Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review

A Ndagi†, A A Umar1, F Hejazi1, M S Jaafar1

1Department of Civil Engineering, University Putra Malaysia, 43400, UPM Serdang, Malaysia

*bagae001@gmail.com

Abstract: As concrete structures age, concrete quality tends to deteriorate for reasons which include frost damage, acid attack, sulphate attack, fire damage or as a result of bad construction practice. Thus, these effects develop as distresses thereby undermining the general performance of a structure. Result from Ultrasonic Pulse Velocity (UPV) test is inevitably affected by the properties of the concrete under test which contributes in abating the test results. Hence, this paper reviews the UPV test by considering arrangement options and common factors which affect the result obtained from the test and attempts to make recommendations to obtaining reliable results. Out of several conclusions drawn, it is worthy to mention that the direct arrangement for conducting UPV test was found to be the most suitable. In addition, the UPV test was learnt to be poor in assessing concrete strength but when combined with a Rebound Hammer Test, which is also Non-destructive, the result is substantiated.

1. Introduction
The high compression strength of Portland Cement Concrete (PCC) has earned it a universal reputation of being the most adopted construction material. In composite constructions, PCC helps to withstand compression forces on the member while steel reinforcing bars withstand tensile stresses. This combination is known to be accompanied with prospects of making good load bearing structural elements and constraints in which defect of concrete would result in a distress in steel or vice-versa. As concrete structures age, concrete quality may tend to deteriorate for reasons which vary from chemical reactions, frost damage, acid attack, sulphate attack and settlement in the soil etc. Grantham [1] categorically stated that from previous experiences, it is comfortable to say that large proportion of deterioration in concrete will be caused by steel corrosion. As a result, these deteriorations will mostly be from carbonation, light cover thickness or the presence of chloride salts. He however added that, in some cases, it could be from alkali-silica reaction, freeze-thaw damage, sulphate attack, structural cracks etc. Considering this, for best performance of a structure, the durability and fitness of the concrete cannot be overlooked.

It has thus become imperative to assess the suitability of concrete structures for its intended use after attaining its design strength. This is preferable to be non-destructive, without causing damage to the concrete and if need be, after then, to semi destructive [2]. A number of tests are available for Non Destructive Testing (NDT) and destructive testing of concrete. To mention a few, they include
Ultrasonic Pulse Velocity, rebound hammer, Ground Penetration Radar (GPR), Carbonation, Electrical Half Cell Potential (HCP), etc. While the semi-destructive tests include pull-out, pull-off, coring etc. Any of these tests are conducted on new or existing structures to assess various parameters such as confirming or locating suspected deterioration of concrete [2] or rather determine the concrete uniformity, possibly preliminary to core cutting and monitor long term changes in concrete properties.

All the aforementioned tests checks for a particular parameter in a concrete structure, but Ultrasonic Pulse Velocity have been known to be very useful in evaluating homogeneity and quality of concrete both in fresh and hardened condition [3]. The Ultrasonic Pulse Velocity (UPV) is a comprehensive method, which provides information on both the uniformity and deterioration of the material investigated which has been in use since the early 1940s [4]. The equipment works on the general principle that voltage pulses produced from a transmitting transducer is transformed into wave burst to a receiving transducer. The transmitting transducer is affixed to the concrete under test with an acoustic coupling material like grease or petroleum jelly rubbed to both surfaces to give a smoother contact and waves are propagated through the concrete. Due to different boundary conditions in the concrete, the wave travels at different phases. A system of waves is developed, which include both longitudinal and shear waves (P-waves & S-waves). Here, the longitudinal waves are the first to arrive at the receiving end and immediately they are transformed to into signals and subsequently the period of travel of the waves are indicated on the instrument [2].

Popovics et al. [5] after an investigation reported that frequencies between 25-250 kHz are widely used since the wavelengths indicate the ability of UPV to detect crack sizes and to overcome aggregate. He added that the use of such wave measurements for estimating concrete properties, like the dynamic modulus of concrete, represents one of the most common NDT techniques for testing concrete in recent days. Debjan et al. [6] also used this method to evaluate the dynamic modulus of asphalt mixtures and found that Ultrasonic Pulse Velocity gave a helpful result.

Since civil engineering structures depreciate both in strength and value as time passes, to avail this, there would be need for the adequate maintenance of these structures and in doing this, critical decisions would have to be taken while opting for a technique and materials for repair of the structure. Prior to rehabilitation, some series of tests needs to be conducted to be able to gain an up-to-date information on the state of the structure and without interrupting the usage of the structure. Ultrasonic Pulse Velocity has proven to reveal vital information on the quality and uniformity of concrete non-destructively. However, this process can be associated with errors and flops that may lead to deceitful results. This paper hence, reviews the applicable methods of conducting the test, factors that can affect the result and presents recommendations on how to obtain best results using Ultrasonic Pulse Velocity in testing concrete structures.

2. Deterioration in Concrete

In general, concrete due to its excellent durability has made it renowned in the world of construction around the globe. However, the attack from external factors results in deterioration in concrete. But for reasons which include limitations in material, design and detailing, construction method, chemical attacks, seismic factors and environmental effects etc. causes concrete to deteriorate which jeopardizes the general functionality of the concrete. Deterioration in concrete can appear in different forms such as cracks and shrinkage, scaling, delamination, spalling efflorescence, honey combing etc [2]. This thus indicates how important it is to monitor concrete structures both during construction and under service loads due to the safety problems it poses. Therefore it has become necessary to understand vulnerabilities of concrete so as to reduce severe damages and costly repair works.
3. Principle of Operation of Ultrasonic Pulse Velocity
The ultrasonic pulse velocity test operates on the principle that an electro-acoustical transducer generates an ultrasonic pulse which is induced into the concrete and which undergoes several reflections at the various material phase boundaries of the concrete specimen. The velocity of the induced pulse depends on the properties of the concrete and the presence of discontinuities i.e cracks. That is to say a good quality concrete produces higher velocity values while a concrete with discontinuities gives up lower velocity values. In obtaining result, electrical signals are converted into mechanical vibrations (transmitting mode) and mechanical vibrations into electrical signals (receiving mode) by the transducers.

When an impulse is propagated through a solid mass, the generated waves are classified into three namely; surface waves, shear/transverse waves (S-waves) and longitudinal waves (P-waves). The Surface waves have an elliptical particle displacement making them the slowest, while the shear or transverse waves having particle displacement at right angles to the direction of travel are faster than the surface waves. Longitudinal waves with particle displacement in the direction of travel are the fastest and considered as more significant than the others since they provide more useful information [7]. These waves are primarily produced by the electro-acoustic transducers with the other wave types being too slow to cause much interference.

4. Device and Methods used in Conducting Ultrasonic Pulse Velocity test
4.1. The Ultrasonic Pulse Velocity Test Instrument.

![Figure 1. Typical Ultrasonic Pulse Velocity Testing Arrangement](image)

The test instrument comprises of components (transducers) which produces wave pulses that propagates through the concrete and the waves being received by a receiving transducer in which the time taken to by the pulse to travel through the concrete is precisely measured.

In Ultrasonic Pulse Velocity, the instrument consists of two transducers (Transmitting and Receiving), a timer and a console. It is possible to connect the instrument to an oscilloscope to observe the pulse being received [8].

Bungey et al. [9] also in his study stated that a transmitting transducer electronically spawns repetitive voltage pulses which are further converted to wave bursts of mechanical energy noting the importance of applying a soft jelly between the contact of the transducer and the concrete surface. On
the other hand, as the wave burst travels, it intercepts a receiving transducer whose distance is known from the point of propagation thereby transforming the earlier generated mechanical energy to voltage pulses but still maintaining a uniform frequency. Then, the electronic timer displays the time of discharge and reception of waves on the device.

Tarun et al. [8] mentioned that based on the required application and nature of concrete material to be tested, transducers are available with differing frequencies. He added that for concrete samples with short length, a transducer with high frequency would be best to use; specifically above 100kHz, meanwhile, low-frequency transducers are best for bigger concrete samples or long length samples, specifically 25 kHz. Also, AIAE [2] in its guidebook advised that transducers with frequencies in the range of 50 kHz and 60 kHz are best to use even though the ones with higher frequencies tends to have a better spectrum at the point of propagation, but as it travels, it is easier for it to get weaker compared to the low frequency waves. However, Bungey et al. [9] (in their research generalized that frequencies in the range of 20kHz and 150kHz from any kind of transducer could be used for concrete. They considered the most commonly used as the piezo-electric crystal but disclaimed that it has a very wide range which could consume more time before one is able to figure out the best frequency to use. This may require many trial frequencies which would be time consuming. Thus, as stated by [8] and [2], these specific ranges of frequencies informs a user best and would save more time by starting with fewer trials of two to three frequencies.

| Path length (mm) | Natural frequency of transducer (kHz) | Min. transverse dimensions of members (mm) |
|------------------|--------------------------------------|------------------------------------------|
| Up to 500        | 150                                  | 25                                       |
| 500-700          | > 60                                 | 70                                       |
| 700 – 1500       | > 40                                 | 150                                      |
| above 1500       | > 20                                 | 300                                      |

Adopted with right from ACI

4.1.1. Types of Ultrasonic Pulse Velocity Test Instrument. The UPV instrument is commercially available worldwide in different configurations. The PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) is the most widely used. The PUNDIT instrument which is manufactured by Proceq in Switzerland comes in different versions which are PUNDIT Live Array Pro, PUNDIT Lab (+), PUNDIT 200, PUNDIT 200 Pulse Echo and PUNDIT 250 Array all with distinguished functions and prospects. PUNDIT Live Array Pro enable connection to iOS devices, PUNDIT Lab (+) is primarily used in the laboratories, PUNDIT 200 supports extended range of measurements and PUNDIT 200 Pulse Echo is applicable to objects where access is restricted to a single side while the PUNDIT 250 Array is most applicable for thickness measurements.

Other UPV instruments popularly used include:
- CUTE 103A (Concrete Ultrasonic Testing Equipment) produced by Canopus in India
- The 58-E4800 UPV tester manufactured by Control Group in Italy also has an advanced version known as PULSONIC 58-E4900 Ultrasonic Pulse Analyser. It is featured with an oscilloscope which will measure Dynamic Modulus of Elasticity of concrete sample. It is also able to quantify the weakness energy undergoes in the course of propagation. This stand out to assess concrete strength which has been a major disadvantage in the use of UPV instruments by incorporating the results of pulse velocity and rebound number from hammering of the concrete.
4.2. Arrangements for Ultrasonic Pulse Velocity Test

In the measurement of concrete deterioration by Ultrasonic Pulse Velocity, it is important that good level of precision is maintained to obtain accurate results [1]. However, for any of the arrangements being adopted, it is essential that the surface where the transducer is to be placed is prepared free of dirt and rubbed with petroleum jelly or soap to achieve good acoustic coupling. If surface is too rough, grease could be used so as to provide a relatively smooth contact with the transducer [10]. In essence, three basic arrangements of transducers for conducting the UPV test are available namely:-

a) Direct or Opposite transmission arrangement  
b) Semi-Direct or Diagonal transmission arrangement  
c) Indirect or Surface transmission arrangement

4.2.1. Direct Transmission. The direct transmission is an arrangement type where both the transmitting and receiving transducers are coupled on the surface of the concrete directly opposite each other. Malhotra et al. [11] commented that regarding the determination of the quality of concrete, using the direct method would be the best option since it provides a well-defined path that could be measured easily. Hannachi and Guetteche [4] concluded to have said that the direct arrangement is the most widely used method because there is maximum pulse energy which is transmitted and received so this is the most satisfactory method. In IAEA Guidebook on Non Destructive Testing of Concrete, the direct method was chosen as the best option to adopt. This arrangement would unarguably yield the best and most satisfactory result since the transmission of the maximum pulse energy is measured at
right angles to the face of transmitter. These indicates that it is a unanimous concept for the direct method to give best result.

4.2.2. Semi-Direct Transmission. The semi-direct arrangement is less sensitive than the direct, but more sensitive than the indirect arrangement. When a semi-direct arrangement is to be used, certain technical rules are advised to be adopted to obtain reliable results. Bungey et al. [9] mentioned them to be maintaining a small angle between transducers and short path length; he further warned that there might be a diffraction of signals if these requirements are not adhered to due to attenuation of the pulse being transmitted.

4.2.3. Indirect Transmission. The last method is known as the indirect transmission where the transducers are positioned on the same platform [12]. Out of the three testing methods, the indirect method is known to give the most unreliable result, due to the fact that amplitude of the received signal could be as low as 3% [11] in comparison to the received signal in a direct transmission and thus it is used only when surface specimen can be tested [13]. This method is carried out mainly when a single side of the element is accessible when it is necessary to determine the depth of a crack or the presence of multiple layers in the same element [4].

5. Factors Affecting Ultrasonic Pulse Velocity

The pulse velocity is not affected in anyway by the geometry or shape of the concrete material being tested. It is however affected by factors such as cement type [14], aggregate type and size, water cement ratio, distance between transducers [15], admixtures, positioning of the transducers and concrete age [4].

In a research by Hannachi et. al. [16], it was found that samples containing aggregates with rounded edges gave up lower propagation speeds than samples containing crushed aggregate. This effect could be seen in both the chemical and physical differences of specimen. For the chemical difference, the British Institute of NDT has observed that concrete samples cured under saturated conditions have higher pulse velocity than samples cured in open air. However, the degree of saturation as a parameter has also been found to affect the pulse speed by almost 4% [10]. A research by Lencis et. al. [17] shows that the rate of changes in UPV values can be said to be approximately equal to rate of concrete saturation in water. They further concluded that there was no definite relationship between moisture content and UPV at the beginning of hydration of concrete.

Panzera [18] in his study which investigated the effect of low water/cement ratio on UPV showed that low pulse velocities were obtained for regions with low compaction or voids which seem to indicate poor water/cement ratio. Furthermore, a research by Ye et. al. [19] which studied concretes with different water/cements concluded that concrete mixes having lower water/cement ratios had higher values of UPV, which indicated a higher amount of solid particles (aggregate components) to liquid. Trtnik et. al. [20] from their research reported that the relationship between amount of capillary voids (which influences the water/cement ratio) and pulse velocity is only significant at the end periods of cement hydration. In addition, Jones [21] in a test conducted in the laboratory, was able to proof that the effect of distance between transducers is more pronounced due to errors caused by the heterogeneous nature of concrete but this is not same when conducted on field because the member length is larger.

Steel in concrete was also found to affect test result of UPV by [14] to cause pulse velocity reduction by 1.2 to 1.9 times less the propagation speed in the presence of steel reinforcement. However, Bungey [10] in his research confirmed that the effect of the presence of steel reinforcement is more pronounced in only the direct transmission method. The research concluded that difference in UPV values in plain and reinforced concrete was smaller when the reinforcement diameter was smaller but such effect was rather not observed in indirect transmission method. Presence of steel should as much as possible be avoided when selecting the position of the transducers especially in
weaker concrete where the effect is more pronounced. If this is unavoidable, correction factors recommended by BS code are available for use in the correction of the effect of reinforcement.

Sturrup et. al. [22] after using pulse velocity to measure the compressive strength of concrete, deducted from his test that unless temperatures exceed 20°C, pulse velocities are not significantly affected by temperature effects but as temperatures exceed 40°C, correlations to pulse velocities can be seen to range between +2 to +5% in air cured concrete and between +1.7 to +4% in water saturated concrete. It is on this note that [15] advised corrections recommended in BS: 1881 Part-203 to be made when temperature of samples exceeds 20°C.

**Table 2. Correlation of Temperature to Pulse Velocity in Air Dried and Water Saturated Concrete.**

| Temperature (°C) | Correlation to the measured pulse velocity | Air dried concrete | Water saturated concrete |
|------------------|------------------------------------------|--------------------|--------------------------|
| 60               | %                                        | +5                 | +4                       |
| 40               | %                                        | +2                 | +1.7                     |
| 20               | 0                                        | 0                  | 0                        |
| 0                | -0.5                                     | -1                 |                           |
| -4               | -1.5                                     | -7.5               |                           |

Adopted with right from ACI

Regarding the positioning of the transducers, Turgut et. al. [7] urged for proper positioning of the transducers for obtaining accurate readings. He added that the type of contact between the transducer and concrete surface is of utmost importance as improper contact may lead to inaccurate pulse speed readings. As important as this is, Bungey [10] also had to stress that the transducer coupling to the concrete surface affects the signal strength at the receiving end and the pulse transit time, therefore adequate coupling should be provided by applying pressure and some coupling agent.

**6. Prospects of Ultrasonic Pulse Velocity Test**

Ultrasonic Pulse Velocity testing is an electronic non-destructive testing that is applicable to both new and existing structures. Concrete evaluation instruments which propagate wave bursts of mechanical energy tends to provide quicker and reliable results with the advantage of not causing any damage to the concrete under test.

Tomsett [23] reported that research on ultrasonic pulse velocity testing has raised some concerns about trusting its results, however, a renowned civil engineering blog (IamCivilEngineer, 2013) disagrees by presenting its view based on the ability of UPV to pass through concrete and revealing information about its internal structure. Jason (2017) also admitted that NDT as a whole is attached with so many prospects such as its cheapness, and ease in use without destroying the concrete sample like coring does.

**7. Limitations of Ultrasonic Pulse Velocity Test**

Due to the non-homogeneity of concrete as a material (it is composed of different materials such cement, aggregates; both fine and coarse and water), it has deficiencies and inconsistencies such as pores, voids, inter-phase differences between cementitious material zones and aggregate zones, and ultimately micro-cracks. These deficiencies make the use of UPV as a technique susceptible to limitations. Therefore a lack of precision exists in the use of UPV for early age detection of damage.
because there exists a difference in sensitivity to frequency by the electro-acoustical waves. For example, high frequency waves are required in determining non-structural cracks at early concrete ages, while for structural cracks found in concrete in service, such high frequency waves require some reduction in value [21]. In concrete samples containing aggregates contaminated with silica, a reaction known as the alkali aggregate reaction occurs which leads to cracks. When these cracks absorb water, they expand to form gels, which means higher frequencies are required to measure the crack depths. This leads to inconsistencies in obtaining the pulse velocities in such concrete specimens [16].

It is not left out that the technique is restricted or limited to regions without cracking when it comes to detection of damage caused by fire, the fact that the technique only provides an estimate of the degree of cracking and the unreliability of the method in detecting damages in wet concrete constitutes a major setback. Hannachi et al. [16] in their study obtains that the use of UPV for the compressive strength evaluation is not recommended due to a number of factors affecting the relationship between concrete strength properties and UPV readings; an idea which [11] also shares considering it as the least suitable method for estimating concrete strength. The only remedy being the existence of correlations carried out before the UPV test is conducted [7]. But Malhotra [11] fears that calibrations are affected by numerous factors that even in an ideal state of a particular calibration, there is tendency that a satisfactory confidence level of 80% cannot be attained in predicting the concrete strength. It is thus emphasized that UPV tests be evaluated and interpreted by engineers with adequate knowledge of the technique. Bungey [10] however regards this as a limitation in the use of UPV as an NDT technique if only well-trained operators and engineers well versed in UPV with knowledge about factors affecting pulse readings would be required to interpret results.

8. Reliability of Test Result from UPV

Bungey [9] reported that UPV method for assessment of concrete test generally suffer disadvantage where concrete strength is required, despite the fact that UPV play valuable role by in-place evaluation of concrete structures. Popovics et al., [5] stated that the UPV test’s reliability for concrete strength prediction is often questioned and criticized making it more commonly used for measuring the homogeneity of concrete. A research by Mahdi et. al. [24] shows that the lowest accuracy obtained under the UPV testing falls under the estimation of strength. Therefore, calibration curves are required for an attempt to be made in making correlations between compressive/flexural strength and pulse velocities. This is because the accuracy falls rapidly as higher strength levels are reached. However significant accuracy levels might be reached when the technique is combined with the rebound hammer test by using calibration curves providing more acceptable precision readings.

In addition, Komlos et al. [25] found that assessment of certain properties of concrete by the use of UPV can be highly uncertain and unpractical due to the fact that UPV is affected by numerous factors and also the inconsistency of procedures and recommendations by different standards of various nations. This technique has been found to give unreliable and inaccurate results when applied for the detection of deterioration of concrete. A mildly accurate result may however be obtained when the method is applied in the assessment of fire damage [26].

Meanwhile, for the assessment of cracks, UPV has been found to be relatively reliable because no comparison between other material properties (such as compressive strength) with pulse velocities are required. However Tomsett [23] found that this is not true for cracks filled with water because water affects the flight path of the pulse. A maximum error of up to 7% has been noticed when detecting cracks using UPV. Similarly, measurement of layer thickness was found by [25] to be accurately conducted using the UPV technique via the indirect method, although the results obtained are pure estimation and restricted to a particular range of thickness.
9. Conclusion
Ultrasonic Pulse Velocity for the last few decades has been one of the most common NDT methods used in the assessment of deterioration in concrete structures. Its reliability, consistency and accuracy in detecting certain distresses in concrete structures cannot be matched by most of the other NDT techniques on their own. Hence, from the study carried out, the following conclusions have been drawn;

1. The direct method of transmission yields the highest accuracy both in the casting and horizontal directions when compared with the indirect and semi-direct methods of arrangement.
2. The UPV technique is affected by several factors. The most significant include presence of reinforcement in the pulse vicinity, water-cement ratio, path length and the positioning of the transducers. The less significant factors include cement type, temperature to a certain extent, shape and type of aggregates and shape of test specimen.
3. UPV is a relatively poor technique for assessing concrete strength unless combined together with other strength tests, such as the rebound hammer.
4. The technique is accompanied with the limitations that:
   • It lacks precision when detecting deterioration during early concrete ages
   • There is inconsistency when it used in assessing deterioration of concretes with silica bound aggregates.
   • The evaluation of UPV results requires high level of knowledge, training and experience.

References
[1] Grantham M. 2003 Diagnosis, inspection, testing and repair of reinforced concrete structures. *Adv Concr Technol*;2:1–54.
[2] IAEA. 2002 Guidebook on non-destructive testing of concrete structures.
[3] Benaicha M, Jalbaud O, Roguiez X, Hafidi Alaoui A, Burtschell Y. 2015 Prediction of Self-Compacting Concrete homogeneity by ultrasonic velocity. *Alexandria Eng J*;54:1181–91.
[4] Hannachi S, Guetteche MN. 2014 Review of the ultrasonic pulse velocity: Evaluating concrete compressive strength on site. *Proc. Sci. Coop. Int. Work. Eng. Branches, Istanbul, Turkey*.
[5] Popovics JS, Rose JL. 1994 A survey of developments in ultrasonic NDE of concrete. *IEEE Trans Ultrason Ferroelectr Freq Control*;41:140–3.
[6] Majhi D, Karmakar S, Roy TK. 2017 Reliability of Ultrasonic Pulse Velocity Method for Determining Dynamic Modulus of Asphalt Mixtures. *Mater Today Proc*;4:9709–12.
[7] Turgut P, Kucuk O. 2006 Comparative relationships of direct, indirect, and semi-direct ultrasonic pulse velocity measurements in concrete. vol. 42..
[8] Naik TR, Malhotra VM, Popovics JS. 2004 The ultrasonic pulse velocity method. *Handb Nondestruct Test Concr*;169–88.
[9] Bungey JH, Grantham MG. 2014 *Testing of concrete in structures*. Crc Press;.
[10] Bungey JH. The Influence of Reinforcement on Ultrasonic Pulse Velocity Testing. *Spec Publ n.d.*;82.
[11] M. Malhotra V, Carino N. 2004 *CRC Handbook on Nondestructive Testing of Concrete*..
[12] Malek J, Kaouther M. 2014 Destructive and Non-destructive Testing of Concrete Structures.
Jordan J Civ Eng; 8.

[13] Hong R. 2012 Damage detection in fiber reinforced concrete with ultrasonic pulse velocity testing. University of Maryland, College Park;

[14] Jones R. 1954 Testing of concrete by an ultrasonic pulse technique, RILEM Int. Symp. Nondestruct. Test. Mater. Struct. Paris, vol. 1,

[15] Jones R, Façoaparu I. 1954 Recommendations for testing concrete by the ultrasonic pulse method. Matériaux Constr 1969;2:275–84.

[16] Hannachi S, Guetteche MN. 1954 Application of the combined method for evaluating the compressive strength of concrete on site. Open J Civ Eng 2012;2:16.

[17] Lencis U, Udris A, Korjakins A. 2013 Moisture effect on the ultrasonic pulse velocity in concrete cured under normal conditions and at elevated temperature. Constr Sci;14:71–8.

[18] Panzera TH, Rubio JC, Bowen CR, Vasconcelos WL, Strecker K. 2008 Correlation between structure and pulse velocity of cementitious composites. Adv Cem Res;20:101–8.

[19] Ye G, Van Breugel K, Fraaij ALA. 2001 Experimental study on ultrasonic pulse velocity evaluation of the microstructure of cementitious material at early age. vol. 46.

[20] Trtnik G, Kavcic F, Turk G. 2008 Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. vol. 49.

[21] Jones R. 1962 Non destructive testing of concrete. University Press;

[22] Sturrup VR, Vecchio FJ, Caratin H. 1984 Pulse velocity as a measure of concrete compressive strength. Spec Publ;82:201–28.

[23] Tomsett HN. 1980 The practical use of ultrasonic pulse velocity measurements in the assessment of concrete quality. Mag Concr Res;32:7–16.

[24] Shariati M, Ramli-Sulong NH, KH MMA, Shafigh P, Sinai H. 2011 Assessing the strength of reinforced concrete structures through Ultrasonic Pulse Velocity and Schmidt Rebound Hammer tests. Sci Res Essays;6:213–20.

[25] Komlos K, Popovics S, Nürnberggerová T, Babal B, Popovics JS. 1996 Ultrasonic pulse velocity test of concrete properties as specified in various standards. Cem Concr Compos;18:357–64.

[26] Hellier C. 2001 Handbook of nondestructive evaluation. vol. 10. Megraw-hill New York;