INVESTIGATION ON APPLICABILITY OF ULTRASONIC PULSE VELOCITY MEASUREMENTS TO ESTIMATE THICKNESS OF REINFORCED CONCRETE WALL PANEL

Z.T.M. FAZLI

(168907G)

Degree of Master of Science in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa
Sri Lanka

JULY 2021

INVESTIGATION ON APPLICABILITY OF ULTRASONIC PULSE VELOCITY MEASUREMENTS TO ESTIMATE THICKNESS OF REINFORCED CONCRETE WALL PANEL

Z.T.M. FAZLI

(168907G)

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa
Sri Lanka

JULY 2021

"I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)."

Signature: ………………………… Date:

The above candidate has carried out research for the Masters thesis under my supervision.

Name of the Supervisor: Dr. Mrs. D. Nanayakkara

Signature of the supervisor: ………………………. Date:

ABSTRACT

In Sri Lanka, Concrete has been widely used as a construction material for more than hundred years and it is necessary to analyse some of these existing old structures to check their structural adequacy, for retrofitting works, repair works and rehabilitation works, etc. For these purposes it is necessary to know the sectional dimensions of structural elements and reinforcement details to evaluate the structural adequacy with the existing strength of concrete. In most of the cases it may not be possible to find the structural drawings to obtain these required structural details and also it may not be possible to measure the required thicknesses of structural elements due to accessibility problems. The objective of this research study is to establish a suitable non destructive method to estimate the thicknesses of various types of concrete members with accessibility problems. Hence, from a thorough literature study, it was found that using ultrasonic pulse velocity methods it could be possible to determine the uniform thicknesses of concrete walls. It is reported that this ultrasonic pulse velocity is affected by the concrete properties as well as the other factors such as temperature, stress history/ level of stress, path length, moisture and curing condition of concrete, presence of reinforcement and size and shape of the specimen.

Accordingly, testing was conducted to study the influence of reinforcement percentages and to observe the influence of some other parameters such as age of concrete, moisture condition and temperature on the accuracy of the thickness predictions using ultrasonic pulse velocity method. Further to verify the results, some existing structures were also investigated. From this experimental study and the field investigations, it is found that the UPV test method could be used to estimate the thickness of concrete walls with a reasonable accuracy.

Specially dedicated to my beloved family and friends…

ACKNOWLEDGEMENTS

My first and foremost sincere gratitude goes to my supervisor, Dr. (Mrs.) D. Nanayakkara for guiding me throughout this research study and her valuable advices. I express my appreciation to Dr. K. Baskaran, the Research Coordinator, for the guidance and motivation towards accomplishing this research study successfully. Also, I take this opportunity to thank the staff members in the Department of Civil Engineering at the University of Moratuwa for their kind assistances.

I wish to acknowledge my friends and colleagues for their feedback, cooperation and encouragement. Also, my most heartfelt appreciation goes to my family who give me invaluable support as always.

Finally, I am grateful to everyone who helped me in various ways to complete this research work successfully.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Principal List of Acronyms and Abbreviations are presented below.

Abbreviation	**Description**
ρ	Density
C	Velocity of sound on the specimen
d	Thickness of Sample
E	Moduli of elasticity
E_d	Dynamic modulus of elasticity
f	Fundamental frequency
f_1	Strength of a standard saturated specimen
f_2	Actual strength of the in-situ concrete
f_n	Corresponding Frequency
G	Moduli of elasticity
k	Constant relative to compaction control
L_s	Length of the r/f bar in mm
MIRA	Ultrasonic Tomography Device
NDT	Non Destructive Test
PUNDIT	Portable Ultrasonic Non- destructive Digital Indicating Tester
QA	Quality Assurance
QC	Quality Control

t	Thickness of the upper layer
UPV	Ultrasonic Pulse Velocity
USA	United States of America
V_1	Pulse velocity in upper layer
V_2	Pulse velocity in lower layer
V_c	Pulse velocity in concrete
V_m	Apparent pulse velocity
V_s	Pulse velocity in steel r/f bar
x	Spacing where the discontinuity of the plot is observed
ν	Dynamic Poisson's ratio
υ	Poisson's ratio
λ_n	Wave length

1.0 INTRODUCTION

1.1 General

Testing of concrete using Ultrasonic Pulse Velocity (UPV) method is a Non Destructive Test (NDT) method, which is used to find surface properties and internal discontinuities such as cracks, voids, laps, blow holes, inclusions and lack of bond in metallic and non-metallic materials (Raj et al. 2007). In addition, it is widely used for testing of concrete for several applications such as, measurement of surface crack depth, investigations on the cement hydration, determining uniformity of concrete, estimating the strength of concrete, studies on concrete durability and determination of dynamic modulus of elasticity.

Moreover, it is used to detect changes in concrete such as freezing and melting and deterioration as a result of aggressive chemical environment as well as to detect internal cracks and other defects (Tarun et al. 2004). Generally ultrasonic testing is used in metals with reflective pulse technique with larger frequencies, however it is not possible to directly apply to concrete due to high scattering that happen at matrix/aggregate interfaces and due to micro cracks. Therefore, testing on concrete is mainly relied on pulse velocity measurements with the through-transmission techniques (Bungey et al. 2006). As commercially produced durable lightweight equipment that can be used for testing either in sites or in laboratories is presently available, this method has become a widely accepted test method (Bungey et al., 2006). Further, a through-transmission ultrasonic measurements are widely used in many industrial applications, since long term monitoring of material properties and characterization can be easily performed by using this method (Raišutis et al. 2008).

1.2 Historical Background

For more than 75 years, the UPV method has been successfully applied for determining the quality of concrete (Tarun et al. 2004). However, over the past two decades, globally, NDT method has been widely accepted to examine the quality of in-situ concrete. The NDT technique includes several tests such as UPV tests, Rebound hammer tests, radiography tests, and penetration tests (Warusavitarana, 2006).

Further, many researchers have also used nondestructive tests to determine the properties of concrete. In 1930s laboratory test specimens were tested using vibrational methods (Tarun et al. 2004), while the first report on the velocity measurements of pulses through concrete which was generated mechanically was initiated in the USA in mid-1940s (Bungey et al. 2006). In these tests, it was found that the velocity is independent of geometry of the concrete, however, largely depended on the elastic properties of the material. Although, this approach had many potential values, many measurement problems were apparent, which led to the development of repetitive mechanical pulse equipment (Bungey et al. 2006).

The stress wave propagation method was expedited on nondestructive testing, since the World War II research. During the same period, pulse velocity method had been used in Canada and England using electro-acoustic transducers, which showed an improved control on the frequency and type of generated pulses. This method of testing had been advanced into modern ultrasonic pulse velocity method, applying pulses in the range of frequency between 20-150 kHz, produced with the use of electronic circuits (Tarun et al. 2004 & Bungey et al. 2006). In England, Jones (1948) developed an instrument which is called Ultrasonic Tester, while Leslie and Cheesman (1949) have developed another instrument which is called Soniscope in Canada.

The history of thickness measurements using resonance method was started by Blitz J. (1959), at an evening course of lectures on “The techniques of non-destructive testing” at Brunal College.

The first application of ultrasonic pulse echo method for the nondestructive testing on concrete structures was recorded in 1991 and it was considered to be unpromising until Krause & Wiggenhauser (1997) presented a state of technology to study the structural geometry of concrete members with the use of ultrasonic pulse echo method.

1.3 Research Gap

Concrete is widely used for structures for more than hundred years in Sri Lanka and it is necessary to analyze these existing old structures to check their structural adequacy. In an already constructed concrete structural element, whether it may be a beam, column, slab, earth retaining structure or even water retaining structure, very often it may not be possible to find the structural drawings to identify the thicknesses for the structural analysis. Moreover, the structural member may not be easily accessible to measure its thickness. In this case it is necessary to further develop a method to estimate its thickness with the minimum error percentage with the use of non-destructive testing methods. Hence, Raj Baldev et al. (2007) indicated that the ultrasonic testing could be used for measurements of wall thickness and for finding of subsurface (volumetric) defects in almost all types of materials. Further, they suggest that ultrasonic measurements may be applied to any material in plate or tube form to measure its wall thickness to a high degree of accuracy. According to Krause & Wiggenhauser (1997), the ultrasonic pulse echo technique could be used to measure the concrete thickness with separate transmission and receiver transducers and a synthetic aperture. However the use of UPV method to estimate the thickness of concrete wall while using the indirect measurements of UPV where other side of the wall is not accessible is not yet investigated thoroughly.

1.4 Objective of the Study

The main objective of the study is to establish a suitable method to estimate the thickness of various types of concrete members with accessibility problems using Ultrasonic pulse velocity measurements.

1.5 Methodology of the Study

The methodology of this experimental study includes;

1. A thorough literature review on previous research work carried out in the area of this study.
2. Identify all the parameters which influence the ultrasonic pulse velocity measurements on concrete.
3. Selection of important parameters that should be considered in this investigation.
4. Experimental investigation
5. Analysis of test results
6. Propose a method to estimate the actual thickness of concrete structural members accurately.

2.0 LITERATURE REVIEW

2.1 Historical Evolution and Findings of the UPV Technique

During a meeting of The Institution of Structural Engineers, held in London on 27th October 1955, a discussion was opened by Dr. R. Jones, of the Road Research Laboratory on the Ultrasonic Testing of Concrete. At that time it was a new subject namely a method of testing actual structures without damaging them which is being called as non-destructive testing these days. During that discussion some of the ultrasonic apparatus was on display where Dr. Jones invited the audience to inspect them.

Jones (1955) reiterated that the conventional method of examining the quality of concrete in structure was to make separate specimens of the same concrete and test them. However, due primarily to differences in compaction, the test specimens were often of better quality than the concrete in the structure. Therefore, it was desirable to have a method of testing the actual structure, preferably on the form of non-destructive. One such method was UPV technique.

The basis of the method was to pass a pulse of vibrations through the concrete and measure its speed. Jones (1955) had briefly explained how pulse velocity was obtained through the simplified circuit waveform as shown in Figure 2.1, for those who were not familiar with the apparatus and measurement.

The time taken for the pulse signal to travel across a known length of concrete was measured. Then, pulse velocity was obtained from the path length divided by the time interval. A pulse of vibrations was produced by a piezo-electric transducer, and it passed through the concrete to a similar transducer which acted as a receiver and transformed the pulse to a comparable electrical signal. Then, that signal was displayed on the trace of a cathode ray tube. The slide showed the timing marks by which the transit time of the pulse was obtained to a high order of accuracy. The time interval between successive marks was 10 microseconds, and there was a device for interpolation between successive pulses to obtain the transit time to an accuracy of 0.1 microseconds in good quality concrete.

Basically, as stated above, the time taken for a pulse of vibrations to travel through a known length of concrete was measured and then the path length is divided by the time of propagation gives the pulse velocity. This pulse velocity is an important parameter to study the quality of material as well as for any study on UPV.

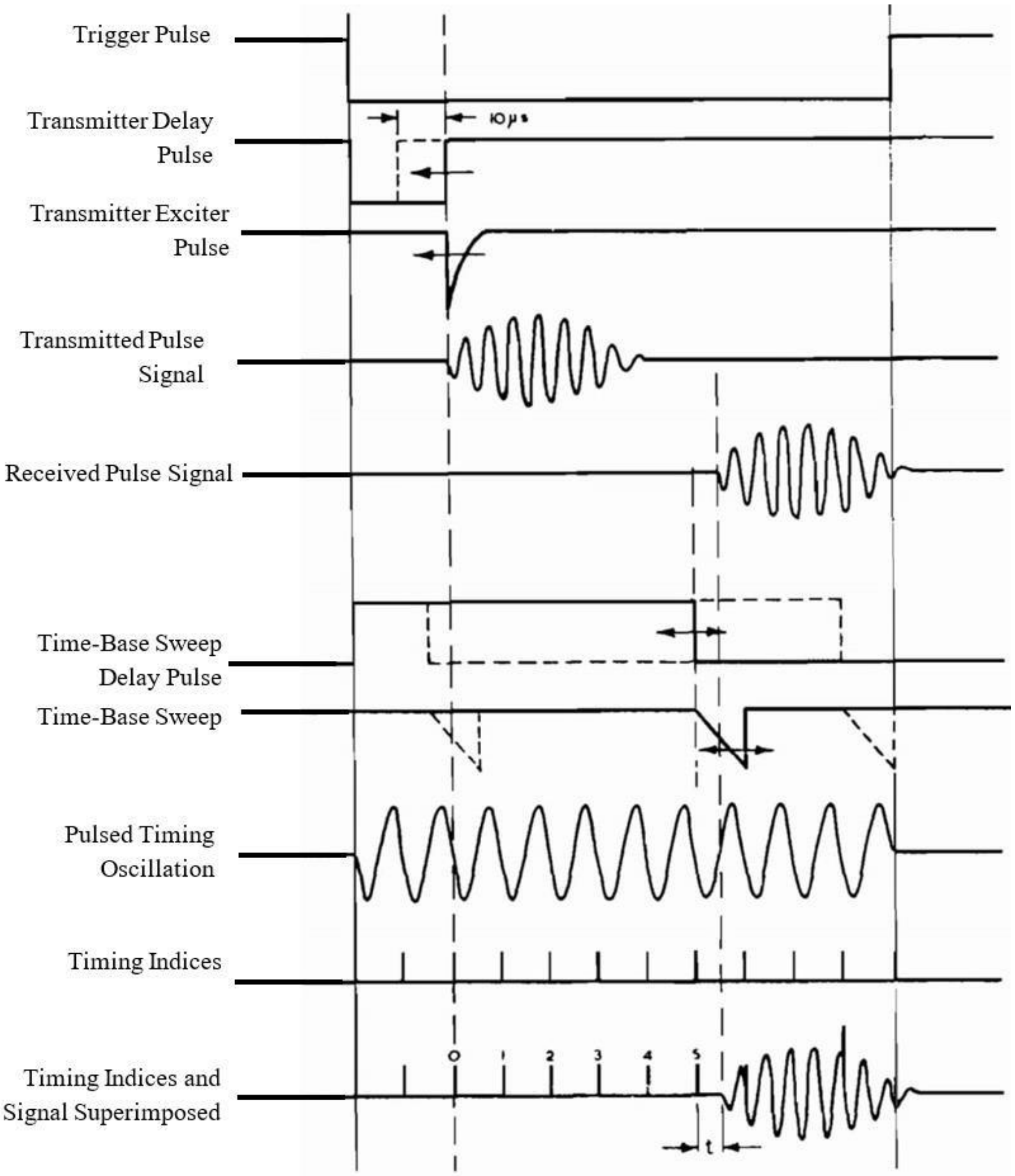


Figure 2.1: Simplified Circuit Waveform (not to scale) of Jones (1955)

The non-destructive testing method for thickness measurement was started by Blitz (1959) with the use of resonance method and presented during an evening course of lectures on “The techniques of non-destructive testing” at Brunal College.

In this resonance method, a quartz crystal was excited by means of a valve oscillator below its fundamental resonance frequency and it was held on the surface of the specimen, of which thickness was required. The frequency of the vibration of the crystal was changed until the sample resonates. Resonance occurred at one of the natural frequencies of vibration of the specimen in its thickness direction, where the thickness of the sample is equal to an exact number of half wave length.

The thickness d is given by,

$$d = n\lambda_n/2$$

(Where for a corresponding frequency f_n the wave length is λ_n and n is a whole number).

Thus, frequency f_n is given by

$$f_n = C/\lambda_n = nC/2d$$

(Where, C represents the velocity of sound on the specimen).

Now, f_n is the n^{th} harmonic of the fundamental frequency f of the specimen so that

$$f_n = nf$$

While increasing the frequency resonance again occurs at the $(n+1)^{th}$ harmonic for which the frequency is f_{n+1} and we have

$$f_{n+1} = (n+1)f = (n+1)C/2d$$

Thus, by subtraction $f_{n+1} - f_n = f = C/2d$

$$d = C/\ 2(f_{n+1} - f_n)$$

Thickness $d = C/2f$

By using the pulse velocity method and its evolution, several findings were identified throughout the period and some of those significant findings as well as the ultrasonic pulse technology evolution are highlighted below.

- Nogueira & Willam (2001) found that the micro crack growth in concrete could be estimated by using UPV method by studying the amplitude of the signal. And with this method mechanical damage in concrete also could be studied.
- A technique which is called “guided wave technique” was used by Pavlakovic et al in 1999 to study the damages on post tensioned tendons in bridges.

- Ultrasonic imaging with an array system was studied by Krause et al in 2003 to examine defects behind dense steel reinforcement and they have examined the defects in the cover to pipe ducts as well as in ungrouted tendon ducts.
- To locate tendon ducts, a Specialized Synthetic Aperture Focusing Techniques (SAFT) was used to provide 3D visualization of defects in concrete structures such as gravel pockets were examined by Koehler et al in 1998.
- To study the structural geometry of the concrete members Krause and Wiggenhauser in 1997 presented the ultrasonic pulse echo technique using synthetic aperture. And they have used 2D and 3D ultrasonic methods to determine the position of tendon ducts on a bridge deck in 2003.
- According to Hoegh, Khazanovich & Yu (2011), an emerging technology which is called ultrasonic tomography could be used for quality assurance or quality control (QA/QC) with the use of portable state-of-the-art ultrasonic tomography device (MIRA) that they have indicated, it could be used for consistent thickness measurement, distress evaluation and to know the reinforcement location even.
- Moreover, it was suggested by Andrews (1993) that there are much more scopes for new usages with further development of computer interpretation and advanced fidelity transducers.
- Due to the alkali-silica reaction concrete will deteriorate and as a result, pulse attenuation characteristic will provide useful data and it was shown by Bungey in 1991. Further, it was noted that the practical problem to reach the coninuous coupling on site.
- Hillger (1993) and Kroggel (1993) explained the current research developments on finding information of internal defects and cracks from tests on concrete surface by using the application of signal processing technique and vacuum coupling system is called “Pulse Echo Technique”.
- Another development involves the usage of receiver scanners and rolling transmitter, integrated with computer data acquisition system without any coupling medium that allows scans of up to 9 meters for straight line within a timescale not greater than 30 seconds. Sack & Olson (1993)

2.2 Applications of Ultrasonic Pulse Velocity Techniques

In several laboratories as well as in field applications the UPV method has been successfully used (Tarun et al. 2004) to analyze deterioration and for quality control. Following wide-ranging UPV applications are highlighted by Tarun et al (2004), Bungey et al. (2006) and Fazli et al. (2004) as the applications of pulse velocity measurements:

- Measurement of Surface Crack Depth and Concrete Uniformity
- Measurement of Layer Thickness and Elastic Modulus
- Studies on the Durability of Concrete and Hydration of Cement
- Estimation of Strength of Concretes and to establish the Homogeneity of Concrete
- Ultrasonic Imaging
- Assessment of Concrete Deterioration
- Detection of Cracking and Honeycombing
- Determination of Dynamic Modulus of Elasticity
- Strength Development Monitoring
- Estimation of Concrete Wall thickness

Out of those UPV applications, some applications were highlighted to determine mechanical properties and some parameters of concrete, such as the moduli of elasticity E and G, Poisson's ratio υ, its dimensions, and fracture strength of non-homogeneous materials like concrete (Prassianakis & Giokas 2003). Thus, in an earlier study by Guha and Wedpathak (1980), they have indicated the frequency range of 20 kHz to 100 kHz is more suitable to test the concrete.

Further, Krause & Wiggenhauser (1997) used UPV method to study the concrete's structural geometry using separate transmitting and receiving transducers. In this study, by a synthetic aperture focusing technique reflected signal was recorded to measure the thickness of concrete and for analyzing tendon ducts.

When the ultrasonic energy instead of the ultrasonic intensity was considered, they have used two examples to present the thickness measurements of concrete members where the depth resolution was improved. They have measured a concrete specimen of 500 mm thick with a maximum aggregate size of 32mm and they have noted that as the shape of Ultrasonic pulse was influenced by the thickness of concrete through which the pulses travel and because of this it depends on a correct integration depth and the integration interval, which had to be calculated for each measurement.

The cracks, defects and other discontinuities of concrete can be determined using the Ultrasonic NDT method including its mechanical properties, such as fracture strength and moduli of elasticity. Further, the concrete homogeneity and internal steel reinforcement can also be determined using the same method (Prassianakis & Giokas, 2003).

A recent study by Hoegh, Khazanovich & Yu (2011) reveals an emerging technology which is called ultrasonic tomography could be used for quality assurance or quality control (QA/QC) during construction of concrete pavements and for making rehabilitation decisions. With the use of portable state-of-the-art ultrasonic tomography device (MIRA) they have indicated that it could be used for consistent thickness measurement, distress evaluation and to know the reinforcement location.

In summary, it can be noted that the use of UPV technique is not limited to some particular applications. Day by day several new applications are being investigated through several researches and it is impossible to list out all the applications of UPV techniques.

2.3 Factors Influencing UPV

Several researchers have studied on the factors influencing UPV. Jones (1955) found that the measured pulse velocity was depended on the elastic properties of the concrete, which in turn were affected by the void content and the degree of hardening which had taken place. On another study by Mackenzie (1950), he has shown theoretically that a change in density of a material due to variation in the void content would give rise to a change in the pulse velocity. Also, quantitative results had shown that for concrete there was an approximately direct relationship between the percentage changes in density and pulse velocity. Moreover, Pulse velocity depends on concrete age, mix, type of aggregate, porosity, cement type, curing, water/cement and aggregate/cement ratios, the conditions of concrete melding, reinforcing bars as well as the concrete thickness through which the pulses travel (Guha & Wedpathak, 1980, Krause & Wiggenhauser 1997, and Prassianakis & Giokas, 2003). In addition, Raišutis et al. (2008) found that the waveform of the signal transmitted through the plastic object is distorted due to many factors such as frequency dependent attenuation, phase velocity dispersion, geometry of boundaries, and diffraction. Hence, these factors have to be considered to increase the accuracy of ultrasonic measurements.

There are two types of factors affecting the pulse velocity (Tarun et al. 2004):
(1) Factors affecting directly from the properties of concrete; and
(2) Other factors.

2.3.1 Effects of Concrete Properties on UPV

From various research studies, factors affecting UPV directly from concrete properties are discussed and categorized as below.

2.3.1.1 Aggregate Size, Grading, Type, and Content

Key factors that affect the pulse velocity are the type and amount of aggregate (Bullock R.E., 1959, Sturrup V.R., 1984, Al-Hamed A.H., 1984, Seals R.K., 1981, Jones R. 1954 & Popovics S., 1991). The pulse velocity on the aggregate is considered to be higher than that of cement paste. “The same concrete mix and at the same compressive strength level, concrete with rounded gravel had the lowest pulse velocity, crushed limestone resulted in the highest pulse velocity and crushed granite gave a velocity that was between these two” (Jones, 1954). However, there is no effect by the aggregate type on the relationship of the modulus of rupture with the pulse velocity.

It is reported that the concrete with the higher aggregate content has a higher pulse velocity with the same strength level (Jones 1962, Bullock 1959, and Kaplan 1959). Figure 2.2 shows the effects of changing the proportion of coarse aggregate on the relationship between “Pulse velocity Vs Compressive strength” in a concrete mixture. This proves that the lower the compressive strength, when higher the aggregate cement ratio to a certain fixed pulse velocity.

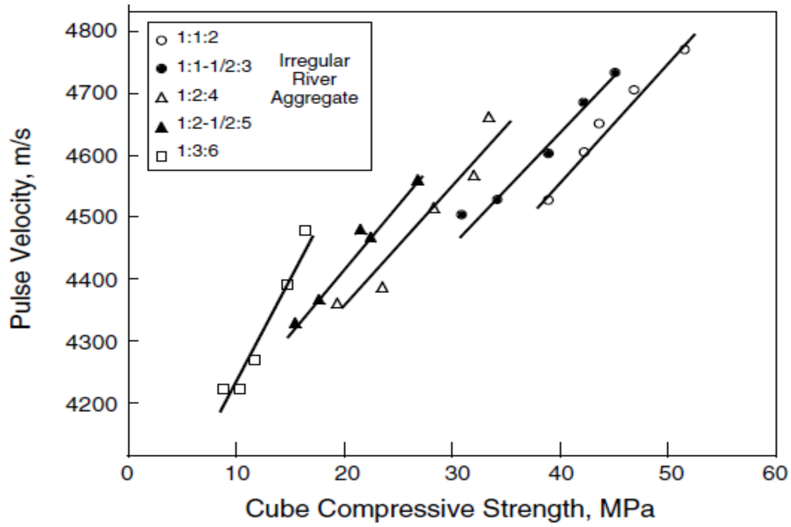


Figure 2.2; Relationship with Pulse Velocity Vs Compressive Strength by Jones (1962)

On a recent study by Tarek Mohammed & Nafiur Rahman (2016), the effect of sand to aggregate volume ratio and types of aggregate on UPV in concrete were studied by using crushed stone, brick chips, round shaped stone and black stone and the sand to aggregate ratios of 0.36, 0.40 and 0.44, with the water cement ratios of 0.45, 0.50 and 0.55. The UPV in concrete is influenced significantly by the compressive strength of concrete, type of aggregate and sand to aggregate ratio (Tarek Mohammed & Nafiur Rahman 2016).

2.3.1.2 Cement Type

Effect on the pulse velocity by the type of cement was studied by Jones (1954) and it was found that there is no significant influence by type of cement on pulse velocity. However, the rate of hydration varies with the different cement types, which will be a factor for the pulse velocity. When the hydration increases, the pulse velocity and modulus of elasticity will increase. When the rapid-hardening cements are used, they produce increased strength for a specific pulse velocity (Jones 1969).

2.3.1.3 Water-Cement Ratio

Kaplan (1959) studied the effects of water-cement (w/c) ratio on pulse velocity and indicated that as the w/c ratio increases, the flexural and compressive strengths as well as the corresponding pulse velocity decrease on the assumption that the composition of the concrete has no other changes.

2.3.1.4 Admixtures

Air entrainment in concrete does not have any influence on the relationship between the compressive strength and the pulse velocity (Jones 1954). Other admixtures will have the same effects on pulse velocity as that the rate of hydration. The setting time of concrete will be reduced by adding calcium chloride, which will result in the increase of the pulse velocity.

2.3.1.5 Age of Concrete

The influence of the age of concrete on the UPV is the same as the influence on development of strength of concrete. In terms of the relationship between the pulse velocity with concrete age, Jones (1954) reported that initially, there is a rapid increase in the velocity, which flattens very quickly. This is a similar trend to the concrete strength vs. age curve for a specific type of concrete, yet velocity of pulse arrives to a limiting value earlier than strength. And further studies concluded that it is difficult to estimate the strength accurately due to experimental errors, when the pulse velocity curve flattens.

2.3.2 Other Factors Effecting UPV

Apart from the factors affecting UPV results directly from concrete properties, other effects which are influencing UPV are discussed below.

2.3.2.1 Temperature

Temperature variation between 5°C and 30°C has no significant effect on the pulse velocity (Jones & Facaoaru, 1969). However, when extreme temperatures are reached, a correction factor is recommended as in Figure 2.3, as a result of the effects of freezing of water within the concrete in very low temperatures and potential internal micro cracking in high temperatures. Similar values are proposed in BS 1881 Part 203, 1986 as well as in BS EN 12504-4.

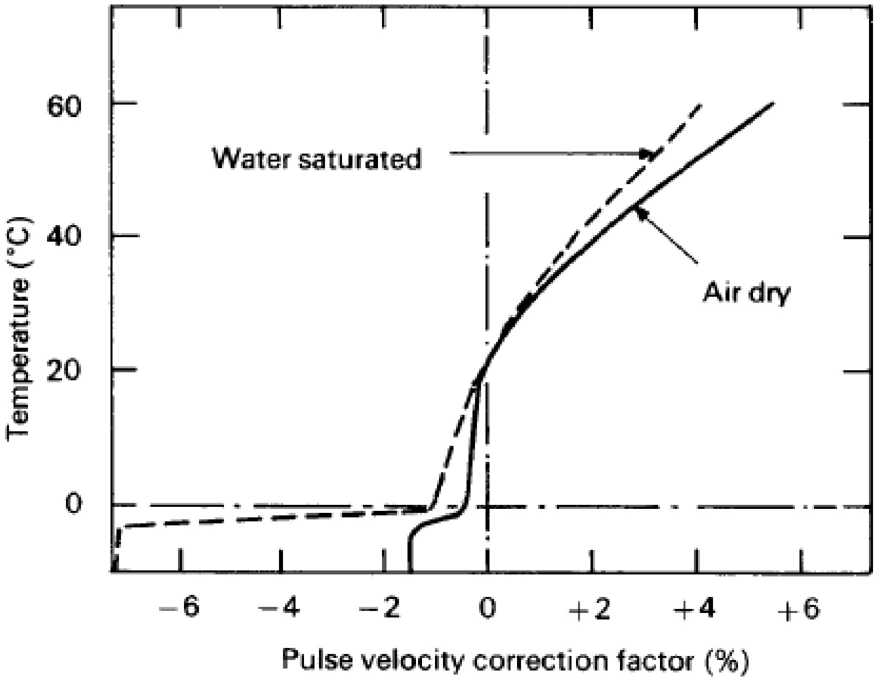
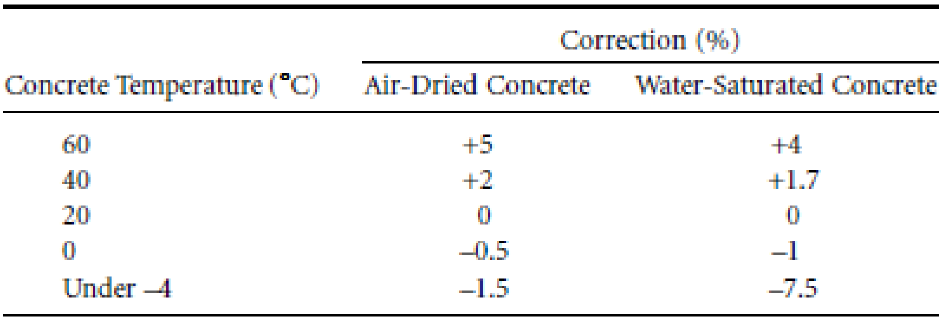


Figure 2.3; Effect of Temperature by Jones & Facaoaru (1969)

Table 2.1; Corrections for Velocity of Pulse Due to Temperature Changes by BS 1881, Part 203, 1986



Concrete Temperature (°C)	Correction (%)	
	Air-Dried Concrete	Water-Saturated Concrete
60	+5	+4
40	+2	+1.7
20	0	0
0	–0.5	–1
Under –4	–1.5	–7.5

2.3.2.2 Stress History/ Level of Stress

The tests on concrete beams showed that pulse velocity on concrete under flexural stress and pulse velocity on laboratory test cubes have the similar behaviours until the beams flexural stress reaches approximately 50% of the crushing strength (Bungey, 1980) and (Nogueira & Willam, 2001). However, the micro cracks develop within the concrete when it is given a very high repeated or static stress level (around 65% of the ultimate strength or more), which will considerably reduce the velocity of the pulse (Popovics 1991, Wu & Lin 1998).

When stresses normally would not exceed one-third of the cube strength under service conditions, the influence of compressive strength on pulse velocity has no significant effect, and on pre-stressed concrete members that pulse velocities would be applied with confidence. The pulse velocities are affected only when a member has been severely over stressed. Similarly, tensile stresses have an insignificant effect even when pulse measurements are parallel to cracks, but cracked regions shall be treated with caution, as they may introduce path lengths below allowable limits (Bungey et al., 2006).

2.3.2.3 Path Length

Wave Frequency (which has the same frequency of transducer) and path length of the wave will not influence the propagation time. As such, it will not affect the pulse velocity. Thus, due to the heterogeneous nature of concrete, smaller path length will give more variable and relatively higher pulse velocity in real situations (Jones, 1962). Similarly, errors may be introduced by physical limitations of the time measuring equipment when there is a short path lengths. These effects are shown by Bungey (1980) in Figure 2.4, where there is an incremental reduction of laboratory specimen in lengths by sawing.

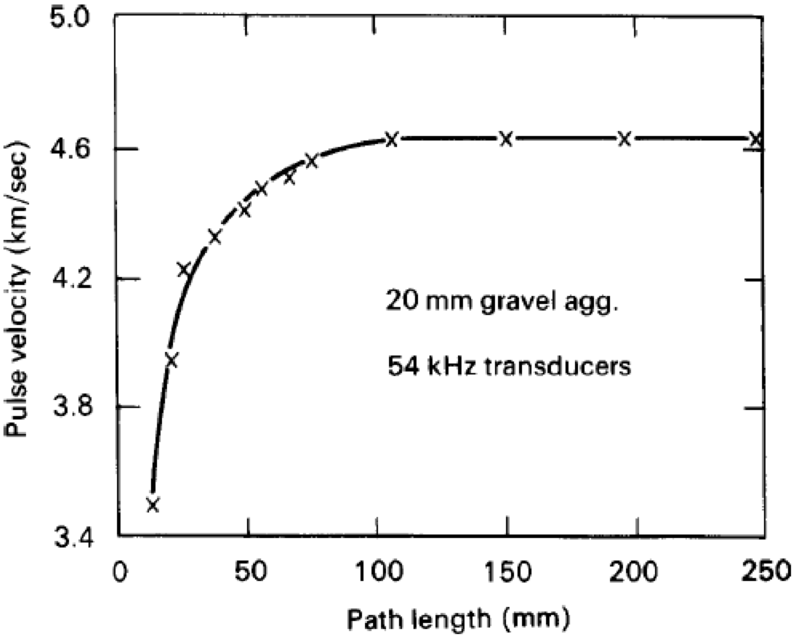


Figure 2.4; Effect of Path Length by Bungey (1980)

Followings are the recommended path lengths by different literature.

(i) RILEM (1972) recommends minimum path lengths as follows:
100 mm for concretes which are having maximum aggregate size of 30 mm
150 mm for concretes which are having maximum aggregate size of 45 mm

(ii) BS EN 12504-4 recommends, path lengths of minimum 100 mm for concretes with aggregate sizes maximum of 20 mm and path length of 150 mm for concrete with aggregate sizes of maximum 40 mm respectively. For unmolded surfaces, a minimum path length of 150 mm and 400 mm need to be adopted for direct and indirect readings respectively.

The measured pulse velocity will decrease when the path length increases, and typically 5% reduction for an increase of 3-6 m path length increase (Malhotra 1976). This is due to attenuation of the pulse of the higher frequency components which produce a less clearly defined onset pulse. Hence, the properties of the measuring equipment become a key factor. Some verification tests are recommended if there is uncertainty, although path length will not create a serious problem in practical context.

2.3.2.4 Moisture Condition and Curing Condition of Concrete

The pulse velocities on saturated concrete is higher than that of air-dry concrete (Jones and Facaoaru 1969). This is due to the influence of moisture on the pulse velocity in concrete because of the porosity difference. Jones (1962) and Bungey (1980) suggested an increase of 4 to 5% in pulse velocity through saturated concrete than the concrete having same properties in a dry condition. There will be relatively high influence for low strength concretes than for high-strength concretes. The influence of moisture condition on the velocity of pulse and concrete strength is another factor making the calibration difficult, due to the reduction of the moisture content of concrete with age.

However, the pulse velocity for specimens cured under laboratory conditions was higher than that for site cured specimens. The velocity of pulse in the laboratory cured specimens was higher than that on columns cast in the site from the same concrete (Kaplan 1958).

A higher pulse velocity is observed in moist specimen, but on a comparable dry specimen measured strength was lower. As a result of drying out, it was observed that the measured pulse velocity is decreased relative to strength (Bungey 1980). Figure 2.5 shows the effect of the results that relevant to identical laboratory specimens, and illustrates the need to correlate the moisture condition of the structure and the test cube during calibration of strength. It is obvious that the application of the strength correlations curves are limited to in-situ concrete without an appropriate moisture conditions.

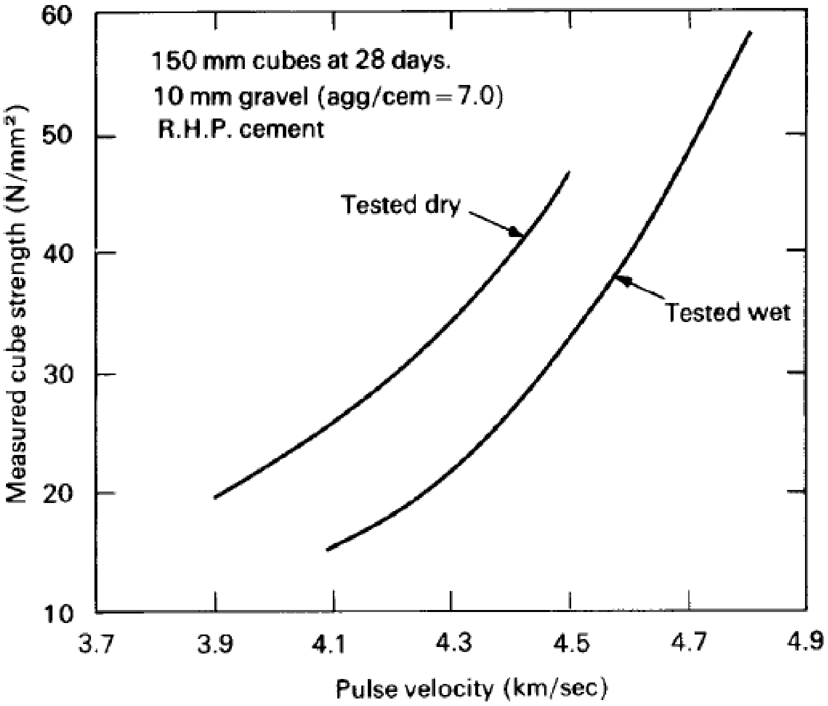


Figure 2.5; Influence of Moisture Condition by Bungey (1980)

A calibration for ‘actual’ in-situ concrete strength can be obtained from a relationship according to the standard controlled specimens (Tomsett 1980).

Following equation shows the correlation between specimens cured under different conditions:

$$\log_e f_1/f_2 = kf_1 (V_1 - V_2)$$

Where, f_1 - Strength of a standard saturated specimen

f_2 - Actual strength of the in-situ concrete

V_1 - Pulse velocity of the standard saturated specimen

V_2 - Pulse velocity of the in-situ concrete

And k is a constant which reflects the compaction control (a value of 0.015 is suggested for common structural concrete or for poorly compacted concrete it is 0.025). This effect is demonstrated in Figure 2.6 below. In a certain curing conditions, a strength/pulse velocity relationship can be determined and a comparison of similar concrete members in a structure from a single relationship, with the same slope as the "standard" saturated specimen relationship. This method shows the strength and moisture differences between control specimens and in-situ concrete.

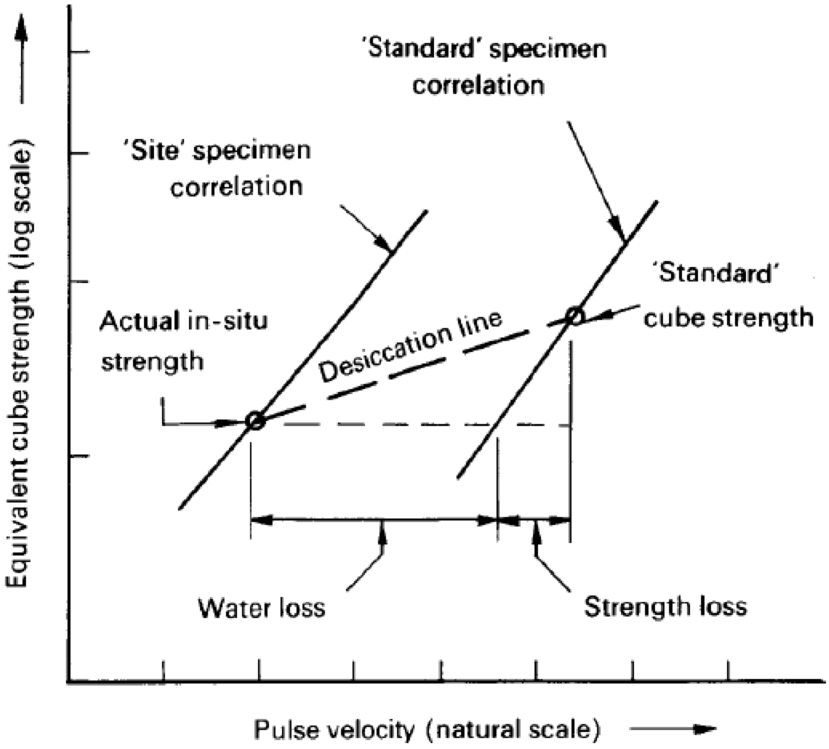


Figure 2.6; Desiccation line Method based on Tomsett (1980)

Based on mix characteristics, a set of similar range *of k* values and these should enable estimation of in-situ strength to within ± 10% (Al-Hamed and Swamy,1984). However, if the correlation is used for other purposes than the comparative applications, it is desirable when the assessment of direct strength of a typical reference specimen of in-situ concretes.

2.3.2.5 Presence of Reinforcement

The velocity of pulse in the concrete is significantly influenced by the presence of reinforcement. The velocity of pulse in steel is 1.4 to 1.7 times the pulse velocity in plain concretes (Tarun et al. 2004). Hence, the pulse velocity readings near reinforcing steel have higher value than that in plain concrete. The test readings shall be taken without reinforcement in the wave path, due to considerable uncertainty in the increased velocity of pulses in steel with possible shortcomings in compaction due to heavily reinforced regions.

The correction factors need to be used as per the RILEM and British Standards when reinforcements cross the wave path. However, determination of these corrections are difficult and the influence of the steel would dominate over the concrete properties which will reduce the confidence in estimated pulse velocities in concrete (Bungey 2006). The velocity of pulse in an infinite steel medium is around 5.9 km/s, but this will reduce with the steel diameter to as low as 5.1 km/s along the length of a 10 mm dia. reinforcing bar in the air (Bungey 1980). The velocity is further affected along a reinforcing bar embedded in concrete by the bond condition between steel and concrete and the pulse velocity in the concrete.

RILEM (1972) recommends two parameters: (a) the velocity of pulse in the surrounding concrete and (b) the path lengths within the concrete and steel. Bungey (1984) included bar diameters as correction factors, although that the obvious increase in pulse velocity through a concrete member depends upon the measurements of the area closer to reinforcing bars, the diameter, the number of bars and their orientation with respect to the propagation path. It will increase if the first pulse to arrive at the transducer in receiving end travels partly in the steel and concrete.

Factors for corrections proposed by RILEM (1972) were an constant average value of pulse velocity in steel with a maximum possible influence of steel. Figure 2.7 shows smaller corrections, whereas British Standard and Bungey (1984) takes bar diameter into account. However, new European Standard BS EN 12504-4 does not provide any specific guidance except to refrain from the steel parallel to the pulse path.

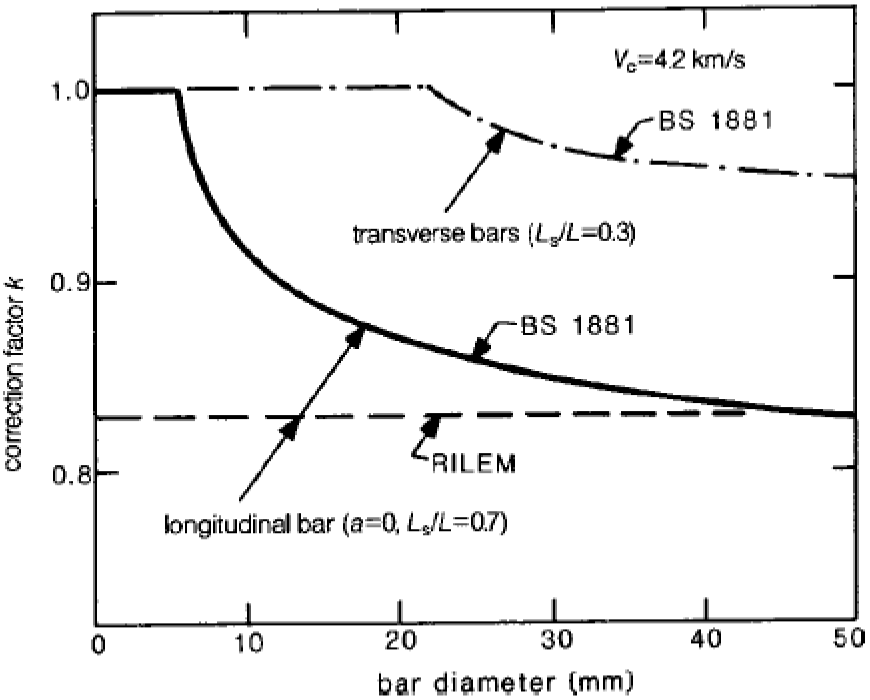


Figure. 2.7; Typical Correction Factors based on Bungey et al. (2006)

Bungey et al (2006) found that, the pulse velocities of 4.0 km/s or above in concrete, with 20 mm dia. reinforcement bars running crossways to the pulse path will have no significant effect upon measured values, however bars larger than 6 mm dia. running along the pulse path will have a significant effect.

There are two main cases:

(i) Axis of reinforcing bars parallel to pulse path

If a reinforcement bar is close to the path, the received first wave would have travelled along the reinforcement bar for its part of journey (See Figure 2.8)

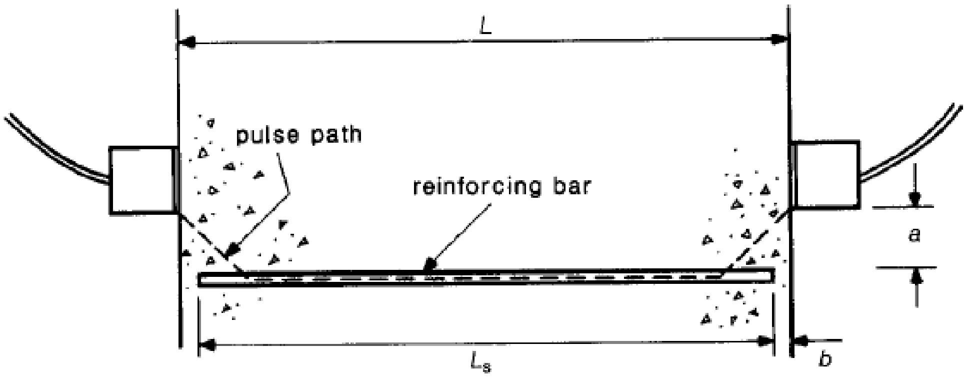


Figure 2.8; Reinforcement Parallel to Pulse Path

It is suggested that a relationship of

$$V_c = \frac{2aV_s}{\sqrt{\text{[illegible]}}} \quad \text{when } V_s \geq V_c$$ (Equation-1)

is applicable, where V_s = pulse velocity in steel r/f bar

and V_c = pulse velocity in concrete

and that this effect vanishes when,

$$\frac{a}{L} > \frac{1}{2}\sqrt{\frac{V_s - V_c}{V_s + V_c}}$$ (Equation-2)

Hence, effects by the steel may be remarkable when a/L < 0.15 in high-quality concrete or a/L < 0.25 in low-quality concrete material. Since it is difficult to decide the value of V_s, applying equation-1 also would not easy.

Therefore, the equation could be expressed as

$$V_c = kV_m \qquad \text{(Equation-3)}$$

Where, V_m is the apparent pulse velocity (L/T) measured in km/s, and k is the factor for correction, which is given by

$$k = \gamma + 2\left(\frac{a}{L}\right)\sqrt{1-\gamma^2} \qquad \text{(Equation-4)}$$

with $\gamma = V_c/V_s$

The γ value could be obtained from Figure 2.9, which shows for a range of common values of V_c and diameter of r/f bars, for a frequency of 54 kHz. It would be replaced in equation-4 (or Figure 2.10), to calculate the correction factor k which is to be used in equation-3.

These equations could be used only, when the offset a is about two times greater than the end cover to the bar b. Otherwise, pulses are probably will pass through the full length of the r/f bar and

$$k = \gamma + 2\left(\frac{\sqrt{a^2+b^2} - b\gamma}{L}\right) \qquad \text{(Equation-5)}$$

If the r/f bar is directly falls on the line with the transducers, a = 0 and the correction factor would be given by

$$k = 1 - \frac{L_s}{L}(1-\gamma) \qquad \text{(Equation-6)}$$

where L_s is the length of the r/f bar in mm.

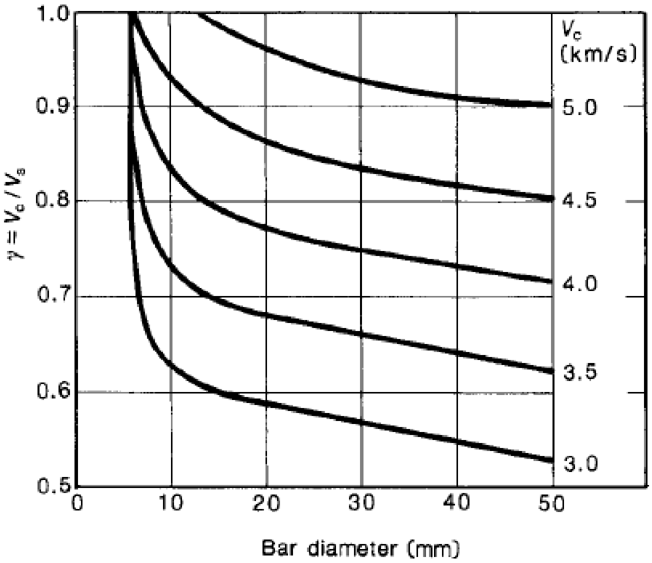


Figure 2.9; Relationship of r/f bar dia. and Ratio of Velocities for r/f bars Parallel to Path of the Pulse based on Bungey (1984)

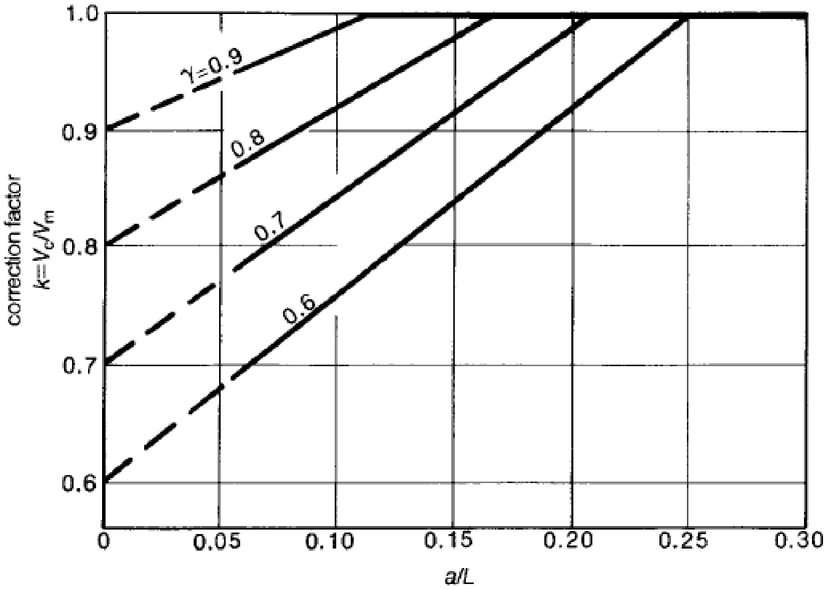


Figure 2.10; Correction Factors for Pulse Path Parallel to r/f bars [*a* > 2*b*] based on Bungey (1984)

An iterative method is needed to find a reliable estimation of pulse velocity in concrete (V_c) and if there is good bond and no cracking of concrete in the test zone the estimated pulse velocities are to be accurate within the range of ±30% (Bungey et al 2006).

A complex r/f bar configuration near the test location would increase uncertainty and careful corrections is required, particularly instead of the body of the material, it is the pulse velocity is being measured which is through the concrete surrounding the bar.

(ii) Axis of reinforcing bars perpendicular to the pulse path

As per Bungey et al (2006), as in Figure 2.11(a), if the total path length across the r/f bar diameter through the steel is L_s, the Figure 2.11(b) shows the maximum possible effect by steel for varying concrete qualities and bar diameters, where pulse velocity in concrete (V_c) is the absolute velocity in the concrete.

To obtain the correction factor *k*, the value of γ is used in equation-6. The effect on the r/f bars on the pulse is complicated, and the effective pulse velocity in the steel is lower than the velocity along the axis of bars of similar size.

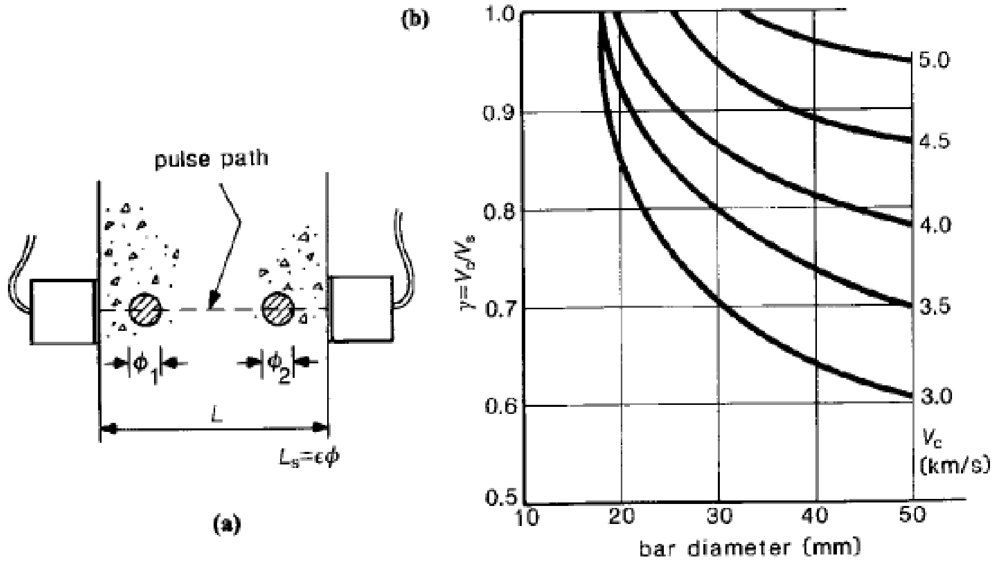


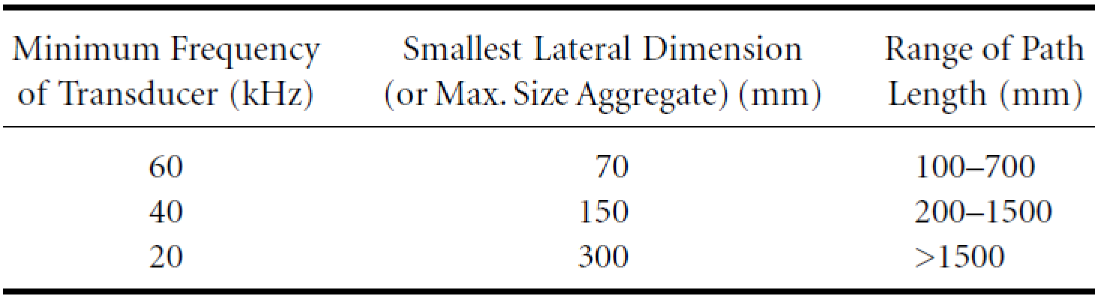
Figure 2.11; Reinforcement is Crossways to Path of the Pulse: (a) Path Travelling Crossways of Reinforcement; (b) Bar dia./Velocity Ratio by Bungey (1984)

In general, typical correction factors based on typical cases for different bar diameters can be found from Figure 2.7.

2.3.2.6 Shape and Size of a Specimen

The velocity of the pulse is independent on the shape and size of the test specimen. Hence, wave length of the pulse would be lower than the smallest lateral dimension of the specimen. Therefore, for longer path lengths the higher-frequency transducers need to be used for shortening the wavelength and for the requirement of relevant least lateral dimension. Further, the wavelength has to be greater than the maximum aggregate size, otherwise the wave energy will attenuate and clear signal could not be detected in the receiver (Tarun et al, 2004). RILEM (1972) recommendations can be used for the maximum aggregate sizes and least lateral dimensions (See Table 2.2).

Table 2.2; Frequencies of Transducer Vs. Least Lateral Dimension by RILEM Recommendations, 1972



Minimum Frequency of Transducer (kHz)	Smallest Lateral Dimension (or Max. Size Aggregate) (mm)	Range of Path Length (mm)
60	70	100–700
40	150	200–1500
20	300	>1500

3.0 EXPERIMENTAL STUDY

3.1 Theory of Pulse Travelling Through the Concrete

By applying an impulse to a solid mass, three types of waves are generated.

(i) Surface Waves
(ii) Shear or Transverse Waves
(iii) Longitudinal Waves or Compression Waves

Surface waves are the slowest waves which is having an elliptical displacement of particle, while shear or transverse waves are faster with displacement of particle at right angles to the direction of the wave which travels. However, longitudinal waves sometimes called as compression waves are the fastest waves with displacement of particle in the direction of travel are the most important waves since these will generally provide more useful information. Primarily, electro-acoustical transducers are producing these longitudinal waves while other types of waves commonly cause little interference due to their lower speed.

The velocities of propagation of shear or compression waves, longitudinal waves depend on the elastic properties and material density. In a given material, it is independent of the frequency of the waves and the material dimensions. Hence, elastic properties could be assessed if the density and velocity of wave propagation are known. For a homogeneous, infinite, isotropic elastic medium, the longitudinal or compression wave velocity would be given by:

$$V = \sqrt{\frac{K.E_d}{\rho}} \qquad (km/s)$$

Where, E_d = Dynamic modulus of elasticity (N/mm^2)
ρ = Density (kg/m^3)
K = $\frac{(1-v)}{(1+v)(1-2v)}$
ν = Dynamic Poisson's ratio

3.2 Pulse Velocity Test Instrument and its Application

The test equipment consists of a transducer which produces and introduces a wave pulse through the concrete and the time taken by the wave to travel through the concrete is accurately measured through a receiver sensing the arrival of the pulse. An Oscilloscope could be connected to the equipment, or any display device, to observe the nature of the receiving pulse. A schematic circuit diagram is shown in Figure 3.1 below:

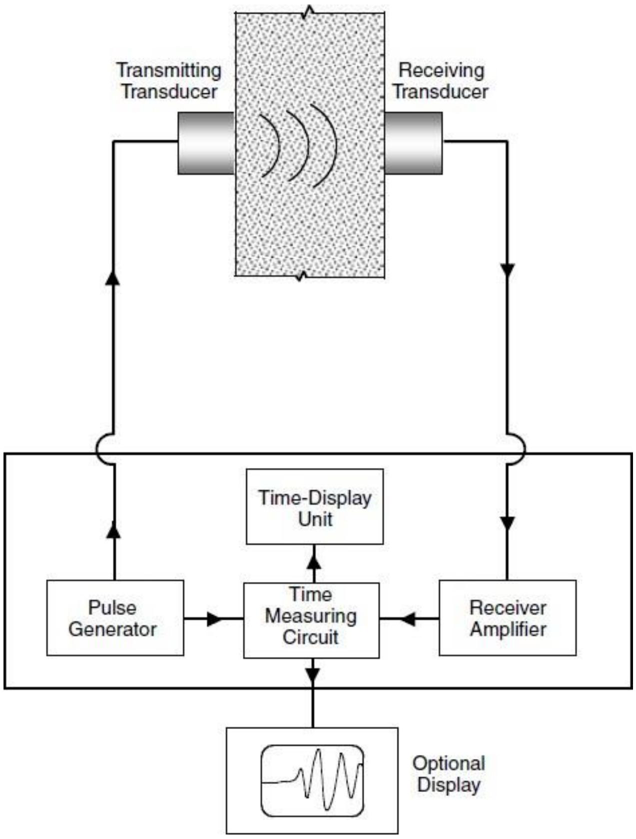


Figure 3.1; Typical UPV Test Circuit Schematic Diagram (Tarun et al., 2004)

Commonly for use with concrete, transducers with the natural frequencies in between 20 kHz and 150 kHz are most suitable (Bungey et al., 2006). A wave is transmitted into the concrete by the transducer of the pulse velocity instrument and the pulse through the concrete at another point is received by the receiver. There are several commercially produced instruments available in the market.

Thus, most popular of these are PUNDIT (Portable Ultrasonic Non- destructive Digital Indicating Tester) and PUNDIT PLUS featuring a large LCD display, having battery life of up to 8 hours. The acceptable ambient temperature range would be of 0-45 °C in most practical situations.

The instrument has to be calibrated by using the special steel bar provided with the instrument and as per the instruction provided in the manual. And the operation is comparatively simple but it needs greater care if it is necessary to obtain reliable results. Figure 3.2 shows the typical UPV testing instrument.

Figure 3.2; Typical UPV Testing Instrument (Tarun et al., 2004)

3.2.1 Use of the Test Instrument

To transmit or receive pulse, the probes have to be in full contact with concrete and it is important to make sure that the good acoustical coupling between concrete surface and the face of the transducer by the use of a medium such as petroleum jelly, liquid soap or grease. Otherwise an air pocket between the transducer and test object may introduce and an error would occur in the transit time. For the rougher surfaces which have not been cast against smooth shutters, thicker grease layer would be recommended. Thus, BS 1881: Part 203: 1986, recommends that “the transducers should be in contact with the concrete surfaces which have been cast against formwork or a mould. Surfaces formed by other means, e.g. trowelling, may have properties differing from those of the main body of material”. Until a minimum value of transit time is obtained, repeated readings at a particular location have to be taken. Any doughtful readings could be repeated if required, with special concentration to the elimination of any other source of even a slight vibration during the test. Moreover, Bungey et al. (2006), emphasize based on their practical experiences that the necessity for an adequately prepared surface to obtain reliable readings.

3.2.2 Transducer Arrangements

Normally three types of transducer arrangements could be made for the ultrasonic pulse velocity testing such as direct transmission, Semi- direct transmission and indirect transmission.

3.2.2.1 Direct Transmission (Opposite faces)

Transducers are placed rightly opposite to each other on opposite faces of the concrete as shown in Figure 3.3. In this method, maximum pulse energy could be transmitted to the face of the transmitter at right angles. Therefore, it is more reliable than the other two methods in measuring transit time as well as the path length measurements.

In this method, the path of the pulse is clearly defined and it could be measured exactly and this method is recommended wherever possible in assessing quality of concrete.

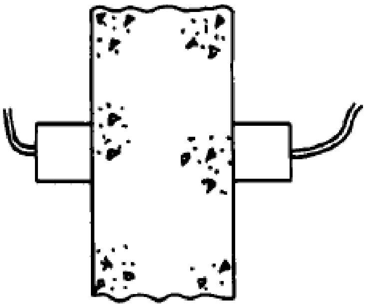
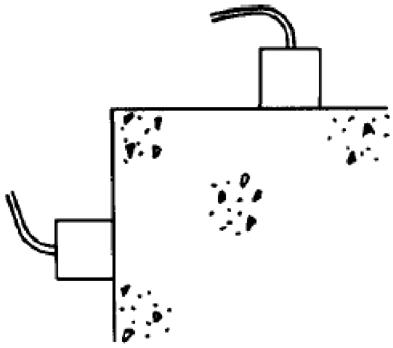


Figure 3.3; Direct Transmission

3.2.2.2 Semi- Direct Transmission (Adjacent faces)

There are some instances the transducers could be placed on different faces but not directly opposite to each other as shown in Figure 3.4. Such method is called as semi-direct transmission. This method is recommended if the angle between the transducers is not too high and if the path length is not too large.



In this method, due to the attenuation of the pulse which was transmitted has the sensitivity in between direct and indirect transducer arrangements.

Thus, it is sufficiently accurate to take distance measurements from center to center of the faces of transducer.

Figure 3.4; Semi-Direct Transmission

3.2.2.3 Indirect Transmission (Same faces)

This method is very useful for the study of this particular research and it could be used when there is only one face of the concrete element is accessible. Also, this method could be used to determine surface cracks or to know the detail of surface concrete which the quality is different relative to the overall quality. Transducer arrangement for indirect transmission is shown in Figure 3.5

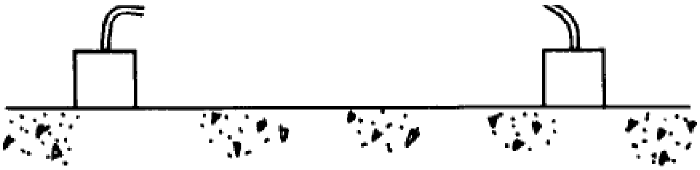


Figure 3.5; Indirect Transmission

The indirect method would be the least satisfying method as the receiving signal amplitude may be lower than 3% compared to the direct transmission method (BS 1881: Part 203: 1986).

Due to this a special procedure is required to determine the average pulse velocity by obtaining the slope of the best fit straight line at a series of fixed incremental points along a chosen radial line by taking a series of readings with the fixed transmitter.

In this method if a discontinuity occurs on the plot, it is due to that either surface crack or an inferior surface would be present. So, this principle would be used to determine the concrete thickness by the fact that the pulse travelled through two different medium such as concrete-air, concrete- water or concrete-soil and by obtaining a discontinuity of the plot and a method proposed by Bungey et al. (2006) as below.

3.2.3 Measurement of Layer Thickness

The thickness of a concrete layer could be estimated by the use of ultrasonic measurements of transit times along the surface based on the fact that due to the separation of the transducers in shorter distance, the pulse travel through the surface layer and the slope of the experimental line gives the pulse velocity in this particular surface layer. When the path length increases and beyond certain distance the pulse shall travel through the underlying layer and the slope of these experimental points gives the velocity of that medium (BS 1881: Part 203: 1986).

Based on the above fact, Bungey et al. (2006), had developed an equation for the measurement of layer thickness.

When the receiver and transmitter are close to each other, the pulse will travel through the surface layer only and when it is moved at grater spacing the path will include the other lower layer. This will be reflected by a discontinuity in the plot of “Transit time Vs Transducer spacing” with the velocities of pulse through the two layers having two different slopes as below (See Figure 3.6).

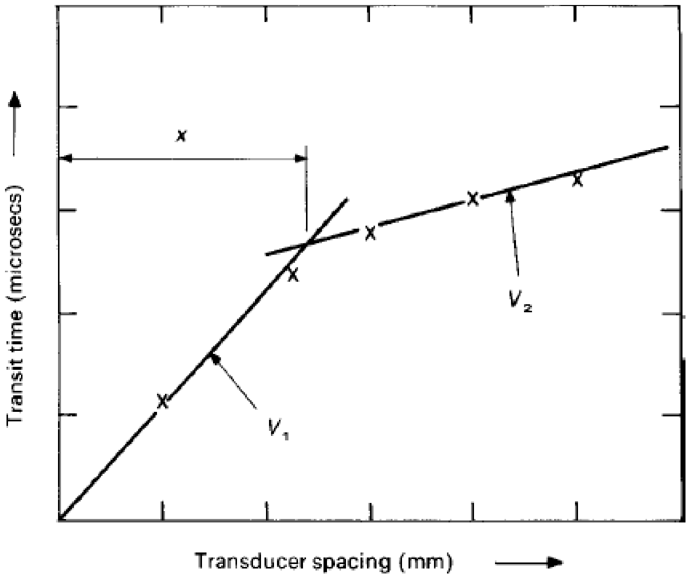


Figure 3.6; Layer Thickness Measurement- Bungey et al., (2006)

As such, the thickness “t” of the upper layer (concrete slab) is relevant to the velocities V_1 and V_2 and the spacing “x” where the discontinuity of the plot is observed by the following equation.

$$\boldsymbol{t} = \frac{\boldsymbol{x}}{\boldsymbol{2}} \sqrt{(\boldsymbol{V}_2 - \boldsymbol{V}_1) / (\boldsymbol{V}_2 + \boldsymbol{V}_1)}$$

Bungey et al. (2006), further emphasized that this method could be most relevant for a distinct layer of uniform thickness, and the thickness value obtained could be only an estimate, and there will be a maximum layer thickness that could be detected by this method of estimation.

Particularly, the results have to be treated with care because of the little information is available by using this method concerning the depth of penetration of indirect readings and in view of the attenuation of signal received.

So, the arrangement of the testing would be the transmitter and receiver of the ultrasonic instrument which will be placed on the same side of the member at various distances, on the fact that as the path length of the ultrasonic wave increases the pulse will travel in different media such as air, water or soil. These effects result a discontinuity on the plot of “Transmit time Vs Transducer spacing”. Popovics et al. (1990) revealed that the pulse velocity is independent on the stresses in concrete to a large extent. Therefore, from the velocity gradients of the plot, it is expected to determine the thickness of the element.

3.3 Experimental Setup

Based on the objectives of the study only parameter which was varied is the reinforcement percentage in concrete. Other than that, other parameters such as Temperature, Stress History/ Level of Stress, Moisture and curing Condition of concrete were not varied throughout the study. Therefore, concrete panels having the thickness of 100 mm were used throughout the study to verify the influence of reinforcement ratio on the estimation of thickness. Further, opposite side of the concrete panels were maintained as air throughout the study.

3.3.1 Initial Testing- (Series 1)

Initially, two concrete panels having the thickness of 100 mm were cast and tested to determine the thickness of panels with UPV method and also to identify whether there is an influence of the percentage of reinforcements present in the panels on thickness measurements. Specimen-1 has no reinforcement inside (Plain Concrete) while the Specimen-2 has high percentage of reinforcement inside. Based on the methodology, suitable dimensions were selected for the panels as in the Table 3.1

Table 3.1; Dimensions of the Test Panels and the Reinforcement Ratios used for Test Series 1

	Length (mm)	Width (mm)	Thickness (mm)	R/F Ratio (%)
Specimen -1	1,500	400	100	0
Specimen -2	1,500	400	100	1.047

All the concrete specimens were made using the same Ordinary Portland Cement (OPC) having the Grade 25 (C25) concrete and the Table 3.2, gives the mix proportions used for the specimen preparation. Figure 3.7 shows the reinforcement arrangement used in the test specimen 2.

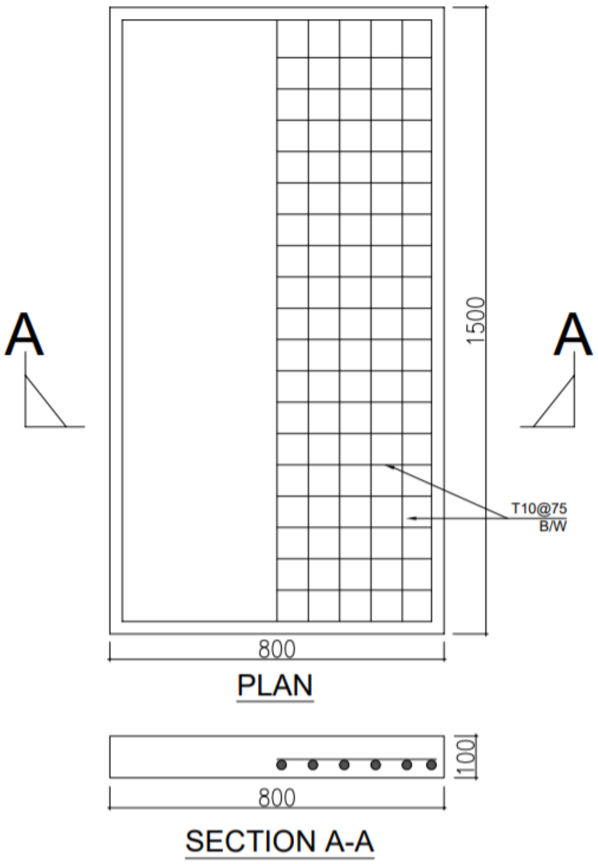


Figure 3.7; Reinforcement Arrangement for the Test Specimen (Series 1)

Table 3.2; Mix Proportions used for the Concrete Panels

Compressive Strength (N/mm^2)	Weight (kg/m^3)			
	Cement	Water	Fine Aggregate	Coarse Aggregate
25	300	200	672	1,278

Once these initial panels were prepared, they were cured and tested after 28 days as described in the methodology. The experiment was conducted according to the procedures stipulated in BS 1881 : Part 203 : 1986.

Particularly, the experiment was set up to verify the results on the opposite medium as air. As such, all the panels were kept in a specific height from the ground level. Moreover, all surface of the panels were cleaned before performing the experiments and the testing was carried out in dry condition as the concern was on the moisture condition would affect the pulse velocities.

Special attention was given on the clause 6.5 of BS 1881 : Part 203 : 1986, where the transducers should be in contact with concrete surfaces which have been cast against formwork or a mould. Surfaces formed by other means, such as trowelling, may have properties differing from those of the main body of material.

Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) instrument was used throughout the experiments.

3.3.2 Experimental Study- (Series 2)

Based on literature review it was identified that the percentage of reinforcement in concrete is one of the main factors, which influences the UPV of concrete. In practical situations also, reinforcement ratios can be different in different structural elements. Therefore, it was decided to further investigate the influence of reinforcement ratio on the accuracy of the thickness predictions using UPV method.

As such, to study the relationship with the reinforcement percentage, a new set of panels were prepared and tested in the same manner as done in the initial testing (See Figure 3.8 (a) and Figure 3.8 (b)). All three panels were prepared with the same dimensions and only the reinforcement percentage was varied among these panels.

Figure 3.8 (a); Test Panels in Series 2

Figure 3.8 (b); Testing for UPV Measurements on Test Panels in Series 2

Table 3.3 indicates the dimensions of each panel and details of reinforcement percentages in these panels.

Table 3.3; Dimensions of the Concrete Panels and Details of Reinforcement Percentage in (Series 2) Concrete Panels

	Length (mm)	Width (mm)	Thickness (mm)	R/F Ratio (%)
Sample- A	1,500	300	100	0.251
Sample- B	1,500	300	100	0.335
Sample- C	1,500	300	100	0.503

3.4 Observations

3.4.1 Initial Observations (Series 1)

Based on the methodology, Time taken (µs) against the distance to the receiver (in mm) was recorded for the two samples in series 1 as below (See Figure 3.9). All test results for series 1 are included in Table 3.4 and the time Vs distance to the receiver, graphs are shown in Figure 3.10 and Figure 3.11.

Figure 3.9; Taking Measurements on the Test Panels in Series 1

Table 3.4; Initial Test Observations (Series 1)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs)	
		Specimen-1	Specimen-2
1	100	38.8	39.4
2	200	78.6	90.3
3	300	102.3	125.1
4	400	135.8	173.1
5	500	172.6	222.4
6	600	215.3	259.3
7	700	249.6	295.6
8	800	275.4	319.8
9	900	292.1	353.1
10	1000	320.9	418.6

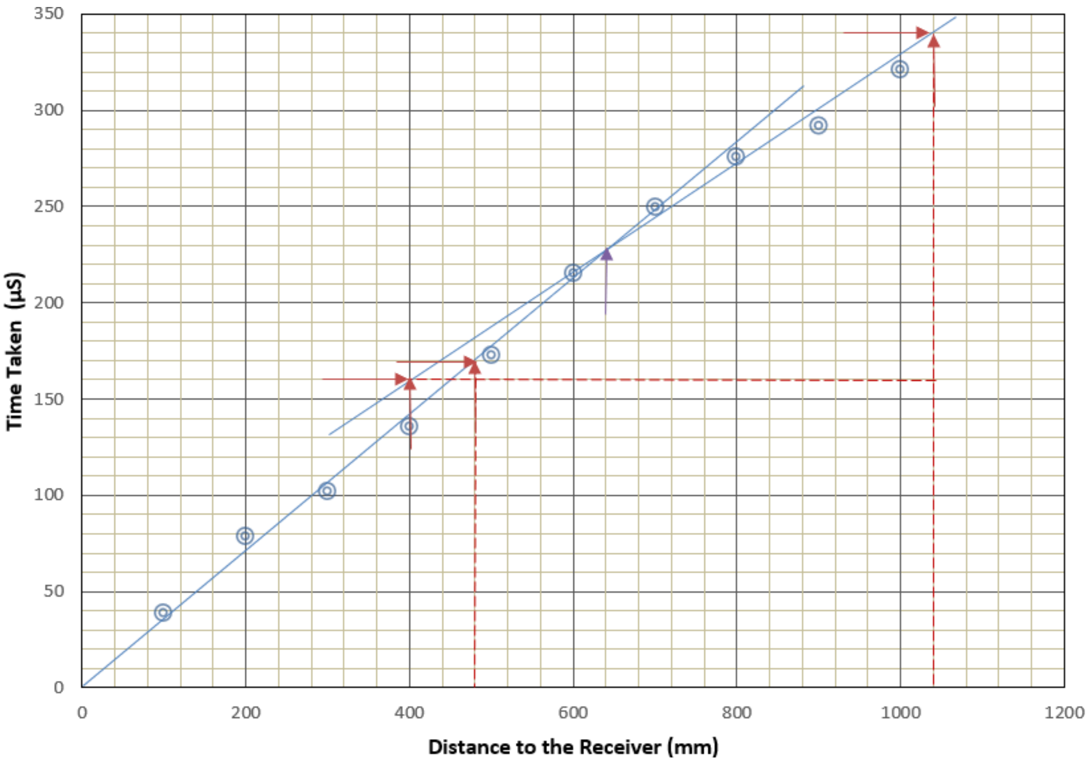


Figure 3.10; Distance to the Receiver Vs Time Taken for Specimen-1 (Series 1)

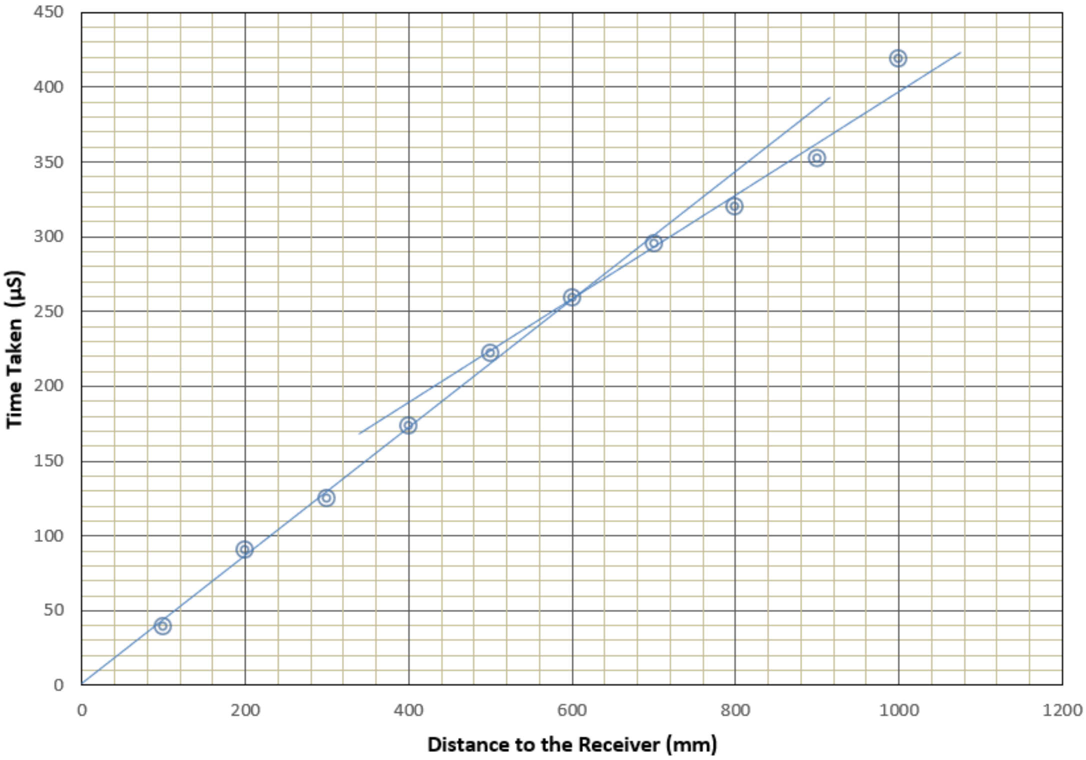


Figure 3.11; Distance to the Receiver Vs Time Taken for Specimen-2 (Series 1)

3.4.2 Observations on Test Series 2

Observations obtained for series 2 are recorded in Table 3.5

Table 3.5; Observations for Test Series 2

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs)		
		Sample-A	Sample-B	Sample-C
1	100	25.6	37.2	25.9
2	200	62.2	61.1	53.7
3	300	87.9	101.7	77.9
4	400	109.1	143.1	100.4
5	500	140.9	165.7	131.1
6	600	180.1	189.7	163.2
7	700	207.9	212.4	184.1
8	800	230.1	233.6	204.6
9	900	251.2	257.9	246.1
10	1000	277.2	321.4	273.7

Figure 3.12, Figure 3.13 and Figure 3.14 show the Distance Vs Time plots for test panels in Series 2

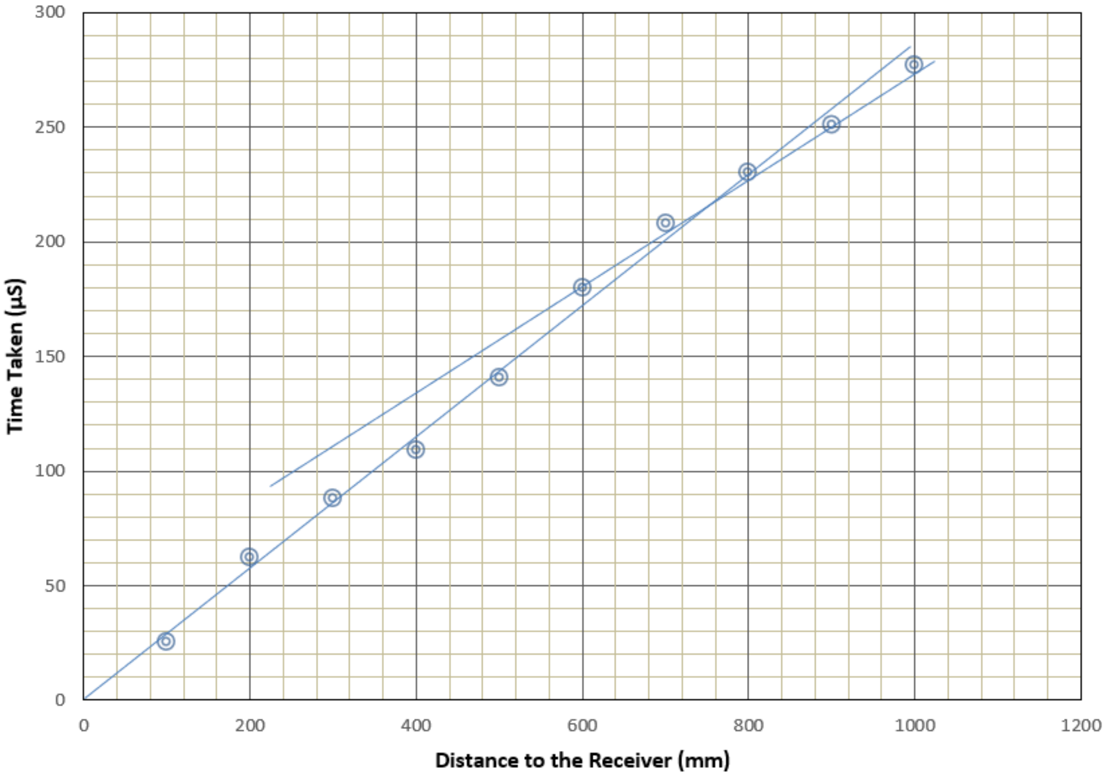


Figure 3.12; Distance to the Receiver Vs Time Taken for Sample-A

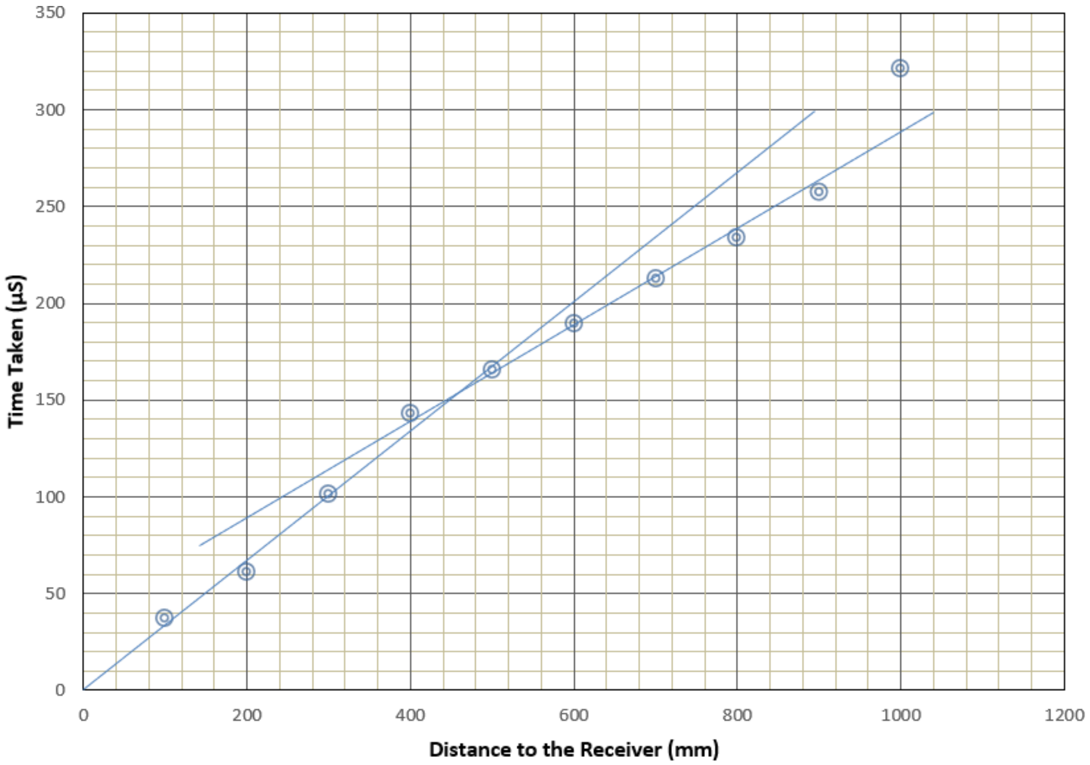


Figure 3.13; Distance to the Receiver Vs Time Taken for Sample-B

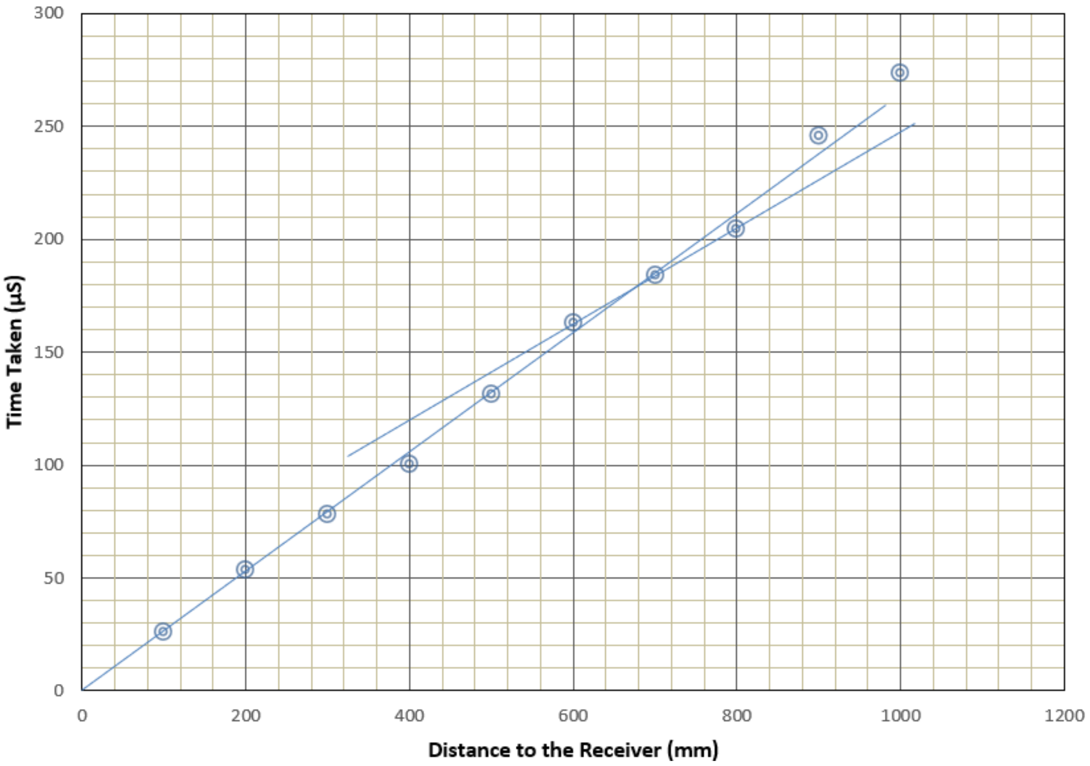


Figure 3.14; Distance to the Receiver Vs Time Taken for Sample-C

3.5 Specimen Calculations

By Considering Figure 3.10;

Velocity,

V_1 = 480 / 170

= 2.824 mm/ µs

V_2 = (1040 – 400) / (340 – 160)

= 3.556 mm/ µs

x = 640 mm (Point of intersection obtained from the Figure 3.10)

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{640}{2}\sqrt{(3.556 - 2.824)/(3.556 + 2.824)}$

Calculated Thickness = 108.4 mm

Actual Thickness = 100 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100

= (108.4 – 100) / 100 X 100

= 8.4 %

3.6 Tabulation of Calculated Thicknesses

Table 3.6 includes the calculated panel thickness “d” using UPV measurements for all test panels in Series 1 and Series 2.

Table 3.6; Calculated Thicknesses for all Panels

Tests		Velocity V_1 (mm/µs)	Velocity V_2 (mm/µs)	x (mm)	d (mm)
Series 1	Specimen-1	2.824	3.556	640	108.4
	Specimen-2	2.333	2.875	600	96.8
Series 2	Sample-A	3.429	4.000	770	106.7
	Sample-B	2.800	4.364	450	105.1
	Sample-C	3.778	4.571	680	104.8

3.7 Results of the experiment

Table 3.7 gives the percentage of reinforcements, calculated thicknesses and the percentage errors for each test panel.

Table 3.7; Results Summary

Test	Reinforcement (%)	Actual Thickness (mm)	Calculated Thickness (mm)	Percentage Error (%)
Specimen-1	0.000	100.0	108.4	+ 8.4
Sample-A	0.251	100.0	106.7	+ 6.7
Sample-B	0.335	100.0	105.1	+ 5.1
Sample-C	0.503	100.0	104.8	+ 4.8
Specimen-2	1.047	100.0	96.8	- 3.2

Figure 3.15 shows the error percentages of calculated thickness against the reinforcement ratios. It could be seen that the results obtained were within the error percentage of 8.5 % even though the reinforcement percentages were varied.

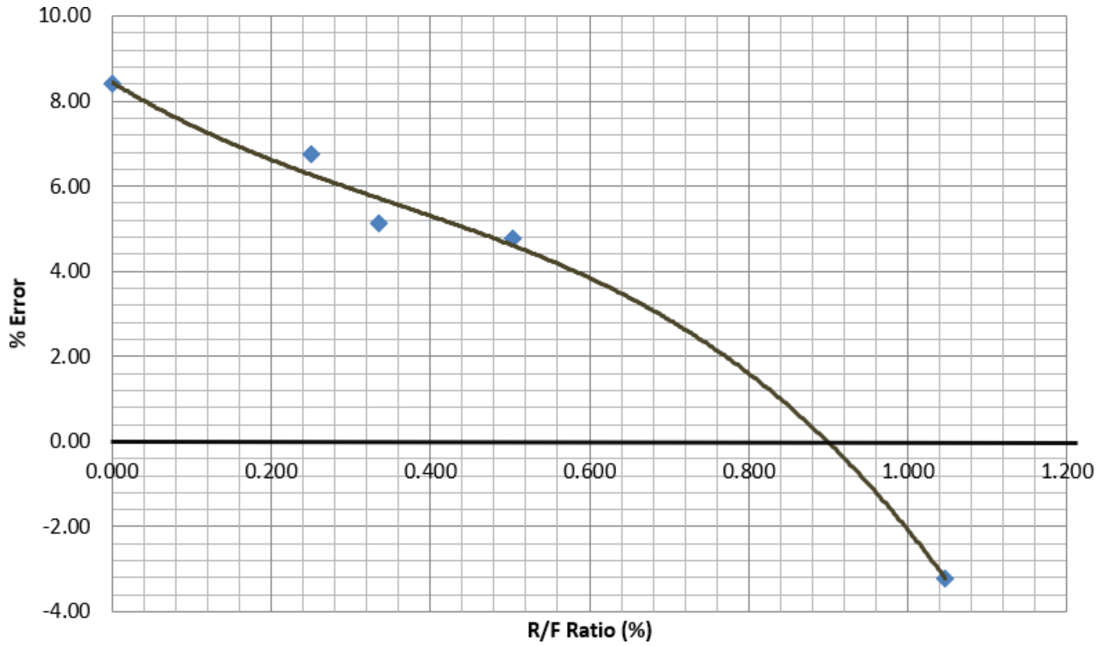


Figure 3.15; Variation of Error Percentages against the Reinforcement Ratio

3.8 Further Experiment to Verify the Effect of Other Parameters

An attempt was taken to re estimate the panel thicknesses of these concrete panels using UPV method after 58 days, aiming to observe the influence of some parameters such as age of concrete, moisture condition and temperature on the accuracy of the thickness predictions using UPV method. Tables 3.8 (a), 3.8 (b), 3.8 (c), 3.8 (d) and 3.8 (e) give the test results and Figures 3.16 (a), 3.16 (b), 3.16 (c), 3.16 (d) and 3.16 (e) show the distance to the receiver Vs time graphs obtained for these panels 30 days after the initial testing data.

Table 3.8 (a); Results Summary for Specimen- 1 (Series 1)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs) 28 days after casting	Time Taken (µs) 58 days after casting
1	100	38.8	37.0
2	200	78.6	74.1
3	300	102.3	101.5
4	400	135.8	116.8
5	500	172.6	152.6
6	600	215.3	181.6
7	700	249.6	264.3
8	800	275.4	295.3
9	900	292.1	303.3
10	1000	320.9	336.3

Table 3.8 (b); Results Summary for Specimen- 2 (Series 1)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs) 28 days after casting	Time Taken (µs) 58 days after casting
1	100	39.4	42.8
2	200	90.3	79.8
3	300	125.1	125.3
4	400	173.1	136.1
5	500	222.4	194.2
6	600	259.3	217.1
7	700	295.6	281.0
8	800	319.8	341.6
9	900	353.1	383.8
10	1000	418.6	400.1

Table 3.8 (c); Results Summary for Sample-A (Series 2)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs) 28 days after casting	Time Taken (µs) 58 days after casting
1	100	25.6	23
2	200	62.2	48.6
3	300	87.9	77.6
4	400	109.1	110.1
5	500	140.9	136.0
6	600	180.1	157.3
7	700	207.9	191.2
8	800	230.1	212.1
9	900	251.2	241.8
10	1000	277.2	272.5

Table 3.8 (d); Results Summary for Sample-B (Series 2)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs) 28 days after casting	Time Taken (µs) 58 days after casting
1	100	37.2	32.5
2	200	61.1	53.1
3	300	101.7	86.6
4	400	143.1	121.8
5	500	165.7	144.1
6	600	189.7	168.2
7	700	212.4	201.8
8	800	233.6	221.1
9	900	257.9	246.5
10	1000	321.4	285.0

Table 3.8 (e); Results Summary for Sample-C (Series 2)

Receiver Position	Distance to the Receiver (mm)	Time Taken (µs) 28 days after casting	Time Taken (µs) 58 days after casting
1	100	25.9	25.5
2	200	53.7	53.6
3	300	77.9	86.8
4	400	100.4	101.6
5	500	131.1	133.1
6	600	163.2	163.8
7	700	184.1	188.6
8	800	204.6	210.8
9	900	246.1	242.8
10	1000	273.7	273.1

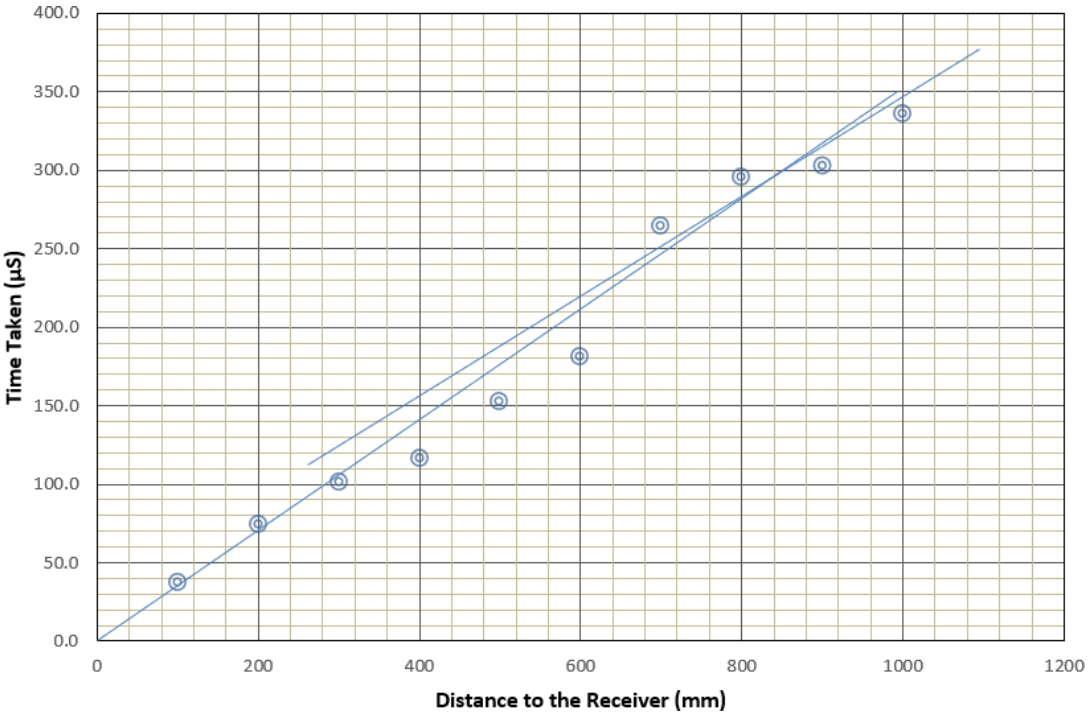


Figure 3.16 (a); Distance to the Receiver Vs Time Taken for Specimen- 1 (Series 1)

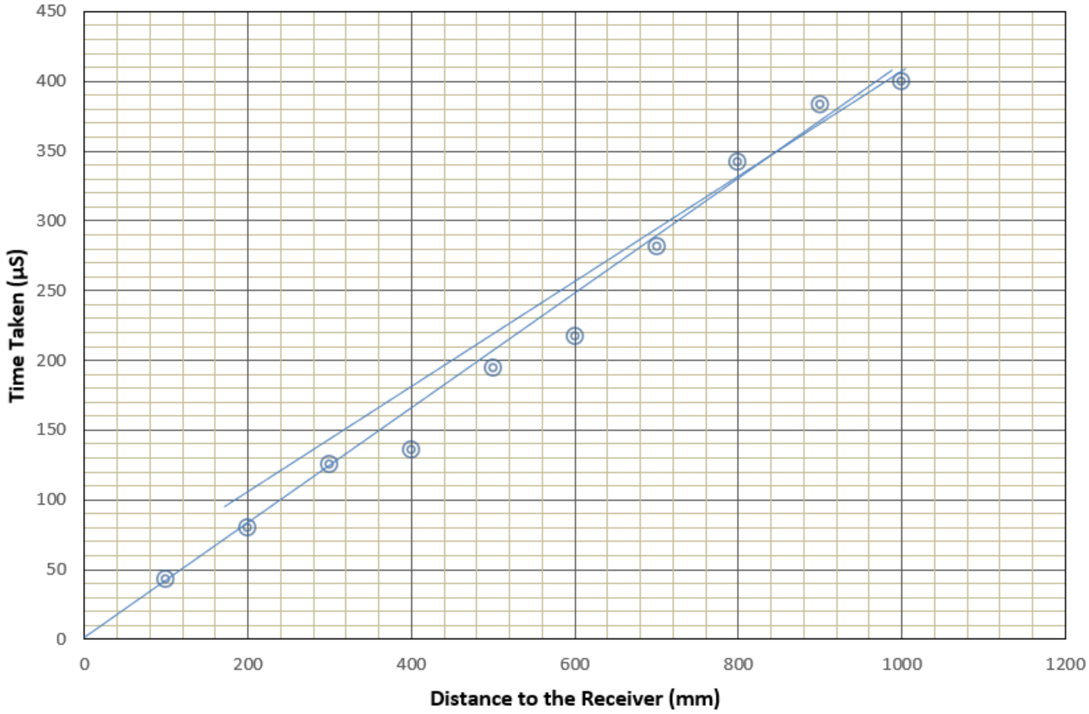


Figure 3.16 (b); Distance to the Receiver Vs Time Taken for Specimen- 2 (Series 1)

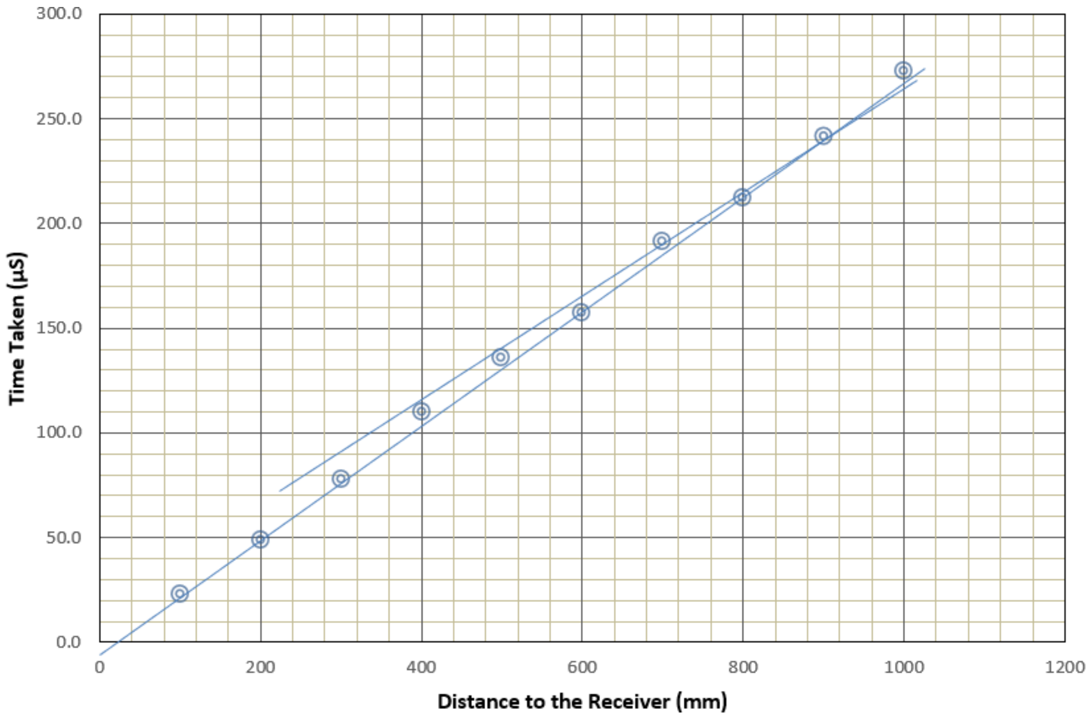


Figure 3.16 (c); Distance to the Receiver Vs Time Taken for Sample- A (Series 2)

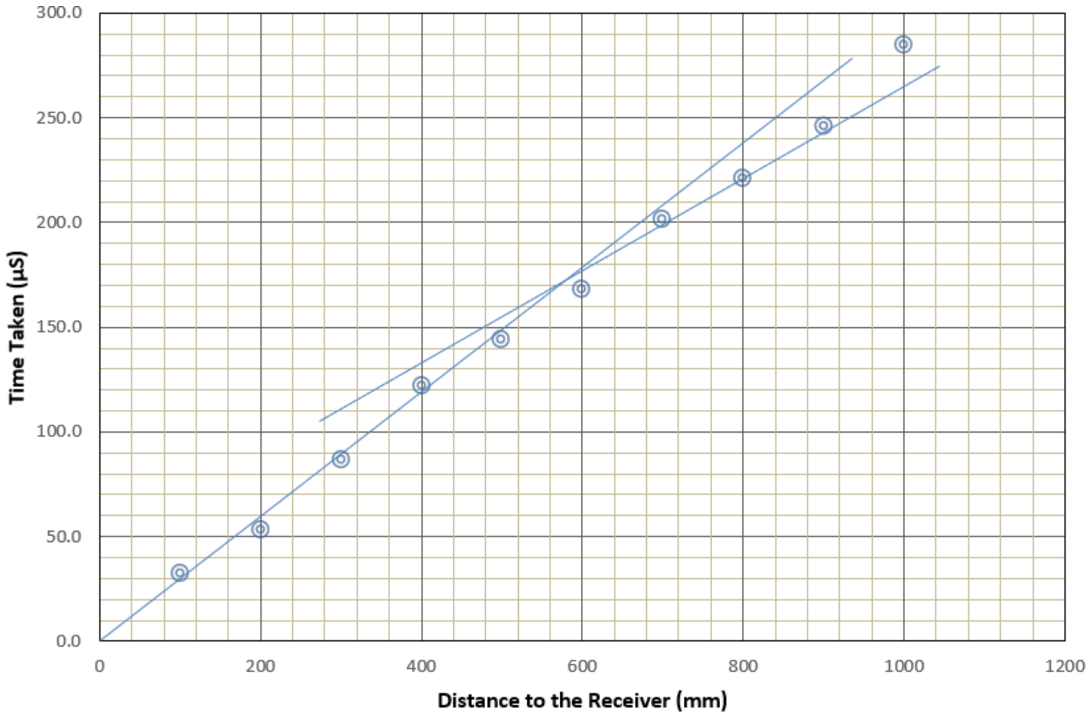


Figure 3.16 (d); Distance to the Receiver Vs Time Taken for Sample- B (Series 2)

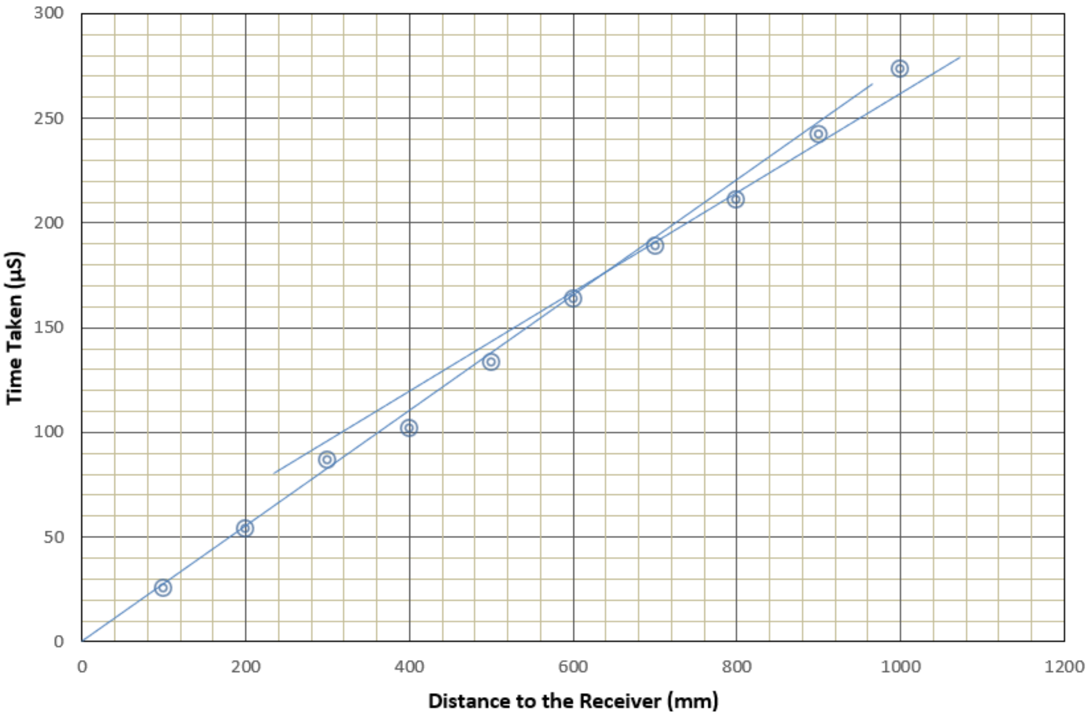


Figure 3.16 (e); Distance to the Receiver Vs Time Taken for Sample- C (Series 2)

Table 3.9 and Table 3.10 shows the calculated thickness and the percentage error for each test panel.

Table 3.9; Calculated Thicknesses for all Panels after 30 days of Initial Test

Tests (At the age of 58 days of concrete)		Velocity V_1 (mm/µs)	Velocity V_2 (mm/µs)	x (mm)	d (mm)
Series 1	Specimen-1	2.800	3.143	840	100.9
	Specimen-2	2.400	2.600	860	86.0
Series 2	Sample-A	3.714	4.154	900	106.4
	Sample-B	3.333	4.444	580	109.6
	Sample-C	3.600	4.182	660	90.2

Table 3.10; Results Summary for all Panels after 30 days of Initial Test

Test	Reinforcement (%)	Actual Thickness (mm)	Calculated Thickness (mm)	Percentage Error (%)
Specimen-1	0.000	100.0	100.9	+ 0.9
Sample-A	0.251	100.0	86.0	-14.0
Sample-B	0.335	100.0	106.4	+ 6.4
Sample-C	0.503	100.0	109.6	+ 9.6
Specimen-2	1.047	100.0	90.2	- 9.8

3.9 Efforts for Further Studies on Real Situations

Further efforts were taken to study some of the existing structures with different conditions. As such, a sewerage treatment plant (Soyzapura Wastewater Treatment Plant) was selected. Where the thickness of that treatment plant is 300 mm and it may be heavily reinforced since it is a water retaining structure. Figure 3.17 shows the practical application of UPV method to determine thickness of concrete walls. The obtained results were tabulated in Tables 3.11 (a) and 3.11 (b).

Figure 3.17; Field Measurements at Sewerage Treatment Plant, Soyzapura

(i) Test Date : 13.11.2019 (Sunny Day)

Location : Soyzapura Wastewater Treatment Plant

Actual Thickness : 150 mm Compost Filter wall with reinforcement (r/f % not known)

Opposite Side Media : Air

Surface : Not smooth

Concrete Grade : Not Known

Table 3.11 (a); Observation for Compost Filter at Soyzapura

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	42.7
2	200	99.4
3	300	134.1
4	400	187.1
5	500	199.4
6	600	261.2
7	700	315.2
8	800	340.7
9	900	375.7
10	1000	520.2

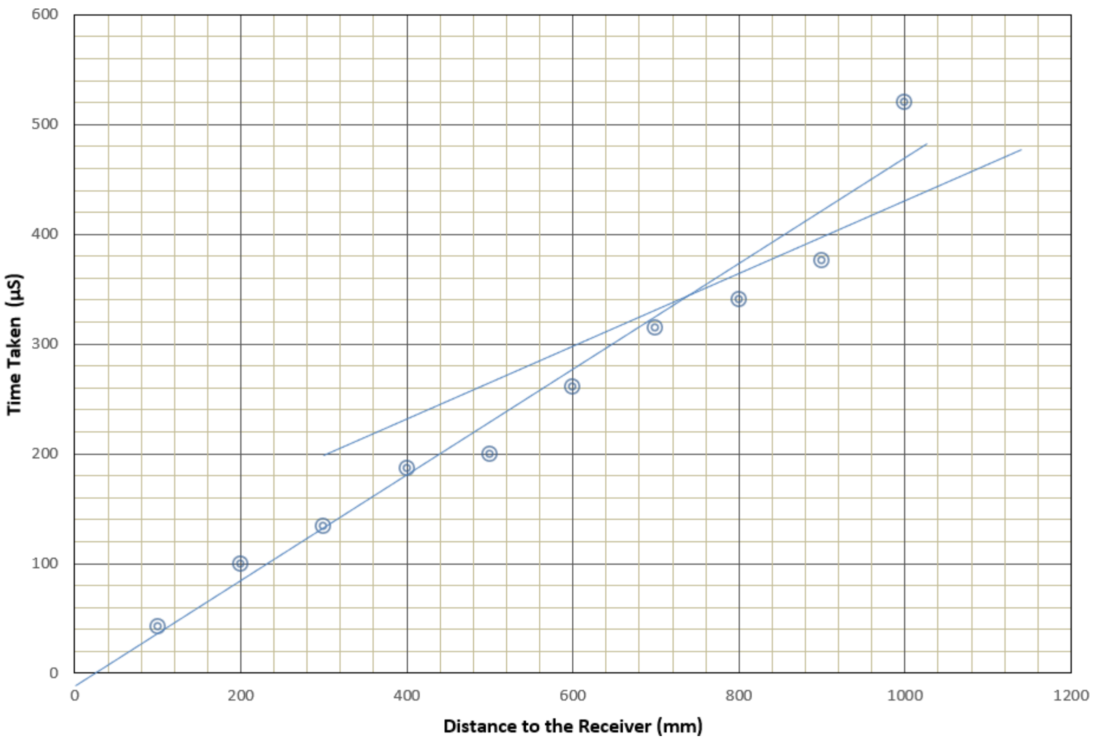


Figure 3.18 (a); Distance to the Receiver Vs Time Taken for Compost Filter Wall at Soyzapura

Velocities,

V_1 = 680 / 320

= 2.125 mm/ µs

V_2 = (1,080 – 520) / (460 – 280)

= 3.111 mm/ µs

x = 740 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{740}{2}\sqrt{(3.111 - 2.125)/(3.111 + 2.125)}$

Calculated Thickness = 160.6 mm

Actual Thickness = 150 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100
= (160.6 – 150) / 150 X 100
= +7.1 %

(ii) Test Date : 13.11.2019 (Sunny Day)

Location : Soyzapura Wastewater Treatment Plant
Actual Thickness : 300 mm wall with heavy reinforcement (r/f % not known)
Opposite Side Media : Water
Surface : Not smooth
Concrete Grade : Not Known

Table 3.11 (b); Observation for Treatment Plant Wall at Soyzapura

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	45.6
2	200	89.7
3	300	104.2
4	400	153.9
5	500	157.9
6	600	223.7
7	700	322.6
8	800	379.4
9	900	389.6
10	1000	400.6

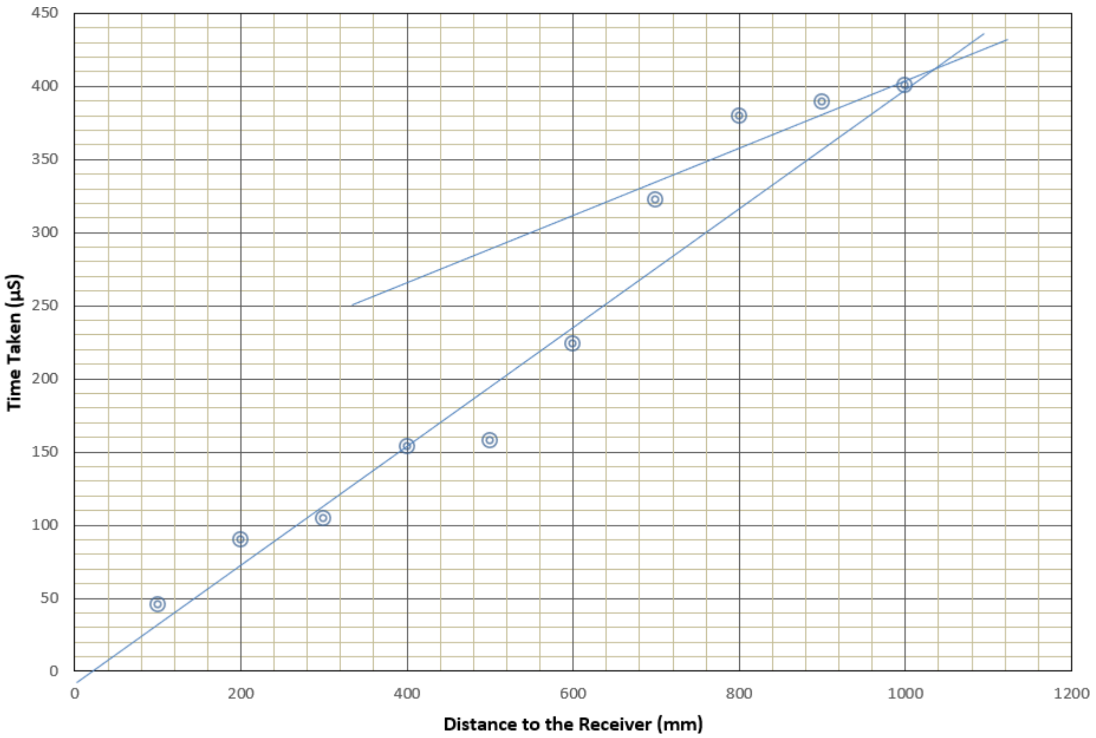


Figure 3.18 (b); Distance to the Receiver Vs Time Taken for Treatment Plant Wall at Soyzapura

Velocities,

V_1 = 320 / 130

= 2.462 mm/ µs

V_2 = (800 – 400) / (360 – 270)

= 4.444 mm/ µs

x = 1,040 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1) / (V_2 + V_1)}$

= $\frac{1040}{2}\sqrt{(4.444 - 2.462) / (4.444 + 2.462)}$

Calculated Thickness = <u>278.6 mm</u>

Actual Thickness = 300 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100
= (278.6 – 300) / 300 X 100
= -7.1 %

In addition, to verify the results, further efforts were taken to study few more concrete panels with different conditions. As such, there were some already prepared concrete panels for some other practical purposes at the Structures Laboratory of University of Moratuwa and these were tested to verify further the proposed method. The observations and results are tabulated in Tables 3.12 – 3.17 and the relevant graphs are shown in Figures 3.19 – 3.24. Summary of all the results are included in Table 3.18.

(iii) Test Date : 01.02.2021 (Sunny Day)

Location : Structures Laboratory, UOM
Actual Thickness : 185 mm panel without reinforcement
Opposite Side Media : Soil (Slab cast on the ground)
Surface : Not smooth
Concrete Grade 25

Table 3.12; Observation for Grade 25 Concrete Panel with 185 mm Thickness

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	65.3
2	200	84.5
3	300	181.6
4	400	257.5
5	500	188.1
6	600	385.6
7	700	417.1
8	800	493.6
9	900	511.2
10	1000	478.6

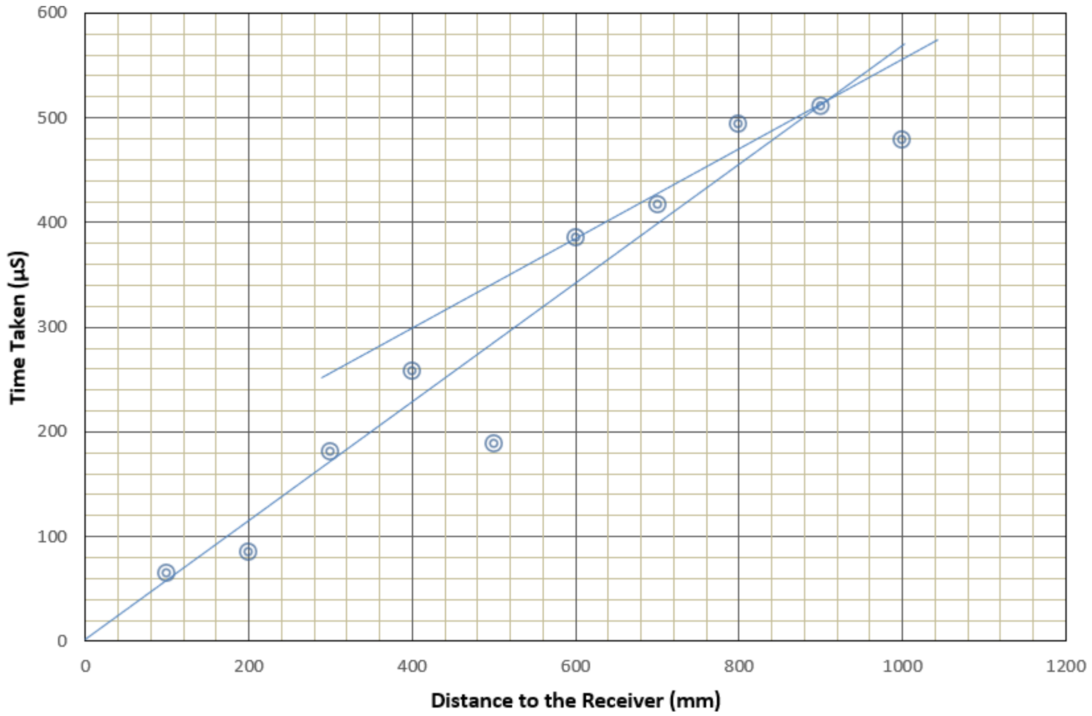


Figure 3.19; Distance to the Receiver Vs Time Taken for Grade 25 Concrete 185 mm Panel

Velocities,

V_1 = 420 / 240

= 1.750 mm/ µs

V_2 = (960 – 540) / (540 – 360)

= 2.333 mm/ µs

x = 900 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{900}{2}\sqrt{(2.333 - 1.750)/(2.333 + 1.750)}$

Calculated Thickness = 170.0 mm

Actual Thickness = 185 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100
= (170.0 – 185) / 185 X 100
= -8.1 %

(iv) Test Date : 01.02.2021 (Sunny Day)

Location : Structures Laboratory, UOM
Actual Thickness : 200 mm panel without reinforcement
Opposite Side Media : Soil (Slab cast on the ground)
Surface : Not smooth
Concrete Grade 30

Table 3.13; Observation for grade 30 Concrete Panel with 200 mm Thickness

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	42.5
2	200	70.1
3	300	166.8
4	400	236.1
5	500	275.3
6	600	296.1
7	700	368.8
8	800	424.0
9	900	476.5
10	1000	482.1

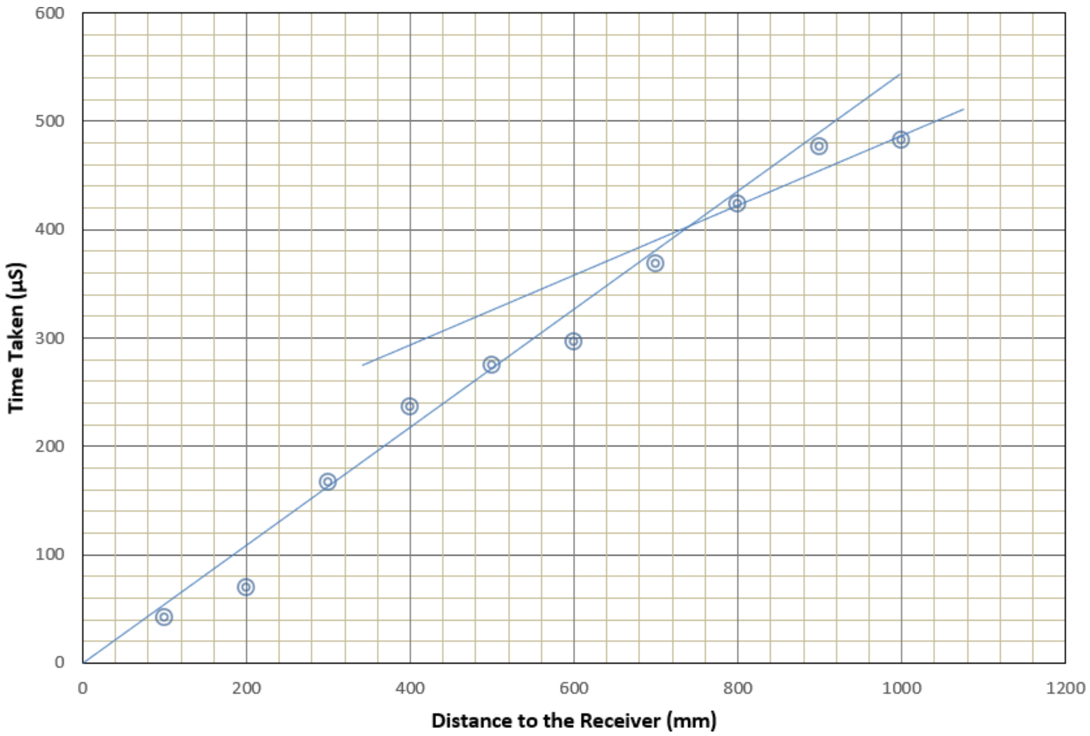


Figure 3.20; Distance to the Receiver Vs Time Taken for Grade 30 Concrete 200 mm Panel

Velocities,

V_1 = 440 / 240

= 1.833 mm/ µs

V_2 = (920 – 480) / (460 – 320)

= 3.143 mm/ µs

x = 740 mm

From theory, d =
$$\frac{x}{2}\sqrt{\frac{(V_2 - V_1)}{(V_2 + V_1)}}$$

$$= \frac{740}{2}\sqrt{\frac{(3.143 - 1.833)}{(3.143 + 1.833)}}$$

Calculated Thickness = <u>189.8 mm</u>

Actual Thickness = 200 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100

= (189.8 – 200) / 200 X 100

= -5.1 %

(v) Test Date : 01.02.2021 (Sunny Day)

Location : Structures Laboratory, UOM

Actual Thickness : 185 mm panel without reinforcement

Opposite Side Media : Soil (Slab cast on the ground)

Surface : Not smooth

Concrete Grade 35

Table 3.14; Observation for Grade 35 Concrete Panel with 185 mm Thickness

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	47.3
2	200	95.8
3	300	101.1
4	400	186.5
5	500	234.5
6	600	229.1
7	700	351.2
8	800	363.5
9	900	448.6
10	1000	445.6

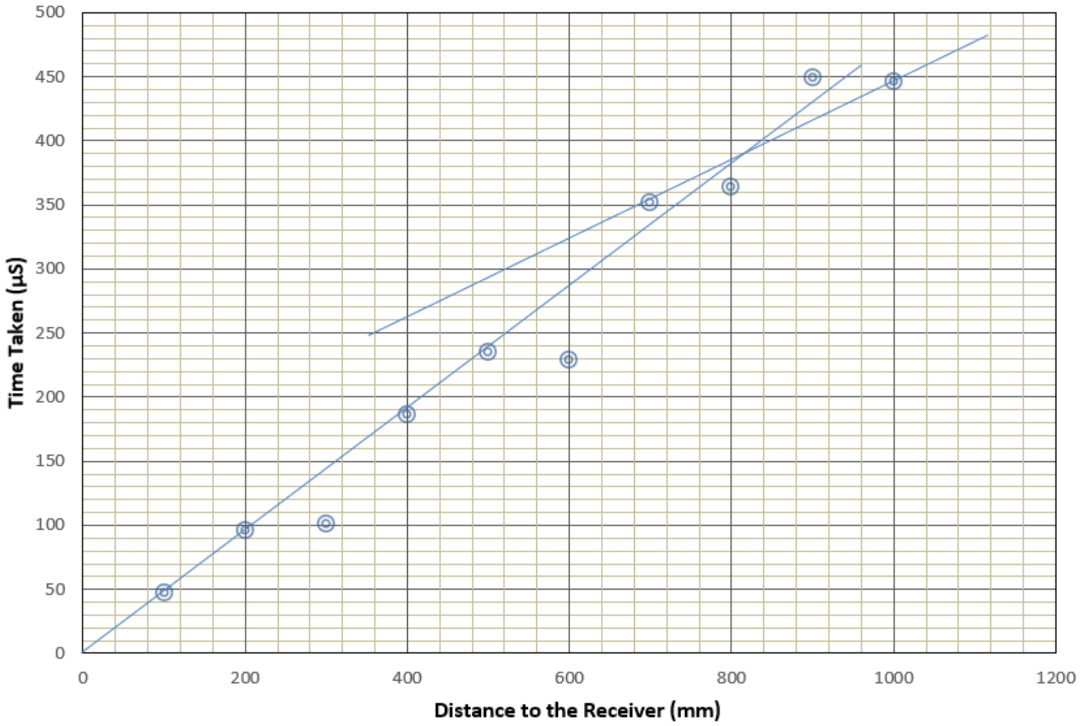


Figure 3.21; Distance to the Receiver Vs Time Taken for Grade 35 Concrete 185 mm Panel

Velocities,

V_1 = 520 / 250

= 2.080 mm/ µs

V_2 = (1,080 – 560) / (470 – 310)

= 3.250 mm/ µs

x = 820 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{820}{2}\sqrt{(3.250 - 2.080)/(3.250 + 2.080)}$

Calculated Thickness = <u>192.1 mm</u>

Actual Thickness = 185 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100

= (192.1 – 185) / 185 X 100

= +3.8 %

(vi) Test Date : 01.02.2021 (Sunny Day)

Location : Structures Laboratory, UOM

Actual Thickness : 90 mm panel with reinforcement (r/f % not known)

Opposite Side Media : Air

Surface : Not smooth

Concrete Grade : Not known

Table 3.15; Observation for 90 mm Panel with Opposite Medium as Air

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	45.8
2	200	121.1
3	300	209.2
4	400	184.3
5	500	298.8
6	600	327.5
7	700	331.8
8	800	390.8
9	900	413.3
10	1000	468.5

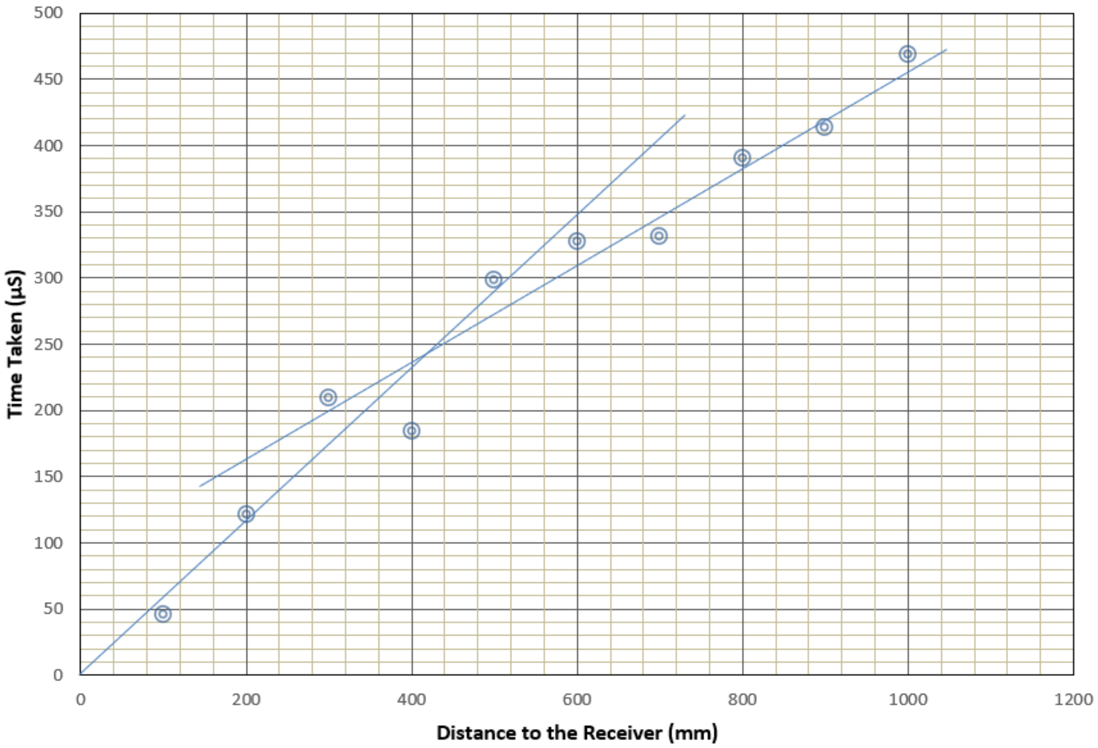


Figure 3.22; Distance to the Receiver Vs Time Taken for 90 mm Panel with Opposite Medium as Air

Velocities,

V_1 = 360 / 210

= 1.714 mm/ μs

V_2 = (840 – 440) / (400 – 250)

= 2.667 mm/ μs

x = 420 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{420}{2}\sqrt{(2.667 - 1.714)/(2.667 + 1.714)}$

Calculated Thickness = <u>97.9 mm</u>

Actual Thickness = 90 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100

= (97.9 – 90) / 90 X 100

= +8.8 %

(vii) Test Date : 01.02.2021 (Sunny Day)

Location : Structures Laboratory, UOM

Actual Thickness : 90 mm panel with reinforcement (r/f % not known)

Opposite Side Medium : Air (Vertically placed panel)

Surface : Not smooth

Concrete Grade : Not known

Table 3.16; Observation for 90 mm Vertically Oriented Panel

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	46.1
2	200	88.1
3	300	119.6
4	400	214.5
5	500	242.1
6	600	256.6
7	700	344.5
8	800	342.5
9	900	416.1
10	1000	485.6

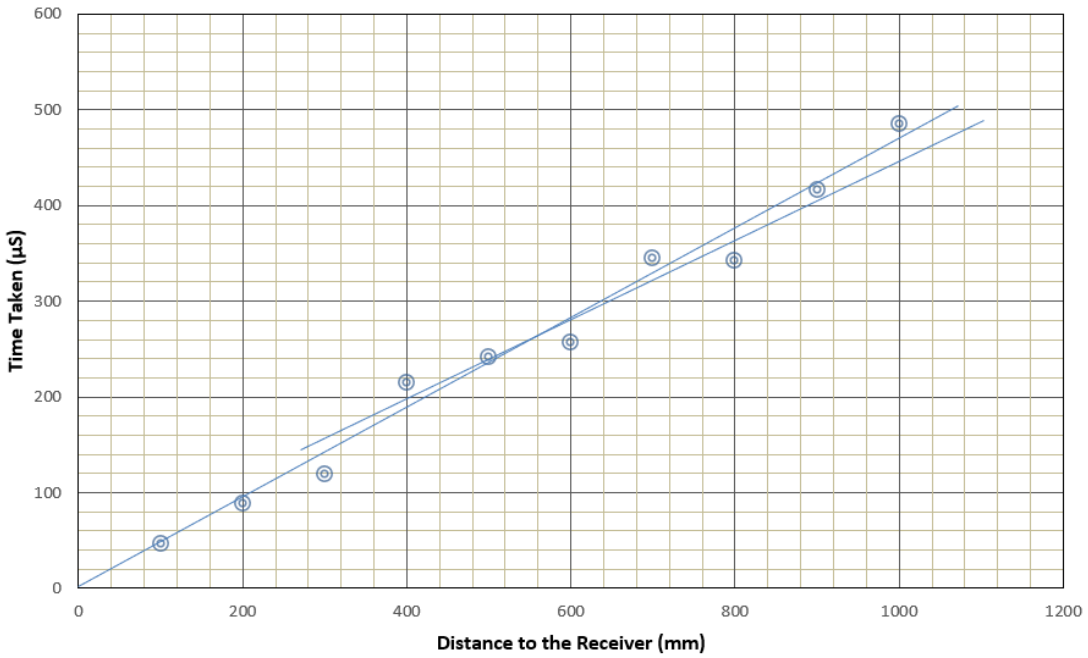


Figure 3.23; Distance to the Receiver Vs Time Taken for 90 mm Vertically Oriented Panel

Velocities,

V_1 = 320 / 150

= 2.133 mm/ µs

V_2 = (660 – 360) / (300 – 190)

= 2.727 mm/ µs

x = 560 mm

From theory, d = $\frac{x}{2}\sqrt{(V_2 - V_1)/(V_2 + V_1)}$

= $\frac{560}{2}\sqrt{(2.727 - 2.133)/(2.727 + 2.133)}$

Calculated Thickness = <u>97.9 mm</u>

Actual Thickness = 90 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100

= (97.9 – 90) / 90 X 100

= +8.8 %

(viii) Test Date : 01.02.2021 (Sunny Day)

Location	: Structures Laboratory, UOM
Actual Thickness	: 60 mm panel with reinforcement (r/f % not known)
Opposite Side Media	: Air
Surface	: Not smooth
Concrete Grade	: Not known

Table 3.17; Observation for 60 mm Panel

Receiver Position	Distance to the Receiver (mm)	Time Taken (μs)
1	100	58.1
2	200	96.2
3	300	138.1
4	400	174.6
5	500	255.8
6	600	275.6
7	700	315.3
8	800	430.6
9	900	651.3
10	1000	492.6

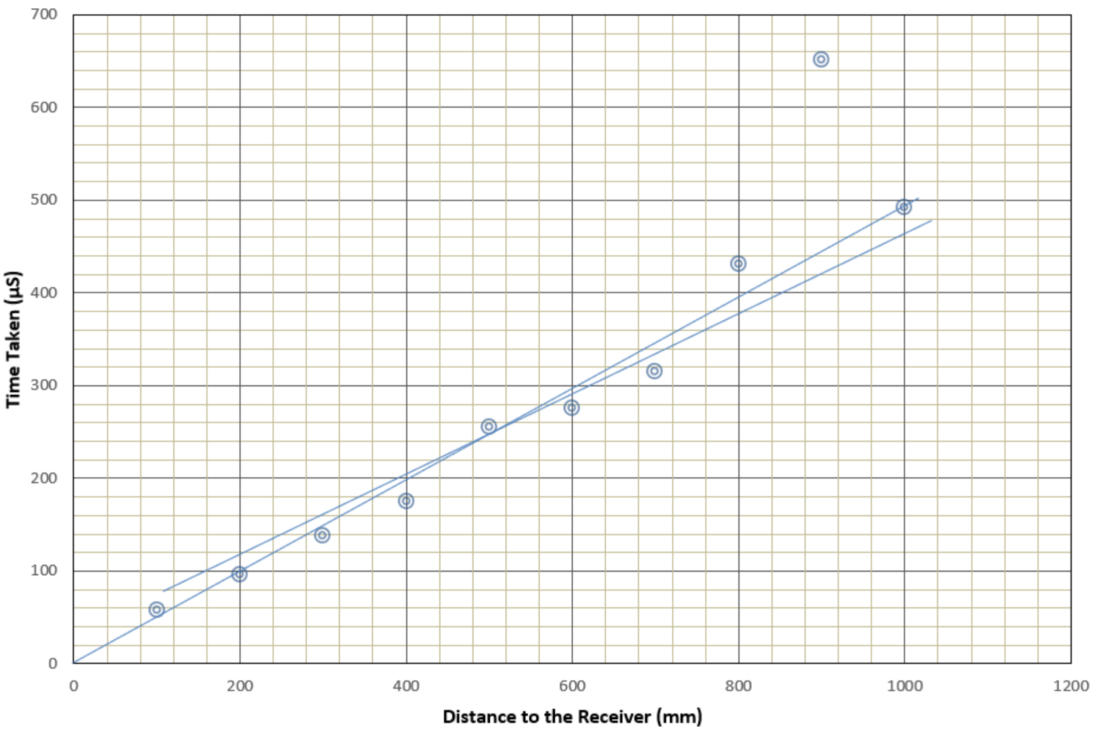


Figure 3.24; Distance to the Receiver Vs Time Taken for 60 mm Panel

Velocities,

V_1 = 240 / 120

= 2.000 mm/ µs

V_2 = (800 – 300) / (380 – 160)

= 2.273 mm/ µs

x = 520 mm

From theory, d = $\frac{x}{2}\sqrt{\frac{(V_2 - V_1)}{(V_2 + V_1)}}$

= $\frac{520}{2}\sqrt{\frac{(2.273 - 2.000)}{(2.273 + 2.000)}}$

Calculated Thickness = <u>65.7 mm</u>

Actual Thickness = 60 mm

Percentage Error = (Calculated Value – Actual Value)/Actual Value X 100
= (65.7 – 60) / 60 X 100
= $\underline{\underline{+9.5\ \%}}$

Table 3.18; Summary of the Results with Some Actual Scenarios with Different Conditions

Date: - 13.11.2019 (Sunny Day)						
Location :- Soyzapura Wastewater Treatment Plant						
Actual thickness (mm)	**Concrete Grade**	**Reinforcement**	**Opposite Medium**	**Surface Condition**	**Estimated Thickness (mm)**	**% Error**
150	Not known	With r/f (% not known)	Air	Not Smooth	160.6	+ 7.1
300	Not known	With heavy r/f (% not known)	Water	Not Smooth	278.6	- 7.1
Date: - 01.02.2021 (Sunny Day)						
Location :- Structures Laboratory, University of Moratuwa						
Actual thickness (mm)	**Concrete Grade**	**Reinforcement**	**Opposite Medium**	**Surface Condition**	**Estimated Thickness (mm)**	**% Error**
185	25	Without r/f	Soil (Slab cast on the ground)	Not Smooth	170.0	- 8.1
200	30	Without r/f	Soil (Slab cast on the ground)	Not Smooth	189.8	- 5.1
185	35	Without r/f	Soil (Slab cast on the ground)	Not Smooth	192.1	+ 3.8
90	Not known	With r/f (% not known)	Air	Not Smooth	97.9	+ 8.8
90	Not known	With r/f (% not known)	Air (Vertically Placed)	Not Smooth	97.9	+ 8.8
60	Not known	With r/f (% not known)	Air	Not Smooth	65.7	+ 9.5

4.0 CONCLUSIONS AND RECOMMENDATIONS

It was reported in literature that the ultrasonic pulse velocity is affected by the concrete properties such as age of concrete, mix, type of aggregate, porosity, type of cement, the aggregate/cement and water/cement ratios, the conditions of concrete casting, curing, reinforcing bars as well as the concrete thickness through which the pulses travel. In addition, the ultrasonic pulse velocity is affected by other factors such as temperature, stress history/ level of stress, path length, moisture and curing condition of concrete, presence of reinforcement and size and shape of the specimen.

However, from this experimental study and the field investigations carried out, it is found that the UPV test method could be used to estimate the thickness of concrete walls with a reasonable accuracy. The error percentage of all the estimated thickness were less than 15%.

It is important to note that the UPV measurements should be taken very carefully and precisely since the estimated thicknesses greatly depend on the accuracy of the readings and the concrete surface condition. It is always better to grind the concrete surface and smoothen before taking UPV readings. There is no clear influence seen of the percentage of reinforcement in concrete on the accuracy of the thickness estimation.

So, it is evident that, even though the opposite medium is either air, water or even soil the thickness could be estimated within an acceptable error percentage.

4.1 Suggestions for Further Studies

In this experimental study, except reinforcement percentage all the other parameters such as concrete grade, panel thickness, aggregate type and size, etc. which may influence the ultrasonic pulse velocity were kept constant throughout the experimental study. Further studies could be carried out by varying the other factors which may influence the ultrasonic pulse velocity, which may lead to increase the accuracy of this method.

As this experimental study was carried out for 100 mm thick concrete panels and in future, the study could be carried out for various thicknesses where it could be suggested up to which thickness level this method could be used and the thickness could be estimated.

In addition, in real life scenario, this method could be useful to estimate the thickness of water retaining structures such as the underground sumps, and other structures such as pump house walls, etc. where opposite side is inaccessible and the opposite medium would be air, water or soil.

Further studies should be carried out to investigate the effect of opposite medium on the accuracy of the estimated thickness using UPV method.

REFERENCES

Al-Hamed A.H. and Swamy N.R., The use of pulse velocity measurements to estimate strength of air-dried cubes and hence in situ strength of concrete, Malhotra V.M., Ed., ACI SP 82, American Concrete Institute, Farmington Hills, MI, 1984, 247

Andrews D.R., Future prospects for ultrasonic inspection of concrete. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 99, Feb. 1993, pp. 71-73

ASTM C597-16, Standard Test Method for Pulse Velocity Through Concrete, Book of Standards Volume: 04.02, 2009

BS 1881: Part 203: 1986, Testing Concrete, Part 203. Recommendations for measurement of velocity of ultrasonic pulses in concrete

BS EN 12504-4, Testing Concrete- determination of ultrasonic pulse velocity, British Standards Institution, London

Bullock R.E. and Whitehust E.A., Effect of certain variables on pulse velocities through concrete, Highway Res. Board Bull., 206, 37, 1959

Bungey J.H., The validity of ultrasonic pulse velocity testing of in-place concrete for strength, NDT International, IPC Press, Dec. 1980, pp. 296-300

Bungey J.H. and Malhotra V.M., The influence of Reinforcement on Ultrasonic Pulse Velocity Testing, ACI SP 82, American Concrete Institute, Farmington Hills, MI, 1984, 229

Bungey J.H., Ultrasonic testing to identify alkali-silica reaction in concrete, British Journal of Non-Destructive Testing, 33, No. 5, 1991, pp. 227-231

Bungey J.H., Millard S.G. & Grantham M.G., “Testing of Concrete in Structures”, Fourth Edition, Taylor & Francis, 2006, pp. 51-81

Fazli Z.T.M., Nizam U.L., Abdeen U.L.S., “Use of Ultrasonic Pulse Velocity Measurements to estimate concrete wall thickness”, E/2004/010, Final Year Project, University of Peradeniya

Guha S.K. and Wedpathak A.V., The practical use of ultrasonic pulse velocity measurements in the assessment of concrete quality, Discussion on a paper published in Magazine of Concrete Research, Volume 32, Number 110: March 1980, pp 61-64

Hillger W., Imaging of defects in concrete by ultrasonic pulse-echo technique. Proc. Struct. Faults and Repairs 93, Eng. Technics Press, Edinburgh, 3, 1993, pp. 59-65

Hoegh K., Khazanovich L., Yu H.T., "Ultrasonic Tomography Technique for Evaluation of Concrete Pavements." Transportation Research Record: Journal of the Transportation Research Board, No. 2232, pp. 85-94, 2011

Hogarth C.A. and Blitz J., Techniques of Non-Destructive Testing, London, Butterworths, 1960, pp. 83-103

Jones, R., The application of ultrasonic to the testing of concrete. Research, London, 383, pp.364-368, 1948

Jones R., Discussion on the Ultrasonic Testing of Concrete, The Structural Engineer, Vol. XXXIII, No. 10, pp. 190-206, 322, 1955

Jones R., Non-Destructive Testing of Concrete, Cambridge University Press, London, 1962.

Jones R., Testing of concrete by an ultrasonic pulse technique, RILEM Int. Symp. on Nondestructive Testing of Materials and Structures, Paris, Vol. 1, Paper No. A-17 January 1954, 137. RILEM Bull., 19(Part 2), Nov. 1954

Jones R. and Facaoaru I., Recommendations for testing concrete by the ultrasonic pulse method, Materials and Structures Res. Testing (Paris), 2(19), pp. 275-284, 1969

Kaplan M.F., Compressive strength and ultrasonic pulse velocity relationships for concrete in columns, ACI J., 29(54-37), 675, 1958

Kaplan M.F., The effects of age and water to cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete, Mag. Concr. Res., 11(32), 85, 1959

Koehler B., Hentges G. and Mueller W., Improvement of ultrasonic testing of concrete by combining signal conditioning methods, scanning laser vibrometer and space averaging techniques, NDT&E International, 31, No. 4, 1998, pp. 281-287

Kroggel O., Ultrasonic examination of crack structures in concrete slabs. Proc. Struct. Faults and Repairs 93, Eng. Technics Press, Edinburgh, 3, 1993, pp. 67-70

Krause M., Wiggenhauser H., Ultrasonic Pulse Echo Technique for Concrete Elements Using Synthetic Aperture, UTonline Application Workshop in May 1997, Vol.2 No. 05

Krause M., Wiggenhauser H., Krieger J. and Schickert M., NDE of a post tensioned concrete bridge girder using ultrasonic echo and impact echo. Proceedings of Structural Faults and Repair 2003, Eng. Technics Press, Edinburgh, 2003, CD-ROM

Krause M., Mielentz F., Milmann B., Streicher D. & Muller W., Ultrasonic imaging of concrete elements: state of the art using 2D synthetic aperture. Proc. NDT-CE 03, DGZfP, Berlin, 2003, CD-ROM

Leslie, J.R. and Cheesman, W.J., 1949. An ultrasonic method of studying deterioration and cracking in concrete structures. Journal of the American Concrete Institute, 21(1), pp.17-36.

Mackenzie, J.K., 1950. The elastic constants of a solid containing spherical holes. Proceedings of the Physical Society. Section B, 63(1), p.2.

Malhotra V.M., Testing hardened concrete: Non-destructive methods. Monograph 9, American Concrete Institute, Detroit, 1976

Nogueira C.L. and Willam K.J., Ultrasonic testing of damage in concrete under uniaxial compression, ACI Materials Journal, 98, No. 3, May-June 2001, 265-275

Pavlakovic B., Lowe M.J.S. & Cawley P., The inspection of tendons in post tensioned concrete using guided ultrasonic waves. INSIGHT- Journal of the British Institute of Non-Destructive Testing, 41, No. 7, July 1999, pp. 446-452

Popovics S. and Popovics J.S., Effect of stresses on the ultrasonic pulse velocity in concrete, RILEM Mater. Struct., 24, 15, 1991

Prassianakis I.N. and Giokas P., Mechanical Properties of old concrete using destructive and ultrasonic non-destructive testing methods, Magazine of Concrete Research, 2003, 55, No. 2, April, pp. 171-176

Raišutis R., Voleišis A., Kažys R., Application of the through transmission ultrasonic technique for estimation of the phase velocity dispersion in plastic materials, ISSN 1392-2114 Ultragarsas (Ultrasound), Vol. 63, No. 3, 2008

Raj, Baldev ; Jayakumar, T ; Thavasimuthu, M., Practical Non-Destructive Testing, 3rd Edition, Publisher: Narosa, New Delhi, ISBN; 9788173197970, 2007

RILEM Recommendation NDT 1, Testing of concrete by the ultrasonic pulse method, Paris, Dec. 1972, pp.73-82

Sack D.A. and Olson L.D., Advanced NDT methods for evaluating concrete bridges and other structures. Proc. Struct. Faults and Repairs 93, Eng. Technics Press, Edinburgh, 1, 1993, pp. 65-76

Sandor Popovics, Joseph L. Rose, John S. Popovics, (1990), The behavior of ultrasonic pulses in concrete, Cement and Concrete Research, Volume 20, Issue 2, March 1990, Pages 259-270

Seals R.K. and Anderson D.A., Pulse velocity as a predictor of 28 and 90 day strength, ACI J., 78, 116, 1981

Sturrup V.R., Vecchio R.J., and Caratin H., Pulse Velocity as a Measure of Concrete Compressive Strength, ACI SP 82-11, American Concrete Institute, Farmington Hills, MI, 1984, 201

Tarek Uddin Mohammed and Md Nafiur Rahman, Effect of types of aggregate and sand-to-aggregate volume ratio on UPV in concrete, Construction and Building Materials 125 (2016), pp. 832-841

Tarun R. Naik, V. Mohan Malhotra, John S. Popovics, The Ultrasonic Pulse Velocity Method, Chapter 8, "Handbook on Nondestructive Testing of Concrete", Second Edition, V.M. Malhotra and N.J. Carino, pp. 8-1 to 8-19, 2004

Tomsett H.N., Ultrasonic pulse velocity measurements in the assessment of concrete quality, Magazine of concrete research, 32, No. 110, March 1980, pp. 7-16

Turgut P., and Kucuk O.F. (2006), "Comparative Relationships of Direct, Indirect, and Semi-Direct Ultrasonic Pulse Velocity Measurements in Concrete, Russian Journal of Nondestructive Testing, November 2006.

Warusavitarana L.I, “Non Destructive Testing of Concrete”, Dissertation of Master of Engineering in Structural Engineering Design, Department of Civil Engineering, University of Moratuwa., 2006

Wu T.T. and Lin T.F., The stress effect on the ultrasonic velocity variations of concrete under repeated loading, ACI Mater. J., 95(5), 519, 1998