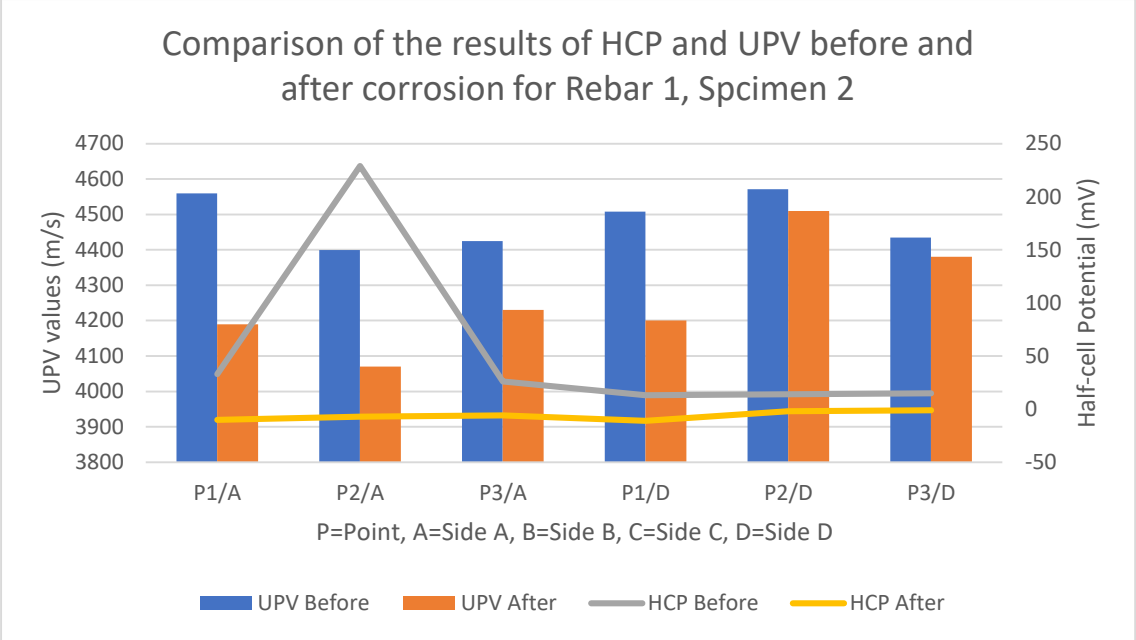

Figure 11: The Comparison of the results of HCP and UPV before and after corrosion for Rebar1, Specimen 2

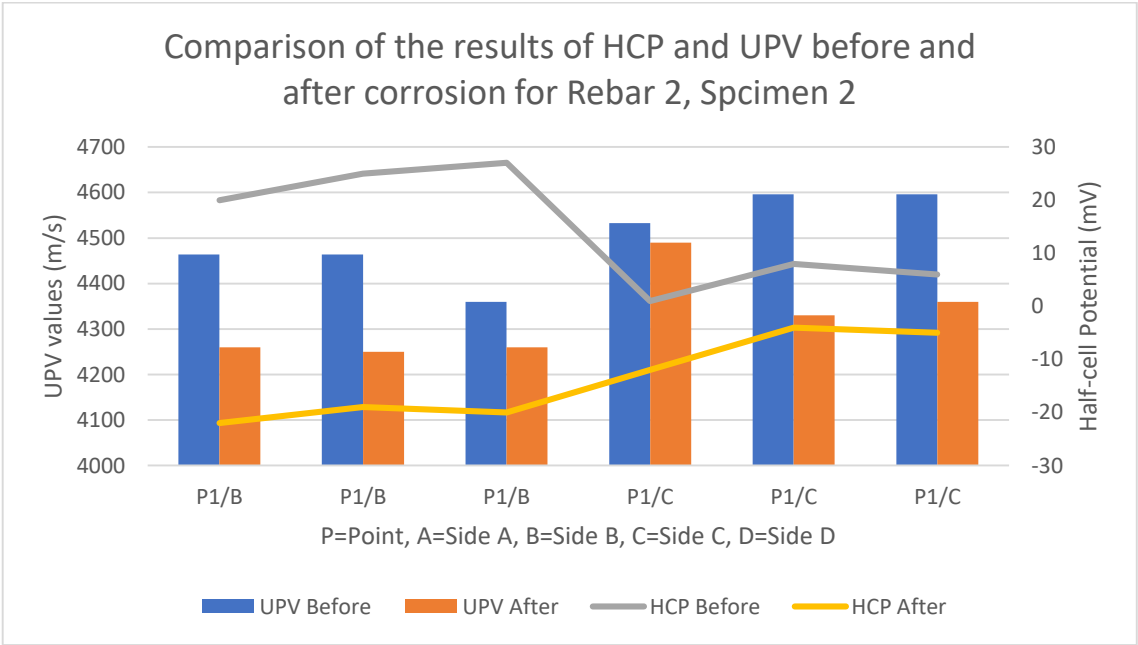

Figure 12: The Comparison of the results of HCP and UPV before and after corrosion for Rebar2, Specimen 2

4. Conclusion

Based on the discussion of the experimental study, the following conclusion can be drawn:

- The results indicated that when there is a reduction in UPV values, there is a possibility that the corrosion had taken place since the HCP reading turned down to a more negative value. A similar trend in the graph had shown that the UPV reading that the velocity of the wave had reduced accordingly.
- The reinforcement corrosion is sensitive to the UPV method and it can be proved by both specimens displaying a similar graph of the comparison of UPV and HCP. Thus, complementary measurement using the Half-cell Potential (HCP) method and Ultrasonic Pulse Velocity (UPV) method in determining the rate of corrosion contribute to the clear, unambiguous, and results in specific results on the reinforcement corrosion as the UPV method itself on the reinforcement corrosion could be misleading.
- The experimental study showed that the Ultrasonic Pulse Velocity test was able to detect the presence of reinforcement of corrosion at a very early stage as a small change in the elastic wave was easily captured by the UPV test. Hence, common deterioration of the concrete structure that requires inspection, maintenance, and rehabilitation can be detected via UPV.
- Half-cell potential method can be accompanied with UPV for classifying and detecting the level of corrosion. Through this experimental research, both of the reinforced concrete specimens were in level 1, which indicates a low risk of corrosion.

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