VOL. 20, NO. 2-3, 2021, 87-92
www.elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

Concrete-Defect Detection Using New Ultrasonic Array

Farah Aina Jamal Mohamad[1], **Ruzairi Abdul Rahim** [1*], **Nasarudin Ahmad**[1], **Juliza Jamaludin** [2], **Sallehuddin Ibrahim**[1], **Mohd Hafiz Fazalul Rahiman**[3], **Nur Arina Hazwani Samsun Zaini**[1] and **Navintiran Rajan**[1]

[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.
[2]Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, 71800 Negeri Sembilan, Malaysia.
[3] Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.

[*]Corresponding author: ruzairi@fke.utm.my, Tel: 607-5535310, Fax: 607-5566272

Abstract: Concrete is the main component in construction of civil infrastructure. However, deformation in concrete such as crack or void may occur either on its early stage or during its usage. Hence, concrete evaluation is a need in determining its strength and quality status. Direct Ultrasonic Pulse Velocity (UPV) method is the most common non-destructive measurement adopted to assess the condition of concrete structure. However, problems arise when there is limited accessible surface to probe the ultrasonic transducers. Hence, this project is undertaken to analyse ultrasonic NDT by utilising different arrangement of sensors on tested concrete. The simulation of the homogenous and non-homogenous concrete system will be done by using COMSOL Multiphysics software. The output signal obtained from the simulation is used for the image reconstruction by using the sensitivity mapping technique. The results are then validated by assessing the actual model of concrete structure using direct, indirect, and semi-direct UPV probing in order to get the exact location of defects. Preliminary result shows that proposed method can help to improve the defects determination in concrete structure.

Keywords: Concrete, non-destructive test, ultrasonic pulse velocity

Article History: received 25 May 2021; accepted 12 June 2021; published 15 October 2021.

1. INTRODUCTION

Concrete is a composite material that is widely used for construction, especially in large critical infrastructure systems such as bridges, pavements and buildings due to its high durability, low production cost and strength flexibility [1]. Degradation of concrete may be affected by environmental factors, mechanical overloading, high-temperature exposure, the routine of application of deicing salts and also due to repeated freezing and thawing cycles [2][3][4], which in time lead to a distributed network of cracking damage in the concrete structure, including fine cracks. Hence, concrete evaluation is very essential to determine the strength and quality of either new or old concrete structure.

The common practices that have been implemented to assess the condition of concrete infrastructure are visual inspection and destructive test method. Visual inspection is not reliable as the hidden damage and deterioration cannot be captured [5]. While the destructive test method seems more suitable and economically beneficial, the implementation of the destructive test may cause complete damage to the concrete specimen [6]. As a result, Non-Destructive Testing (NDT) is required to provide an accurate and sensitive result for an effective monitoring and maintenance procedures of a concrete structure, without damaging the concrete structure.

NDT is the process of materials' analysis that is performed without destroying the internal structure of test materials [7]. It is performed to determine flaws as well as detect variation in structures, presence of cracks and other physical discontinuities that might contribute to loss of strength in the concrete structure without causing any damage to the test materials. NDT is performed by adopting several techniques considering the type of materials to be tested, the type of defect, and the location of the occurring defect [8]. Direct Ultrasonic Pulse Velocity (UPV) is one of the popular ultrasonic NDT techniques. However, problems occur during direct UPV in concrete testing when there is no access to the two opposing sides of the concrete [9]. Although there are many research conducted on the direct UPV on concrete testing, the study on the usage of direct, indirect, and semi-direct UPV is very limited.

Hence, this paper will focus on NDT to analyse concrete structure by utilising different array of ultrasonic sensors.

2. ULTRASONIC NDT

2.1 Ultrasonic Testing

Ultrasonic testing is a non-destructive testing technique that used the propagation of high frequency ultrasonic waves to evaluate testing materials. It can be used to detect flaws and discontinuities accurately.

2.2 Work Principle of Ultrasonic Testing

The operation principle of ultrasonic testing is similar to the echo-sounding. A short ultrasonic pulse is sent to generate stress wave in concrete materials. This evaluation system consists of a transmitter and receiver circuit, transducer tool, and display devices [7]. The stress wave generated is sent using a sending transducer and received by the receiving transducer. Vibrations or high-frequency sound is propagated through the specimen and the time of wave propagation is measured. The time and distance of the travelling stress wave through the test materials enables the determination of the location, size, orientation, and other properties of defects on the concrete structure [10]. An ultrasonic wave travelling into concrete is directly proportional to the strength and age of the concrete [8]. The wave will be diffracted around the discontinuity area when defects are found. Figure 1 shows the summary of working principle of ultrasonic testing.

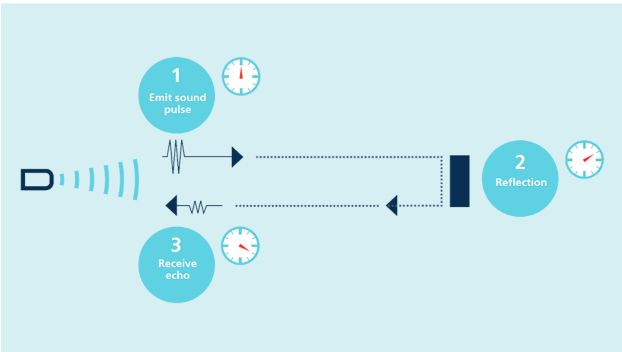


Figure 1. Working principle of ultrasonic testing

2.3 Method in Ultrasonic NDT

Ultrasonic NDT consists of various method such as pulse-transmission method, pulse-echo method, impact echo method and many others. The most common applications adopted in ultrasonic NDT are Ultrasonic Pulse Velocity (UPV) and Ultrasonic Pulse Echo (UPE) [7].

2.3.1 Ultrasonic Pulse Velocity (UPV)

UPV method is also known as through-transmission method. This method employed an ultrasonic pulse to generate waves on a tested concrete structure. An ultrasonic pulse is produced by an electro-acoustical transducer, which is positioned in contact with the specimen as ultrasonic waves cannot travel through air or vacuum. The ultrasonic pulse will undergo repeated reflections at the boundaries of a distinct phase of materials within the concrete once it is induced from a transducer. A complex system of stress waves consists of longitudinal (compressional), shear (transverse) and surface (Rayleigh) waves are generated [10]. The receiver senses the fastest waves which are the longitudinal waves. Hence, homogenous concrete material (without the presence of defects and cracks) has a higher velocity compared to the non-homogenous one.

UPV is applicable to assess the uniformity of concrete structure, also to detect its internal defects and crack depth [11]. As shown in Figure 2, UPV uses a pair of ultrasonic transducers to measure the time-of-flight of the longitudinal wave. There are three different techniques of probing that can be adopted, in which all of these techniques, similarly, require access to a good surface condition of specimen to give accurate and precise velocity values [8]:

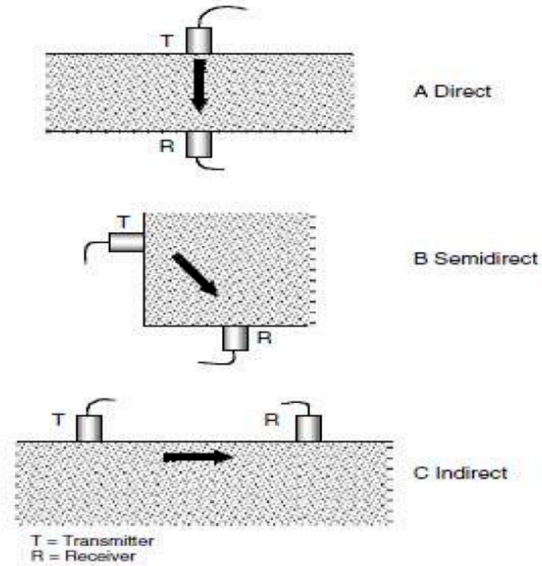


Figure 2. Various positions for probing transmitter and receiver [8]

i. Direct (cross) probing – The transmitter and receiver are located opposite to each other.
ii. Semi-direct probing – The transmitter and receiver are located on any two perpendicular surfaces of the specimens
iii. Indirect (surface) probing – The transmitter and receiver are located along the same surfaces of the specimens.

2.3.2 Ultrasonic Pulse Echo Method

UPE is the simplest and most effective methods for NDT. This method can be assessed to thick concrete, internal honeycomb, cold joint and delamination [11]. Transmitter introduces a stress pulse into the concrete materials on its accessible surface. The propagation of pulse into the concrete is then reflected by cracks, voids, or delamination. This reflected wave is known as echo, which is recorded at the surface by the same transducer. The output of the receiver is either displayed on an oscilloscope or stored for further processing. Different from UPV, UPE requires only one point to propagate the short pulse into the testing concrete. The reflected echoes generate the compressional and shear waves, that determine the strength of the material [12].

3. RESEARCH METHODOLOGY

3.1 Research Flowchart

Figure 3 shows the flowchart of this research. This project is divided into three sections: concrete specimen modelling, image reconstruction, and actual model validation. The process of modelling and simulation of concrete specimen are using COMSOL Multiphysics software. This research is limited to the study of crack and air hole detection in concrete. To illustrate and construct the defect image area, sensitivity mapping technique is employed by utilising the signal amplitude obtained from the software simulation. The arrangement of ultrasonic transducers to evaluate the actual model of concrete structure involves three techniques of UPV which is direct probing, indirect probing, and semi-direct probing. Position of these transducers are varied in order to obtain accurate data and results.

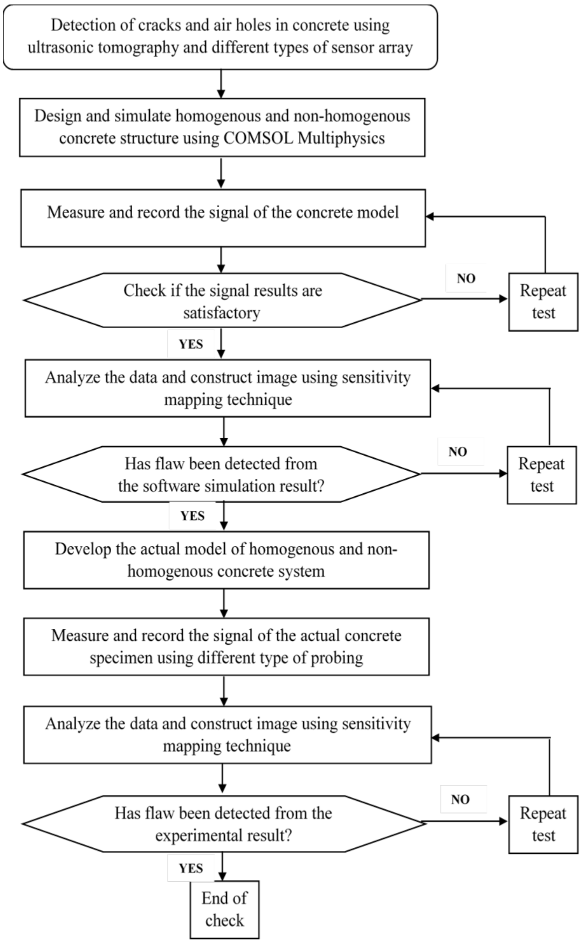


Figure 3. Flowchart of research

3.2 System Modelling

The model of homogenous and non-homogenous concrete systems are first built by using COMSOL Multiphysics software, before being validated by the actual experimental model. This software modelling aims to give an overview for the actual real model of concrete structure system, besides to verify the signal that pass through the concrete. Figure 4 and Figure 5 (a) and (b) shows the model of homogenous and non-homogenous concrete structure, respectively.

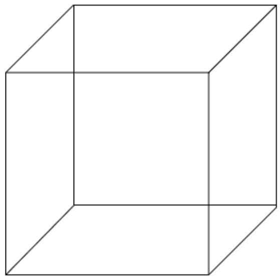
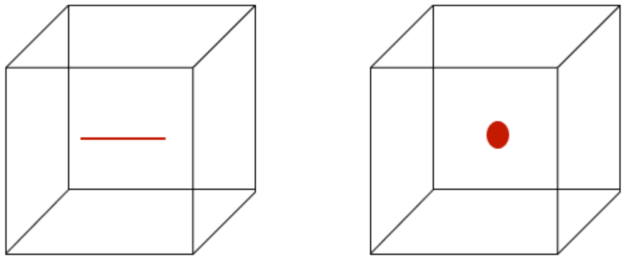


Figure 4. Homogenous concrete system



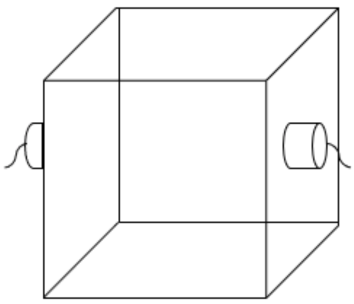
(a) (b)

Figure 5. Non-homogenous concrete system with (a) crack and (b) void/air hole

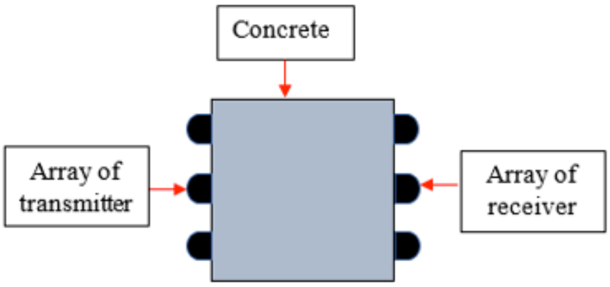
Homogenous concrete system is built without any defects while non-homogenous system includes the presence of defects in the structure. In this experiment, the defect comprises of two categories, which is crack and air hole (void). The data from the homogenous concrete system are used as a reference to the non-homogenous one.

3.3 Probing Method

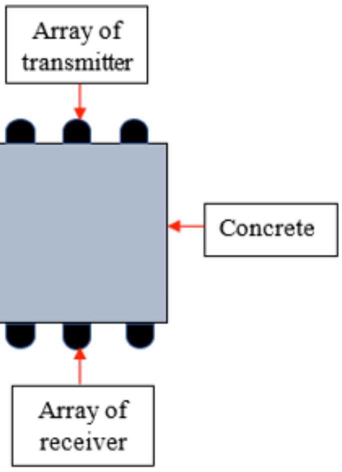
This experiment employs the concept of UPV. There are five methods of probing to be adopted, which are horizontally and vertically direct probing, horizontally and vertically indirect probing, and semi-direct probing. Figure 6, Figure 7, and Figure 8, shows the probing method adopted, respectively.



(a)

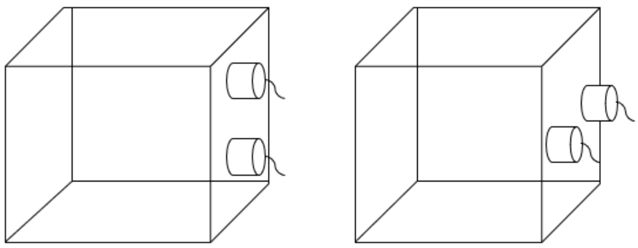


(b)



(c)

Figure 6. (a) Direct probing on concrete structure with (b) vertically probing and (c) horizontally probing



(a) (b)
Figure 7. (a) Vertically indirect probing and (b) horizontally indirect probing

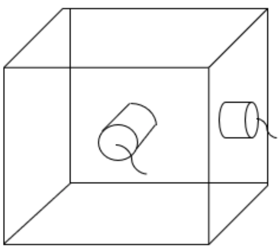


Figure 8. Semi-direct probing

Before the probing method is done, a cubic-designed of concrete model will first be marked with a grid of measuring points. Probing is done repeatedly to measure the ultrasonic wave (signal) velocity of the system. Ultrasonic sensor with frequency range of 50 kHz is used in this experiment as it is the most suitable for the concrete structure [13]. For the correct implementation of the method, sufficient acoustic coupler is used between the transducers and the concrete to allow the wave travel through the concrete specimen without reflecting [14].

3.4 Image Reconstruction

Sensitivity mapping technique is used to locate the defect area in specimen by comparing the output signal from the receiver of both homogenous and non-homogenous concrete structure, and classified using threshold method. The sensitivity mapping technique is constructed in Labview software. Figure 9 shows the applied threshold in sensitivity mapping technique.

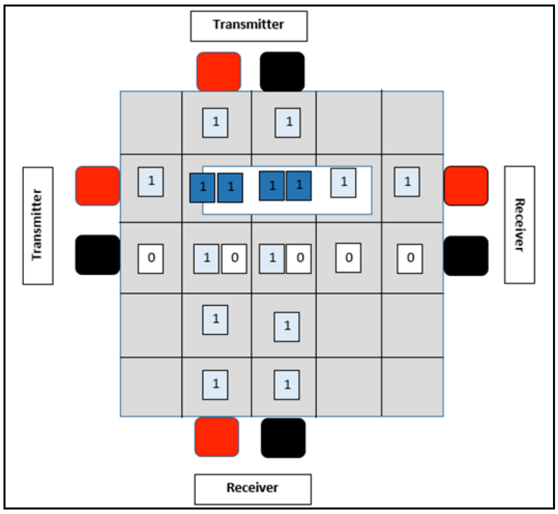


Figure 9. Sensitivity mapping technique [15]

If there are high differences on the output signal, the threshold method classifies it as ‘1’ (HIGH). If there are too small or no differences in the output signal, then it will be classified as ‘0’ (LOW).

4. EXPECTED FINDINGS

4.1 Homogenous Concrete System

Figure 10 shows the sketchup of homogenous concrete system designed in COMSOL Multiphysics. Ultrasonic sensors are located around the concrete modelling, based on different probing shown in Figure 6, Figure 7, and Figure 8. The data from the homogenous system used as the references for detecting the location of defects in non-homogenous concrete system.

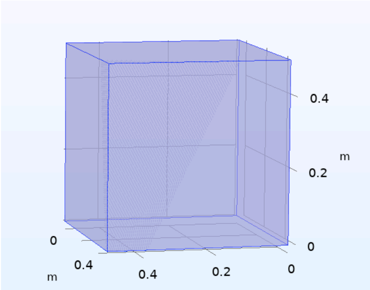


Figure 10. Homogenous concrete system

4.2 Non-Homogenous Concrete System

Figure 11 shows the sketchup of non-homogenous concrete system designed in COMSOL Multiphysics. The intact defects will be located in the concrete (in the sphere zone). By using different probing shown in Figure 6, Figure 7 and Figure 8, cracks and air hole in the concrete can be detected.

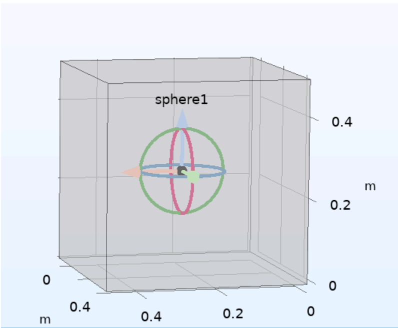
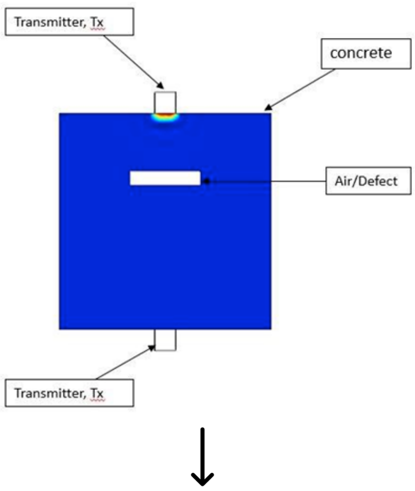


Figure 11. Non-homogenous concrete system

4.3 Sensitivity Mapping Technique

From the data comparison in homogenous and non-homogenous system, a mapping is developed to show the location of defects in concrete structure. The threshold method categorise the difference of the output signal from the receiver, in both systems. The expected result for direct probing is as shown in Figure 12.



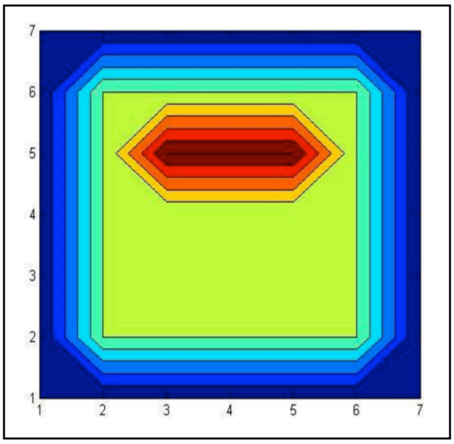


Figure 12. Sensitivity mapping for direct probing [15]

The non-destructive test using UPV method was to determine the location of defects in the concrete structure, without destroying the concrete specimen. The test is carried out by using different array of ultrasonic sensors, located around the concrete structure. The array of the sensors are shown in Figure 6, Figure 7, and Figure 8.

5. CONCLUSION

The work presented in this paper is the current research conducted to improve UPV method for concrete-defect detection. This improvement could provide a better solution for preventive and maintenance needs in assessing concrete structure. For future works, simulation of the homogenous and non-homogenous concrete system using COMSOL Multiphysics will be done to provide early information about the status of concrete. Defect image area are to be constructed by using sensitivity mapping technique to improve the identification of concrete defects. The implementation of different UPV probing methods on actual model of concrete structure will show the effectiveness of the proposed measurement system to be applied in real structure for preventive and maintenance needs.

ACKNOWLEDGMENT

The authors would like to thank Universiti Teknologi Malaysia for supporting the research study. The research is supported by the UTM Encouragement Research Grant (QJ13000.3851.19J63).

REFERENCES

[1] J. A. I. N. Harshit, and V. H. Patankar, “Advances in Ultrasonic Instrumentation for Inspection of Concrete/RCC Structures,” 2019.

[2] A. G. Davis, G. G. Clemena, N. A. Cumming, R. S. Jenkins, K. M. Lozen, L. D. Olson, R. Poston, P. H. Read, W. M. K. Roddis, M. J. Sansalone, and B. P. Simons, “Nondestructive test methods for evaluation of concrete in structures,” *American Concrete Institute, ACI, 228*, 1998.

[3] H. Azari, S. Nazarian, and D. Yuan, "Assessing sensitivity of impact echo and ultrasonic surface waves methods for nondestructive evaluation of concrete structures," *Construction and Building Materials*, 2014, vol. 71, pp. 384–391. doi: 10.1016/j.conbuildmat.2014.08.056.

[4] S. K. Dwivedi, M. Vishwakarma, and P. A. Soni, "Advances and Researches on Non Destructive Testing: A Review," *Materials Today: Proceedings*, 2018, vol. 5(2), pp. 3690–3698. doi: 10.1016/j.matpr.2017.11.620.

[5] M. Moore, B. M. Phares, B. Graybeal, D. Rolander, G. Washer, and J. Wiss, *Reliability of visual inspection for highway bridges, Final Report: volume 1* (Report No. FHWA-RD-01-105), Turner-Fairbank Highway Research Center, 2001.

[6] A. Carrión, V. Genovés, J. Gosálbez, R. Miralles, and J. Payá, "Ultrasonic signal modality: A novel approach for concrete damage evaluation," *Cement and Concrete Research*, 2017, vol. 101, pp. 25-32. doi: 10.1016/j.cemconres.2017.08.011.

[7] S. Gholizadeh, "A Review of Non-Destructive Testing Methods of Composite Materials," *Procedia Structure Integrity*, 2016, vol. 1, pp. 50–57. doi: 10.1016/j.prostr.2016.02.008.

[8] T. Kalyan and J. C. Kishen, "Experimental Evaluation of Cracks in Concrete by Ultrasonic Pulse Velocity," *APCNDT 2013, Asia Pacific Conference on Non-Destructive Testing, India,* 2013.

[9] P. Turgut and O. F. Kucuk, "Comparative relationships of direct, indirect, and semi-direct ultrasonic pulse velocity measurements in concrete," *Russian Journal of Nondestructive Testing,* 2006, vol. 42(11), pp. 745–751.

[10] L. Nobile and M. Bonagura, "Accuracy of non-destructive evaluation of concrete compression strength," *The 12th International Conference of the Slovenian Society for Non-Destructive Testing*, 2013, pp. 57–64. doi: 10.1504/IJMMP.2014.066920.

[11] M. K. Lim and H. Cao, "Combining multiple NDT methods to improve testing effectiveness," *Construction and Building Materials*, 2013, vol. 38, pp. 1310–1315. doi: 10.1016/j.conbuildmat.2011.01.011.

[12] H. Merdjana, A. Boukabou, and M. Grimes, "A high accuracy ultrasonic measurement system using the prism technique," *Measurement.*, 2017, vol. 114(2018), pp. 195–202. doi: 10.1016/j.measurement.2017.09.042.

[13] M. Slonski, K. Schabowicz, and E. Krawczyk, "Detection of Flaws in Concrete Using Ultrasonic Tomography and Convolutional Neural Networks," *Materials*, 2020, vol. 13(7), pp. 1–16.

[14] L. Pedreros, F. Cárdenas, N. Ramírez, and E. Forero, "NDT Non-Destructive Test for Quality Evaluation of Concrete Specimens by Ultrasonic Pulse Velocity Measurement," *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 844(1). doi: 10.1088/1757-899X/844/1/012041.

[15] M. U. Faruq, "NDT-Defect Detection on Concrete using Ultrasonic (through Transmission Method)," *B. Eng. thesis, Faculty of Engineering, Universiti Teknologi Malaysia*, 2016.