Recent Trends in Civil Engineering and Built Environment Vol. 2 No. 1 (2021) 160–170

RTCEBE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/rtcebe
e-ISSN : 2773-5184

Evaluation of Corrosion in Reinforced Concrete: A Review on the Application of UPV Method

Fatin Zulaikha Othman[1], **Sallehuddin Shah Ayop**[2,*]

[1]Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Parit Raja , Batu Pahat, Johor, 86400, MALAYSIA

[2]Jamilus Research Centre, Faculty of Civil and Built Environment
Universiti Tun Hussein Onn Malaysia, Parit Raja , Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author Designation

DOI: https://doi.org/10.30880/rtcebe.2021.02.01.018
Received 30 January 2021; Accepted 28 April 2021; Available online 30 June 2021

Abstract: Corrosion can be considered as one of the problems that threatens the performance of reinforced concrete structures. Corrosion of reinforced concrete steel may leads to concrete cracking that eventually will affects the bearing capacity of concrete members. Non-destructive tests (NDT) are frequently used method in monitoring corrosion of reinforced concrete. This study is conducted to analyse the capability of UPV method as corrosion detection of reinforced concrete. The aims of this study is to review and analyse the behavior of corrosion expansion of reinforcement steel that undergo accelerated corrosion test by using UPV method and to analyse the effect of corrosion products on concrete-steel interface by examining the corrosion crack and the weight loss of reinforcement steel. The utilization of UPV method from previous researches were collected in this study to review the application of this method in detecting corrosion by analyzing the results of UPV reading obtained from previous researches. Weight loss of reinforcement steel also were studied to evaluate the effect of corrosion towards the condition of reinforced concrete. Analysis from the previous findings showed that the UPV readings recorded a reduction in values as corrosion time increases with cracking appeared on the concrete surface and reinforcement steel showed an increase in weight loss at the end of accelerated corrosion test. Hence, from this study, it was able to validate the reliability of UPV method to be adopted as one of the alternative method to evaluate corrosion of reinforced concrete.

Keywords: UPV, Corrosion, Reinforced Concrete

**Corresponding author: sallehs@uthm.edu.my*

1. Introduction

Reinforced concrete is a construction materials in which steel is embedded inside concrete such a manner that the two materials act together in order to enhance its strength to withstand external forces and is known to possess a long life service. Upon further studies, reinforced concrete is no exception would face threats like corrosion that will affects the durability of concrete structures. However, corrosion in reinforced concrete cannot be observed easily and there is a key issue in the research of concrete durability on how to identify and measure the corrosion of rebar without damaging the structure.

Non-destructive tests have been mostly adopted to assess and measure corrosion of reinforcement steel in concrete structures. According to Watanabe et al. [1], half-cell potential method is one of the non-destructive test (NDT) that is frequently used to evaluate the corrosion of reinforced concrete. Nonetheless, even though this method has become the best approach to detect corrosion due to it practicality, it is unable to detect the corrosion rate and cracking in concrete as it only works to analyse the possibility of rebar corrosion [2]. Hence, there is demand to develop measurement technologies for the NDT of reinforcement steel corrosion within concrete structure by considering a more practical and applicable methods.

Nowadays, recent studies had been conducted to evaluate the corrosion of reinforced concrete by using elastic-waves as these methods can ensure that a concrete structure will not undergo any serious damage upon conducting this tests. Ultrasonic Pulse Velocity (UPV) is one of the elastic-wave methods that functioning by transmitting the wave signals to concrete structure in order to test mechanical properties and internal defects of concrete [2]. This study is conducted to review the application of UPV as corrosion detection of reinforced concrete by collecting and analyzing data from previous researches.

1.1 Objectives of the Study

Objectives of this study are as follow:

a. To investigate the corrosion expansion of reinforcement steel that undergo accelerated corrosion test by applying the UPV method.
b. To study the effect of corrosion products in the form of rust on concrete-steel interface by examining the weight loss of reinforcement steel and corrosion cracks.

2. Literature Review

2.1 Corrosion Process

Corrosion process of reinforced concrete can be summarized in three stages in which it started when the corrosion products in the form of rust expands and fill the voids between rebar-concrete interface, then corrosion products would induced pressure that caused tensile stress in which cracking is starting to appear on the concrete cover and finally the cracks are continuously filled with the rust products [2]. Figure 1 illustrated the cross-section of reinforced concrete that consisted of concrete surface, concrete cover and passive layer.

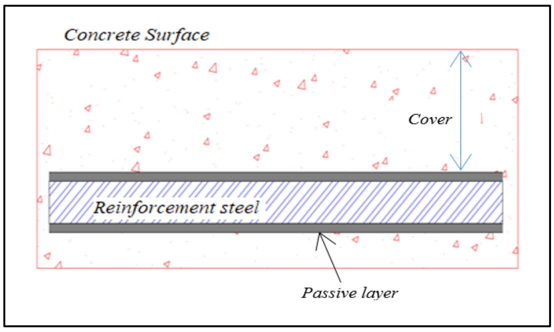

Figure 1: Cross-section of a reinforced concrete

The passive layer is formed due to concrete's chemical behavior that has high pH value that is between 12 to 13 and thus provides an alkaline environment to the reinforcement steel [3]. This passive layer can be destroyed under two conditions which are penetration of chloride ions into the concrete pore solution around the rebar or any reaction that resulted in the reduction of pH value surrounding the concrete and in most cases is the reaction of concrete with carbon dioxide (CO_2) or termed as carbonation.

When the passive layer destroyed, the corrosion products would appeared on the surface of the steel in the form of rust. The corrosion of reinforcement steel in concrete happened when the process of oxidation occurred at the anode region leads into the dissolution of steel, while reduction process occurred at the cathode region resulted in the reduction of dissolved oxygen thus forming hydroxyl ions, [OH^-] [4].The hydroxyl ions combined with the ferrous ions, [Fe^{2+}] that released into the electrolyte at the anode, to form ferrous hydroxide, $Fe(OH)_2$, a slightly soluble jellylike substances which, in the presence of oxygen, is promptly converted into some other form of iron oxide such as insoluble or some ferric oxide, $Fe_2O_3.H_2O$, which is rust [5]. The process is illustrated in Figure 2 below:

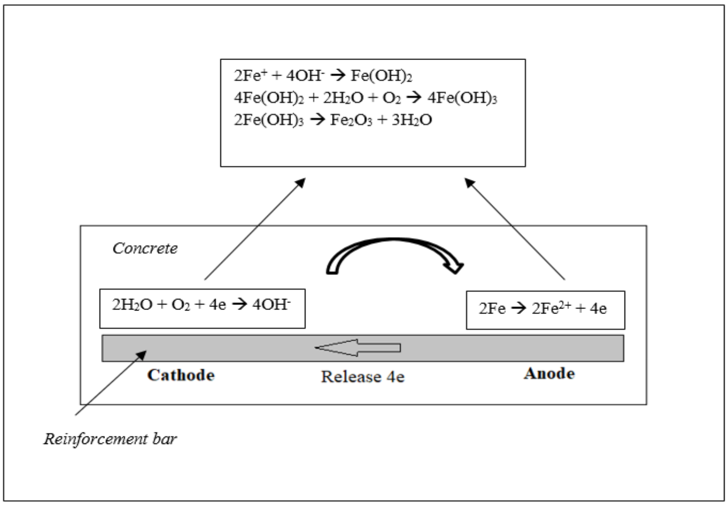

Figure 2: Corrosion reaction on a reinforced concrete

When rust started to appear on the reinforcement steel, the corrosion products would eventually occupied for up to two to three times more volume than the volume of the destroyed steel. As the volumetric expansion of the corrosion products exceed the volume of the steel, it would created tensile stress that lead to the cracking and spalling of the concrete cover. Corrosion of reinforcement steel reduced the cross-sectional area of the steel bars and thus affecting the load-bearing capacity and the performance of the concrete structure [3].

2.2 Ultrasonic Pulse Velocity Method (UPV)

Ultrasonic pulse velocity test (UPV) is one of the elastic wave methods that is used to detect the condition of construction materials specifically reinforced concrete. Concrete monitoring by using UPV method is usually employed to assess the uniformity of structural concrete, properties of concrete and the quality of concrete through the measure of it compressive strength. According to Watanabe et al. [1], UPV method have been standardized as a test to inspect the compressive strength and depth of surface-crack of concrete in Japan.

As described by Kashif Ur Rehman et al. [6], waves pulse that generates from transmitter would passed through structural member and the receiver received the waves signals and presented the data in the form of time. When defects occurs along the propagation path, the wave signals are reflected back to the surface thus increasing the duration for the waves to receive by receiver. This is supported by Xu and Jin [2], who stated that air voids have lower acoustical impedance than concrete that resulted in reduction of waves energy and longer duration caused by the reflection of wave signals at corrosion surface. The longer duration of wave signals thus resulting in the reduction of wave velocity.

UPV waves propagated a long distance along the reinforcement steel and have been found to be sensitive to the interface conditions between the reinforcement steel and concrete [7]. Concrete structure that possess the good quality can be monitored by the higher value of UPV meanwhile lower UPV value indicates the concrete structure is in poor quality [8]. The statement can be supportd by the research conducted by previous researchers that recorded that the corrosion of steel reinforcement will affected the value of UPV of the concrete [1–3, 8, 9].

3. Methodology

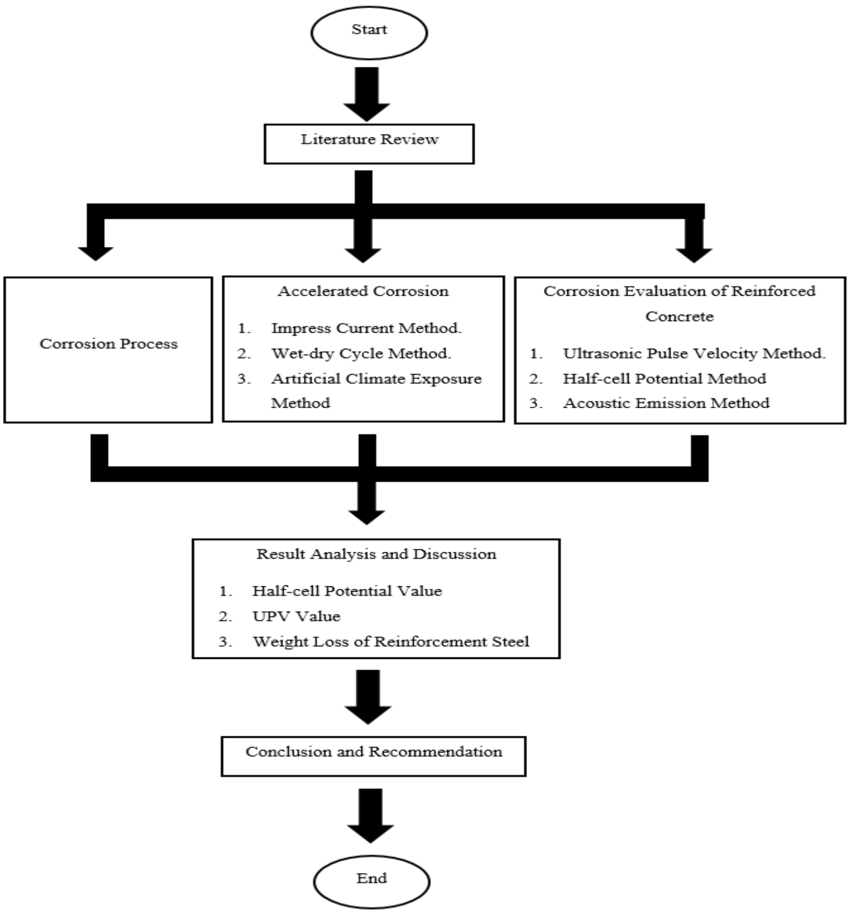

Figure 3: Methodology flow chart

3.1 Literature Review

Literature review is conducted by collecting all information from previous researches that related to this study. The research journals were obtained from online databases provided by the UTHM Library.

3.1.1 Review on Corrosion Process

Based on the journals that have been collected from online resources, the information regarding corrosion process of reinforced concrete were made. The basic principles of corrosion on reinforced concrete is studied for better understanding and the brief theory on the process is drawn in this report.

3.1.2 Review on Accelerated Corrosion Tests

This study reviewed several accelerated corrosion tests that were frequently adopted in laboratory testing to accelerate the corrosion process for research purposes. Three accelerated corrosion tests were highlighted in this study which are impress current method, wet-dry cycle method and artificial climate exposure method. Two previous journals for each accelerated corrosion tests were reviewed to study the basic concept of the tests.

3.1.3 Review on Corrosion Evaluation of Reinforced Concrete

Corrosion evaluation of reinforced concrete was strongly emphasized in this study. Related journals regarding the application of non-destructive tests (NDT) to monitor corrosion of reinforced concrete were collected and being reviewed. Three alternative methods including ultrasonic pulse velocity (UPV), half-cell potential method (HCP) and acoustic emission method (AE) were considered in this study by reviewing the basic principles of these methods and its application in detecting corrosion on reinforced concrete structures.

3.2 Result Analysis and Discussion

This research provided an in-depth systematic analysis review to determine the capability of UPV method as an alternative method to detect corrosion on reinforced concrete. The findings and results of previous researches are being collected and presented in a tabular form. Weight loss of reinforcement steel from previous researches were also being reviewed to provide a relation between the UPV values analysis and the weight loss of reinforcement steel that being exposed to accelerated corrosion tests. The findings obtained were reviewed and analyzed to complete the findings of this research.

4. Analysis and Discussion

4.1 Results Review

From the previous journals that have been collected, the results and findings were then tabulated in a table form as in Table 2.

4.2 Analysis on UPV Results from Previous Research

Many studies conducted by previous researchers had assessing the deterioration of reinforced concrete due to corrosion by employing UPV method [1–3, 8, 9]. A research conducted by Watanabe et al. [1] indicated that the UPV values reduced at certain test points when samples that undergo accelerated corrosion being test after 2 days elapsed and the reading gradually become much slower after 10 days elapsed (Figure 4). The research also recorded an increase of the mass-decrease rate of reinforcement steel and crack width as the accelerated corrosion increase (Figure 5). Even with the continuous development of corrosion activity, the UPV values from 20 days to 33 days elapsed recorded almost similar reading between 3000 m/s to 4000 m/s thus indicated that UPV values are not correlated to amount of reinforcement steel corrosion.

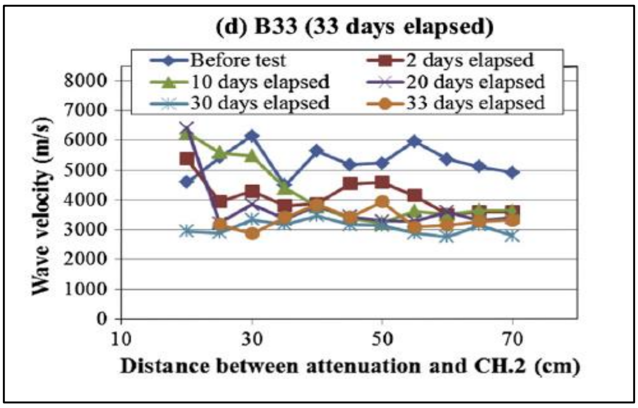

Figure 4: Graph relation of UPV values and accelerated corrosion test at 33 days [1]

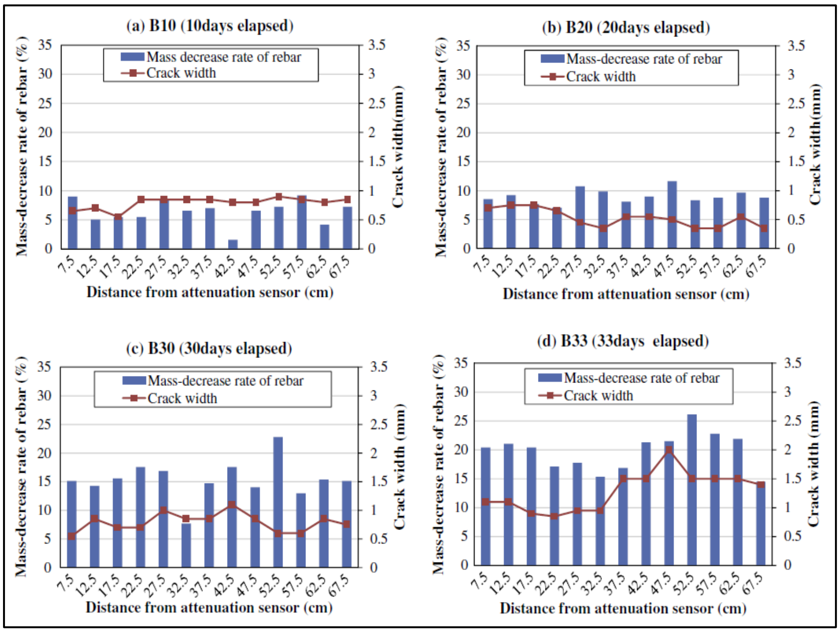

Figure 5: Graph of mass-decrease rate of reinforcement steel and crack width during accelerated corrosion [1]

However, in recent work conducted by Maddumahewa et al. [9], it is found that there was a relation between the UPV value and the percentage weight loss of reinforcement steel. The research indicated a reduction in UPV values over time in which UPV reading significantly reduced after 12 days with the lowest UPV values of 4210 m/s and 4520 m/s for 10 mm and 16 mm diameter of reinforcement steel respectively at day 14. The evaluation on the percentage weight loss of reinforcement steel also recorded an increase in weight loss as the corrosion time increase. The researcher plotted the value of UPV against weight loss of reinforcement steel as in Figure 6 and the results indicated that there is a correlation between UPV measurements with amount of reinforcement corrosion.

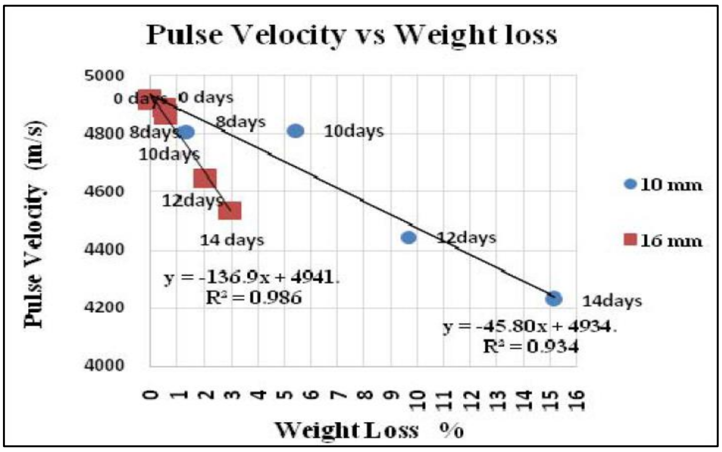

Figure 6:Pulse velocity reading versus weight loss of reinforcement steel [9]

Experimental work conducted by Al-Akhras and Aleghnimat [3], expressed the change in the UPV results due to corrosion through the value of Damage Index (DI) and recorded that the reduction in UPV values is reflected by the higher value of DI. DI value is a term to describe the percent difference of UPV after corrosion with respect to initial UPV before corrosion. Based on Figure 7 and Figure 8, study showed that direct and indirect DI values increases as the corrosion time increases in which indirect DI recorded higher DI values.

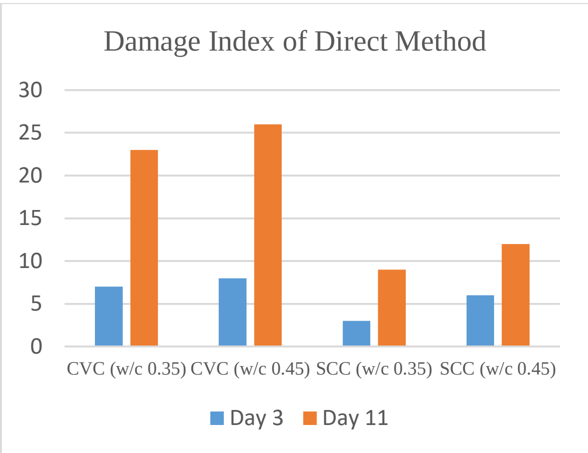

Figure 7: DI values of direct method

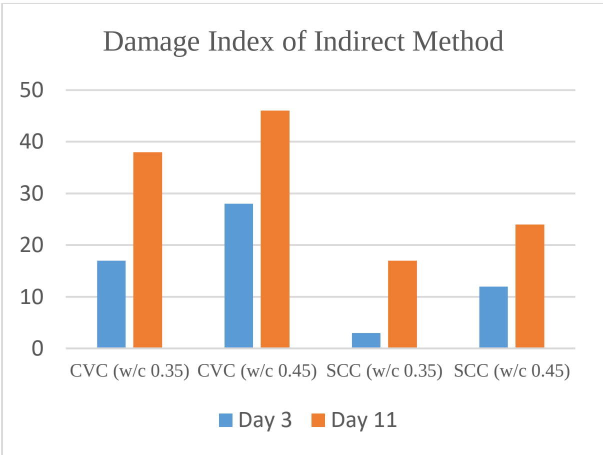

Figure 8: DI values of indirect method

The study conducted by Ongpeng [8] assessed the defects due to corrosion of reinforced concrete by the application of UPV under direct transmission method. The provided data was calculated and presented in the value of percent difference of strength of reinforced concrete samples that undergo accelerated and non-accelerated corrosion to express the change of UPV values with time. The study recorded that at day 14, the percent difference of strength in reinforced concrete that undergo accelerated corrosion was reduced more than 10% and at day 28, the strength decrease for up to more than 20%. Based on Figure 9, the results also shown that higher UPV reading would resulted in the lower percent difference of strength of reinforced concrete.

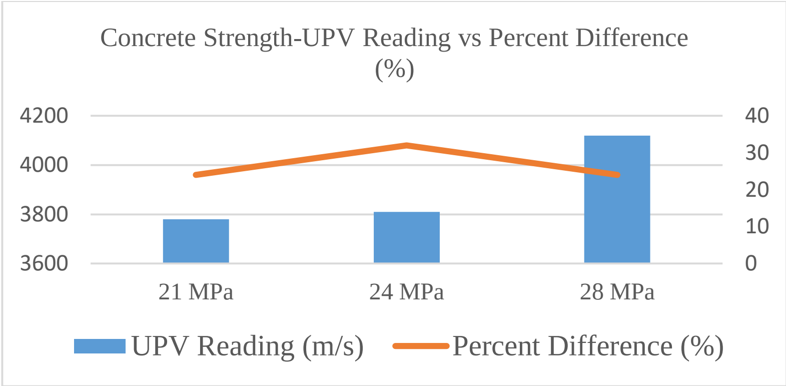

Figure 9: Concrete strength-UPV reading versus percent difference of strength

Based on the analysis review from previous researches that adopted UPV method as a corrosion detection of reinforced concrete, it is found that the UPV values would recorded a significant reduction as the corrosion time increases. UPV method is based on the concept of pulse velocity where when the elastic wave signals passed through a deteriorated concrete structure, the pulse reading will be affected by the defect presence in the concrete member. Before corrosion of reinforced concrete, there is a stable propagation path that allow a smooth transmission of pulse velocity due to low presence of cracks and corrosion. In the case of corrosion of reinforced concrete, the corrosion would resulted in the reduction of volume of the reinforcement steel thus producing voids within concrete-steel interface. When performing the UPV test towards the corroded reinforced concrete, the voids would led to the reduction in UPV reading when compared to the values before reinforcement corrosion. The products of the corrosion process would affected the propagation path that resulted in diffraction of the ultrasonic waves. Then, the ultrasonic waves would scattered and reflected thus, causing a reduction in pulse velocity reading [2].

4.3 Analysis on Weight Loss of Reinforcement Steel and Crack Width

Degree of corrosion or corrosion level can be expressed by calculating the weight loss of reinforcement steel [4, 10, 11]. Weight loss of reinforcement steel can be measured by following the gravimetric test according to ASTM G1 [2, 8, 9]. This method works by extracting the reinforcement steel from reinforced concrete upon the end of UPV method evaluation. The corroded reinforcement steel would then undergo de-rusting process to remove the rust produced from the accelerated corrosion process. As the rust is removed, the final weight of the reinforcement steel, m_1, was measured and weight loss ratio was calculated with respect to initial weight of reinforcement steel before rebar corrosion, m_0, by using Equation 1 below. Result from previous experimental works are showed on the Table 1 below:

$$\eta = \frac{m_0 - m_1}{m_0} \times 100\% \qquad \text{Eq. 1}$$

Table 1: Results of weight loss of reinforcement steel and crack width

References	Weight loss of steel (%)	Crack width (mm)
[1]	15-25	0.5-2.0
[9]	15(10mm Ø) 3(16 mm Ø)	Not specified
[8]	7	Multiple crack propagation appeared
[2]	C20: 7.94 C25: 5.29 C30: 3.89 C30: 2.58 C35: 1.03	Not specified
[3]	Not specified	SCC: 0.4 and 0.8 CVC: 3.1 and 4.0

Based on the previous researches, results recorded an occurrence of cracks at concrete surface and reinforcement steel experienced an increase in weight loss ratio at the end of corrosion time. The presence of corrosion products occupied more volume than the volume of reinforcement steel destroyed that resulted in the induced of expansive pressure which creates tensile stresses around the concrete-steel interface. As the stresses continues to progress, cracking will starts to appear in the concrete. When the rust is removed through the gravimetric test, corrosion level can be measured by the value of weight loss of reinforcement steel and it is found that the weight loss ratio gradually increases as corrosion time increases.

5. Conclusion

This study review has highlighted the evaluation of corrosion of reinforced concrete by using UPV method. Based on the analysis review that had been conducted, the conclusion that can be drawn are as follows:

a. Objective 1: To investigate the corrosion expansion of reinforced steel that undergo accelerated corrosion test by applying UPV method.
    - Results from previous researches recorded a reduction in UPV values as the accelerated corrosion time increases.
    - Reduction of UPV values with time can be presented by the increase in value of Damage Index (DI) or percent difference of concrete strength.

b. Objective 2: To study the effect of corrosion products in the form of rust on concrete-steel interface by examining the weight loss of reinforcement steel and corrosion cracks.

- Corrosion of reinforcement steel can be measured by using the gravimetric test to calculate the weight loss of reinforcement steel.
- Corrosion process would resulted in the expansion of rust that caused in the increase of the weight loss of reinforcement steel and presence of cracking on reinforced concrete.

This study proved that UPV method can serves as an alternative technique to detect corrosion of reinforced concrete without entirely damage the concrete structure.

Table 2: Result from previous researches adopting UPV method

References	[3]	[2]	[9]	[8]	[1]
Bar Ø (mm)	14	12	10, 16, 20, 25	6 mm and 2 nos of 10 mm	13
Type of concrete	SCC and CVC beams & prisms	Mix design of C20, C25, C30, C35	Grade M30	Grade 40	Grade 20
Corrosion Test	Impressed current	Chlorine salt wet-dry cycle & impressed current	Impressed current	Non-accelerated (air drying) & accelerated corrosion (impressed current)	Impressed current
Corrosion time	3, 5, 11	Not specify	8, 10, 12, 14	14, 28	10, 20, 30, 33
HCP Result (mV)	SCC: -110 to -310 CVC: -110 to -470	Not specify	Not specify	Not specify	-350 (dormant stage)
UPV Result	Expressed in DI value	Decrease after rebar corrosion	Decrease after 12 days. 4210 m/s (10 mm) & 4520 m/s (16 mm)	Significant reduction in UPV values for accelerated corrosion	Decrease after 2 days
DI/ Percent difference Value	SCC (Direct DI): 9% (w/c 0.35) & 12% (w/c 0.45) SCC (Indirect DI): 3-17% (w/c 0.35) & 17-24% (w/c 0.45). CVC (Direct DI): 23% (w/c 0.35) & 26 % (w/c 0.45) CVC (Indirect DI): 17 -38% (w/c 0.35) & 38-46 % (w/c 0.45).	Not specify	Not specify	Increase over time. 10 % (day 14) and more than 20 % (day 28)	Not specify
Crack Width	SCC – 0.4 & 0.8 mm CVC – 3.1 & 4.0 mm	Not specify	Not specify	Multiple crack propagation appeared	Increase over time. 15 to 25 % (day 33)
Weight Loss of Rebar	Not specify	7.94 (C20), 5.29 (C25), 3.89 (C30), 2.58 (C30), 1.03 (C35)	10 mm rebar: 15% 16 mm rebar: 3%	7 %	Increase over time. 0.5 to 2.0 mm (day 33)

References

[1] T. Watanabe, H. T. H. Trang, K. Harada, and C. Hashimoto, "Evaluation of corrosion-induced crack and rebar corrosion by ultrasonic testing," *Constr. Build. Mater.*, vol. 67, pp. 197–201, 2014.

[2] Y. Xu and R. Jin, "Measurement of reinforcement corrosion in concrete adopting ultrasonic tests and artificial neural network," *Constr. Build. Mater.*, vol. 177, pp. 125–133, 2018.

[3] N. Al-Akhras and R. Aleghnimat, "Evaluating corrosion deterioration in self-compacted reinforced concrete beams and prisms using different tests," *Constr. Build. Mater.*, vol. 256, p. 119347, 2020.

[4] W. Zhang, J. Chen, and X. Luo, "Effects of impressed current density on corrosion induced cracking of concrete cover," *Constr. Build. Mater.*, vol. 204, pp. 213–223, 2019.

[5] S. S. Ayop and J. J. Cairns, "Critical Study of Corrosion Damaged Concrete Structures," vol. 5, no. 2, pp. 43–50, 2013.

[6] S. Kashif Ur Rehman, Z. Ibrahim, S. A. Memon, and M. Jameel, "Nondestructive test methods for concrete bridges: A review," *Constr. Build. Mater.*, vol. 107, pp. 58–86, 2016.

[7] A. Zaki, H. K. Chai, D. G. Aggelis, and N. Alver, "Non-destructive evaluation for corrosion monitoring in concrete: A review and capability of acoustic emission technique," *Sensors (Switzerland)*, vol. 15, no. 8, pp. 19069–19101, 2015.

[8] J. M. C. Ongpeng, "Ultrasonic pulse velocity test of reinforced concrete with induced corrosion," *ASEAN Eng. J.*, vol. 7, no. 2, pp. 9–17, 2017.

[9] K. K. Maddumahewa, N. P. A. Madusanka, S. A. K. V. M. Piyathilake, and V. Sivahar, "Ultrasonic nondestructive evaluation of corrosion damage in concrete reinforcement bars," *3rd Int. Moratuwa Eng. Res. Conf. MERCon 2017*, pp. 79–82, 2017.

[10] H. Lin, Y. Zhao, J. Ožbolt, and H.-W. Reinhardt, "Bond strength evaluation of corroded steel bars via the surface crack width induced by reinforcement corrosion," *Eng. Struct.*, vol. 152, pp. 506–522, 2017.

[11] S. Bhalgamiya, G. Tivadi, and M. Jethva, "Techniques for Accelerated Corrosion Test of Steel Concrete for Determine Durability," pp. 4399–4402, 2018.