The study of ultrasonic pulse velocity on plain and reinforced damaged concrete

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Abstract. An ultrasonic pulse velocity (UPV) test is often applied to determine the quality of concrete structures. It is well known that there are several factors which can influence the reading of ultrasonic velocity in concrete. One of the factors is the presence of steel reinforcement. Therefore, this paper is intended to evaluate the ultrasonic pulse velocity propagation either in plain or reinforced damaged concrete. A study on sound concrete is also provided as a comparison. Three mixes of concrete were provided, with 25 MPa, 35 MPa, and 45 MPa target compressive strengths. The specimens were 200x200x200 mm cube concrete specimens and 100x150x1100 mm reinforced concrete beam specimens. Each specimen was examined for velocity readings in sound and damaged concrete (25% and 50% of maximum load). In all concrete grades of both plain and reinforced concrete, the ultrasonic velocity decreases as the damage level increases. During intact conditions, the velocity of reinforced concrete is around 4.5% higher than that of plain concrete. However, damaged reinforced concrete has a lower velocity than plain damaged concrete. Furthermore, a new equation for predicting ultrasonic pulse velocity in reinforced concrete is proposed.

1 Introduction

The ultrasonic pulse velocity method is a form of non-destructive testing in materials. In concrete application, this method has been used successfully for more than 60 years [1]. It has been applied to investigate the quality of concrete materials such as detecting any defects, internal cracking, and durability. In addition, the use of ultrasonic testing enables the users to predict in situ concrete compressive strength and the dynamic modulus of elasticity [1,2].

The principle technique of ultrasonic testing is through recording wave propagation in concrete materials. An ultrasonic wave pulse through the concrete is produced by a transmitter sensor at a point on the concrete surface and received by a receiver sensor on another surface. The travelling time between points is measured. The length between two sensors is known, allowing for the determination of velocity [1].

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Research on ultrasonic pulse velocity in concrete has been developed [3,4,5]. Most research studies the relationship between ultrasonic pulse velocity and the mechanical properties of concrete. According to measurements, the ultrasonic pulse velocity in steel is higher than that in concrete. Therefore, it is commonly supposed that when there is significant concentration of steel reinforcement in concrete, the velocity increases [1,6,7]. However, this condition is not always found during the testing. In some cases, the velocity is not obviously affected by the presence of reinforcement [8]; furthermore, the reinforcement decreases the pulse velocity in concrete [9]. Therefore, it must be recognized that the exact evaluation of reinforced concrete in structures using ultrasonic methods is still challenging. Moreover, besides the effect of reinforcement, various concrete damages can also be found during the measurement which influence the velocity. Therefore, this paper emphasizes the study of ultrasonic pulse velocity in plain and reinforced damaged concrete.

2 Theory and previous related research

The compressional wave velocity in concrete for the shear and surface waves are normally 60% and 55%, respectively. The specific velocity of a wave depends on the elastic properties and density of the materials. The compressional wave velocity in a homogeneous solid material in elastic conditions given by Equation (1).

$$V = \sqrt{\frac{KE}{\rho}} \tag{1}$$

where: V = compressional wave velocity, K = (1-μ)/((1+μ)(1-2μ)), E = dynamic modulus of elasticity, ρ = density, μ = dynamic Poisson's ratio.

The principles of the pulse velocity method in concrete are shown in Fig. 1. The transmitter sensor of the pulse velocity device transmits a wave into the concrete, and the receiver sensor, at a distance *L*, receives the wave through the concrete at another location.

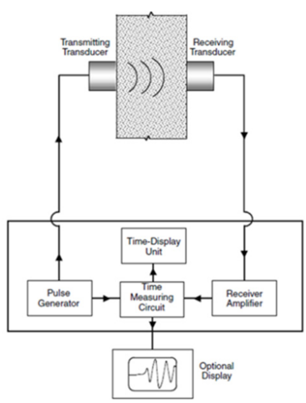

Fig. 1. Schematic diagram of pulse velocity test circuit [1].

The pulse velocity equipment display informs the transit time, Δ*t*, a time for the compressional wave propagating through the concrete. The compressional wave pulse velocity *V* is the length, L, divided by the pulse travelling time as shown in Equation (2).

$$V = \frac{L}{\Delta t} \tag{2}$$

For the same composition of concrete, the pulse velocity measured in reinforced concrete in the surrounding area of reinforcing bars is usually higher than in plain concrete. The reason is because the compressional pulse velocity in bars is 1.4 to 1.7 times that of plain concrete. The arriving wave at the receiving transducer travels partly in concrete and partly in steel. The increase in pulse velocity depends on the location of the reinforcing bar to the sensors, the dimensions and number of the reinforcing bars, their orientation with respect to the propagation path, and the pulse velocity in the surrounding concrete [1].

The pulse velocity in reinforcing steel is around 5900 m/s, but this has been shown to reduce with the bar diameter to as little as 5.1 km/s along the length of a 10 mm reinforcing bar in air. Beside the velocity pulse in concrete, the velocity along a bar inside of concrete is further affected by the condition of the bond between the steel and concrete as well. Some equations proposed have been established to consider the influence of reinforcing steel depending on the proximity of the measurements to the reinforcing bars, the diameter and number of bars and their orientation with respect to the propagation path [1,6] as shown in Equation (3).

$$\frac{V_c}{V} = 1 - \frac{L_S}{L}\left(1 - \frac{V_c}{V_S}\right) \tag{3}$$

where: V_c = velocity in concrete; V = velocity in reinforced concrete; V_s = velocity in steel; L = transmission length; L_s = total length of steel.

Various ultrasonic devices have been applied for research to determine longitudinal, transverse and surface wave propagation in concrete by direct and indirect methods. Measuring in rebar zones and in plain concrete, it was established that the obtained results are influenced by specific conditions, which was proven by significant UPV variations and changes obtained by comparing the measurement data obtained at various points. The results of the present research differ from previously formulated assumptions of UPV increasing in concrete rebar zones [9].

3 Experiments

3.1 Material

To study the effect of reinforcement on velocity in concrete, some target concrete compressive strengths were designed for 25 MPa, 35 MPa, and 45 MPa. The specific gravity of the coarse aggregate and fine aggregate were 2.56 and 2.65 respectively. Local crushed stone was used for the coarse aggregate with a 20 mm maximum diameter. The mixture proportions are shown in Table 1.

Table 1. Concrete mixture proportion.

Target Strength (MPa)	Water-Cement Ratio	Cement (kg/m^3)	Water (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)
25	0.56	360	205	740	1110
35	0.48	427	205	713	1070
45	0.42	477	205	693	1040

For each target strength of concrete, there are two kinds of specimen: plain concrete and reinforced concrete. The plain concrete was in the shape of 200 mm x 200 mm x 200 mm cubes; meanwhile the reinforced concrete was in the form of 100 mm x 150 mm x 1100 mm beams. There were three specimens manufactured for each type of plain concrete.

3.2 Method

Testing was conducted after all of the specimens reached 28 days' curing time. Ultrasonic pulse velocity testing measurement was developed from 'Pundit Plus CNS Farnell' and consisted of a transmitter, a receiver sensor, and ultrasonic device. Ultrasonic testing met the requirement of the American Society for Testing and Materials (ASTM) C597-09 "Standard Test Method for Pulse Velocity through Concrete". This standard adds some explanation that the ultrasonic pulse velocity in reinforcing steel will be higher than in plain concrete [10]. Direct measurement was adopted. Before testing, a thin layer of grease was attached to the surface of specimen to ensure that the waves could be transmitted correctly to the concrete. Fig. 2 shows the ultrasonic testing devices.

Fig. 2. Ultrasonic testing devices.

The ultrasonic wave was measured at some damaged condition of the concrete. Damage level was determined by a percentage of loads from maximum load, set by 25% and 50% of maximum load. Therefore, the wave was recorded during three conditions, which were sound (0% damage), 25% damage, and 50% damage. The concrete cubes were subjected to axial compression load; meanwhile the beam specimens were subjected to flexural load based on the third point loading mechanism. The experimental testing is shown in Fig. 3.

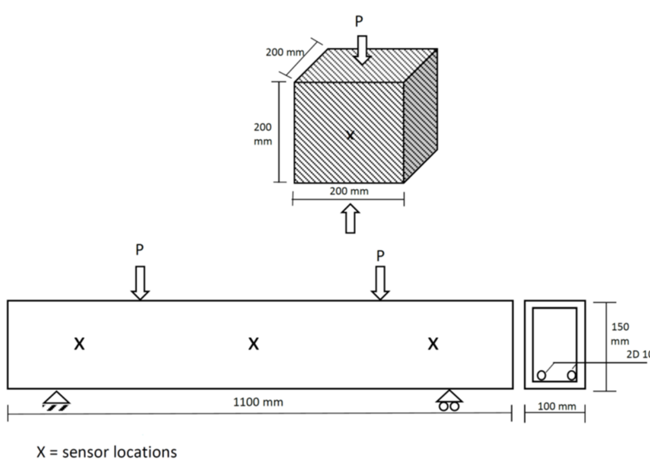

Fig. 3. Experimental testing.

4 Result and discussion

4.1 Ultrasonic pulse velocity of plain damaged concrete

In all concrete grades, the ultrasonic velocity decreases as the damage level increases. The sound concrete has the highest velocity, followed by the velocity of the 25% damaged concrete, while the lowest velocity was found at the concrete with 50% damage level as shown in Fig. 4. In this figure, it is also clearly stated that the higher compressive strength of the concrete gains the higher ultrasonic pulse velocity. However for damaged conditions, the velocity decrease in higher-grade concrete is more significant than in that in the lower grade ones.

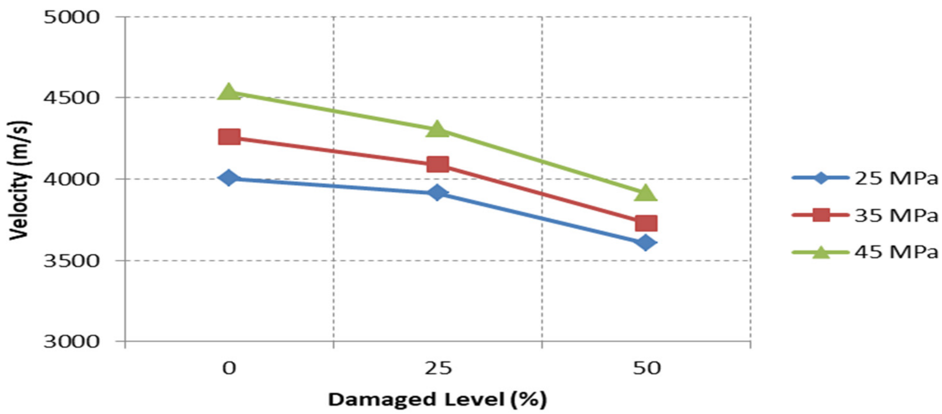

Fig. 4. Ultrasonic pulse velocity in plain damaged concrete.

Concrete with a 45 MPa compressive strength has an average velocity of 4535 m/s compared to the 4004 m/s of concrete with a compressive strength of 25 MPa. Furthermore, the velocity of 4535 m/s drops by 5.03% and 13.69% for the 25% and 50% damage specimens respectively. Compared to the 45 MPa target strength, 25 MPa concrete possesses an average velocity of 4004 m/s in a sound condition; however, this value falls by only 2.25% and 9.9% for the 25% and 50% damage specimens respectively. Lower graded concrete shows a better performance of wave propagation in each damage level.

4.2 Ultrasonic pulse velocity of reinforced damaged concrete

Similar to plain concrete, in all concrete grades, the ultrasonic velocity decreases as the damage level increases. The sound reinforced concrete has the highest velocity, followed by the velocity of the 25% damaged concrete, while the lowest velocity was found at the 50% damaged concrete as shown in Fig. 5. In this figure, it is obvious that the higher the compressive strength of concrete, the higher the ultrasonic pulse velocity. Unlike plain concrete, the velocity decreases more in lower grade concrete.

The sound reinforced concrete with 45 MPa compressive strength has average velocity of 4650 m/s compared to the 4182 m/s of the concrete with a compressive strength of 25 MPa. Furthermore, the velocity of 4650 m/s drops by 8.34% and 18.25% for the 25% and 50% damaged specimens respectively. Meanwhile for the 25 MPa target strength, this concrete has an average velocity of 4182 m/s in sound condition, and this value falls greater by 11.81% and 21.09% for the 25% and 50% damaged specimens respectively. Higher-graded concrete shows better velocity decreases in each damage level. This behaviour is different from that of plain concrete, because in reinforced concrete the mechanism after damage is more complex due to the presence of reinforcing bars and load.

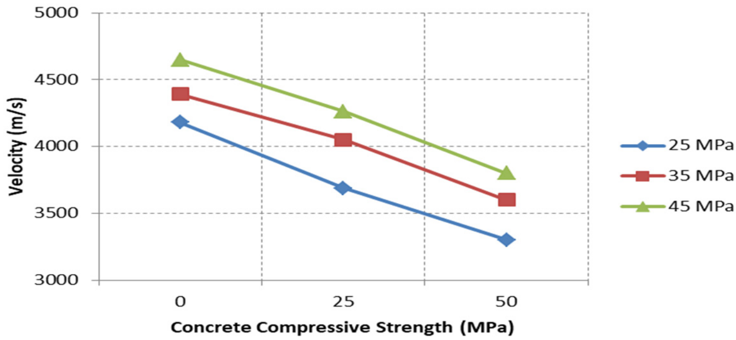

Fig. 5. Ultrasonic pulse velocity in reinforced damaged concrete.

4.3 Influence of damage level to the ultrasonic pulse velocity of plain and reinforced concrete

It is generally observed that higher damage levels produce lower ultrasonic pulse velocities in all concrete grades as illustrated in Fig. 6. In addition, in a sound condition, reinforced concrete has a higher velocity than plain concrete for each concrete strength. It is observed that the velocity of plain concrete and reinforced concrete were 4004 m/s and 4182 m/s respectively for 25 MPa. The velocity of plain concrete is 4.5 % higher than that of reinforced concrete. Similar behaviour is found in other grades, with the average difference of velocity being 3.36%. This is in line with previous research and theories that ultrasonic pulse velocity in reinforced concrete is higher than that in plain concrete [1,6,9]. The velocity of steel is around 5900 m/s; therefore it influences the overall velocity of reinforced concrete.

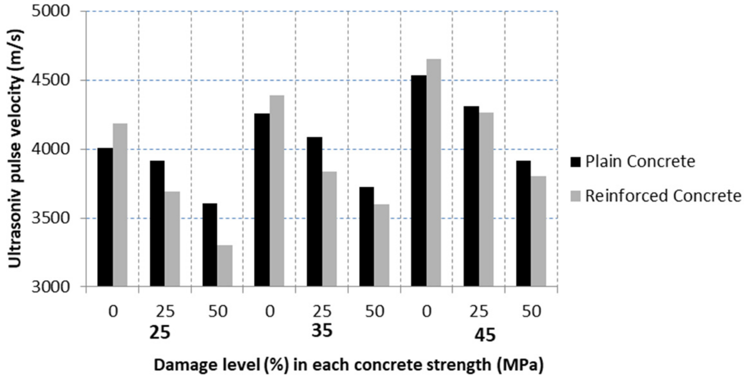

Fig. 6. Effect of damaged level to the velocity.

However, unlike the undamaged concrete, the velocity is different in damaged specimens for all concrete grades. The velocity of damaged reinforced concrete is lower than plain damaged concrete. For example, it is found that for 25 MPa, with respect to the 25% and 50% damaged specimens, the velocity of the plain concrete are 3914 m/s and 3604 m/s respectively; meanwhile the velocity of the reinforced concrete decreases to 3688 m/s and 3300 m/s respectively. The average velocity reading decrease in damaged reinforced concrete is around 4.61% compared to the average velocity reading in plain damaged concrete. This is parallel to recent previous research as reveals that there is a decrease of velocity in rebar concrete [9]. Some new findings are found as well regarding the ultrasonic pulse velocity in this research, that the damaged reinforced concrete possesses a lower velocity than the plain damaged one. The higher the damage level, the lower the observed velocity decrease. Dismantling of the reinforcing bar from the concrete surfaces and some cracking in the concrete might occur in damaged concrete, causing more time propagation of the waves and resulting in a lower velocity reading.

4.4 Comparison of experimental result with theoretical method

The experimental result of the pulse velocity in plain and reinforced concrete are then compared to Equation 3. The apparent experiment result for the ultrasonic pulse velocity is almost similar to the theoretical method adopted from [1] as shown in Table 2. It is applicable for all concrete grades.

Table 2. Comparison between experiment result and theoretical method.

Concrete Compressive Strength (MPa)	Ultrasonic Pulse Velocity (m/s)			Difference (2)/(3)
	Plain Concrete	Reinforced Concrete		
		Experiment	Theoretical	
	(1)	(2)	(3)	
25	4004	4182	4110	1.02
35	4259	4391	4345	1.01
45	4535	4650	4596	1.01

In this paper, the theoretical method can only be applied for intact reinforced concrete due to the higher velocity obtained compared to plain concrete during the experiment. However, the theoretical method cannot be applied to damage concrete due to the lower velocity obtained than that of plain concrete during the experiment. Therefore, a new equation is proposed in this research to predict the ultrasonic pulse velocity in reinforced damaged concrete based on experimental results as shown in Fig. 7. This proposed equation is applicable for normal strength concrete and reinforcing bars as explained in 3.

$$y = -18.60x + 4411.8 \tag{4}$$

Where: y = ultrasonic pulse velocity in reinforced concrete (m/s); x = concrete damage level (%).

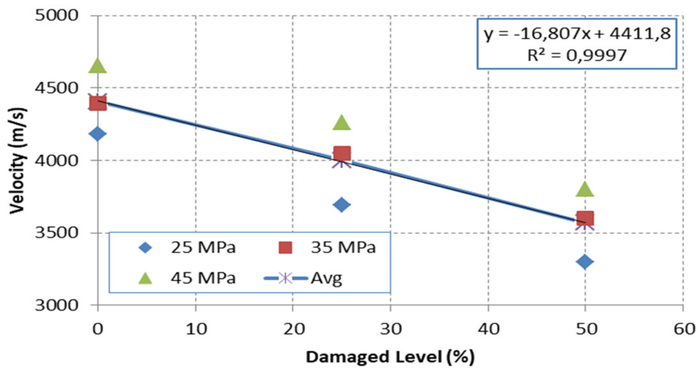

Fig. 7. Ultrasonic pulse velocity prediction for damage reinforced concrete.

5 Conclusion

This paper studies the ultrasonic pulse velocity in plain and reinforced damaged concrete with various concrete grades of 25 MPa, 35 MPa, and 45 MPa. In all concrete grades of both plain and reinforced concrete, the ultrasonic velocity decreases as the damage level increases. During intact conditions, the velocity of reinforced concrete is around 4.5% higher than that of plain concrete. However, damaged reinforced concrete has a lower velocity than plain damaged concrete. The higher the damage level, the lower the recorded velocity. Reinforcing bar dismantling from the concrete surfaces and some cracking might occur in damaged concrete, causing more propagation time of the waves and resulting in a lower velocity reading. Furthermore, a new equation for assuming ultrasonic pulse velocity in reinforced concrete is proposed in this paper.

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