The Effect of Coupling Media on the Pulse Velocity of Concrete

by

Sura Faleh Aziz Al-Khafaji

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Declaration

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publication has been included. The contribution of the candidate and the other author to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Parts of the work in chapter 4, have appeared in the following publications:

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Dedication

To my beloved parents, for their endless love, support and encouragement

To those who said I couldn’t

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Abstract

Ultrasonic methods have been widely used in civil engineering for the non-destructive evaluation of the concrete structures. Measurements of the velocity of the ultrasonic wave in concrete can be used to assess the quality of the concrete. As the concrete is a heterogeneous multiphase material which is acoustically inhomogeneous, propagation of ultrasonic waves through it will be a complex process comparing to other solid materials.

This thesis involved testing the hypothesis, suggested by previous studies using ‘non-contact’ apparatus, that a coupling effect might exist between the ultrasound wave and the constituent materials of concrete.The velocity of sound in concrete samples measured by the traditional ultrasonic pulse velocity testing apparatus (PUNDIT), different coupling media of varying acoustic impedance was placed between the transducers and concrete. The coupling effect was evaluated in terms of the couplant used, compressive strength, aggregate content and maximum size of coarse aggregate. Analysis of variances (ANOVA) was performed to determine if there are statistically significant differences between the measurements recorded using a conventional system and a coupled system.

In accordance with the experimental results, coupling materials have an effect on the pulse velocity measured in a given concrete. The effect varies depending on the material used. The UPV measurements with solid coupling were higher than those from the liquid coupling at all strength levels.

For concrete with a specific w/c, the pulse velocity increased as the aggregate content increased. The conventional and rubber tests showed more sensitivity to the changes in aggregate content than the liquids tests. When the aggregate content is constant, concretes with larger MAS generally yielded higher pulse velocities than those with smaller MAS. In the coupling tests, the UPV measurements were more affected by the couplant used than the change in MAS of the mix. While the rubber test showed significant differences between the measurements of the two MAS at each strength level, the propanol test recorded approximately similar values for both MAS at all compressive strength levels.

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Chapter 1 Introduction

1.1 Introduction

Due to the vast urban expansion in many countries over the last few decades, the demand for high strength, high-performance concrete in the construction industry has increased. Concrete is not a simple material anymore. Apart from producing concrete using cement, water, and aggregate, mineral and chemical admixtures are now being added to improve the quality of concrete (Nassif and Suksawang, 2003).

However, concrete in structures may be exposed to a range of environmental degradation factors, such as freezing and thawing, thermal stress cycles, sulphate attack, sudden failures or damage by fire. Thus, quality assessment for concrete properties and evaluation of the performance of structural concrete members will require testing the concrete in situ. Ideally, these methods need to be non-destructive so as they do not affect the function of the structure.

There are several diverse of non-destructive methods for monitoring the concrete quality and assessment of the existing concrete structure. These methods can be categorised broadly into surface hardness methods, vibration methods, radiometric methods, electro methods, and magnetic methods. Each method is based on specific theoretical principles and has its own particular advantages and limitations.

Among those methods, ultrasonic pulse velocity method is a well established non-destructive tool for diagnostic examination of concrete. It is based on the principle that the velocity of ultrasound waves propagate through a solid material is depending on the density and the elastic properties of that material, which is related to the internal conditions of the concrete under investigation Deteriorated concrete will return lower velocity whereas sound concrete returns higher velocities. It is particularly preferred as it is easy to perform, quick and inexpensive (Raouf and ALsamari, 1999). Ultrasonic pulse velocity method has been used for assessing concrete strength, investigating the homogeneity of concrete, studying the durability of concrete, and measuring the depth of surface cracks in concrete. However, the wave velocity measurements in concrete are sensitive to many variables, the researchers were working on improving the reliability of measurements of the pulse velocity technique by investigating the effect of these variables.

Enormous research has been undertaken in this field, where the influence of concrete parameters has gained more attention by the researchers. These variables are including aggregate content and size, moisture content, mix proportions, the age of concrete and others. There are some factors other than the concrete parameters that have been also investigated by the researchers such as temperatures, reinforcement bars, path length, shape and size of the specimen and stress history in concrete as they could introduce extraneous variability to the ultrasonic pulse velocity measurements in concrete.

An essential part of any application of ultrasonic testing methods is providing a good acoustic coupling between the transducers and the concrete. A Couplant must be applied between the transducers and faces of concrete to facilitate the transmission of the ultrasonic wave energy into the concrete. The amount of energy that is transmitted at the interface between the transducer and the test area will be depended on the acoustic impedance of the transducer, the coupling medium and the material being tested. Thus, if the acoustic impedance of the transducers and concrete are kept fixed in ultrasonic testing, it would be expected that the couplant layer will have an important effect on the velocity measurements. Few studies have investigated the effect of coupling on pulse velocity measurement. One of those studies has investigated the potential of using air-coupled (i.e. non-contact) ultrasonic equipment compared to traditional ultrasonic equipment (PUNDIT) (Purnell et al., 2004). The researchers hypothesised that a preferential coupling effect might exist between the ultrasound wave and the constituent materials of concrete .i.e. that the speed of sound measured depends on the couplant used. Therefore, this work seeks to investigate the hypothesis of preferential coupling effect with the use of different coupling media of varying acoustic impedance.

1.2 Aims and objective

The main aim of this research is to test the hypothesis that a preferential coupling effect (or related phenomena) could occur between the ultrasound wave and the consist materials of the concrete. The coupling effect was originally proposed in (Purnell et al., 2004) work, where the air was used as a coupling medium. In this work, different coupling media of varying acoustic impedance is used to replicate the effect. The research will be divided into four stages:

1. To validate whether a coupling effect exists in the conventional ultrasonic pulse velocity test, with the use of solids and liquid coupling materials of different acoustic impedances.

2. To determine the effect of mix proportions (aggregate maximum size and content and compressive strength level) on the measurements of the pulse velocity through concrete in presence of coupling medium.

3. To propose modifications to enhance the apparatus' testing performance in case the coupling medium use leads to more precise results in the concrete testing,

1.3 Outline of the thesis

This thesis consists of seven chapters as follows:

Chapter 1: presents an introduction to ultrasonic pulse velocity testing of concrete

Chapter 2: displays the literature review on the ultrasonic pulse velocity test of concrete. It provides some background information on the propagation of the waves in solids, a reflection of waves at the interface and the attenuation of waves in solids. A review of the existing ultrasonic techniques and their advantages and limitations were discussed. The applications of ultrasonic pulse velocity method in concrete and factors that affecting measurements of the pulse velocity are also described.

Chapter 3: includes a description of materials that used in the experimental programme and the experimental tests.

Chapter 4: describes experimental work conducted to investigate the hypothesis that a preferential coupling effect (or related phenomena) could occur between the ultrasound wave and the consist materials of the concrete.

Chapter 5: the effects of maximum aggregate size and content on the measured pulse velocity by the conventional and coupling testing system are investigated in this chapter.

Chapter 6: presents the conclusions drawn from the present study as well as a recommendation for future studies.

Chapter 2 Literature Review

2.1 Introduction

This chapter presents some background information on concrete characteristics and the basic properties of ultrasound wave propagation through solids. It then reviews some of the ultrasonic techniques used in the inspection of the concrete structures. Finally, it gives a detailed description of the pulse velocity method, equipment, factors that affect the pulse velocity through concrete, and the application of this method.

2.2 Concrete characteristics

Concrete is the most substantially used construction material in the world, mainly due to its low cost, versatility, durability, availability, and ability to resist severe weather environments. Concrete quality usually evaluated by measuring the compressive strength of the concrete, as it is easily measured and can be directly related to the internal structure of the concrete (Neville and Brooks, 2010). As the concrete is a composite material consisting of three phases: cement paste, aggregate and the transition zone between them, its internal structure is very complex and the concrete strength and other properties are strongly linked to the characteristics of each of the three phases. Although concrete is relatively strong in compression, it is characterised by its limited capacity for withstanding tensile stress. Therefore, steel bars are used to reinforce the concrete to handle tensile stresses (Mays, 2002).

An important aspect of the quality control of the concrete on construction sites is the well- known that the properties of concrete are controlled by the process variables which may be varied at the design and/ or on-site stages. Water to cement ratio is the major factor which controls most of the mechanical properties of concrete, including compressive strength. Compressive strength is the most important property of structural concrete since the concrete is mainly designed to resist compressive stress and many other properties of interest are linked to it. The relationship between water to cement ratio and compressive strength has long been a matter of interest for researchers. Several design factors other than water-cement ratio show a considerable influence on the compressive strength and the mechanical properties of concrete as well. These factors include mix proportion, aggregate characteristics, porosity, curing temperature and curing humidity. Moreover, additional factors related to construction techniques such as compaction, curing practices and reliability of materials supply (Waddell and Dobrowolski, 1998).

Proper compaction will enable the fresh concrete to reach its potential design strength, density and permeability by expelling the entrapped air and packing the aggregate particles together so they entirely surrounded by cement paste. The effect of compaction on the properties of concrete is more closely related to member type and location within the structure. Lower levels of structures will experience greater compaction due to hydrostatic effects related to member depth, such that density tends to be higher at the base than in the upper region. Also, compaction may be hindered by reinforcement leading to voids and density variations (Neville and Brooks, 2010).

The aim of curing is to provide sufficient moisture, temperature and time to enable the hydration and hardening process to progress sufficiently. Continued hydration is achieved by maintaining a relative humidity in the concrete of greater than 80% which leads the concrete to gain the desired strength (ACI 308R-16, 2016). Therefore, it is observed that the strength of moist cured concrete will be higher than that of concrete cured in air (Popovics, 1998).

As concrete is a heterogeneous multiphase material, changes in its strength and other properties can be caused by small discrepancies in mix design, raw materials and subsequent placing procedures, especially when it is placed in-situ rather than being prefabricated. Undoubtedly there will be flaws in the concrete of varying severity; as a result, many methods of fault detecting and testing concrete have been developed. Because of the difficulties and damages associated with destructive testing, non-destructive techniques have been developed over the years to inspect concrete, that work by relating acoustic, chemical or electrochemical parameters measured by various transducers to compressive strength and/or other mechanical and physical properties of the concrete.

2.3 The need for inspection

Maintaining safe and reliable concrete structures in the civil infrastructure system is concerned with the efficiency of the existing structure and its future performance. Concrete structures include buildings, roads, bridges, airfields and dams. Concrete in service is may be exposed to environmental effects (e.g. caused by weather), internal or external harmful chemical reactions (e.g. caused by carbon dioxide, chlorides or alkali-aggregate reactions) and unexpected mechanical loading (e.g. impact damage, overloading) and because of its physical and chemical nature of a heterogeneous composite material with complex microstructure, it may deteriorate as a result (Perkins, 2002). Another contributory factor that can be added to the deterioration of concrete structures is the bad quality of concrete which is resulting from either poor design or poor site practice. Where inadequate cover to the reinforcement bars, incorrectly made construction joints, gout leakage, poor compaction, segregation and poor curing are responsible for the deterioration of concrete in structures. Thus, quality control, structural assessment and maintenance are essential not only for the existing structures but also for the new structures during construction to extend their operational service life (Mutlib et al., 2016).

In-situ, non-destructive testing methods offer an interesting approach to evaluating of concrete structures, as they easily access to material properties while subsisting quick and at reasonable cost comparing to destructive tests. These methods require a correlation between what is measured (speed of sound, voltage etc.) and the actual property of interest; these correlations are of widely varying reliability. There are many non-destructive techniques, each method based on specific theoretical principles, and many factors determine whether a particular testing method will be chosen, or a combination of two or three non-destructive techniques. These factors include access, cost, damage type, speed, reliability, and the physical properties of the construction materials of the structures. It also depends on the investigation to be undertaken is that; the strength of the concrete, or the location of defects, whether the reinforcement is corroding etc.

Some of the non-destructive techniques have been successfully applied for the investigation of concrete such as rebound hammer (surface hardness methods), Half-cell potentiometer (electrochemical methods), Rebar cover-meter (electromagnetic method) and pulse velocity (ultrasonic methods). The rebound method is a measure of the surface hardness which has been used for assessing the uniformity of concrete, determining the deterioration areas in concrete and estimating the strength of concrete by pre-established correlation. It is based on rebound principle, the rebound of an elastic mass relies on the hardness of the surface against which the mass strikes (Malhotra, 2004).

One of the most popular techniques for assessing corrosion conditions in the reinforcing bars in concrete is the half-cell potential method. It is an electrochemical technique, measuring the potential of the embedded steel reinforcement bar against a reference half-cell which placed on the concrete surface. Data from a half-cell potential measurements can be presented in the form of an equipotential contour map to point out those areas that have the greatest risk of corrosion (Clifton and Carino, 1982).

Rebar cover meter is an electromagnetic device in operation, commonly used for determining the thickness of concrete cover overlying the reinforcement bars embedded in the hardened concrete and locating the reinforcement bars and their orientation and diameter. This information is vital to starting any maintaining works in a construction site and also for assessing the structural durability. The test method is involved generating a magnetic field which propagates through the concrete. The presence of reinforcing bars within the concrete will affect the electromagnetic field and these variations will be detected and recorded (BS 1881-204, 1988).

Among these methods, the ultrasonic pulse velocity method has gained an important place in testing concrete regarding quality control, defect characterization and assessment of mechanical and physical properties because of its ease use at a reasonable cost (Karaiskos et al., 2015) and also a long history of accepted correlations between pulse velocity and mechanical properties of concrete (Petro and Kim, 2012).

Based on the theory of the sound propagation in solids, sound wave transmission velocity is a function of the elastic properties and the density of the material. Thus the internal condition of the concrete will affect the ultrasonic wave propagation characteristics. The wave velocity, relative amplitude and attenuation can be used as a measure of the integrity of the concrete under investigation (Nogueira, 2010). However, the concrete is an inhomogeneous material compose of three phases (cement paste, aggregate and transition zone) each of them has a different acoustic impedance, thus the propagation of ultrasonic wave through it will accompany by complex processes of attenuation, reflection, and refraction of waves composing this pulse (Kim and Kim, 2009).

The estimation of in situ concrete strength and detection of voids and cracks within concrete are regarded as the most important applications for the implementation of ultrasonic pulse velocity measurement in concrete (Aggelis and Shiotani, 2008).

2.4 Ultrasonic methods

The main objective of the application of ultrasonic methods in concrete is to provide a reliable assessment of the integrity of, or defects detection in, concrete structures. It based on the propagation and detection of mechanical vibrations that have interacted with the internal condition of concrete structures. The variation in the characteristics of ultrasonic wave propagation can be used to: characterise elastic properties; detect flaws within the concrete, determine the member thickness; and estimate compressive strength using mathematical and/or empirically-derived relationships.

Ultrasonic testing methods can be divided into two major areas: through-transmission techniques and reflection techniques. Through-transmission techniques are based on measuring the time taken for the ultrasound waves to propagate through the concrete between a sending and receiving point while the reflection techniques are based on monitoring the reflections of the ultrasound waves from geometrical boundaries or flaws within the concrete. The following reviews the basic principle of ultrasound wave propagation in solids and a selection of ultrasonic techniques.

2.4.1 Historical review of ultrasonic testing

In the 1930's, vibration testing methods started to be used in testing specimens in laboratories, Powers (1938), Obert (1939), Hornibrook (1939), and Thompson (1940) were the first to start extensive research using these techniques such as the resonant frequency method. They conducted this method to determine dynamic modulus of elasticity of concrete by measuring the natural frequency of vibrating concrete prismatic specimen. The natural resonance frequency of a vibrating structural member is depended on its dynamic modulus of elasticity, density and dimensions. The testing system comprises primarily of two parts, one part generates mechanical vibrations and the other one detects the vibrations. However, the application of this method was limited to laboratory testing rather than testing concrete in-situ (Ramachandran and Beaudoin, 2000). In the late 1940's, a major development was the application of ultrasonic pulse methods to the inspection of concrete. This method has a definite advantage over the resonance method, in that the test method is not confined to regularly shaped laboratory specimens and thus it is applicable to field testing. The application of this method is based on the principle that, the velocity of a stress wave through a solid medium is a function of its density, elastic constant Young's modulus and the Poisson's ratio.

In 1946, the Hydro-Electric Power Commission of Ontario in Canada developed a testing equipment called Soniscope to investigate the extent of cracking in mass concrete by measuring the transit time of ultrasound wave diffracted from the crack tip (Whitehurst, 1951). The main feature of the Soniscope is using transducers with a low frequency of about 20 kHz in which the ultrasonic wave can travel in path length up to 15m of concrete and the accuracy of the measured transit time is ±3% (Best, 1978). The field application of this device was reported by Leslie and Cheesman (1949), they showed that this device was suitable for detecting internal cracks in mass concrete, estimating the depth of surface cracks and determining the dynamic modulus of elasticity of the concrete for any part of a structure regardless the shape of the structure. In the same time, Jones (1948) in the United Kingdom developed an ultrasonic pulse apparatus, which was known under the name of the ultrasonic concrete tester (UCT) to assess the quality of concrete in structures especially the concrete pavement which involved short path lengths (i.e. high frequencies are needed). Thus the device was developed using transducers with frequencies ranged from 60 to 200 kHz. The testing frequency was chosen according to the type of concrete structure and the composition of tested concrete. The transit time was measured with an accuracy of ±1%. He also investigated the relationship between pulse velocity and strength of concrete. Jones demonstrated that there are many factors can affect this relationship, there was a noticeable variation in the UPV measurements of specimens with different water to cement ratios and aggregate contents. He also recommend that it necessary using calibration curves based on measurements of pulse velocity of concrete similar to that concrete under test in order to obtain an accurate estimation of compressive strength from the measurements of pulse velocity (Jones, 1963).

In the United States, the Portland Cement Association grant the permission from the Hydro-Electric Power Commission of Ontario to build testing equipment similar to the Soniscope for their own use. The Portland Cement Association conducted their tests on different concrete structures including dams, pavements and bridges which were reported by Whitehurst (1951). Based on these experimental data, (Whitehurst) published tentative classification of the velocity measurements that can be used as an indicator of the quality of concrete as shown in Table (2-1). However, the use of these classifications was limited as they based upon the basis of measurements of the pulse velocity through normal concrete with a density of about 2400 kg/m^3(Carino, 1994). Elvery and Vale (1970) reported the development of a portable device which was called the Pundit (Portable Ultrasonic Non-destructive Digital Tester). The basic features of this device; it had a resolution of 0.5 µs, could be powered by rechargeable batteries and it weight about 3.2 kg.

Table 2-1 tentative classification for normal concrete based on the measurement of pulse velocity (Carino, 1994)

Pulse velocity (m/sec)	Condition
Above 4570	Excellent
3660 to 4570	Generally good
3050 to 3660	Questionable
2130 to 3050	Generally poor
Below 2130	Very poor

Anderson and Nerenst (1952) conducted an experimental investigation using ultrasonic longitudinal wave propagation velocity measurements to study the progress of the hardening process in concrete. A Danish timing device that developed by the Danish National Institute of Building Research, the condenser chronograph was used in this work. The pulse generator was a hammer operated electrically as the impact source and pair of pick-up crystal as the transducers. They proposed formulas for the relationship between the wave velocity and the age which covering the hardening period from 1 to 28 days for specimens cured in water. They found that the wave velocity is increasing at a diminishing rate with the time.

In 1958 (Kaplan) investigated the relationship between the compressive strength of concrete and the ultrasonic pulse velocity in concrete structural building columns and standard laboratory specimens of concrete. The samples were divided into two groups: one of them cured continuously and the other one cured in the same condition as the columns in the building. He stated that the relationship between compressive strength and pulse velocity is dependent on aggregate/ cement ratio and with an increase in this ratio, the compressive strength decreases for a given pulse velocity. Results of investigation also indicated that measurements of pulse velocity of the concrete in the columns gave lower values than these for both cubes groups either which cured under laboratory or site conditions for the same compressive strength level.

In 1959 (Kaplan) reported that the relationship between pulse velocity and compressive strength is dependant on age and water /cement ratio and this behaviour is more apparent in high strength concrete than in low compressive strength concrete. In 1960 (Kaplan) he conducted another experimental study to investigate whether the relationship between the compressive strength and the pulse velocity is independent of variation of age and mix proportion for concrete mixes having the same workability. He founded out that the variation in age and mix proportions are not affecting the pulse velocity and compressive strength in the same way. Therefore, the relationship between pulse velocity and compressive strength will be dependent on age and mix proportion. However, this dependency is not so clear at low compressive strength concrete.

In the United States, the American Society of Testing and Materials adopted the proposed method by Leslie (1955) to measure pulse velocity in the late 1960s. A tentative test method standard was issued ASTM C 597-67T which replace later by a standard test method in 1977 (ASTM C 597-77). In 1967 (Galan) used the measurements of two acoustic characteristics, the pulse velocity which represented the elastic properties and the damping constant of the ultrasonic pulse which represented the inelastic properties to estimate the compressive strength of the concrete by a regression analysis.

In Europe, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (Sturrup et al., 1984)(RILEM) appointed Jones as a chairman for research working group to investigate the application of non-destructive testing methods (Carino, 1994). In 1969, (Jones and Fącąoaru) published draft recommendations for testing concrete by the ultrasonic pulse method. These recommendations introduced a general gaudiness for measuring longitudinal ultrasonic pulse velocity through concrete and the application of this testing method in concrete. A discussion of the influence of test conditions on measurement accuracy was also included. In addition, corrections for pulse velocity measurements due to ambient temperature changes were proposed and consideration regarding path length, transducers frequency and the least lateral dimension of the specimen were pointed out. However, these recommendations were limited to few samples. Based on this recommendation and experimental work by other researchers, the Cement, Gypsum, Aggregates and Quarry Products Standards Committee in the British Standards Institution (BSI) developed a standard test method BS 4408-5 in 1974, which was withdrawn and replaced by BS 1881-203:1986. The BS 1881-203:1986 was then replaced by BS 12504-4:2004.

Since then researchers continued to explore the acoustic methods and its application to the quality evaluation of concrete and the assessment of existing concrete structures (Karaiskos et al., 2015, Popovics and Rose, 1994). Generally, these methods are based on the principle that when a solid material is disturbed by a vibrating load or mechanical impact three typed of stress waves are generated: longitudinal waves (compression waves), shear waves (transverse waves) and Rayleigh waves (surface waves). The propagation of these waves will be affected by the internal conditions of the concrete structure.

2.4.2 Theory of wave propagation through a medium

The sound is the oscillation of the particles throughout the elastic medium. When the particles are displaced from their equilibrium position, they will start to oscillate about their equilibrium positions producing a mechanical wave. Sound waves with frequencies higher than 20 kHz are classified as ultrasound waves, as the range of human hearing is between 20Hz to 20 kHz.

Ultrasonic waves can propagate in different modes depending on the way that the particles will oscillate, although not all modes of oscillation are supported in all media. In solids materials, ultrasonic waves can propagate as longitudinal waves (compression waves), shear waves (transverse waves), and Surface waves (Rayleigh waves) each of which will travel at different velocities through that material. The longitudinal wave is the fastest, followed by the shear wave and Rayleigh waves (Tarun et al., 2004). In longitudinal waves, the particles are oscillating in the direction of the wave propagation direction. As the energy in this type of mode wave propagation travels by series of compression and expansion movement, it can be generated in solids, liquids, and gases.

The velocity of the longitudinal wave V_L through a solid medium is a function of its density ρ, elastic constant Young's modulus E and the Poisson's ratio υ, and is given by the following equation(Galan et al., 1990):

$$V_L = \sqrt{\frac{E\ (1-\upsilon)}{\rho\ (1+\upsilon)(1-2\upsilon)}} \qquad (2\text{-}1)$$

In shear waves (transverse waves), the particles oscillate in a direction perpendicular to the direction of the wave propagation. Shear waves can propagate in solids and highly viscous liquids. Shear wave velocity V_S through a solid medium is a function of its density ρ and shear modulus G, and is given by the following equation:

$$V_S = \sqrt{\frac{G}{\rho}} \qquad (2\text{-}2)$$

In isotropic material Young's and shear moduli are related by this equation:

$$E = 2G(1+\upsilon) \qquad (2\text{-}3)$$

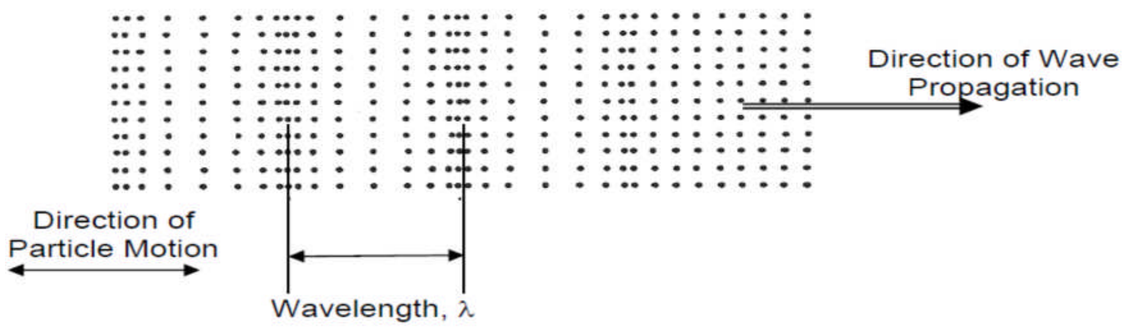
By substitution of equation (2-3) into equation (2-2), the shear wave velocity is given as follows:

$$V_S = \sqrt{\frac{E}{2\rho(1+\upsilon)}} \qquad (2\text{-}4)$$

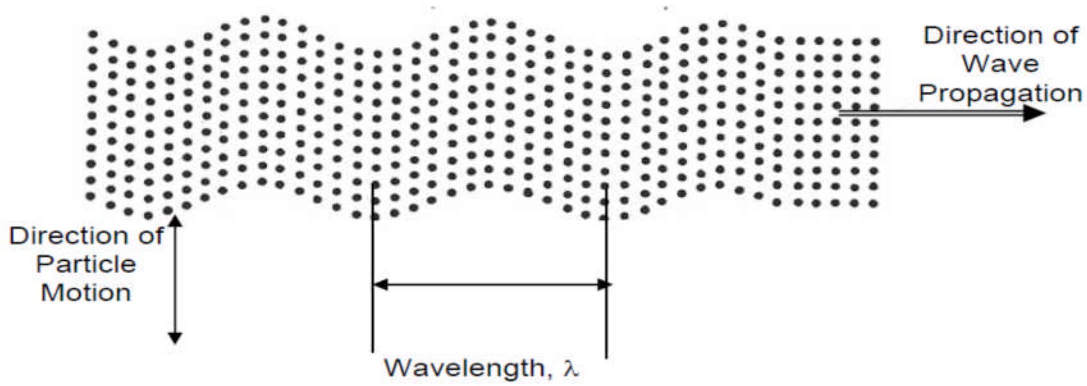
The ratio of shear wave velocity to longitudinal wave velocity will be as following:

$$\frac{V_S}{V_L} = \sqrt{\frac{(1-2\upsilon)}{2(1-\upsilon)}} \qquad (2\text{-}5)$$

Equation (2-5) demonstrates that the relationship between the wave velocities propagating through a solid material is governed by the Poisson's ratio of that material and that $V_L > V_S$ as the value of Poisson's ratio for isotropic solid materials ranged between (0 to 0.5) (Kumar et al., 2003). Thus, the shear waves will always travel slower than the longitudinal waves. A schematic diagram showing the propagation of the longitudinal and shear waves are shown in Figure (2-1).



(A) Longitudinal waves



(B) Shear waves

Figure 2-1 Schematic of particle motion in (A) longitudinal and (B) shear waves (Krautkrämer and Krautkrämer, 1977)

Another mode of wave propagation can occur at surfaces and interfaces between two mediums. The Rayleigh waves (Surface waves) can propagate only along the surface of a solid. In this mode of the wave, the particles move in an elliptical shape (Rose, 2004). In concrete, the velocities of surface and transverse waves are typically 55% and 60% respectively, of the longitudinal wave velocity (ACI 228.2R-13, 2013). Similar to the Rayleigh waves are the Lamb waves, i.e. particles move in an elliptical orbit, but they can only exist in thin plates. The most common modes of these waves are symmetrical (extensional) and asymmetrical (flexural) waves (Viktorov, 1970).

Ultrasonic methods for the inspection of concrete are based on the evaluation of one or more of these velocities, where the propagation of these waves will be affected by the internal conditions of the concrete structure.

2.4.3 Reflection of ultrasound waves at an interface

When an ultrasonic wave impinges on a plane boundary between two media with different acoustic impedance at normal incidence, some of the energy transmits through that boundary into the medium, and some reflect back. The amount of energy that is transmitted and reflected depends on the difference in the acoustic impedance (Z) between the two mediums, so the larger mismatch in the acoustic impedance the greater amount of wave energy will be reflected at the boundary. Thus at concrete – air interface, almost a total reflection of the propagating waves would occur at the interface as the acoustic impedance of the concrete is greater in ranges between (9×10^6 and 12×10^6) $kg/m^2.s$, compared to the acoustic impedance of air of 431 $kg/m^2.s$. The coefficient of reflection at water – concrete interface ranges between (0.6 and 0.8) since the acoustic impedance of the water is 1.43×10^6 $kg/m^2.s$ (Galan et al., 1990).

These differences between coefficients of reflections at the interface in concrete make possible to distinguish between reflections from flaws filled with air or water and from steel reinforcement bars. From this aspect, the non-destructive methods which are based on the propagation of stress pulses have been a powerful tool in locating defects and voids in solids. The transmission and reflection process is shown in Figure (2-2).

For normal incidence of an ultrasound wave at the interface, the transmission (T) and reflection (R) coefficients can be calculated by the following equations:

$$T = \frac{2Z_2}{Z_1 + Z_2} \tag{2-6}$$

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2} \tag{2-7}$$

Where Z_1 and Z_2 are the acoustic impedance of the medium 1 and medium 2. The acoustic impedance of a material is depended on the density ρ of the material and wave velocity V through that material. It can be calculated from this relationship.

$$Z = \rho V \tag{2-8}$$

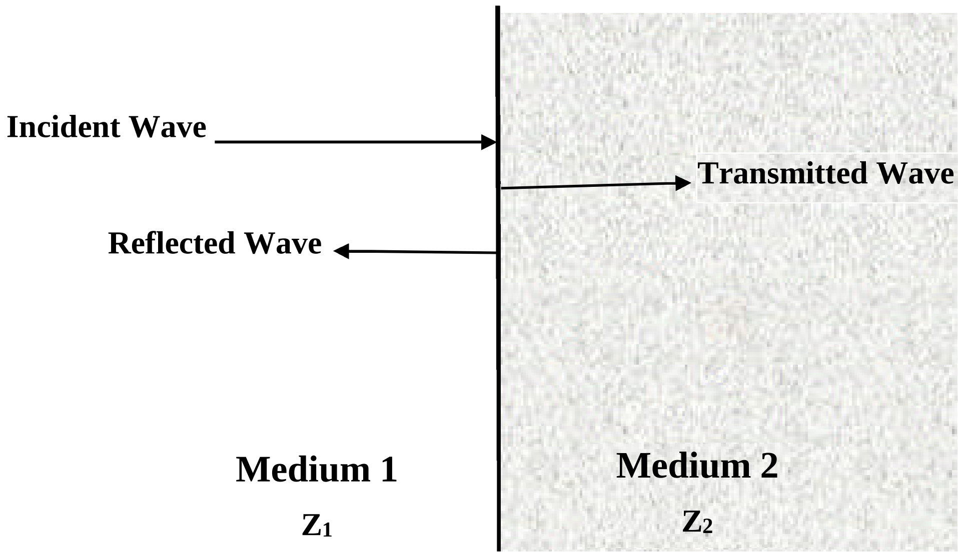


Figure 2-2 schematics of the transmission and reflection of longitudinal wave on a boundary at normal incidence

When the incident ultrasound wave strikes the boundary at an oblique angle, some of part of the energy will be reflected and the angle of reflection is equal to the incident wave angle (Θ) since both waves are travelling the same medium, and thus they will have the same velocity. The other part (transmitted part) will be refracted away from the direction of the incident wave at a refraction angle (β). The relationship between the angles and velocities of the wave is determined by Snell's law:

$$\frac{\sin\theta}{V_1} = \frac{sin_\beta}{V_2} \tag{2-9}$$

Where V_1 and V_2 are the velocities in the first and second mediums respectively. A schematic diagram of the reflection and refraction of a plane wave incident interface at an oblique angle is shown in Fig (2-3). At the oblique incidence, the reflection and transmission coefficients will be calculated as a function of the incident angle using the following equation (Cox, 2013):

$$T(\theta_{i)} = \frac{2Z_2\,COS(\beta)}{Z_1\,COS(\theta) + Z_2 COS(\beta)} \tag{2-10}$$

$$R(\theta_i) = \frac{Z_1 COC(\theta) - Z_2 COS(\beta)}{Z_1 COS(\theta) + Z_2 COS(\beta)} \tag{2-11}$$

In the more general situation, ultrasound waves may subject to a mode conversion (change in the mode of propagation) as they hit the boundary at oblique incidence, some part of the energy of the incident longitudinal wave will refract as shear wave mode. As the shear waves travel slower than the longitudinal waves, the converted shear waves will be reflected and refracted at small angles than that of the longitudinal waves. Thus the velocity difference between the incident longitudinal wave and the refracted shear wave will not be as great as between the incident and refracted longitudinal wave (Drury, 2004).

Figure 2-3 shows the reflection, refraction and mode conversion for a longitudinal ultrasound wave at oblique incidence. Snell's law can be generalised as the following for oblique incidence:

$$\frac{\sin\theta_{1L}}{V_{1L}} = \frac{sin\beta_{2L}}{V_{2L}} = \frac{sin\beta_{2S}}{V_{2S}} = \frac{sin\theta_{1S}}{V_{1S}} \qquad (2\text{-}12)$$

Where subscript 1L and 1S refer respectively to the incident longitudinal wave and the reflected shear wave while 2L and 2S refer respectively to the refracted (transmitted) longitudinal and shear waves.

As the incident angle (at oblique incidence) increases, an increasing portion of the incident longitudinal wave energy will convert into the shear wave mode. When the incident angle increased to a particular value Θ_c, the longitudinal wave will be refracted through an angle of 90° and converted into surface wave travelling along the interface and decays rapidly while the shear wave propagates into the material. This angle (Θ_c) is known as the first critical angle (Laugier and Haïat, 2011).

Beyond the first critical angle, the transmitted longitudinal wave will be totally reflected at the interface and only the mode-converted shear wave will be propagated through the material. However, in many situations there is also another an angle that makes the angle of refraction for the converted shear wave is 90°, this angle is known as the second critical angle, at which the refracted shear wave is transformed into a surface wave which is sometimes referred to it as creep shear wave (Rokhlin and Wang, 1989).

The propagation of an ultrasonic pulse in concrete (acoustically inhomogeneous, each of the three phases have a different acoustic impedance) is even more complicated as it accompanies by complex processes of attenuation, reflection, and refraction of waves composing this pulse. Thus, it is likely that the longitudinal wave would subject to a mode conversion while propagating through concrete as it undergoes multiple reflections at the boundaries between the different phases and as a result, the propagating will be a combination of longitudinal and share waves which are travelling at different speeds and direction (BS 12504-4, 2004).

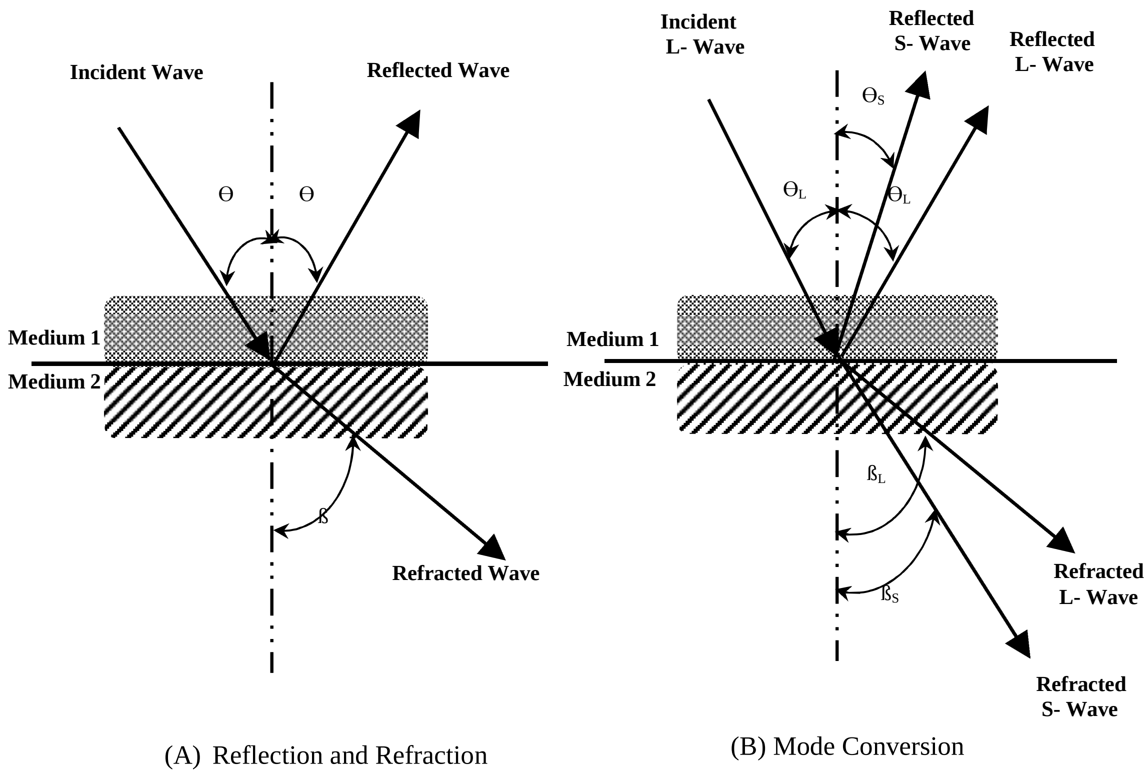


Figure 2-3 Schematic of the behaviour of longitudinal wave incident on a boundary at an oblique angle: (A) reflection and refraction and (B) mode conversion (Carino, 2004)

2.4.4 Attenuation of ultrasonic wave

When ultrasound wave propagates through a medium, it will be subjected to energy loss (attenuation) where the amplitude and the intensity of ultrasound wave diminish with distance. The amplitude change of a decaying plane wave can be expressed by the following:

$$A = A_o \, e^{-\alpha z} \qquad (2\text{-}13)$$

Where A is the amplitude, A_o is the incident amplitude; z is the travelled distance, and α is the attenuation coefficient. The attenuation is a result of two mechanisms: geometric and material attenuation. Geometric attenuation (spreading of the sound beam) can be expressed by the decrease in the wave amplitude as the waveform diffuses over a wide area as it travels away from the source.

The material attenuation can be caused by either scattering or absorption. Scattering is defined as a random reflection in which some of the initial energy of the propagating wave changes its direction away from the original wave path when it encounters discontinuities in the medium (Anuongda et al., 2001). The scatter losses depend on; on the intrinsic length scale of the scatterer, a number of scatterers per volume, distribution of scatterers in relation to the base material. Depending on the ratio of the scatterer diameter to the wavelength of propagating single there are three reigns of scattering can occur (Jacobs and Owino, 2000). Rayleigh scattering regime occurs when the diameter of the scatterer is very small comparing to the wavelength of the propagated wave, where the scattering coefficient is varied with the 4^{th} power of the frequency (Gaydecki et al., 1992).

$$\alpha = a\, f + b\, D^3 f^4 \qquad (2\text{-}14)$$

Where a is the absorption coefficient, f is the frequency; b is the scattering coefficient and D is the diameter of the scatterer. Stochastic scattering regime happens when the diameter of the scatter approximately in the same order of magnitude as the wavelength of the propagated wave, where the scattering coefficient is proportional to the 2^{nd} power of the frequency (Gaydecki et al., 1992).

$$\alpha = a\, f + b\, D^2 f^2 \qquad (2\text{-}15)$$

When the wavelength of the propagated wave is smaller than the diameter of the scatterer, then diffuse scattering regime occurs, where most of the energy of the propagated wave will be scattered (Gaydecki et al., 1992).

$$\alpha = a\, f + b\, D^{-1} \qquad (2\text{-}16)$$

In concrete, voids, cracks, and aggregate particles act as scatterers. Transducers with low frequency (long wavelength larger than the maximum size of the coarse aggregate) needed to be used in testing concrete with ultrasonic techniques to avoid the diffuse scattering. Usually set of standard transducers with a centre frequency of 54 kHz is being utilised for the measurement of ultrasonic pulse velocity in concrete, where the associated wavelength is about 68mm (Tarun et al., 2004). Based on the ratio of the diameter of the scatter to the wavelength of the propagating pulse, a Rayleigh scattering regime would be expected to be taken place in when testing concrete with a maximum size of aggregate 20mm. The upper limit of the usable frequency of ultrasound wave in concrete is about 500 kHz as the associated wavelength is about 10mm, which will be in the range of aggregate particles size (Carino, 2004). However, using low frequency will reduce the sensitivity of the propagation waves to the small flaws in the concrete. Thus, using longitudinal wave propagation method for the inspection of concrete will have inherent limitations in the size of defect or discontinuity that can be detected.

Absorption losses are material effects, which results from any mechanism that caused by the conversion of energy from the original state to a new state (Ensminger, 1988). In concrete, this conversion of energy could occur due to the internal friction between the particles, other causes such as irreversible changes in concrete structure, and viscoelastic properties (Galan et al., 1990). Another kind of loss is the relaxation losses, in which the kinetic energy is converted into internal energy within particles of the material (Ensminger, 1988).

2.5 Testing methods

2.5.1 Pulse-echo

The ultrasonic pulses echo method is based on stress wave reflection techniques in detecting of flaws in solids. Stress pulses are introduced into the concrete surface by a piezoelectric transducer; after being reflected at a discontinuity (possibly subject to single or multiple reflections), the propagating pulses will be received on the same surface by the same transducer or a second transducer (pitch-catch) (Blitz and Simpson, 1995). The testing principle of the pulse-echo method is shown in Figure (2-4). By measuring the entire round travel time of the stress pulses, which are reflected at interior interfaces or backscattered at flaws and knowing the speed of stress pulse, the depth location and the estimated size of flaw can be determined (ASTM E 114-15, 2015).

Time domain analysis is usually used for displaying the received signal as a function of time (Carino, 2004). Broadband transducers with low frequency (long wavelength larger than the maximum size of the coarse aggregate) are required for the pulse-echo application in concrete to reduce attenuation of the propagating waves as the aggregate particles act as scatterers. However, using low-frequency transducers will lead to reducing the sensitivity of the transmitting wave to detect small defects.

This technique was first used successfully in detecting of flaws in metals, over the years attempts have been made to develop this technique for the inspection of concrete structures from a single surface, Bradfield and Gatfield (1964) suggested using separate transmitting and receiving transducers of identical form. Howkins (1968) recommended using a large mosaic ultrasonic transducer. Alexander (1980) reported that special transducers could be built to have a flat transfer ration over a short range of frequencies which help in reducing the sensitivity of the receiver transducer and hence a reduction in the recorded signal to noise.

A new ultrasonic transducer was described by Andrews and Hughes (1991), the design incorporated a composite of tungsten-loaded epoxy and mineral fillers as faceplate and the damping block was made using the same composite. A fast setting mortar was used as a coupling material between the transducer and concrete surface. The new transducers showed an excellent acoustic fidelity and sensitivity together with wideband chirp signals. It is additionally have suggested that applying a signal processing algorithms will have the potential to improve the pulse-echo inspection in concrete. Schickert (1995) introduced an implementation of using ultrasonic SAFT reconstruction (Synthetic Aperture Focusing Technique) in imaging the reflected signals at the interior defect in concrete. The SAFT reconstruction results showed an improved image with high resolution comparing to those of the conventional A- and B-scan techniques.

Krause and Wiggenhauser (1998) reported on using separate transmitting and receiving transducers with advanced signal processing techniques in the inspection of structural concrete members. Three-dimensional SAFT reconstruction has been used for imaging the measured data and scanning laser vibrometer was also used as the ultrasonic sensor. He stated that the experimental results showed an essential improvement in thickness measurement of concrete members and concluded that the use of the pulse-echo method in testing concrete is still required a lot of research work to endorse identification of voids. McCann and Forde (2001) demonstrated that the pulse-echo method is less practical in testing concrete and masonry because of the heterogeneous nature of concrete.

The presence of air voids, cement paste-aggregate interfaces and reinforcing steel bars will cause a multitude of echoes that obscure those from the real defects. Carino (2004) stated that there is a difficulty in developing low frequency, broadband transducers that produce short stress pulses with defined wavelength and direction. Also, the size of the required transducers will become larger which results in difficulties in the coupling to the concrete surface under test. As a consequence of these difficulties, there are no currently accessible commercial transducers for the pulse-echo testing of concrete. Thus, most researchers have alternatively used the pitch-catch system in which the transmitter is a heavily damped transducer, and the receiver is a lightly damped transducer.

Krause et al. (2008) presented the progress that has been achieved in locating of grouting faults in post-tensioned concrete structure (tendon ducts) based on the pulse-echo method. They stated that this technique is not applicable in testing those concrete structures as they included: steel sheet of ducts, stands, grouting mortar in addition to interfaces between cement paste and aggregate which made the interpretation of the ultrasonic echo data is not normally possible as the measurements were taken from a single point. The proposed testing method was a combination of pulse-echo method with synthetic aperture approach. The data are needed to be measured along a line or two-dimensional area and then evaluated using 2D or 3D SAFT reconstruction or FT-SAFT (SAFT based on Fourier Transform techniques).

The main limitation of the pulse-echo method is the difficulty of constructing low frequency, broadband transducers with preferred directional characteristic where the size of the required transmitting transducer will become larger. Thus, the need for a bulky transducer and the advanced signal processing which presently restrict the application of this in the field. (Karaiskos et al., 2015, Carino, 2004). An alternative approach for this technique was the impact echo method by replacing the transmitting transducer with a mechanical impactor which provides a much higher energy input.

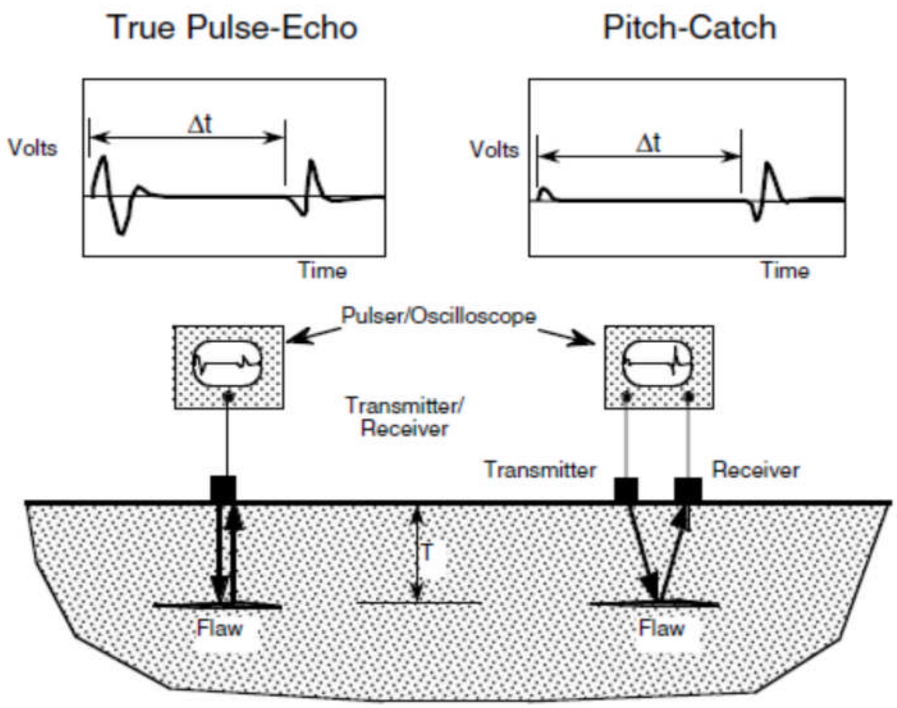


Figure 2-4 schematics of the testing principle for pulse echo and pitch-catch systems

2.5.2 Impact echo

This technique has been widely used for flaw detection in concrete. It is based on the propagation of low-frequency stress pulses generating by a mechanical impact on the surface of the concrete under test, amplitude of the reflected waves will be determined which can be related to the presence of a defect in concrete (Helal et al., 2015). As the stress pulses propagate through the concrete, it will undergo multiple reflections between the concrete surface and the reflecting interface (internal defects or outer boundaries). A periodic displacement will produce in each time the pulses arrive at the concrete surface under test which is measured by a receiving transducer (Carino and Sansalone, 1984). These displacements are recorded by a data acquisition system as time domain waveforms. The time domain waveforms contain different resonant frequencies that associated with the displacement caused by the impact, fast Fourier transform (FFT) technique is applied to convert these waveforms into the frequency domain (amplitude spectrum) for interpreting the test results (Bracewell, 1965). A schematic of impact echo test is shown in Figure (2-5).

The frequency of the periodic displacement is equal to the inverse of the time interval, Δt, between successive arrivals of the reflected pulses. The time interval is the round trip travel distance, 2T, divided by the compression pulse speed V_p and is given by the following:

$$f = \frac{1}{\Delta t} = \frac{V_P}{2T} \qquad (2\text{-}17)$$

The amplitude spectrum displays the amplitudes of the different frequencies contained in the waveform. The amplitude of the peak can be directly related to the reflecting interface due to the mismatch in acoustic impedance (Carino, 2001). Thus, if the peak value of the frequency in the amplitude spectrum has been determined, the depth of the reflector can be calculated by the following:

$$T = \frac{V_p}{2f} \qquad (2\text{-}18)$$

The impact echo method has been primarily used in evaluating the integrity of concrete piles and then extended to testing concrete structures other than piles (Hoła and Schabowicz, 2010). The time domain signal analysis was used for detecting the discontinuities (Steinbach and Vey, 1975, Davis and Dunn, 1974). The technique was also known as the sonic echo or seismic echo method.

Carino and Sansalone (1984) developed an impact method for testing concrete structures other than piles. The experimental work was done by the National

Bureau of Standard; they use this method to detect a flaw in relatively thin concrete elements. The use of frequency domain analysis was the key to developing this method. This approach has been applied to identify various types of defects including cracks and voids, delamination in slabs, honeycombed in concrete and voids in tendon ducts (Sansalone and Carino, 1986, 1989; Sansalone et al., 1991; Carino and Sansalone, 1992; Jaeger et al., 1996, 1997). The application of this method has been expanded to include prismatic members, such as beams and columns (Lin and Sansalone, 1992). Finite element simulations of the impact test performed in combination with experimental work for modelling elastic stress pulse propagation through bonded solids containing flaws to determine the expected impact response of those solids (Sansalone et al., 1987, Sansalone and Carino, 1990, Lin et al., 1990).

Sansalone and Streett (1997) demonstrated that the lateral dimensions of the reflecting interface are the critical factor in the impact response of the object under test. When the lateral dimension of a void or planar crack is exceeding 1/3 its depth, the flaw depth can be determined. If the lateral dimension is exceeding 1/2 its depth, the flaw will act as a plate with a thickness equal to the flaw depth. The amplitude spectrum of the waveform, in this case, will show two frequency peaks; the higher one is corresponding to the flaw depth, and the lower is corresponding to the plate thickness.

(Popovics and Achenbach, 1996) reported application of the impact echo method for the evaluation of airport pavements. The experimental work was undertaken at The Centre for Quality Engineering and Failure Prevention (CQEFP) at Northwestern University. They suggest electromagnetic transducers for generation stress pulses which will allow for a high degree of control of the input signal. Grosse et al. (2004) reported a novel approach for the impact echo method to evaluate the quality control in cementitious materials by combining ultrasonic pulse velocity and impact echo tests results for monitoring the setting and hardening process. The preliminary results showed the new approach has the potential to be used in quality control investigation.

A new concept for the impact-echo testing method was presented by Grosse et al. (2013). An automatic impactor was introduced to the testing system which operated on the base of high-speed tubular solenoids which will allow the operator to control the impact generation and furthermore feedback about the impact time and duration will be provided.

Developing a standard test method for the impact echo method in testing concrete structures was relatively difficult, due to the variety of the defects (voids, delamination, distributed microcracking) and the members of the concrete structure (slab, beam, column) that each case will have different conditions (Carino et al., 1986, Karaiskos et al., 2015). In 1998, ASTM (ASTM C 1383) adopted a test method of the impact echo method to determine the thickness of plate-like concrete members. The plate has been defined as a structure or portion of a structure in which its lateral dimensions are at least six times its thickness.

The basic of the impact echo method is generating stress pulses by the mechanical impact on the surface of the object under test. For an impact point source, the generated pulses will propagate into the object in all direction and thus the reflected echoes may arrive from many directions. The multiple reflections between the object surface and reflection interface lead to a complicating interpretation of the recorded waveforms as the amplitude spectrum will become more complex. It will need to distinguish between the echoes that are reflected by internal defects and the surface waves which travel along the surface away from the impact point. Also the presence of aggregate may cause three-dimensional dispersion (McCann and Forde, 2001). For these reasons, the application of this method has been limited to piles and relatively thin concrete structures.

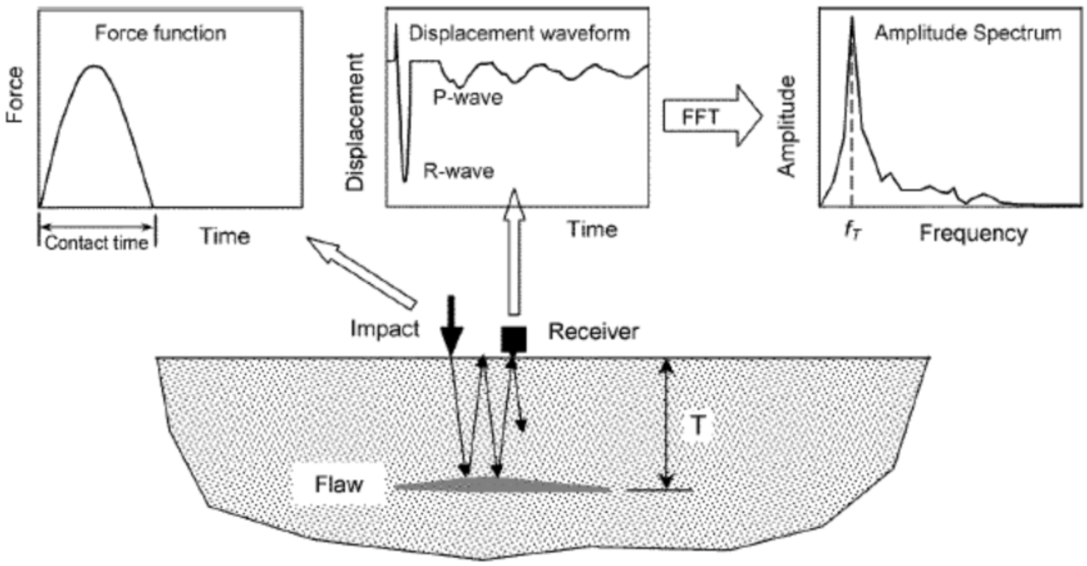


Figure 2-5 schematics of the impact echo method (CARINO, 2015)

2.5.3 Spectral analysis of surface waves-SASW

This testing method is based on the use of surface wave (Rayleigh waves) velocity measurements for the assessment of layered concrete structures by determining the stiffness profiles of the underlying materials as a function of time and depth. The SASW testing system consists of impact resource which is usually a small hammer or steel sphere, two receivers (geophones or accelerometers), and a recording device. The recording device is a two-channel spectral analyser used for recording and studying the phase of the frequency content of the surface waveforms (Heisey et al., 1981). A schematic of the SASW method is shown in Figure (2-6).

The surface waves will introduce to the concrete surface using the impact source. The surface wave motion is then measured by the transducers which are placed at a certain distance from the impact source. By determining the travel time for each frequency component between the two receivers, the phase velocities of the received signals are calculated. Digital signal processing is applied to obtain the dispersion curve by plotting the phase velocity versus frequency as a first step. The second step is determining shear moduli profile from the dispersion curve by using the inverse analysis (Krstulovic-Opara et al., 1996).

The applicability of the SASW method was successful in evaluating the layered structures such as soil sites, asphalt pavement and concrete pavement. It was first investigated by Jones (1962b) for determining the elastic moduli and the thickness of the pavement layers by measuring the wavelength and velocity of surface waves of particular frequency along the road surface. In the 1980's this method was developed by (Nazarian et al., 1986), a mechanical impactor was used instead of a steady state vibrator so that the generated surface waves will contain a broad range of frequencies of different wavelengths rather than single frequency.

The high-frequency components, .i.e. short wavelength, will propagate into the top layer with speed determined by the shear wave speed (which depends on the shear modulus and density) and Poisson's ratio, the lower frequency components will penetrate into a larger depths (underlying layers). The speed of propagation of these components will be influenced by the properties of those layers. Thus, a layered structure acts as a dispersive medium for the surface waves, where the different frequency components in the surface wave will travel at different velocities, which are called phase velocities (Nazarian et al., 1983).

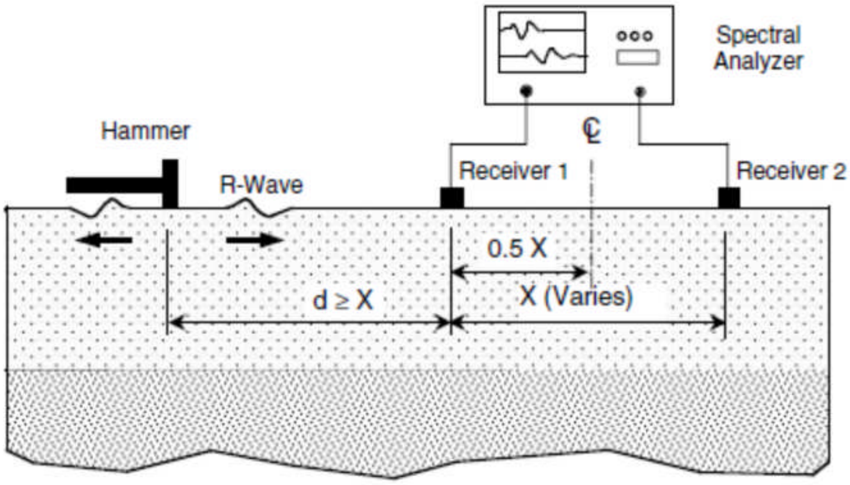


Figure 2-6 A schematic of the spectral analysis of surface waves (SASW) test method (Carino, 2004)

A similar technique was reported by (Wu and Fang, 1997), is based on measurement of the skimming longitudinal wavefront and Rayleigh waves (surface waves) velocities using horizontally polarised conical transducers for determining elastic constants of a concrete plate. Kim et al. (2006) proposed the IE–SASW method which is combining the impact echo (IE) method with the SASW method for detecting the defects in the concrete members. The SASW method was employed for the measurement of longitudinal wave velocity based on the measurements of the surface wave velocity without coring where the IE test is carried out. The complicated inversion process did not implement as the concrete member assumed as a single layer. The experimental work performed using different concrete slab samples of known dimensions, which contain various types of inclusions.

Kumar and Rakaraddi (2013) investigated the effect of variation height fall of the dropping mass on the maximum and minimum wavelength and the associated frequencies of the surface waves (depth of the evaluated zone) that the shear wave velocity profile would be able to determine the different layers of the concrete and asphaltic pavements. Effect of the distance between the impact source and the first receiver was also studied. The results showed that the increase in the height of fall of the dropping mass leads to an increase in the maximum wavelength of the surface waves and the effect was clearer in concrete pavement than the asphaltic pavement. Furthermore, for a given height of drop, the distance between the impact resource and the first receiver needs to be kept a little greater when testing concrete pavement comparing with the asphaltic pavement.

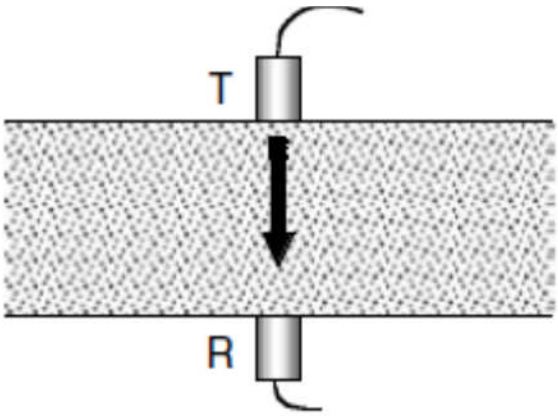
The main limitations of this testing method are that the signal processing procedure for the recorded signals is very complicated, highly skilled operators are required for interpreting the test data, and it is only applicable for the multi-layered systems where the structure act as a waveguide resulting in limiting its application for testing pavement and slabs.

2.5.4 Pulse velocity method

The ultrasonic wave velocity measurements for the evaluation of concrete quality have been used since 1940’s, and have remained as the simplest and most commonly used non-destructive test methods for concrete over the years (Hertlein, 2013). Most countries have standardised the procedure of the measurement of pulse velocity (Komlos et al., 1996). The basic principle of this method involves generating ultrasonic pulse by an electro-acoustic transducer, which is held in direct contact with the concrete surface. After travelling through the concrete, an ultrasonic pulse is received by a second transducer at the opposite site which converts it into an electrical signal. By determining the time taken by the pulse to be transmitted and received, the velocity of the pulse can be computed by the following relationship:

$$V = D/T \tag{2-19}$$

The standard configuration for the ultrasonic testing of concrete is the direct transmission (see Figure 2-7). It considered the most satisfactory arrangement since most of the pulse energy transmitted is received. Also, the path is clearly defined and the wave velocity can be measured accurately.

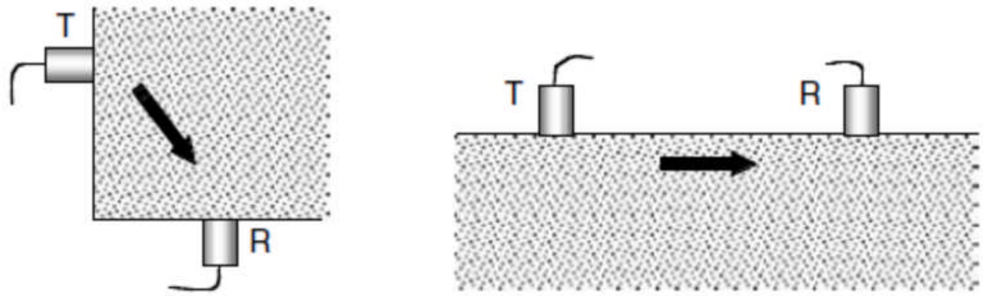


T = Transmitter transducer

R = Receiver transducer

Figure 2-7 Direct transmissions (Tarun et al., 2004)

The transducers may be arranged in a semi-direct transmission or indirect transmission as shown in Figure 2-8. The semi-direct transmission can also be used successfully, although care should be taken to have the transducers close to each other so that the transmitted pulse cannot be attenuated. The indirect transmission is the least satisfactory arrangement since the received signal amplitude can be less than 3% of that received by the direct transmission (Bungey et al., 2006).



T = Transmitter transducer

R = Receiver transducer

Figure 2-8 Semi-direct and indirect transmission (Tarun et al., 2004)

Also, the calculation of the pulse velocity may become more complicated, where a special procedure is needed for determination of the speed of pulse. The transmitter transducer fixed at a specific location while the receiver transducer will be located at a series of a fixed incremental point along a line on the concrete surface and a series of transit time readings taken as shown Figure 2-9. The direct distance between the two transducers is plotted on the x-axis against the corresponding transmit time reading on the y-axis, then the pulse velocity is given by the slope of the best straight line (Bungey et al., 2006). However, this arrangement is used for estimating the layer thickness or when is a lack of access to the structure to use the direct and semi-direct arrangements.

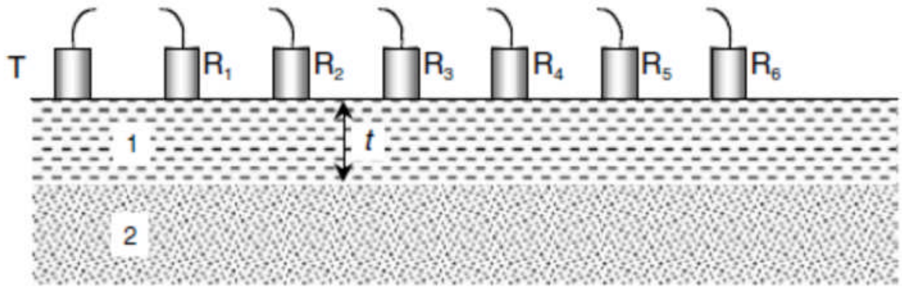


Figure 2-9 Shows the transducers arrangement in indirect method (Tarun et al., 2004)

In the measurement of ultrasonic pulse velocity, it is necessary to ensure a good acoustical coupling between the face of the transducer and that of the concrete surface, and it can be achieved by using a couplant. Otherwise, an air pocket between the area under test and the transducer will exit causing an error in the measured transit time. There are different couplants used such as petroleum jelly, grease, liquid soap, and various pastes. The couplant layer should be as thin as possible, although a thicker layer is recommended for rough surfaces. If the surface of the concrete is very rough, it should be ground or a smoothened by using a quick-setting mortar or plaster of Paris cement.

2.5.5 Pulse velocity test equipment

The test equipment consists of means generating and producing an ultrasonic pulse which is transmitted into concrete, receiving and amplifying the pulses, measuring and displaying the time taking the pulse to transmit through the concrete. An oscilloscope can connect to the equipment to observe the nature of pulse by displaying the waveform Figure 2-10 shows the basic circuit requirements.

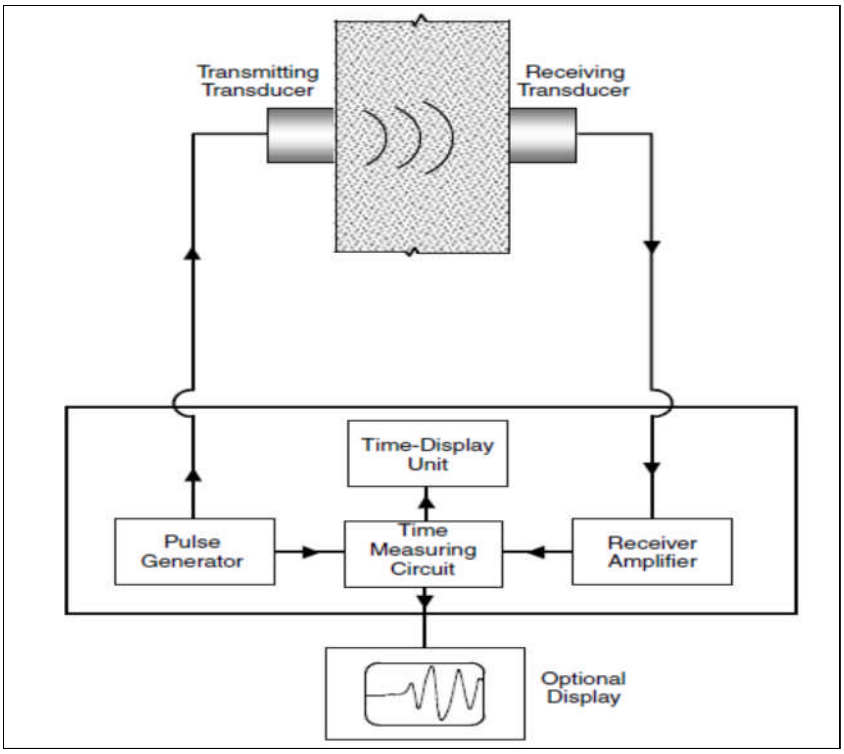


Figure 2-10 Schematic diagram of pulse velocity test circuit (ASTM C 597-16, 2016).

The PUNDIT is the most popular ultrasonic testing device for concrete in situ as it is simple to operate. It measures the transit time that the pulse takes to pass throughout the concrete from the transmitting transducer to the receiving transducer.

Typically, it measures the transit time to an accuracy of ± 1%. Set of two transducers supplied with the PUNDIT having a centre frequency of 54 kHz, one for transmitting and another for receiving the pulse. Usually, transducers with the natural frequency of 25 to 100 kHz are the most suitable for testing concrete (Tarun et al., 2004). It is preferable to use the high frequencies for short path concrete lengths as they attenuate and low frequencies for long path lengths. A calibration reference bar is also supplied. This reference bar has known characteristic, and is used for setting zero control of the device before each use.

2.6 Applications of ultrasonic pulse velocity method

2.6.1 Estimation compressive strength of concrete

Quality characterization of concrete in situ is usually assessed by measuring the compressive strength of the concrete, as it is the basic mechanical property of concrete which can be directly related to the internal structure of the concrete. The velocity of an ultrasonic wave propagating through concrete depends on the elastic properties and the density of concrete according to the theory of the sound propagation in solids (Bungey et al., 2006). Thus the internal conditions of the concrete that affecting the compressive strength is also affecting the ultrasonic pulse velocity. From that point of view, it is believed that the compressive strength of concrete can be estimated from pulse velocity measurements by the pre-established relationship between pulse velocity and compressive strength (Tarun et al., 2004).

The use of ultrasonic pulse velocity method in prediction the compressive strength of concrete has been widely studied by researchers (Breysse, 2012). However, the relationship between compressive strength and pulse velocity is not unique and many factors (aggregate size, type, and content; cement type and content; age, mix proportions and moisture content) have an influence on this relationship. Thus, the estimation of compressive strength from the measurements of pulse velocity should be made by using pre-established calibration curves of concrete similar to that concrete under investigation (Anderson and Seals, 1981).

To provide statistical reliability for this relationship, sufficient numbers of samples that cover a range of concrete strengths are required to be tested. The British Standards (BS 12504-4, 2004), the American Concrete Institute (ACI 228.1R-03, 2003) and the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM 1972) have provided guidelines on developing this relationship, that could be used in estimating the in-place concrete strength depending on the measurements of ultrasonic pulse velocity.

Sturrup et al. (1984) studied the relationship between the compressive strength and the pulse velocity and the factors affecting this relationship. He demonstrates that this relationship would be less affected by the cement type and air-entrainment and cure temperatures compared to other factors: age, moisture content, curing conditions and components composition and proportions.

Kheder (1999) stated that the use of the ultrasonic pulse velocity test in combination with the rebound hammer test in predicting concrete strength yield more reliable results, compared to use the ultrasonic pulse velocity test alone to evaluate concrete.

Phoon et al. (1999) developed a probabilistic model by using linear regression analysis to estimate compressive strength of the concrete from ultrasonic pulse velocity measurements. A consistent statistical quality assurance criterion can be accomplished by using this model with site data (in place concrete). Popovics (2001) reported the differences in the extent that certain parameters affect the compressive strength and the pulse velocity, while the pulse velocity is affected by the type and content of the coarse aggregate, the water to cement ratio and curing conditions. The compressive strength of concrete is strongly affected by the water to cement ratio than the aggregate content. He also stated that using the surface waves (Rayleigh waves) instead of the longitudinal waves in testing concrete could increase the accuracy of estimating the compressive strength by 25%.

Lin et al. (2007) proposed five simulation curve for the relationship between the compressive strength and pulse velocity of concrete with a coarse aggregate of 700, 800, 900, 1000, and 1100 kg/m^3, where the coarse aggregate content is considered the ruling factor in establishing these curves see Figure 2-11.

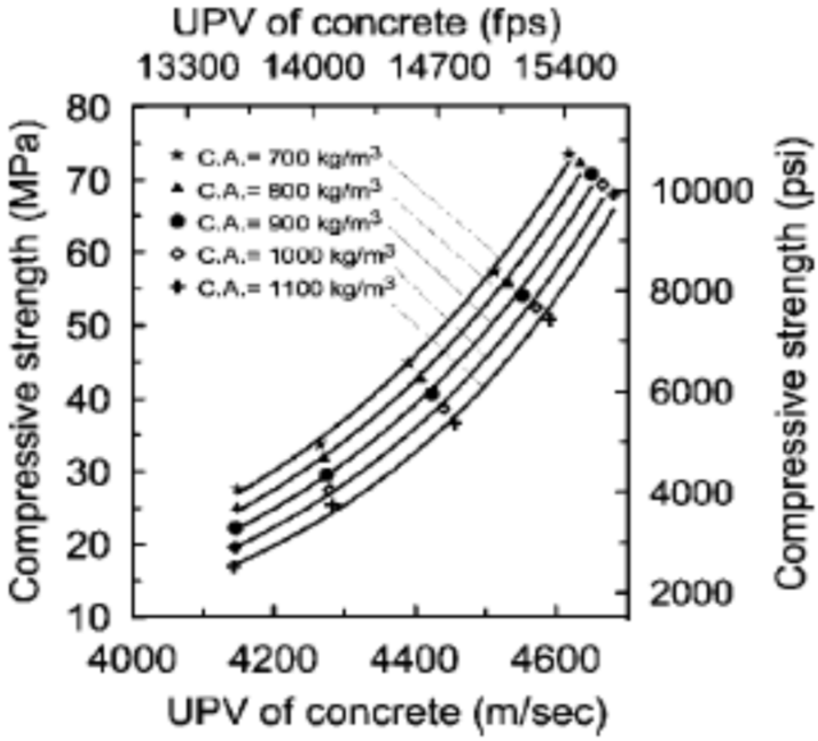


Figure 2-11 Simulated UPV-strength curves of concrete with five kinds of coarse aggregate contents (Lin et al., 2007).

A further study by Trtnik et al. (2009) conducted an experimental investigation on the effect of gradation and type of aggregate, w/c ratio, type of cement, initial concrete temperature and environmental temperature on the relationship between the ultrasonic pulse velocity and compressive strength as a first stage of the study. The second stage was establishing a numerical model to predict compressive strength, static and dynamic Young's modulus of elasticity and shear modulus of the concrete based on the experimental measurements of the ultrasonic pulse velocity using the Matlab programming environment.

The results showed that the aggregate phase had a crucial effect on the pulse velocity measurements and needed to be considered in the numerical methods for the estimation of compressive strength and other mechanical properties of the concrete. They also indicated that the artificial neural network had a great potential to produce flexible numerical methods for the compressive strength estimation of the concrete by using the ultrasonic pulse velocity data and some of the mix parameters of concrete.

(Bogas et al., 2013) conducted an experimental study investing the feasibility of using the pulse velocity measurements to estimate compressive strength of structural lightweight aggregate concrete. Effect of different parameters on the pulse velocity and compressive strength relationship was studied. The results showed that cement type and aggregate initial wetting conditions had a little effect on this relationship. A simple empirical equation was proposed with regardless of the concrete compositions. Lin et al. (2016) reported that the moisture content needed to be treated as a ruling factor in establishing relationship curves for the estimation of concrete strength using measurements of ultrasonic pulse velocity test.

2.6.2 Assessment of concrete homogeneity

The measurements of pulse velocity in concrete can provide a means of assessing the homogeneity of concrete, and thus, the quality of concrete by using a system of measuring points, i.e. grid pattern, which could consistently cover an appropriate part of concrete in structure to be evaluated. Heterogeneities within concrete members will cause variations in the measurements of pulse velocity. Heterogeneities in concrete can be referred to deterioration, interior cracks, honeycombing, and discrepancy due to the variations in mix proportions; curing; placement and consolidations of the concrete (Lorenzi et al., 2014).

The number of test points can be determined depending on the size of the structure to be assessed, concrete variability and the accuracy required. A grid of 1m spacing is usually adequate relying on the thickness of the member being evaluated, for small units a finer grid, of 300mm spacing or greater, should be firmed (Tarun et al., 2004). Statistical parameters such as the coefficient of variation or standard deviation for the pulse velocity measurements taken over a grid can be used to precise the homogeneity of concrete in structures (ACI 228.1R-03, 2003).

Tomsett (1980) demonstrated that for the quality assessment of concrete in situ using pulse velocity method, the pulse velocity measurements needed to be analysed using complementary techniques in which the results can be presented in the form of patterns, i.e. contour map or histogram. Deviation from these patterns will refer to a defect in the areas of concern. He suggested that a 1.5-2.5% coefficient of variation of pulse velocity for a single load of concrete in one unit or small units, could show good construction standards. The suggested values for the coefficient of variation would rise to 6-9% over the whole structure. Tomsett (1980) also developed a quality analysis system for large-scale integrity assessment projects using non-destructive testing methods. The ultrasonic pulse velocity method was chosen as the main non-destructive tests. The observations that made based on the pulse velocity measurements were checked directly against those observations from the testing of cores drilled completely through the structural member. Using the thermography technique for data collection was investigated also showing a potential for satisfactory results.

Olson and Sack (1995) reported the use of several non-destructive testing techniques based on stress waves propagation that can be used to evaluate the concrete conditions in large-scale structures, i.e. dams, piles, and foundations. The presented methods are impacting echo, spectral analysis of surface waves (SASW), ultrasonic pulse velocity tomography and the cross hole sonic logging (CSL), where used for the evaluation of the Rogers Hydro Station's concrete spillway on the Muskegon River in Western Michigan in the USA. (Petro Jr and Kim, 2012) used the pulse velocity test in the direct transmission to detect the delamination in concrete. The delamination was simulated using polystyrene boards of the thickness of 6mm and different sizes placed at different depths. It was concluded that the travelling time of the wave and the size of the delamination are qualitatively correlated.

2.6.3 Measurements of surface crack depth

Pulse velocity method is widely used for the detection of both internal and surface defects in structural materials. The application of this wave transmission method in determining the crack depth is based on a delay time measurements of surface waves diffracted from the crack (Mak, 1985).

In concrete surface, cracks are probably the most commonly seen kind of flaws. They may occur as a consequence of several deterioration mechanisms such as drying shrinkage, chemical attacks, overloading, freeze and thaw cycles, differential settlements and temperature variations. The most important threat is the exposure to the metal reinforcement to environmental factors that lead to its oxidation (Aggelis and Shiotani, 2007, Shiotani et al., 2005).

For damage assessment in the concrete due to cracking, it is fundamental to quantify the crack parameters; width, extension and the most significantly the crack depth. An estimate for the crack depth can be obtained by measuring the transit time of ultrasound wave travelling through the concrete along the crack surface where the wave will be diffracted by the tip of the crack (as it will go around the crack) (Sansalone and Streett, 1997). Thus, the transit time will be longer in characterising surface cracks than in similar sound concrete. However, there are crucial limitations about the application of this technique in detecting flaws or cracks. If the crack or flaw are filled with water or the crack tip is ill-defined, it might not be detected as the apparent velocity will not be significantly decreased (Tomsett, 1980).

An estimation of the depth of a crack can be obtained by measuring the transit time passing through the crack tip. The suitable arrangement for the transducers is the indirect mode transmission configuration where the transducers are placed at an equidistant distance from the crack on opposite sides from it as shown in Figure (2-12). The EN BS 12504-4 (2004) present a mathematical expression to calculate the depth of crack h using this special arrangement for the transducers where two values of the distance x will be chosen and the corresponding transit times will be measured, is given by:

$$h = x\sqrt{\frac{4t_1^2 - t_2^2}{t_1^2 - t_2^2}} \qquad (2\text{-}20)$$

where:

t_1 is the transit time at a distance x

t_2 is the transit time at a distance 2x

Bungey et al. (2006) also present a mathematical expression based on the same arrangement of transducers from the sides of the crack. In this method, the pulse velocity for the sound concrete need to be measured and just one measurement of the transit time will be needed to calculate the depth of the crack as given by the following:

$$h = x\sqrt{\frac{t_c^2}{t_s^2} - 1} \qquad (2\text{-}21)$$

where:

t_o is the surface travel time through sound concrete

t_s is the travel time around the crack

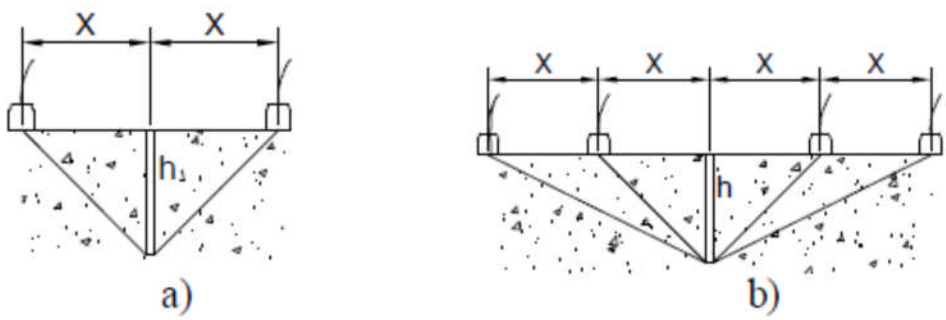


Figure 2-12 scheme for measurement of crack depth for (a) Bungey's and (b) BS 1881-203 methods (Pinto et al., 2007)

It should be noted that these equations were derived by assuming that the crack is perpendicular to the concrete surface. Thus, a check is needed to be made to determine if the crack is laying in a plane perpendicular to the surface or not by moving each transducer in turn, away from the crack. If a decrease in the transit time happens when the transducer is moved, that will indicate the crack slopes is towards that transducer, i.e. oblique crack.

Silk (1976) presented a theoretical discussion about the use of ultrasonic surface wave in measuring the depth of the surface crack. He also presented some approaches to improve the surface wave transmission technique, i.e. mode-converted shear waves monitoring and frequency modulation. Doyle and Scala (1978) reviewed the ultrasonic techniques that have used in estimating the depth of surface cracks in structural materials: scattered amplitude methods, timing methods, and ultrasonic spectroscopic analysis.

Date et al. (1982) evaluated the accuracy and reliability of ultrasonic timing methods for measuring the crack depth of inclined defects. Two methods were studied, surface and bulk waves timing. The bulk wave timing included two techniques; one is based on the diffraction of longitudinal waves at the crack tip, and the other one is based on the reflection of shear waves at the crack tip. The results revealed that according to just accuracy considerations, the surface wave transmission method gave the highest accuracy among the other timing methods. Lin and Su (1996) modified the impact echo method to measure the crack depth of surface opening cracks in concrete. Tow receiving transducers used instead of one transducer (as in the conventional method) on the opposite sides of the surface crack and analysing the waveforms primarily in the time domain and then completed by the frequency analysis.

Popovics et al. (2000) conducted an experimental study to develop the ultrasonic methods that based on the signal transmission or attenuation for practical application in detecting and sizing the surface breaking cracks in concrete structures. They introduce the self-compensating signal transmission measurement to be used for the measurements of surface cracks depth in concrete where this technique performed successfully in metals (Achenbach et al., 1992). In the experimental setup of this technique, two stress wave resources (solenoids drove impactors) and two receivers are placed on the surface of concrete that contains the surface cracks. The result showed that the self-compensating signal transmission measurements had an excellent potential for practical application in detecting and sizing of the surfacing cracks in the concrete structure. They showed an excellent sensitivity to the presence of cracks even when these cracks were closed tightly, or tip of the crack was not well defined. The values of signal transmission were independent on the type of the transmitters and receivers used in the test. With respect to the wavelength of the propagating pulse, the relationship between the signal transmission measurements and the crack depth normalised appeared not to be broadly affected by the nature of the crack or the type of concrete.

Pinto et al. (2007) developed two graphically-based methods to estimate the depth of surface opening cracks in concrete by measuring the transit time of ultrasound wave passing through the crack tip. This method was developed as an extension to the existing methods that presented in EN BS 12504-4 (2004). The transducers needed to be placed at least four positions from the surface crack along a chosen line, i.e. in each position the transducers will be placed at an equidistant distance from the sides of the crack. New mathematical expressions were found, the crack depth can be determined by plotting the results. The results demonstrated that the newly developed methods could estimate the surface crack with an error of 10% which was smaller than those from the other methods. Aggelis and Shiotani (2007) conducted an experimental study using the Rayleigh waves for the detecting and sizing the surface cracks by searching for correlation between the crack depth and the wave parameters that could lead to the characterization as a first stage and to assess the efficiency of repair treatments for the crack as a second stage. A simple multivariate analysis was combined to increase the accuracy of crack depth measurements.

Arne et al. (2014) introduced a comparison between two different non-destructive methods to estimate the depth of surface opening cracks in concrete beams that caused as a consequence of the steel bars corrosion in reinforced concrete. These methods were based on measurements of the ultrasonic parameters; the impact echo method which is based on the measurements of the travel time of stress waves that generated near a surface crack and propagated through the concrete from which the crack depth can be estimated and the diffuse ultrasonic techniques. This method is related the diffuse ultrasonic parameters (diffusivity and dissipation) of the concrete to surface cracks sizing, i.e, estimating the crack depth. The results of the comparison showed that the diffusion method was more accurate in determining the depth of surface cracks in concrete structures.

2.6.4 Determination of dynamic modulus of elasticity

The dynamic modulus of elasticity is an essential and important parameter when assessing the performance and quality of the structural concrete. One of the most direct applications of the pulse velocity method is determining the dynamic modulus of elasticity for the concrete (Jones and Fącąoaru, 1969). The relationship between the elastic constants and the velocity of an ultrasonic pulse travelling through an isotropic elastic material is defined by the theory of wave propagation (see equation 2-1). Thus, if the values of the density and Poisson's ratio are known, it is possible to use that equation to compute the dynamic modulus of elasticity in concrete.

This method has a definite advantage over the other techniques, i.e. resonance method, in that the test method is not confined to regularly shaped laboratory specimens. However, there is some limitation for using the pulse velocity method for this application. Measurements are affected by the heterogeneity of concrete (cement paste and aggregate phases which they have different elastic properties) leading to an overestimation for the dynamic modulus of elasticity. The Poisson's ratio is needed to be computed accurately where a change in Poisson's ratio from 0.16 to 0.25 will reduce the measured dynamic modulus by 10% (Philleo, 1955). As the resonance method is only slightly affected by Poisson ratio, the dynamic modulus of elasticity obtained from the pulse velocity measurements will be higher even when the Poisson's ratio is known.

Many researchers reported the estimation of the dynamic modulus of elasticity in concrete by using the measurements of ultrasonic pulse velocity. Leslie and Cheesman (1949) in their work on the Soniscope, they estimated the dynamic modulus of elasticity based on the pulse velocity method and compared the results with those obtained by the resonance method. The comparison revealed that the dynamic modulus determined from the pulse velocity was higher than from the resonance by 8%. A similar series of tests were conducted by Whitehurst (1966) also the pulse dynamic modulus was greater than the resonance with an average of 15.4%.

Lydon and Iacovou (1995) studied the dynamic modulus of high strength concrete as the major concern was about the compressive strength of this type of concrete using the pulse velocity and resonance methods. Also, they investigated the development of the dynamic modulus with age and the effect of silica fume, maximum size and type of aggregate and curing regimes on the values of the dynamic modulus. The results show that the values of dynamic modulus of high strength concrete with compressive strength ranged (75 -115 MPa) were varied between (47- 55 GPa) at the same age. Also, increase in dynamic modulus from 28 days to about 6 months was depended on the mix proportion and concretes with limestone aggregate showed the largest increase. The dynamic modulus of specimens cured in water at 20°C was higher than those of sealed and air-dried curing regime. Silica fume had no significant effect on the values of dynamic modulus of concrete. A modification of the previous model (Bache and Nepper-Christensen, 1965) for predicting the dynamic modulus was also proposed.

Wen and Li (2000) conducted an experimental study on the modulus of elasticity of concrete based on the triaxial compressive experiments and measurements of pulse velocity through concrete. The triaxial compressive experiments were performed at three different levels of confining pressure and the loading rates were divided into four levels. They proposed two empirical equations for the calculation of static and dynamic modulus of elasticity when the dynamic Poisson's ratio varies around 0.2.

Choudhari et al. (2002) proposed an empirical equation to determine the dynamic modulus of elasticity based on the measurement of ultrasound wave velocity in concrete. They also derived a mathematical correlation to evaluation the dynamic Poisson's ratio depending on the measurement of the pulse velocity in the longitudinal and shear mode of propagation where different transducers were used.

Zheng et al. (2008) investigated differences in the dynamic properties of rubberized concrete and conventional concrete. These properties include dynamic modulus of elasticity, the natural frequency of vibration and vibration damping. Ultrasonic pulse velocity method was used to determine the dynamic modulus of elasticity for both concretes. The effect of content and type of rubber particles on the dynamic properties was also investigated, where the scrap tire rubber used as a coarse aggregate in the rubberized concrete. The results revealed that the rubberized concrete had a dynamic modulus lower than that of a plain concrete and the damping ratios of the rubberized concrete were improved considerably in accordance to the conventional concrete. They also showed that the ground rubberized concrete had a higher dynamic and static modulus of elasticity but lower damping properties than the crushed rubberized concrete.

2.7 Factors affecting the ultrasonic pulse velocity

There are some factors that have an effect on the propagation velocity of the ultrasound wave in concrete. For reliable measurements of pulse velocity, it is required to consider these that could affect the measurements.

2.7.1 Aggregate, content, type and size

The amount and aggregate type have a significant influence on the pulse velocity. In general, the speed of sound through the cement paste is lower than that in the aggregate. Jones (1954) demonstrated that at the same strength level and the same mix proportion, concrete with crushed limestone had the highest pulse velocity while the round gravel concrete had the lowest pulse velocity. The pulse velocity of concrete with crushed granite was between the two mixes. Abo-Qudais (2005) studied the effect of the maximum size of aggregate, water to cement ratio, and the curing time on the pulse velocity. The nominal maximum size of 25, 4.75, 19.3, and 12.5 mm and four different water to cement ratios were used (0.4, o.45, 0.5, and 0.55). Two slabs (30×30×10) mm were cast for each combination of coarse aggregate gradation and water-cement ratio.

The results showed that the mix of the larger maximum size of aggregate had pulse velocity lower than mix with the smaller maximum size of aggregate. This behaviour was clearer with mixes with higher water to cement ratios. He pointed out that using larger mix coarse aggregate is associated with more porous transition zone, for the same w/c ratio mix with larger mix coarse aggregate will consume less mixing water than the smaller size leaving more water in the transition zone which lead to increase the volume of capillary voids and microcracks. Kaplan (1959) work on testing concrete using ultrasonic pulse method showed that the concretes with similar strength level; but different aggregate contents, the concrete with higher aggregate content gave higher pulse velocity reading.

Berriman et al. (2005) investigated the influence of aggregate content and storage humidity on the pulse velocity of the ultrasound wave in concrete by using air-coupled ultrasonic equipment as a non-contact system and a traditional ultrasonic equipment (PUNDIT) as contact system. They found that there is a strong positive linear correlation between the aggregate content and the pulse velocity. A positive correlation between the storage humidity and the pulse velocity also observed, and a correction factor for humidity employed. However, the contact system gave high values for the pulse velocity and a strong dependence on the aggregate content than the non-contact system. The researchers hypothesised that this discrepancy was due to the effect of preferential coupling between the ultrasound wave and the constituent materials of concrete. Thus, the PUNDIT may be measuring more about the aggregate than the cement paste.

2.7.2 Moisture conditions

The moisture content has a significant influence on the measurements of the pulse velocity in concrete. The ultrasonic pulse velocity in saturated concrete is higher than in dry concrete. Most of the difference in the measurements between these concretes is attributed to the effect of curing conditions on the hydration process of cement while some part of that difference is related to the free water which existing in the voids. However, concretes with high strength (low w/c ratio) will be less affected by the changes in moisture conditions comparing with low strength concretes due to the difference in the porosity of these concretes. An increase up to 5% can be expected in pulse velocity measurements of the saturated concrete comparing to that of dry concrete of same composition

(ASTM C 597-16, 2016). According to Kaplan (1958), the pulse velocity of concrete samples cured in the laboratory is higher than of those cured in the site. Ohdaira and Masuzawa (2000) studied the effect of degree of saturation on the pulse velocity. Three concrete mixes with different mix proportion were used, and five cylindrical specimens of (100×200) mm were cast for each mix. The test specimens were kept in moist conditions for about 50 days and then weighted. Different moisture contents were obtained by placing the samples in the dryer for various time intervals, and the measurement was taken at each time. The procedure was repeated until there is no change observed in their weight. The direct transmission method used with a range of frequency of (20 to 100) kHz. They found that the decrease in the velocity of the ultrasonic pulse is linearly proportioned to the reduction in the moisture content.

2.7.3 Concrete temperature

When the temperature varies between 10℃ and 30℃, there is no significant effect on the measurement of the pulse velocity of concrete. For temperature beyond this range, corrections to pulse velocity measurements are recommended to make as given in table 2-1 by the British standards (EN BS 12504-4, 2004)

Table 2-2 Correction for the measured pulse velocity (EN BS 12504-4, 2004)

Temperature C̊	**Correction to the measured pulse velocity**	
	Air-dried concrete %	**Water-saturated concrete %**
60	+5	+4
40	+2	+1.7
20	0	0
0	-0.5	-1
-4	-1.5	-7.5

2.7.4 Path length

In general, path length travelled by the wave through the concrete should not influence the pulse velocity. However, the testing apparatus may indicate a slight reduction in the pulse velocity measurements with longer path lengths due to the heterogeneous nature of the concrete. Attenuation process for the propagating wave will increase with the path length, (Tarun et al., 2004) reported that an average reduction of 5% in the pulse velocity measurements for path length range approximately from 3m to 6m. (Jones, 1962a). British Standard (EN BS 12504-4, 2004), recommends the following minimum path lengths:

- 100 mm for concrete have a maximum aggregate size of 20 mm.
- 150 mm for concrete have a maximum aggregate size of 40 mm.

2.7.5 Size and shape of the specimen

The velocity of the ultrasonic pulse is nominally independent of the size and the shape of the specimen in which they are transmitted through. However, when the lateral dimension of the specimen is smaller than the wavelength of the pulse, then the pulse velocity may reduce appreciably. The range of this reduction depends on the ratio of the wavelength to the least lateral dimension of the specimen. Table 2-2 shows the relationship between the pulse velocity, transducer frequency and the minimum permissible lateral dimension of the specimen as given by the British Standards (EN BS 12504-4, 2004).

Table 2-3 Transducer frequency vs. minimum lateral dimension (EN BS 12504-4, 2004)

Transducer frequency (kHz)	**Pulse velocity in concrete (km/s)**		
	V_C = 3.5	**V_C = 4.0**	**V_C = 4.5**
	Minimum permissible lateral specimen dimension (mm)		
24	146	167	188
54	65	74	83
82	43	49	55
150	23	27	30

2.7.6 Stress history

In general, pulse velocity of ultrasonic wave travelled through concrete is not affected by the level of stress of the element under test. However, when the concrete is subjected to high level of stress, an apparent decrease in pulse velocity will be observed due to the formation of microcracks within concrete (Bungey et al., 2006).

2.7.7 Reinforcement bars

In fact, the ultrasonic pulse travels much faster in steel than in plain concrete. As a result, the ultrasonic pulse measurements are expected to rise significantly with the presence of steel reinforcement in the concrete. The apparent increase in pulse velocity through reinforced concrete depends on upon the proximity of the measurement to the reinforcement bars, the diameter and number of bars and orientation on the wave propagation path (Bungey, 1984). Thus, wherever possible, test measurements should be taken in such a way that the steel bars are avoided or not close to the wave path between the transducers. Specific correction factors are needed to be considered in the calculation of the measured velocities when the reinforcement bars cross the wave path, and these are provided by the British Standards (EN BS 12504-4, 2004).

2.7.8 Couplant (coupling medium)

The most vital part of any application of ultrasonic testing methods is the means by which the acoustic energy is transmitted from the transducer into the test object. The acoustic energy is not effectively transmitted through the air due to the large mismatch in the acoustic impedance between air and solids, almost a total reflection of the propagating waves would occur at the interface (Krautkrämer and Krautkrämer, 1977). The function of the coupling medium is to facilitate transmission of the ultrasonic wave energy from the transducer to the test area. The couplant layer will fill the air gaps between the face of the transducer and the concrete surface providing an efficient path for the ultrasonic wave energy to cross the interface between these surfaces.

The ideal couplant should have certain characteristics, such as acoustic impedance similar to that of the test piece, low attenuation coefficient, low cost. There are different couplants used in the application of ultrasonic testing methods such as glycerine, oils, water, petroleum jelly, grease, liquid soap, and various pastes. Usually, a thin layer of the couplant layer is applied, although a thicker layer or viscous couplant is recommended for rough surfaces. If the surface of the concrete is very rough, it should be ground or a smoothened by using a plaster of Paris cement or quick-setting mortar (Andrews and Hughes, 1991). However, using such these quick-setting mortars will be not practical in testing large concrete structures. In addition, the removal such couplants (mortar or viscous liquids) is inconvenient.

Many attempts have been made to overcome the need of liquid or mortar coupling in the form of dry couplants by using compliant solid materials such as rubber between the transducer and the piece test (Dickson, 1982). In general, there are two common designs in forming the rubber as a couplant: static and wheel probes. The static probe by which a rubber tip is attached to the face of conventional transducer, the coupling mechanism will be achieved by pressing the transducer toward the test surface, Billson and Hutchins (1993) have reported the use of a new, low loss synthetic rubber coupling medium that can be used whit static probe operating at a centre frequency of 5 MHz. Drinkwater and Cawley (1997) described also using another loss synthetic rubber coupling medium for the static probe but the operating frequency of this probe was 7 MHz. For the wheel probe, the rubber is designed in shape of a tyre which is free to roll over the surface of tested area, the transducer will be placed on the wheel axis, Drinkwater and Cawley (1994) reported the use of such design for a wheel probe operated at a centre frequency of 3.8 MHz. However, the main limitation of using rubber as a coupling medium is the high attenuation in most types of rubber (Ginzel et al., 1994).

Another possible way to overcome the limitations that associated with the use of coupling media is using non-contact techniques. These techniques include laser generation and optical holographic or interferometric detection, electromagnetic acoustic transducers (EMATs) and air-coupled transducers (Green Jr, 2004). In this subsection, the application of air-coupled transducers in testing concrete is discussed. Zhu and Popovics (2002) reported the application of air-coupled sensors (highly directional microphones) and impact source (steel balls with an electrically-controlled impactor) to generate leaky surface wave was used for detecting flaws in concrete structures. For signal digitising and acquisition, a 4-channel digital oscilloscope was used. The air-coupled sensors showed a good sensitivity and accuracy comparing to the contact sensors.

Purnell et al. (2004)Purnell et al. (2004) investigated the potential of using air-coupled transducers (capacitive film electrostatic transducers) and pulse compression signal averaging in the inspection of concrete compared to traditional ultrasonic equipment (PUNDIT). Preliminary results showed that the air-coupled ultrasonic equipment could be used as a non-destructive method for testing concrete of thickness up to 75 mm.(Purnell et al., 2004) A strong correlation between the pulse velocity and the compressive strength was observed in both systems. However, the slope of the curve was much steeper in the air-coupled test than the PUNDIT test. The PUNDIT tests gave much higher values of pulse velocity for concrete mixes of normal compressive strength (i.e. <50 MPa) than the air-coupled tests. The researchers hypothesised that this discrepancy was due to the effect of preferential coupling between the ultrasound wave and the constituent materials of concrete.

(Berriman et al., 2005) have used the same air-coupled ultrasonic system in an experimental study investigating the effect of aggregate content and storage humidity on the pulse velocity of ultrasound in concrete and compared to a PUNDIT contact system. They found that there was a strong positive linear correlation between the aggregate content and the pulse velocity. A positive correlation between the storage humidity and the pulse velocity was also observed, and a correction factor for humidity deduced. However, the contact system once again consistently gave high values for the pulse velocity and also displayed a stronger dependence on the aggregate content than the non-contact system.

The researchers again attributed this discrepancy preferential coupling between the ultrasound wave and the constituent materials of concrete and thus, the PUNDIT may be measuring more about the aggregate than the cement paste.

The same research group (Berriman et al., 2006), have advanced their work with the air-coupled transducers for ultrasonic imaging in concrete using time-frequency analysis. Three techniques of time-frequency analysis have been performed: short-term Fourier transform, the Wavelet transform, and the Wigner-Ville distribution. To retrieve the data form in the time-frequency plane, the Hough transform has been applied as a filter. The concrete samples were plates of (30×30×30) mm where each plate contained a 10mm reinforcement bar. The result showed that time-frequency techniques could provide sufficient information to produce an image with a reasonable quality where the location of the reinforcement bar has been spotted successfully. The authors demonstrated that the Wigner-Ville approach was the best time-frequency method in accordance to the other techniques.

Other investigators have investigated air coupling without comparison to contact methods. (Popovics et al., 2009) proposed a development of the testing system of the air- coupled impact- echo test using generated seismic waves for scanning the bridge deck and the air- coupled ultrasonic tomography. The former technique was used to inspect the internal defects in concrete by means of capacitive micro-machined transducers, time averaging and compression technique for signal processing. An adequate algorithm was also applied to present the ultrasonic data as tomographic images.

For the impact- echo test the researchers manufactured reinforcement concrete slab sample. It was simulated a real deck bridge in Illinois state, contained a double layer of thin polymer sheets placed above the steel bar grid as a corrosion –made delamination flaws. The results showed that the proposed air-coupled impact-echo testing configuration could be applied effectively for characterizing and imaging the defects. The ultrasonic test was carried out on two sets of samples, each set contains three cylinders (150 × 300) mm prepared with different inclusions. The first set was prepared with Polyvinyl Chloride (PVC), the second set was cast with concrete. The preliminary results showed that this approach was more successful in the inspection of defects in PVC than concrete. However further developments are indispensable for this application

Cetrangolo and Popovics (2010) developed a contact-less (air-coupled) ultrasonic test setup for scanning embedded flaws in concrete by using modified piezoelectric transducers and digital signal processing. Balsa wood was added to traditional ultrasonic transducers of 54 kHz central frequency as a matching layer between the transducer crystal and the air. Time averaging technique and continuous wavelet transform analysis was used for processing the signals. A proposed algorithm was then applied for automatic detecting of the interior defects in concrete.

A (400×400×100) mm concrete sample was cast for this work before casting fabricated inclusions that were added to the mould for defects stimulation. The results showed that the locations of the inclusions were identified successfully according to the two-dimensional image of air- coupled ultrasonic scanning. Although air-coupling techniques have shown positive practical results (Chimenti, 2014), they do not become easily applicable outside the laboratory environment.

The efficiency of a medium as a couplant can be evaluated by the proportion of signal energy that is transmitted at the interface between the transducer and the test area. The amount of transmitted energy is depend on the acoustic impedance of the transducer, the coupling medium and the material being tested, as these media have close acoustic impedance values, more energy will be transmitted.

The amplitude of the transmitted signal is strongly depended on the properties and thickness of the coupling medium layer, the roughness of the surface under testing and the pressure exerted on the transducers (Canella, 1974). If the acoustic impedance of the transducers and concrete are kept fixed in ultrasonic testing, it would be expected that the couplant layer will have an important effect on the transmission of the ultrasonic energy from the transducer to the concrete and on the propagation of the ultrasonic wave through concrete and thus on the velocity measurements. In most studies this effect is neglected by the researcher, they presumed that as long as the thickness of the couplant layer is small compared with the dimensions of transducer and concrete under test then the effect of coupling medium can be ignored.

2.8 Summary

The ultrasonic techniques have been widely used in the inspection of the mechanical properties and integrity of concrete structures. The choice of most appropriate technique to provide the required information is depended on the purpose of the investigation to be undertaken and the limitations and advantages of each technique.

Pulse-echo technique was commonly used in detecting of flaws in metals and then developed for the inspection of concrete structures from a single surface. The main limitation was the difficulty of developing a suitable constructing low frequency, broadband transducers with preferred directional characteristic, as the size of the required transmitting transducer will become larger. Impact echo technique has little difficulty in the control of the frequency content received echoes that arrive from many directions which lead to a complicating interpretation of the recorded waveforms. Thus, the application of this technique was limited to piles and relatively thin concrete structures. The SASW method is based on using the surface wave (Rayleigh waves) velocity measurements for the assessment of layered concrete structures by determining the stiffness profiles of the underlying materials as a function of time and depth. the signal processing procedure is very complicated, highly skilled operators are required for interpreting the test data, and its application limited to pavement and slabs as they act a waveguide.

Comparing to the above techniques, pulse velocity method can be considered the simplest method. It based on the principle that the velocity of the ultrasound wave propagates into concrete is a function of its density and modulus of elasticity. The wave velocity is determined by measuring the time taken the wave to travel between transmitting and receiving transducers over a known path length through concrete. A coupling medium is needed to be used between the face of the transducers and the surfaces of concrete. It has been used for assessing concrete strength, investigating the homogeneity of concrete, studying the durability of concrete, and measuring the depth of surface cracks in concrete. However, the wave velocity measurements in concrete are sensitive to many variables which will affect the accuracy of this method.

The high attenuation of concrete limits transducer frequencies to below 100 kHz (Anuongda et al., 2001), which is generally thought for that reason the ultrasonic pulse velocity method will not be developed further. Thus, the researchers were working on improving the reliability of measurements of the pulse velocity technique by investigating the factors that can affect the pulse velocity measurements of the concrete. Based on the conducted literature review, it can be noted that the aggregate content and the water to cement ratio has a vast impact on the measurements of the pulse velocity. However, an important factor was not addressed in these studies, the effect of the coupling medium on the propagation of the ultrasound wave through concrete and how it can be affected the measurements of the pulse velocity.

The research studies by Purnell et al. (2004) and Berriman et al. (2005) on the use of air-coupled ultrasonic as a non-destructive testing method for concrete demonstrated that for the same concrete mixes, the air-coupled system returned lower values for the pulse velocity than the contact system (PUNDIT). The researchers hypothesised that this discrepancy was because of a preferential coupling occurs between the ultrasound wave and the constituent materials of concrete, in essence suggesting the PUNDIT measurements may have been dominated by the properties of the aggregate rather than those of the cement paste, yet it is the properties of the paste that dominate the properties of the concrete. Although the air-coupling test showed positive results, no literature has been published to date examining the coupling effect of other different coupling media on the pulse velocity of the ultrasonic wave. Therefore, this thesis investigates this approach. As will be seen, the approach gives some interesting results, which seem to give a greater insight into character and degree of effect of the coupling media on the propagation velocity of the ultrasound wave in concrete as a function of the compressive strength level, maximum size and content of coarse aggregate, water to cement ratio.

Chapter 3 Experimental Work

3.1 Introduction

The main aim of this work is to investigate the effect of coupling media on the pulse velocity measurement of the ultrasonic wave in concrete. Detailed information about the materials that used in concrete, mix proportion, and the experimental tests are presented in this chapter.

3.2 Materials

3.3 Cement

High strength finally ground Portland cement (52.5R) was used in this work. It was stored in airtight bags to ensure minimum exposure to the environment and therefore to maintain its dryness. The physical properties of and chemical test results of this cement are presented in Table 3-1 as given by the manufacturing factory, which conforms to the British Standards (BS EN 197-1, 2011).

Table 3-1 Physical and mechanical properties of the cement

Property	Test results	Standard Requirements BS EN 197-1:2011
Soundness (expansion)	1.1 mm	10 mm≤
Initial setting time	110 min	≥ 45 min
Compressive strength 2 days 28 day	27 MPa 58 MPa	≥ 30 MPa ≥ 52.5 MPa
Sulfate content (SO_3)	2.60 %	4.0 %≤
Chloride content (Cl)	0.01 %	0.10 %≤

3.3.1 Fine aggregate

Fine aggregate that used in this work was washed natural river sand with a maximum size of 5mm. Table 3-2 and Figure 3-1 illustrates the grading of the fine aggregate. Results of the grading indicating that the fine aggregate grading is within the requirements of the British Standard (EN BS 12620, 2002). The fine aggregate was oven dried in the laboratory using the drying parker plant with a drying rate of 7 kg/min. Two days after drying, the fine aggregate was cooled in a hopper.

Table 3-2 Grading of fine aggregate

Sieve size	Passing %	Standard requirements EN BS 12620, 2002
10 mm	100	100
5 mm	98	89-100
2.36 mm	86	60-100
1.18 mm	72	30-100
600 µm	50	15-100
300 µm	31	5-70
150 µm	12	0-15
75 µm	1	-

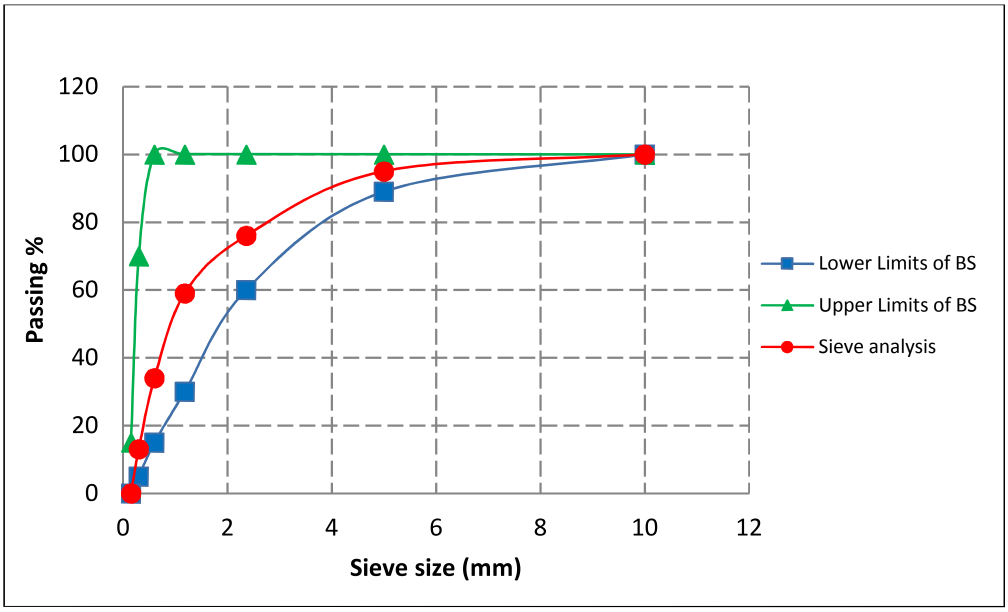


Figure 3-1 Grading of fine aggregate

3.3.2 Coarse aggregate

A natural quartzite aggregate with a maximum size of 20 mm and 10mm was used in this work. It was oven dried in the laboratory, after that the coarse aggregate was cooled and sorted. The grading of coarse aggregate is given in Tables 3-3 and 3-4 which conforms to the British Standard (EN BS 12620, 2002).

Table 3-3 Grading of coarse aggregate maximum size 20mm

Sieve size mm	Passing %	Standard requirements EN BS 12620, 2002
20	100	85-100
14	66	0-70
10	15	0-25

Table 3-4 Grading of coarse aggregate maximum size 10mm

Sieve size mm	Passing %	Standard requirements EN BS 12620, 2002
14	100	100
10	89	80-100
5	6	0-25
2.36	0	0-5

3.3.3 Water

Tap water will be used as mixing water for all concrete mixes as it is suitable for drinking and conforms to (BS EN 1008, 2002).

3.3.4 Superplasticizer

Sika Viscocrete 25 MP will be used as a Superplasticizer this conforms to the British Standard (BS EN 934-2, 2009). Table 3-5 shows the technical description of Sika Viscocrete 25 MP.

Table 3-5 Technical description of the Sika Viscocrete 25 MP

Technical description	Properties
Appearance	Viscous liquid
Colour	Yellow
Specific gravity	1.06 kg/l at +20˚C
PH- value	4.5 ± 0.5
Storage life	Up 12 months in unopened containers.

***According to the manufacturer.**

3.3.5 Coupling materials

Different solids and liquids will be used as coupling materials through this work. These materials were chosen based on availability, suitability for use as a couplant, and to cover a range of varying acoustic impedance. The coupling materials with their details are shown in Table 3-6.

Table 3-6 Details of the coupling materials (Galan et al., 1990, Kaye and Laby, 1973)

Materials	Material Status	Longitudinal pulse velocity m/sec	Density kg/m^3	Acoustic Impedance $Kg/m^2.s$
concrete	solid	(4430-4960)	(2300-2460)	$(6\text{-}9)\times10^6$
Cement paste	solid	(2206-2533)	(1480-1660)	4×10^6
Aggregate	solid	5750	2650	14.5×10^6
Rubber (Neoprene)	solid	1600	1310	2.10×10^6
Perspex (Poly-methacrylate)	solid	2750	1190	3.26×10^6
Carbon fibre composite (CFRP)	solid	4260	1470	6.26×10^6
Water	liquid	1480	1000	1.48×10^6
Propanol (n-polyalcohol)	liquid	1220	804	0.98×10^6
Vegetable Oil (Sunflower)	liquid	1450	920	1.34×10^6

3.4 Concrete Mixes

The results of previous work with air coupling showed that there may be a transition in behaviour between normal and high-strength concrete but did not test a full enough range of mixes; mixes thus chosen to give a range of compressive strength from 25 to 100 MPa target. Design of mixes was performed in accordance with Building Research Establishment Method (Teychenné et al., 1997). Two groups of concrete mixtures were cast of total 16 mixture.

The first group divided into two sets according to the maximum size of aggregate (MAS) that used i.e. 20mm (M1-M5) and 10mm (M6-M10). Each set contained five mixes of concrete with target 28-day mean compressive cube strength of 25, 40, 60, 80 and 100 MPa. The mixes proportions were specified in order to produce a range of concrete strengths ranges by varying the w/c ratio. The aggregate content was kept constant such that the effect of the coupling materials on the pulse velocity measurements could be assessed more easily. The influence of strength and MAS on the UPV measurements were investigated also. Details of the mixes are given in Tables 3-7 and 3-8.

The second group contained also two sets; each set divided into three mixes with different aggregate contents and a constant w/c ratio. The w/c ratio was kept constant at 0.5 for the first set (M11-M13) and 0.36 for the second set (M14-M16). These mixes used to investigate how the aggregate content effects pulse velocity measurements of the coupling materials. Details of the mixes are given in Table 3-9.

Table 3-7 Mix proportion of the concrete mixes (M1-M5)

Mix number	Target 28-day mean compressive strength MPa	Aggregate size (mm)	Mixture Proportion kg/m^3				
			Cement	Water	Super-plasticizer	Fine Aggregate	Coarse Aggregate
M1	30	20	290	170	-	742	935
M2	40	20	405	195	-	830	935
M3	60	20	550	215	-	695	935
M4	80	20	550	143	5.5	695	935
M5	100	20	550	138	11	695	935

Table 3-8 Mix proportion of the concrete mixes (M6-M10)

Mix number	Target 28-day mean compressive strength MPa	Aggregate size (mm)	Mixture Proportion kg/m^3				
			Cement	Water	Super-plasticizer	Fine Aggregate	Coarse Aggregate
M6	30	10	355	199	-	740	935
M7	40	10	470	226	-	690	935
M8	60	10	550	209	-	695	935
M9	80	10	550	165	5.5	695	935
M10	100	10	550	132	11	695	935

Table 3-9 Mix proportion of the concrete mixes (M11-M16)

Mix number	Target 28-day mean compressive strength MPa	Aggregate size (mm)	Mixture Proportion kg/m^3				
			Cement	Water	Super-plasticizer	Fine Aggregate	Coarse Aggregate
M11	40	20	350	163	-	737	1063
M12	40	20	350	163	-	540	1260
M13	40	20	350	163	-	1080	720
M14	60	20	550	198	-	615	950
M15	60	20	550	198	-	470	1095
M16	60	20	550	198	-	939	626

3.5 Casting and Curing

The cement, aggregate and water were weighted and batched according to the mix proportion of each mix. A total of 16 concrete mixes were prepared to be cast, for each mix 6 prisms of 100×100×500 mm and 9 cubes of 100×100mm were cleaned and the internal faces thoroughly oiled to avoid adhesion with the concrete after hardening. The casting was carried out in layers of 50mm deep and compaction was performed by means of a vibrating table. Each layer was compacted for a sufficient time to reach full compaction. Finally, the concrete surfaces will be levelled. After that, the specimens will be placed in the curing room until the time of testing.

3.6 Testing of Concrete

3.6.1 Ultrasonic pulse velocity test

The ultrasonic pulse velocity test was conducted according to the British Standards (BS 12504-4, 2004), at age of 7, 28, and 90 days and for each mix, six samples were tested at each age using prisms of (100×100×500) mm. The testing apparatus (PUNDIT Lab^{+}), manufactured by Proceq Switzerland is shown in Figure 3-2. The direct transmission configuration will be used through this work. The transmitter and receiver transducers will be held at opposite concrete surfaces of the sample. For the conventional test, a very thin layer of gel couplant was applied between the transducers and the test sample as is normal practice on-site.

For the solid coupling testing, slices of the solid material with a dimension of (100×100) of varying thickness mm will be inserted between the transducers and the concrete surfaces as shown in Figure 3-2. Liquid coupling testing will be performed by using a plastic tube. The transducer will be inserted with one end and the other end will be placed on the concrete surface and sealed with silicon The tube will be filled by injection of a liquid through a hole in the top its surface. A wooden fame will be used to hold and fix the transducers with the tubes to the concrete surface as shown in Figure 3-3. Each sample will be removed from the curing room and placed to dry at room temperature for half an hour before taking the measurements.

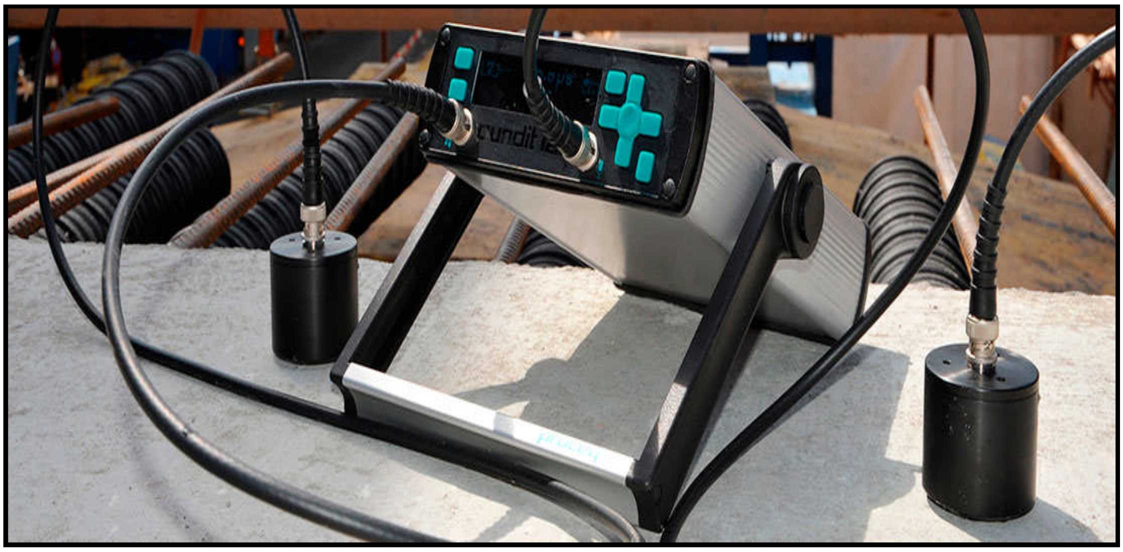


Figure 3-2 Ultrasonic pulse velocity test instrument (PUNDIT Lab^{+})

Ten readings per sample will be taken for each type of ultrasonic testing method. By measuring the time (t) taken by the pulse to be transmitted and received over a known path length (d), the velocity of the pulse can be computed from the following relationship:

$$V = d/t \tag{3-1}$$

Corrections were applied to the coupled test, as the recorded time is the transit time within the concrete sample and the coupling material. Before starting the coupled test, the transit time within the coupling material was recorded by measuring the transit time through the coupling material using direct transmission configuration. Thus, the transit time through concrete can be calculated using the following relationship:

$$t_{concrete} = t_{total} - t_{coupling\ material} \tag{3-2}$$

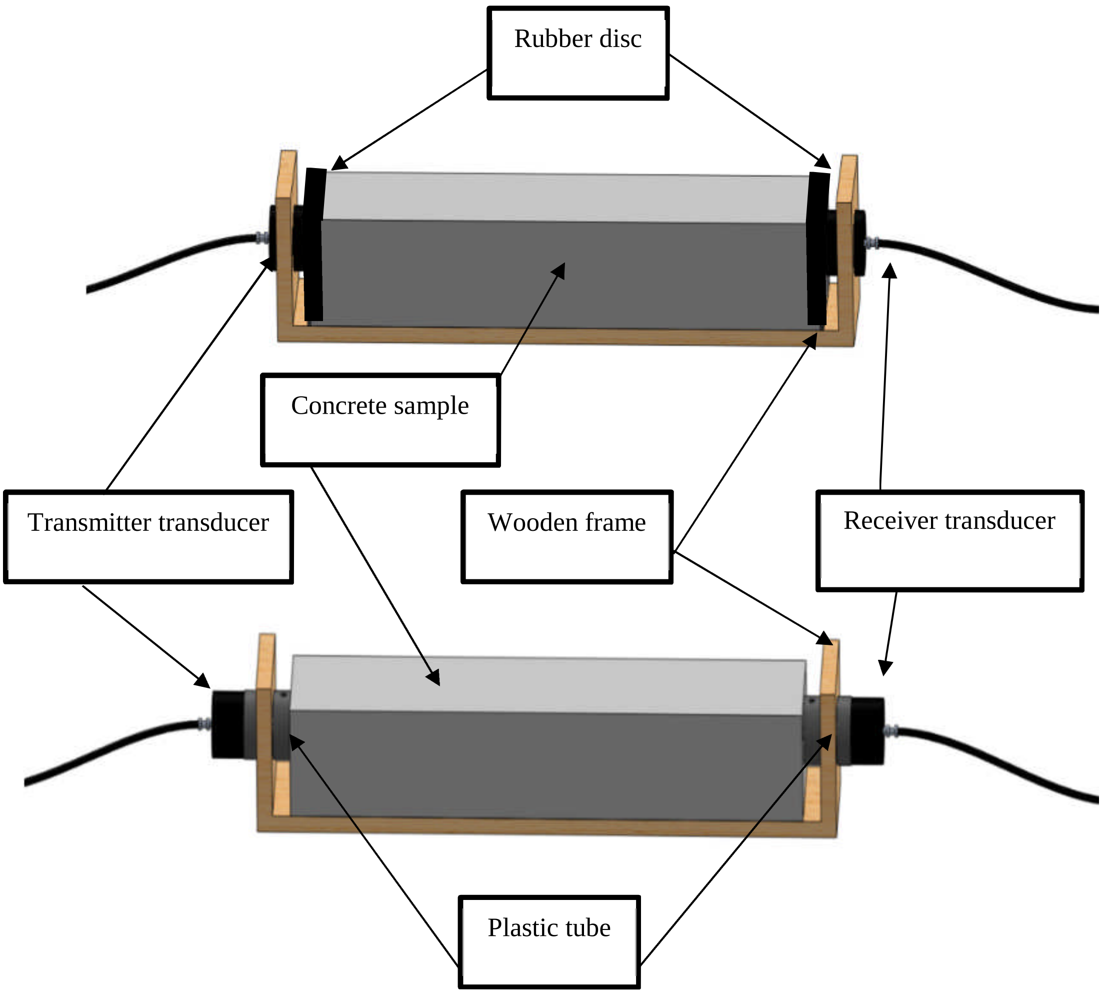


Figure 3-3 concrete test with solid and liquid coupling

3.6.2 Compressive strength test

The compressive strength of the concrete was carried out using three100mm cubes at each age test of 7, 28, and 90 days in accordance with British Standards (BS EN 12390-3, 2009). The Servocon system digital compressive test machine was used to determine the compressive strength of the sample. The machine used was computerized; the test configurations were all controlled using the Servocon software.

3.7 Statistical analysis

3.7.1 Analysis of variance (ANOVA)

One of the most common applications of the statistics in experimental research is to compare a measured value with either a known value or another measured value. The statistical analysis that including a contemporaneous comparison of multiple groups of measurements is called analysis of variance (ANOVA). Generally, ANOVAs can be classified into three ways: one-way ANOVA, two-way ANOVA, and N-way Multivariate ANOVA. Using one of these ways is depended on the research design i.e. the number of independent variables. One-way ANOVA has been applied through this research as it involves one independent variable (coupling materials) with more than two levels and different conditions. The one-way ANOVA test compares the measurements means of these levels (groups) to determine whether any of these groups are significantly different from the measurement of the conventional test and from each other by analysing the variance.

Variance can be defined as the average of the squared deviations of the measurements from their mean (SS). Thus if we have a sample of n points, the sample variance σ^2 can be calculated by the following equation (Mann, 2010):

$$\sigma^2 = \frac{\Sigma(X_i - \bar{X})^2}{n-1} \tag{3-3}$$

$$SS = \Sigma\,(X_i - \bar{X})^2 \tag{3-4}$$

Where: X_i is an individual data point, $\bar{X}$ is the mean of the sample.

The one-way ANOVA test relies on the F-test to statistically examine the equality of means. It is based on a comparison of two estimates of variance, the variance between the group means and the variance within the groups, difference among these variances is calculated as the ratio (F- statistics). A large F- statistic indicates that not all the groups are equal i.e. there is more variability between the groups than within each group (Mann, 2010).

$$F = \frac{SS_{between}/(k-1)}{SS_{within}/(N-k)} \quad (3\text{-}5)$$

Where: k is the number of different groups and N is the total number of all the data points combined.

The ANOVA test is considered an omnibus test because it will indicate if there is an overall significant difference between the groups. To identify which specifics groups significantly differ, follow-up tests needed to be conducted. These tests involve comparisons between pairs of group means.

In this research, the one-way ANOVA test was used to analyse UPV measurements of the coupled system to determine if there are statistically significant differences between the coupled and conventional measurements as a first step and to determine whether any of these coupling materials measurements are significantly different from each other as a second step. The following are the basic requirements of the one-way ANOVA test.

3.7.2 Assumptions

The results of a one-way ANOVA test can be considered reliable as long as the following assumptions are met:

- Independence of measurements: this assumption means that the measurements in each group of the independent variable must not be influenced by any measurement of another group. The groups of measurements need be independent where there are no relationships between the measurements in any of these groups. It is important to expound that one-way ANOVA test is not robust to the violation of this assumption (Stevens, 2012)
- Normal distribution: the assumption of normality asserts that the measurements within each group of the independent variable are normally distributed across their means. This assumption is necessary for testing the statistical significance using the one-way ANOVA test. However, the one-way ANOVA test is fairly robust to

the violation of the normality assumption, particularly when the group sizes (number of measurements in each group) are equal or nearly equal (Kirk, 1995). Which means that some violation of this assumption can be accepted and the valid results test will still be provided. There are many different statistical techniques for assessing the normality, the most common technique is the Shapiro-Wilk test.

- Homogeneity of variance: according to the assumption of homogeneity of variances, all groups of the independent variable should have the same variance. Usually, this assumption is examined by conducting Levene's test for equality of variance. When this assumption is violated, alternative approach needed to be used to perform the one-way ANOVA as the F test is not robust to the deviation of this assumption (Brown and Forsythe, 1974a). Welch's Test is a good approach for performing an ANOVA analysis. It is a form of one-way ANOVA that does not assume equal variances, where adjustment to degrees of freedom is applied (Brown and Forsythe, 1974b).

3.7.3 Null and alternative hypotheses

The main purpose of conducting the one-way ANOVA test is to determine whether the group's means of the independent variable are different from each other. To achieve this, there are two hypotheses that are sampling F distribution in the ANOVA test. The first one is the null hypothesis which is stated that there is no difference between the group's means, all groups have equal mean. The second one is the alternative hypothesis which is stated that there are differences between the group's means of the independent variable, at least one group has a different mean.

As mentioned above, the one-way ANOVA will calculate the F statistic based on the variability between groups against the variability within groups. The P-value or the calculated probability is the probability of finding the observed measurements given that the null hypothesis is true (Shaver, 1993). The P-value will then compare with the significance level (alpha) which is the pre-chosen probability i.e. must be determined before conducting the statistical test. The significance level can be defined as the probability of rejecting the null hypothesis when the null hypothesis is true (Tabachnick and Fidell, 2007). Thus if the P-value less than the chosen alpha then the null hypothesis will be rejected and the result of one-way ANOVA test is reported that there is the statistically significant difference between groups of the independent variable.

3.7.4 Follow-up tests

When the ANOVA test is conducted, it will examine if there are significant differences among the different groups of the independent variable. The test results will indicate that there is a statistical significant on overall the groups. Thus, a follow-up analysis is performed to determine which specific pairs of the group are different. This analysis can be applied by using two techniques, either post-hoc test or planned contrasts test.

The post-hoc test is used when the researcher wants to explore the whole set of comparisons, all possible combinations of the groups. There are different post-hoc tests which make different assumptions about equality of variance. One of the most commonly used post-hoc tests is the Tukey's Honestly Significant Different test (HSD), is based on assumptions of equal variances for the two group in the comparison (Abdi and Williams, 2010). When the assumption of homogeneity of variance is violated, post-hoc test which does not assume equal variance will be used for the pairwise comparisons. There are several post-hoc tests that conducted when there is a deviation from an assumption of homogeneity of variances, the Games-Howell test is widely used in these comparisons (Toothaker, 1991).

When the researcher is interested in following up analysis just for some specific groups, then the planned contracts will be more appropriate to test the significance of differences between these groups as it designed for custom comparisons. The hypotheses for these type of comparisons should be orthogonal, which is independent of each other. One of the approaches to performing planned contracts is using the Bonferroni correction for multiple comparisons by adjusting the p-value in accordance to the number of planned comparisons (dividing the P value by the number of comparisons intending to make). The statistical significance of the test will be then calculated based on the new modified P-value (Tabachnick and Fidell, 2007).

3.7.5 Two way ANOVA test

The two-way ANOVA is another statistical test that belongs to the family of analysis of variance which is used to determine the effect of two independent variables on the dependent variable (measured variable). The test was conducted to examine the joint effect of the coupling materials and the compressive strength on the measurements of the pulse velocity i.e. if there is any interaction between effects of the two variables.

The interaction effect means that the effect of one independent variable on the measured variable is depended on the level of the second independent variable (Aiken et al., 1991). In other words, if the effect of coupling materials on the pulse velocity is depended on the level of compressive strength. In the same the test it will be determined if differences that caused by each of the types of coupling materials and the level of the compressive strength of the measured values of the pulse velocity are statistically significant.

Thus, there will be three null hypotheses to test, the first hypothesis stated there is no interaction between the effect of coupling materials and the effect of compressive strength level. The second hypothesis stated that there are no differences in the measurements of pulse velocity due to effect compressive strength level. While the third hypothesis asserts that there are no differences in the measurements of pulse velocity due to the effect of coupling materials. The alternative hypotheses will be also three hypotheses: there is an interaction effect between the two independent variables, there are differences in the measurements of pulse velocity due using coupling materials and compressive strength level has an effect on the pulse velocity measurement (Sokal and Rohlf, 1969).

The assumptions of the two- way ANOVA test are the same as of the one-way ANOVA test: independence of the measurements, normality distribution of the measurements and homogeneity of variance among the groups of the measurements (Rencher, 2003). According to the outputs of two-way ANOVA test, all the measurements were normally distributed as evaluated by the Shapiro-Wilk test at the 5% level of significance. There was the homogeneity of variances as assessed by Levene's test at the 5% level of significance.

3.7.6 t- test

When there are only two independent groups wanted to determine if there are any statistical significant differences between their measurements, it is typically using the independent t-test for this comparison. The t-test assesses whether the means of these two groups are statistically different from each other. This test is also known by other names; unpaired t-test, Student's t-test and between-subjects t-test. The other two types of t-tests are one sample t-test which compares the mean of a single group to a predefined value and the paired sample t-test which compares means from the same group but at different condition (Sheskin, 2003).

The t-test is based on t-values (test statistic), in which the test statistic follows a t- distribution (Student's t distribution). The test statistic is a ratio between the difference between the means of two groups and the difference between the groups or the variability in the measurements. The larger t-value, the more difference is between the groups. There are two hypotheses that are governed this test; the null hypothesis which is stated that there is no difference between the group's means, both groups are having the same mean. The alternative hypothesis is stated that there is a difference between the group’s means (Pallant, 2013). The P-value is calculated for the t-value and then compared with a significance level (alpha) of 5%. Thus if the P-value less than the chosen alpha then the null hypothesis must be rejected and reported that there is the statistically significant difference between group’s means. Before conducting the t-test there is a need to check the assumptions related to this statistical test which is basically the same as of the one-way ANOVA; independence of the measurements, normality distribution of the measurements and homogeneity of variance among the two groups (having equal variances) (Myers et al., 2010).

The t-value is calculated by the following equation:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_1}}} \quad (3\text{-}6)$$

Where:

$\bar{X}_1$= mean of the first group of data points
$\bar{X}_2$= mean of the second group of data points
S_1= standard deviation of the first group of data points

S_2= standard deviation of the second group of data points

n_1= total number of data points in the first group

n_2= total number of data points in the second group

The standard deviation is calculated by the following equation:

$$S = \sqrt{\frac{\Sigma(X - \bar{X})^2}{n - 1}} \quad (3\text{-}7)$$

Where:

$\bar{X}$ = individual data point

$\bar{X}$= mean of the data points

n = total number of data points

Chapter 4 Preliminary Experiments

4.1 Introduction

The purpose of this work was to examine any discrepancy in pulse velocity measurements that could be traced to coupling effects by exploring different coupling materials with the conventional testing device PUNDIT over a range of specifically mixed concretes. A comparison between the values obtained for pulse velocity with the coupling testing system, and those obtained using the traditional testing system was then carried out by conducting a statistical analysis. Analysis of variances (ANOVA) was performed to confirm whether there are statistically significant differences between measurements obtained using the two systems.

4.2 Preliminary experiments

Preliminary experiments were conducted to examine whether a coupling effect might exist between the ultrasound wave and the constituent materials of concrete when conducting UPV test in concrete. i.e. that the pulse velocity measured depends on the couplant used. Experimental tests involved using the PUNDIT Lab+ with six different coupling materials of varying acoustic impedance, were placed between the concrete test prism surface and the transducers in a direct transmission arrangement. For the conventional test, a very thin layer of gel couplant was applied between the transducers and the concrete test prism as is normal practice on-site.

The UPV test using the PUNDIT Lab+ was very sensitive and therefore for the most accurate results, the sample was placed in a cradle which held it firmly place, allowing for the distribution of a constant pressure from the transducers to the sample. The transit time readings that were recorded were based on the average of 10 readings were taken. Corrections were applied to the coupled samples measurements, as the recorded time is the transit time within the concrete sample and the coupling material. The pulse velocity was calculated for the two systems and correlate with the compressive strength of the concrete mixes. Five concrete mixes with target mean 28-day compressive strength of 25, 40, 60, 80 and 100 MPa (M1-M5) (Table 3-7) were cast using Portland cement, sand and a constant coarse aggregate content of maximum aggregate size of 20mm. The measurement was taken at age of 7, 28, and 90 days. Variation of UPV versus compressive strength is plotted in Fig (4-1).

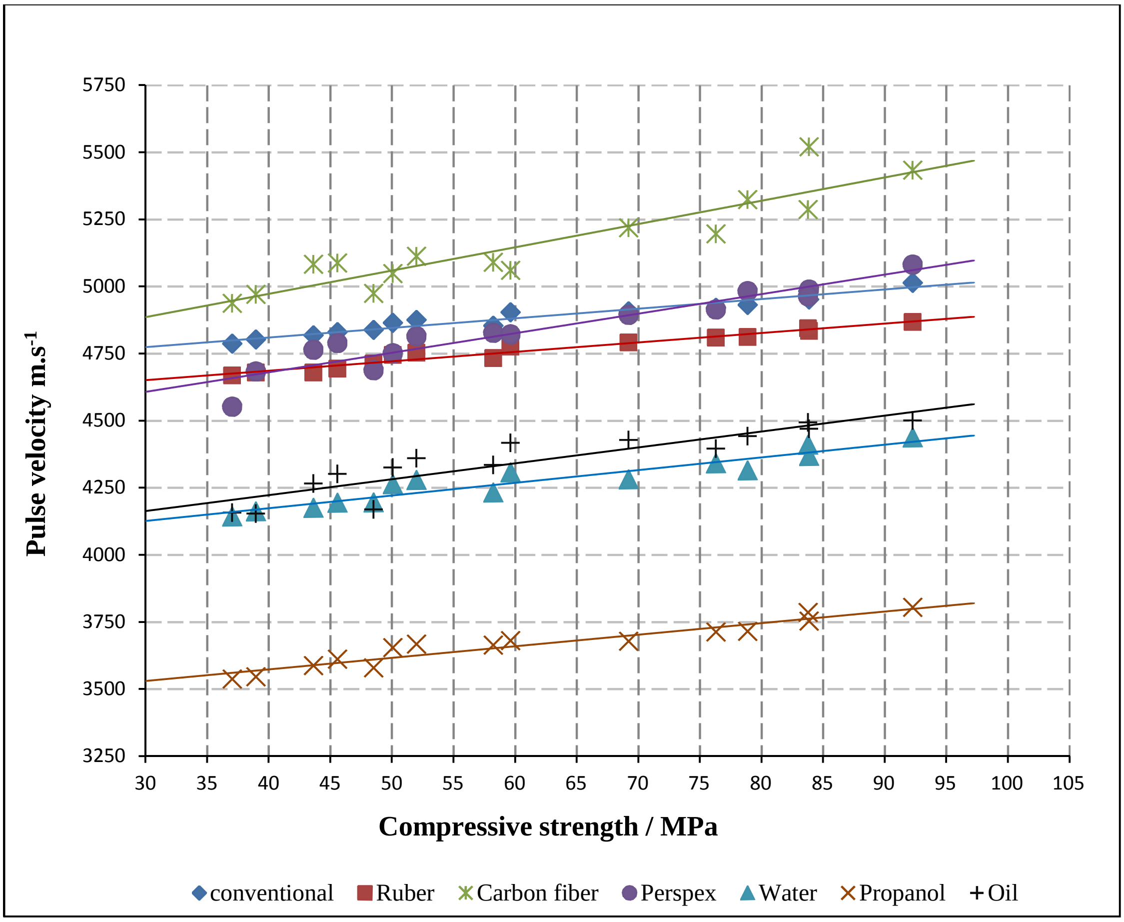


Figure 4-1 Pulse velocity vs compressive strength: solid coupling, liquid coupling and conventional test

The results in Fig. (4-1) clearly, show that the coupling tests return different measurements for the pulse velocity of the concrete from that of the conventional test. Generally, all the coupling materials return lower values for the pulse velocity than that of the conventional test (except the carbon fibre), and the measurements recorded for the liquid coupling tests were lower than those for the solids coupling. To investigate if these differences are really significant. Analysis of variances (ANOVA) was performed to confirm that there are statistically significant differences between the measurements recorded using a conventional system and a coupled system.

4.3 Results of the ANOVA test

The ANOVA test is considered the following hypotheses: the null hypothesis which stated there are no differences between the means of the pulse velocity measurements of different coupling materials tests and the measurement of the conventional test. The alternative hypothesis stated that at least one coupling material has a different mean from that of the conventional test.

In order to get reliable results from the one- way ANOVA test, certain assumptions needed to be satisfied before running the one-way ANOVA test. These assumptions are; independence of the measurements in each coupling material test, the measurements of pulse velocity should be approximately normally distributed for the conventional test and each coupling material tests, and there is the homogeneity of variances for the measurements of the pulse velocity of coupling tests and the conventional test.

The mean and standard deviation of the coupling tests and the conventional test were shown in Table (4-1). All the measurements were normally distributed as evaluated by the Shapiro-Wilk test at the 5% level of significance as shown in Table (4-2). According to the outputs of ANOVA test, there was heterogeneity of variances as assessed by Levene's test at the 5% level of significance as shown in Table (4-3). As the assumption of homogeneity has been violated a one way Welch's ANOVA was used to determine if measurements means of the coupling system was statistically different from that of the conventional system. The Welch's ANOVA showed that there was the statistically significant difference in pulse velocity measurements between the two systems at the 5% level of significance which presented in Table (4-4).

As the ANOVA test was statistically significant it can be concluded that at least one coupling material has different mean measurements from the conventional test. To determine which material or materials is/are different, a post hoc test was used to test all possible combinations of pairwise comparison between the coupling material tests and the conventional test at the 5% level of significance. These pairwise combinations were conducted by Games-Howell post hoc test to determine whether the mean differences of these pairwise comparisons are statistically significant.

The results of pairwise comparisons for the solid coupling showed that the difference in mean measurements between the Perspex and the conventional test was statistically not significant and between the Perspex and rubber as well. The results for the liquid coupling comparisons showed that the difference in mean measurements was found not significant between the water and oil measurements only as presented in Table 4-5. Figure 4-2 shows means of the pulse velocity measurements of the conventional test and the coupling materials with the errors bars of ± standard deviation, when the errors bar of two groups of measurements are overlapped it will be find that there is no statistical significance between them. The reason of insignificance in mean differences is that the tests of these coupling media returned almost similar values for the pulse velocity so the differences were quite small between them. However, all the other comparisons were statistically significant. Thus, the Perspex and the oil will be excluded from the next experiments.

The highest pulse velocity was measured using the couplant with the closest match of acoustic impedance with concrete (carbon fibre) (Kaye and Laby, 1973). The steel transducer (i.e. conventional system) has a very high acoustic impedance (>40), but it not clear why this should give a lower speed of sound than the carbon fibre yet a higher speed of sound than the liquid couplants. However, carbon fibre is basically a composite material that consists of two parts: carbon fibres which are responsible for the strength and rigidity of composite material and matrix which is usually a polymer resin to bind the fibres together. This kind of composite materials is considered an anisotropic material, which means properties of the composite material is directionally dependent. Thus, properties of the carbon fibre are depended on the layouts of the fibres within the matrix and also on the proportion of the fibres to the polymer. As the propagation of the acoustic waves through a medium depends on the elastic properties of that medium, thus it would be expected that the anisotropic nature of the composite material will lead to a complex wave behaviour (Pearson and Murri, 1987).

As a result, the nature of fibrous composite will not permit of coherent wave propagation for either compression mode or shear mode propagating in the off principle direction (Kim and Park, 1987). Wilkinson and Reynolds (1974) demonstrated in their work with carbon fibre reinforced plastic, that a mixed type wave (compression and shear) was observed in the most direction in the composite which called the pseudo-L wave. This wave is propagating in a two-section dog-leg path leading to minimising the recorded transit time. This observation could give some explanation to the high pulse velocity recorded with carbon-fibre couplant. Due to the complexity of wave propagation behaviour through this coupling material and as the concrete is a composite material also, it was decided to exclude this material in the next experiments.

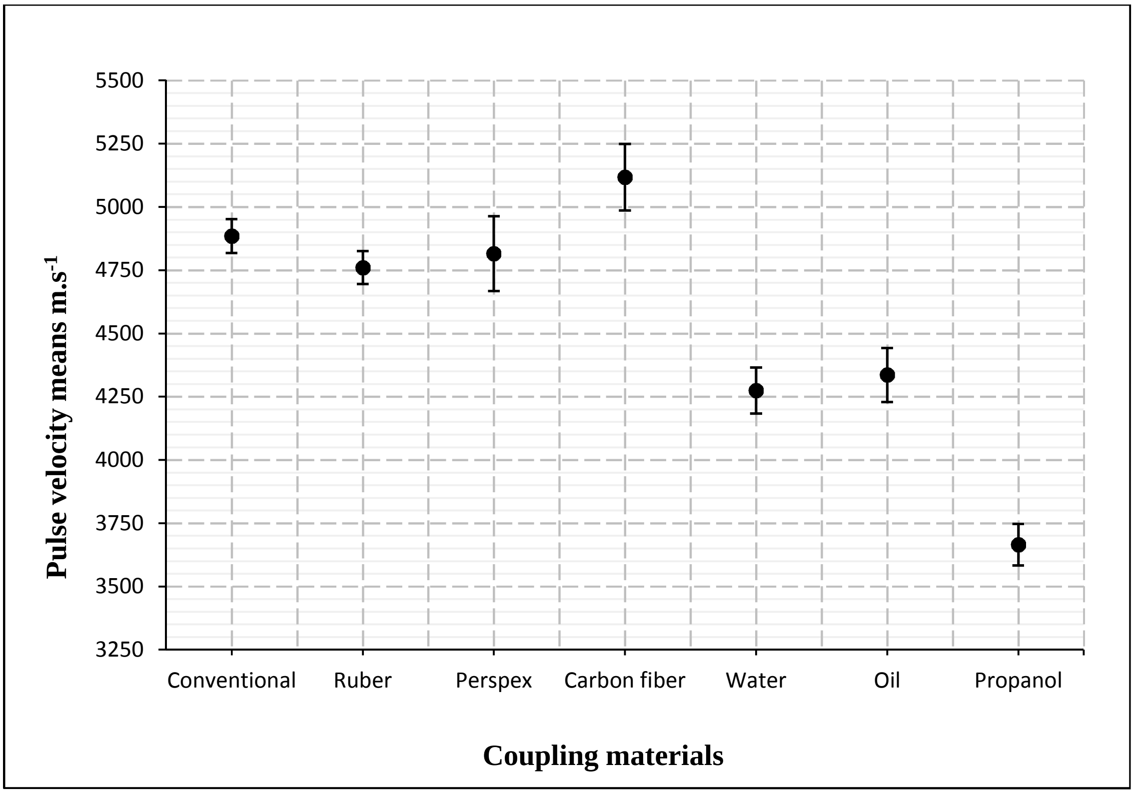


Figure 4-2 Means of the pulse velocity measurements of the conventional test and the coupling materials. Errors bars are ± standard deviation**.**

Table 4-1 Second moment statistics of the of the one way ANOVA for the coupling tests with mixes of constant aggregate content and MAS of 20mm

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Conventional	15	4885.2000	66.75135	17.23512	4848.2343	4922.1657
Rubber	15	4760.3333	65.17193	16.82732	4724.2423	4796.4243
Carbon Fibre	15	5156.0000	171.69824	44.33230	5060.9167	5251.0833
Perspex	15	4834.4667	139.46677	36.01017	4757.2325	4911.7008
Water	15	4274.0000	90.80749	23.44639	4223.7125	4324.2875
Propanol	15	3665.0000	81.76884	21.11262	3619.7179	3710.2821
Oil	15	4347.9333	118.77738	30.66819	4282.1566	4413.7101
Total	105	4560.4190	478.14618	46.66229	4467.8860	4652.9521

Table 4-2 Test of normality of the of the one way ANOVA for the coupling tests with mixes of constant aggregate content and MAS of 20mm

	Shapiro-Wilk			
	Test statistic	df	P-value	Test significant
Conventional	0.971	15	0.875	sig.
Rubber	0.946	15	0.467	sig.
Water	0.962	15	0.725	sig.
Propanol	0.965	15	0.781	sig.
Carbon Fibre	0.949	15	0.504	sig.
Perspex	0.989	15	0.999	sig.
Oil	0.963	15	0.747	sig.

Table 4-3 Test of homogeneity of variances of the of the one way ANOVA for the coupling tests with mixes of constant aggregate content and MAS of 20mm

	Test statistic	df1	df2	P-value
Levene test	2.525	6	98	0.026

Table 4-4 ANOVA test of the coupling tests with mixes of constant aggregate content and MAS of 20mm

	Test statistic	df1	df2	P-value	Test significant
Welch test	435.410	6	43.213	0.000	sig.

Table 4-5 Games-Howell post hoc test of the one way ANOVA for the coupling tests with mixes of constant aggregate content and MAS of 20mm

(I) Coupling Material	(J) Coupling Material	Mean Difference (I-J)	Std. Error	P-value	Comparison results
Conventional	Rubber	124.86667*	24.08751	0.000	sig.
	Water	611.20000*	29.09953	0.000	sig.
	Propanol	1220.20000*	27.25422	0.000	sig.
	Carbon fibre	-231.93333*	38.06487	0.000	sig.
	Perspex	69.73333	41.93556	0.646	not sig.
	Oil	549.20000*	32.57682	0.000	sig.
Rubber	Conventional	-124.86667*	24.08751	0.000	sig.
	Water	486.33333*	28.85987	0.000	sig.
	Propanol	1095.33333*	26.99818	0.000	sig.
	Carbon fibre	-356.80000*	37.88196	0.000	sig.
	Perspex	-55.13333	41.76961	0.835	not sig.

	Oil	424.33333*	32.36292	0.000	sig.
Water	Conventional	-611.20000*	29.09953	0.000	sig.
	Rubber	-486.33333*	28.85987	0.000	sig.
	Propanol	609.00000*	31.55117	0.000	sig.
	Carbon fibre	-843.13333*	41.25067	0.000	sig.
	Perspex	-541.46667*	44.84724	0.000	sig.
	Oil	-62.00000	36.24822	0.615	not sig.
Propanol	Conventional	-1220.20000*	27.25422	0.000	sig.
	Rubber	-1095.33333*	26.99818	0.000	sig.
	Water	-609.00000*	31.55117	0.000	sig.
	Carbon fibre	-1452.13333*	39.97033	0.000	sig.
	Perspex	-1150.46667*	43.67247	0.000	sig.
	Oil	-671.00000*	34.78423	0.000	sig.
Carbon fibre	Conventional	231.93333*	38.06487	0.000	sig.
	Rubber	356.80000*	37.88196	0.000	sig.
	Water	843.13333*	41.25067	0.000	sig.
	Propanol	1452.13333*	39.97033	0.000	sig.
	Perspex	301.66667*	51.12168	0.000	sig.
	Oil	781.13333*	43.77310	0.000	sig.
Perspex	Conventional	-69.73333	41.93556	0.646	not sig.
	Rubber	55.13333	41.76961	0.835	not sig.
	Water	541.46667*	44.84724	0.000	sig.
	Propanol	1150.46667*	43.67247	0.000	sig.
	Carbon fibre	-301.66667*	51.12168	0.000	sig.
	Oil	479.46667*	47.17777	0.000	sig.
Oil	Conventional	-549.20000*	32.57682	0.000	sig.
	Rubber	-424.33333*	32.36292	0.000	sig.
	Water	62.00000	36.24822	0.615	not sig.
	Propanol	671.00000*	34.78423	0.000	sig.
	Carbon fibre	-781.13333*	43.77310	0.000	sig.
	Perspex	-479.46667*	47.17777	0.000	sig.

4.4 Effect of coupling materials on the pulse velocity

In the light of the statistical analysis results, pulse velocity measurements of the three coupling materials (rubber, water and oil) will be considered. As it can be seen the coupled system returned lower values for the pulse velocity than the conventional test at all compressive strength levels. The marked difference between the two testing systems has been seen in previous air coupling tests. Where the air coupling test records lower values for the pulse velocity than the PUNDIT test, but return approximately similar values for mixes with higher compressive strength (target 28-day compressive strength of 60 MPa) (Purnell et al., 2004). The concrete mixes that were used in the air coupling work had different coarse aggregate contents, while in this work mixes with a constant coarse aggregate content were used and the target 28-day compressive strength ranged between 25and 100 MPa.

The pulse velocity was the lowest when using the propanol couplant which recorded velocities from 3537 to 3885 m/sec. When compared to the conventional test where the transducers are in a direct contact with the concrete surface, the readings recorded were from 4787 to 5013 m/sec. Both of these measurements are across samples with compressive strength ranged from (37-92) MPa as shown in Table 4-6. The differences between the conventional velocities test and the coupling tests were expressed as a percentage of the conventional velocity for the concrete sample. The percentage discrepancy for each coupling system was calculated based on the difference between the two systems relative to the reading of the conventional test. It can be easily expected that the rubber couplant recorded the lowest average discrepancy of 2.56%. For the liquid couplants, the averages of percentages in discrepancies were for water couplant 12.51 and 24.97 % for propanol couplant.

Based on the results, it is clear that the measured speed of sound depends on the couplant used. In term of the acoustic impedance, the amount of energy transmitted through an interface depends on acoustic impedances of the two media. Thus, if the two media have close impedance values, more energy will be transmitted (Kaye and Laby, 1973). As the solid materials have an acoustic impedance higher than those of liquids compared to concrete’s impedance, thus it is thought that the more energy will be transmitted through the interface solid-concrete.

The basic assumption that underlines this approach: a coupling effect could occur between the ultrasound wave and the constituent materials of the concrete. Concrete is a multiphase material, where the speed of sound in aggregate is generally higher than that through cement paste, and the two phases will have slightly different acoustic impedance i.e. acoustic impedance of the aggregate (quartz) and the cement paste is 14.5×10^6 and 4×10^6 $kg/m^2.s$ respectively (Galan et al., 1990). It is thus reasonable to assume that the value of recorded velocity could be vary depending on the phase that the acoustic energy would have initially transmitted preferentially through it. The research conducted by (Purnell et al., 2004), proposed that when using the PUNDIT the acoustic energy would be initially coupled to the aggregate (propagating through paths that maximize the aggregate content) while with non-contact system where the air is couplant medium the acoustic energy would initially be coupled into the cement paste primarily.

Based on that assumption, it can be assumed that when the rubber couplant is used the acoustic energy would couple into the aggregate initially and hence returning a closer measured velocity of the ultrasonic pulse to that of the conventional test. Conversely, with the liquid couplants, it was assumed that the acoustic energy would initially transmit to the cement paste returning lower values for the pulse velocity. However, the propagation of an ultrasonic pulse in concrete which acoustically inhomogeneous is even more complicated as it accompanies by complex processes of attenuation, reflection, and refraction of waves composing this pulse.

4.5 Effect of compressive strength on the pulse velocity

Figure (4-3) also shows the variation trend of the pulse velocity, c, and the compressive strength, S. It can be seen that the relationship between the pulse velocity, c, and the compressive strength, S, of the conventional test was approximately linear with $\Delta c/\Delta S$ of about ± 4 m/Mpa.sec. Most of both the solids and liquids coupling tests returned similar values for Δc/ΔS; i.e., the c/S lines are simply “shifted vertically” with respect to that of the conventional test. These behaviours are rather different to that of previously reported air coupling tests where the slope of the c/S curve was much steeper in the air-coupled test than the conventional test (PUNDIT test) with a Δc/ΔS value of approximately 45 m/Mpa.sec (Purnell et al., 2004). However, the concrete mixes that were used in the air coupling work had different coarse aggregate contents and on the other hand, the acoustic impedance of the air is much lower than of the couplants used in this work as it can be seen in Table 3-7.

The results of previous work with air coupling showed that there may be a transition in behaviour between normal and high-strength concrete but did not test a full enough range of mixes; mixes thus chosen to give a range of compressive strength from 25 to 100 MPa. To have further details, UPV measurements of the mixes (M1-M5) has been plotted against compressive strength for each of the conventional test and coupling tests (rubber, water, propanol) at age of 7, 28, and 90 days in Figures 4-4 to 4-7.

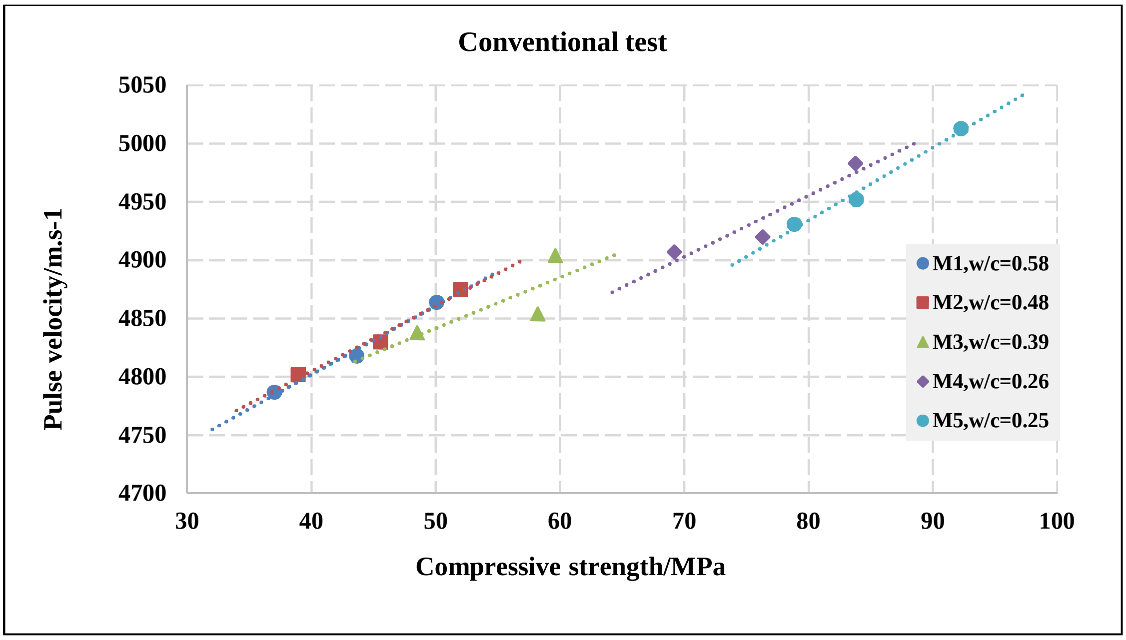


Figure 4-3 Pulse velocity vs compressive strength of the conventional test for mixes with different compressive strength level and constant aggregate content.

It can be observed from Figure (4-4) of the conventional test, that there are two separate data groups regarding the strength of mix, normal strength group (≤ 60 MPa) and high strength group (> 60MPa). The normal strength group are M1, M2 and M3, for the conventional test the averages of UPV were 4824, 4837 and 4865 m/sec respectively. While the averages of compressive strength were 44, 46 and 55MPa. The high strength group are included M4 and M5 where the average of the average of UPV were 4937 and 4966 m/sec respectively for which compressive strength were76 and 85MPa.

As it can be seen that the change in UPV measurements due to a change in w/c ratio is larger at high strength concrete than at normal strength at a given coarse aggregate content. There was a pronounced separation in UPV between M3 and M4, where M3 has a w/c ratio of 0.39 and M4 of 0.26. While when the w/c ratio changed from 0.48 (M2) to 0.39 (M3), the UPV slightly increased. UPV measurements of M4 and M5 showed that the small variation in w/c ratios of high strength concretes (from 0.26 to 0.25) has led to increases in UPV slightly as shown in table 4-6. Which means the change in w/c ratio does not affect pulse velocity in the same way as the does the on strength of concrete (Popovics et al., 1990). However, (Lin et al., 2016) stated that for a specific coarse aggregate content, the strength- pulse velocity relationship was negligibly affected by the variations in w/binder ratio. This behaviour can be explained by the fact that the variation in w/c ratio was not large enough to show a noticeable effect on UPV measurements, where w/c ratios of the tested mixes varied between 0.34 and 0.4.

Table 4-6 measurements pulse velocity of the coupling tests with mixes of constant aggregate content and MAS of 20mm

Mix	w/c ratio	Test age	Compressive strength	Pulse velocity			
				Conventional	Rubber	Water	Propanol
M1	0.58	7	37	4787	4669	4143	3537
		28	44	4818	4680	4175	3588
		90	50	4864	4745	4264	3654
M2	0.48	7	39	4802	4680	4162	3546
		28	46	4830	4694	4195	3611
		90	52	4875	4754	4279	3667
M3	0.39	7	49	4838	4713	4196	3579
		28	58	4857	4733	4233	3664
		90	60	4904	4776	4308	3681
M4	0.26	7	69	4907	4792	4282	3678
		28	76	4920	4810	4341	3713
		90	84	4983	4844	4410	3785
M5	0.25	7	79	4931	4812	4315	3745
		28	84	4952	4835	4369	3773
		90	92	5013	4868	4438	3885

The coupling tests followed the same trend as the conventional test, the relationship between pulse velocity and compressive strength was approximately linear of mixes with constant coarse aggregate contents and different w/c ratios. In rubber test, M1 and M2 returned almost similar values (the average of UPV was 4697 and 4709 m/sec) while there was a clear difference in measurements of M3 and M4 (the average of UPV was 4740 and 4815 m/sec).

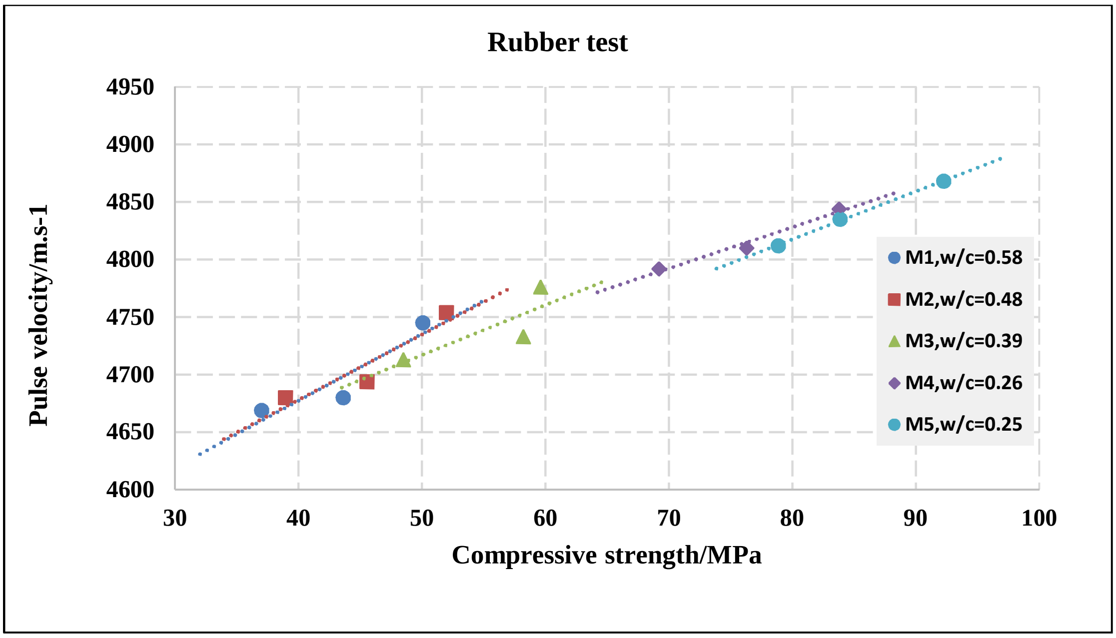


Figure 4-4 Pulse velocity vs compressive strength of the rubber test for mixes with different compressive strength level and constant aggregate content

Liquid couplant (water, propanol) results tracked the same behaviour as the rubber, the recognisable difference also was just between M3 and M4, for the water test the average of UPV was 4247 and 4343 m/sec and the average of UPV was 3641 and 3725 m/sec for the propanol test.

However, the difference between UPV measurements between M4 and M5 was more clearly compared to rubber test and conventional test as well. Also, it can be noted that UPV of M3 shows a clear separation from M2 and M1 regarding that of the rubber couplant and the conventional test. It seems the UPV with the liquid couplant is more sensitive to the change of w/c as the compressive strength of concrete increased. These differences arise from the acoustic coupling to the sample in each case i.e. depending on the couplant used. Although there are variations in the acoustic impedances of the three couplants and hence in the amount of energy that are transmitted through the interface, it seems that these differences are not sufficient to cause such a marked discrepancy in the measurements of the UPV when the liquid couplants are used compared to the rubber couplant.

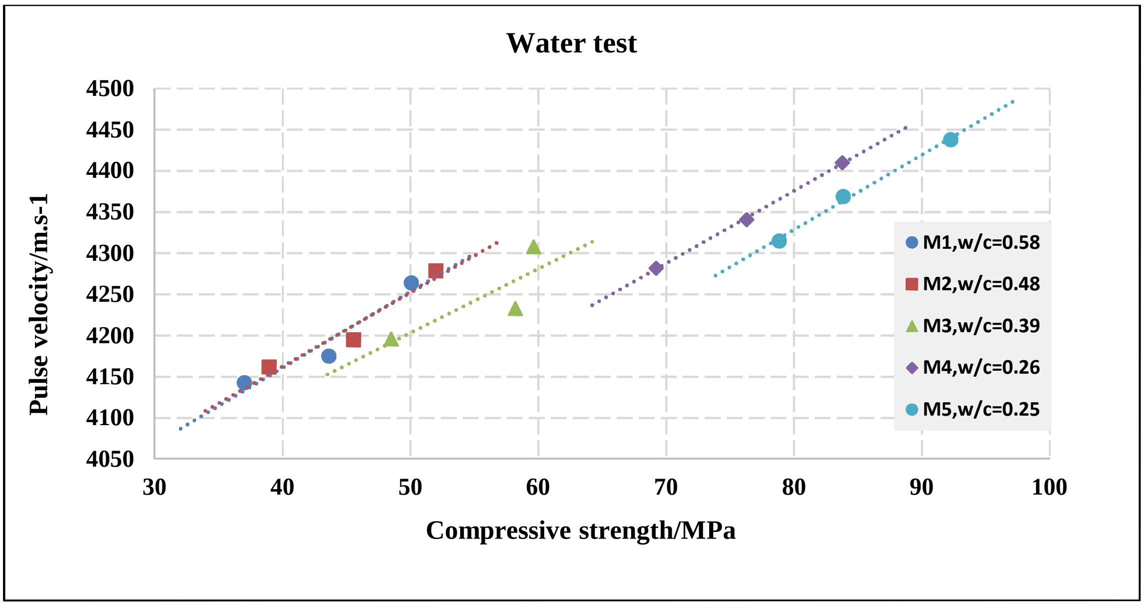


Figure 4-5 Pulse velocity vs compressive strength of the water test for mixes with different compressive strength level and constant aggregate content

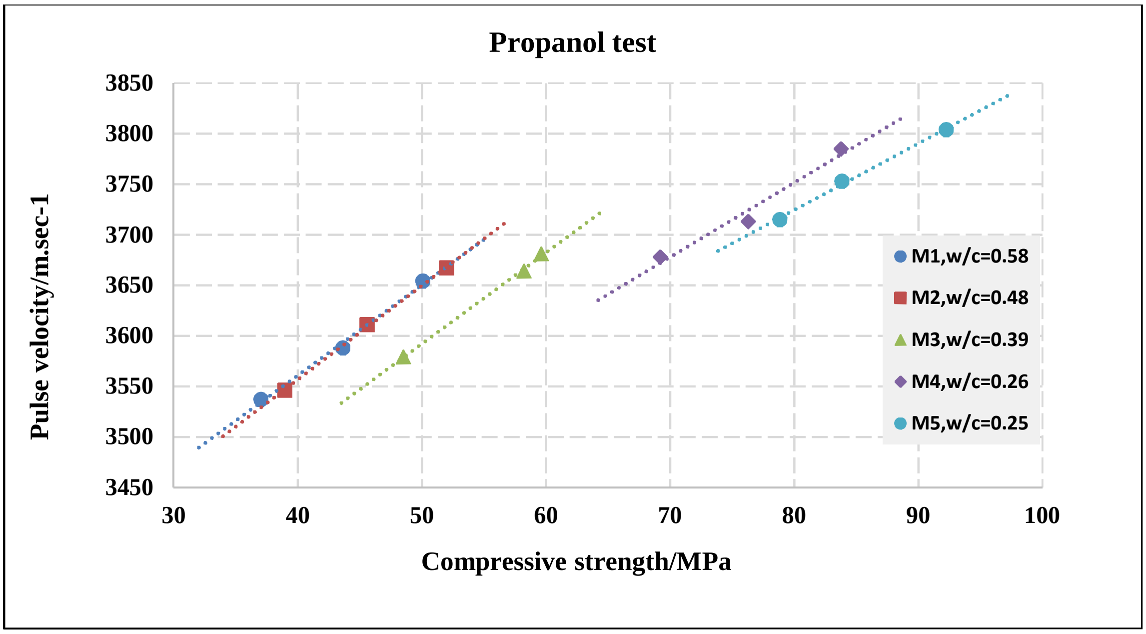


Figure 4-6 Pulse velocity vs compressive strength of the propanol test for mixes with different compressive strength level and constant aggregate content

4.6 Two-way ANOVA

This test was conducted to examine the joint effect of the coupling materials and the compressive strength on the measurements of the pulse velocity i.e. if there is any interaction between effects of the two variables. According to the outputs of two-way ANOVA test, there was the homogeneity of variances as assessed by Levene's test at the 5% level of significance as shown in Table (4-7).

The two-way ANOVA showed that there is no interaction effect between the coupling materials and the level of compressive strength which means the effect of coupling materials on the pulse velocity measurement is not depended on the level of compressive strength of the tested concrete. It also showed that there was a statistically significant difference in mean of the pulse velocity measurements among the groups of coupling materials and also among the groups of compressive strength levels at the 5% level of significance which presented in Table (4-8).

As the two-way ANOVA test was statistically significant a post hoc test was applied to test all possible combinations of pairwise comparison between the coupling material tests and the conventional test with the compressive strength levels at the 5% level of significance to determine if the effect of each coupling material is statistically significant at each level of the compressive strength. This pairwise comparison was done by carrying out simple main effects analysis using the Bonferroni adjustment as presented in Table (4-9). The results of this analysis showed that the at each compressive strength level, differences between coupling materials and the conventional measurements are statistically significant.

Table 4-7 Test of homogeneity of variances of the two way ANOVA for coupling tests with mixes of constant aggregate content and MAS of 20mm

	Test statistic	df1	df2	P-value
Levene test	2.525	19	292	0.000

Table 4-8 Two way ANOVA for coupling tests with mixes of constant aggregate content and MAS of 20mm

Source	Sum of Squares	df	Mean Square	F	P-value	Test significant
Corrected Model	73097302.228	19	3847226.433	874.401	0.000	sig.
Intercept	6012607638.703	1	6012607638.703	1366550.94	0.000	sig.
Compressive strength	1221924.216	4	305481.054	69.430	0.000	sig.
Coupling Material	71682630.224	3	23894210.075	5430.698	0.000	sig.
Compressive strength * Coupling Material	13765.841	12	1147.153	0.261	0.994	not Sig.
Error	1284753.739	292	4399.842			
Total	6108017578.323	312				.
Corrected Total	74382055.967	311				

Table 4-9 Bonferroni adjustment post hoc test of the two way ANOVA for coupling tests with mixes of constant aggregate content and MAS of 20mm

Compressive strength	(I) Coupling Material	(J) Coupling Material	Mean Difference (I-J)	Std. Error	P-value	Test significant
30 MPa	REF	RUB	126.926*	23.452	0.000	sig.
		WAT	630.184*	23.452	0.000	sig.
		PRO	1230.569*	23.452	0.000	sig.
	RUB	REF	-126.926*	23.452	0.000	sig.
		WAT	503.258*	23.452	0.000	sig.
		PRO	1103.643*	23.452	0.000	sig.
	WAT	REF	-630.184*	23.452	0.000	sig.
		RUB	-503.258*	23.452	0.000	sig.
		PRO	600.384*	23.452	0.000	sig.
	PRO	REF	-1230.569*	23.452	0.000	sig.
		RUB	-1103.643*	23.452	0.000	sig.
		WAT	-600.384*	23.452	0.000	sig.

40 MPa	REF	RUB	127.972*	25.071	0.000	sig.
		WAT	624.791*	25.071	0.000	sig.
		PRO	1228.536*	25.071	0.000	sig.
	RUB	REF	-127.972*	25.071	0.000	sig.
		WAT	496.819*	25.071	0.000	sig.
		PRO	1100.564*	25.071	0.000	sig.
	WAT	REF	-624.791*	25.071	0.000	sig.
		RUB	-496.819*	25.071	0.000	sig.
		PRO	603.744*	25.071	0.000	sig.
	PRO	REF	-1228.536*	25.071	0.000	sig.
		RUB	-1100.564*	25.071	0.000	sig.
		WAT	-603.744*	25.071	0.000	sig.
60 MPa	REF	RUB	123.759*	23.452	0.000	sig.
		WAT	617.609*	23.452	0.000	sig.
		PRO	1223.511*	23.452	0.000	sig.
	RUB	REF	-123.759*	23.452	0.000	sig.
		WAT	493.851*	23.452	0.000	sig.
		PRO	1099.752*	23.452	0.000	sig.
	WAT	REF	-617.609*	23.452	0.000	sig.
		RUB	-493.851*	23.452	0.000	sig.
		PRO	605.901*	23.452	0.000	sig.
	PRO	REF	-1223.511*	23.452	0.000	sig.
		RUB	-1099.752*	23.452	0.000	sig.
		WAT	-605.901*	23.452	0.000	sig.
80 MPa	REF	RUB	121.888*	23.452	0.000	sig.
		WAT	593.369*	23.452	0.000	sig.
		PRO	1211.984*	23.452	0.000	sig.
	RUB	REF	-121.888*	23.452	0.000	sig.
		WAT	471.481*	23.452	0.000	sig.
		PRO	1090.097*	23.452	0.000	sig.
	WAT	REF	-593.369*	23.452	0.000	sig.
		RUB	-471.481*	23.452	0.000	sig.
		PRO	618.616*	23.452	0.000	sig.
	PRO	REF	-1211.984*	23.452	0.000	sig.
		RUB	-1090.097*	23.452	0.000	sig.
		WAT	-618.616*	23.452	0.000	sig.
100 MPa	REF	RUB	128.859*	23.452	0.000	sig.
		WAT	592.159*	23.452	0.000	sig.
		PRO	1209.712*	23.452	0.000	sig.
	RUB	REF	-128.859*	23.452	0.000	sig.

		WAT	463.299*	23.452	0.000	sig.
		PRO	1080.853*	23.452	0.000	sig.
	WAT	REF	-592.159*	23.452	0.000	sig.
		RUB	-463.299*	23.452	0.000	sig.
		PRO	617.553*	23.452	0.000	sig.
	PRO	REF	-1209.712*	23.452	0.000	sig.
		RUB	-1080.853*	23.452	0.000	sig.
		WAT	-617.553*	23.452	0.000	sig.

4.7 Conclusions

It has been shown that the coupling tests return different measurements for the pulse velocity of the concrete from that of the conventional test. It is thought that these differences due to a preferential coupling occur between the ultrasound wave and the constituent materials of the concrete. The measurements that recorded for the liquid coupling tests were lower than that of the solids coupling. All the coupling materials return lower values for the pulse velocity than that of the conventional test, except the carbon fibre. The relationship between the pulse velocity and the compressive strength was approximately linear for both the coupled and uncoupled systems, with similar slope but significant offset. It has also shown that the differences in pulse velocity measurements between the coupled system and the uncoupled system are statistically significant, except the Perspex. The comparison between the liquids couplant revealed that there was no significant difference in measurement of the water and oil. Further experimental work is conducted to investigate the phenomena described here and it will continue with rubber, water and propanol couplants.

Chapter 5 Effect of Aggregate Content and Maximum Size on the Pulse Velocity of Concrete

5.1 Introduction

The previous chapter outlined the hypothesis that a coupling effect could occur between the ultrasound wave and the constituent materials of the concrete. Where different coupling media of varying acoustic impedance are used to investigate the coupling effect. The coupling tests return different measurements for the pulse velocity of the concrete from that of the conventional test, where the measured speed of sound depends on the couplant used. The relationship between the pulse velocity and the compressive strength was approximately linear for both the coupled and uncoupled systems, with similar slope but significant offset.

The wave velocity measurements in concrete are sensitive to many variables. These variables are including aggregate content and size, moisture content, mix proportions, thr age of concrete. To further ratify the preferential coupling hypothesis, effect of some variables on the measured pulse velocity, focussing on the effects of aggregate content and maximum size. The samples were tested by the coupling and the conventional systems.

5.2 Effect of coarse aggregate content variation

For the investigation of coarse aggregate content effect, set of three mixes were cast with varying coarse aggregate contents and constant w/c ratios of 0.5. The w/c ratio was kept constant and thus strength of the cement paste will be approximately constant over the same group mixes. Details of the mixes are listed in Table (3-7), M11, M12 and M13 and their coarse aggregate contents are 1063, 1260 and 720 kg/m^3 respectively. The samples were tested with both systems after 7, 28, and 90 days of curing. Figure 5-1 shows the relationship between the UPV and compressive strength for different coarse aggregate content and constant w/c ratio of 0.5 of the conventional test.

As can be observed, the UPV increased as the coarse aggregate content increased and mixes with larger and lower coarse aggregate contents recorded the highest and the lowest UPV values, M12 and M13 where the aggregate content are 1260 and 720 kg/m^3. Since the velocity of the ultrasonic wave in aggregate is higher than the cement paste, thus increasing aggregate content for a given cement paste content will increase the overall pulse velocity. Such trend was previously reported by (Lin et al., 1997) for high-performance concrete mixes with different coarse aggregate contents and a constant water/ binder ratio of 0.36. The results showed that strength- pulse velocity curve was slightly shifted up to the right as the coarse aggregate content increase, where the best-fit curve was plotted according to data of the mix who had the lowest aggregate content. (Trtnik et al., 2009) also showed that the UPV increased with increase in coarse aggregate content, at the same strength level the highest UPV was recorded for the mix with highest coarse aggregate content.

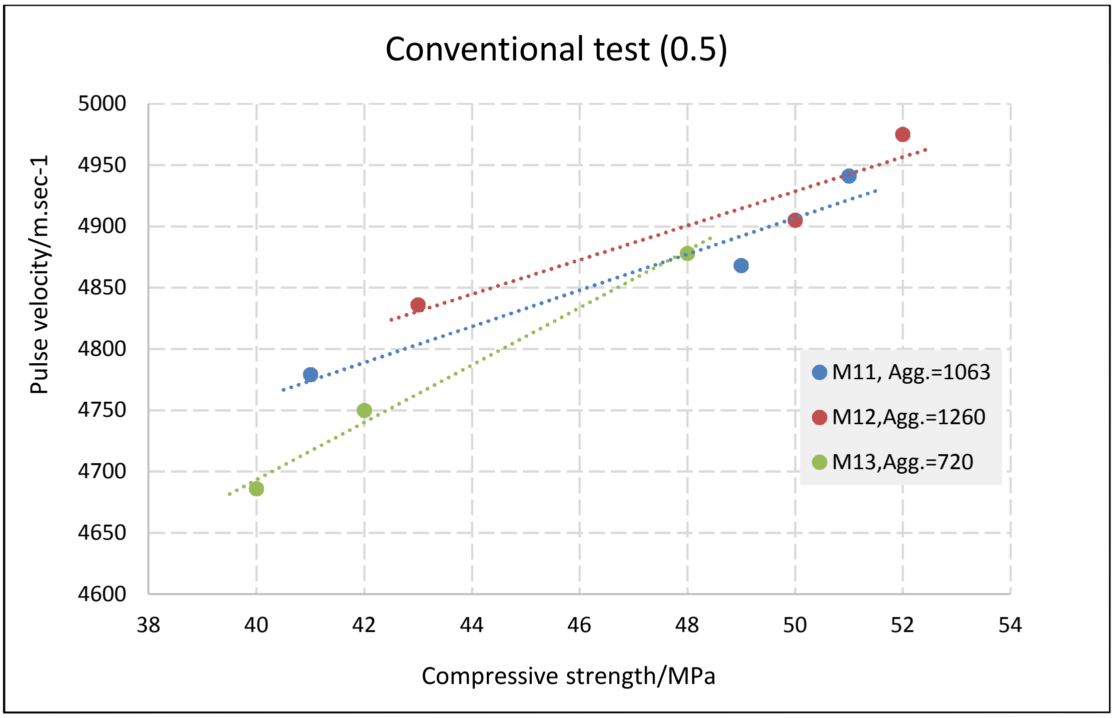


Figure 5-1 Pulse velocity vs compressive strength of the conventional test for different coarse aggregate content and a constant w/c of 0.5

Coupling tests of pulse velocity also are affected by the change of the coarse aggregate content, the measured values increased with the increase of coarse aggregate content. Figures 5-2, 5-3 and 5-4 show the relationship between the UPV and compressive strength of the coupling materials for different coarse aggregate content mixes and constant w/c of 0.5. As the conventional test, the curves of the three coarse aggregate contents are almost parallel. The measured UPV was depended on the couplant used. For the rubber couplant test, there was no discernible difference from UPV measurements of the conventional tests. It almost returned the same mean differences for UPV between the mixes of the different aggregate content. The mean difference between M12 and M13 was 127 m/sec for the conventional test and the rubber test returned 115 m/sec for the same mixes.

Comparison to the conventional test measurements, the liquid couplant tests returned lower values of the UPV for the same mixes. The difference was clearly recognisable, the average of UPV recorded by the propanol test were 3868, 3938 and 3824 m/sec for mixes M11, M12 and M13 respectively. While the average UPV of the conventional test were 4862, 4905 and 4771 m/sec for mixes M11, M12 and M13 respectively. A strong positive linear correlation between aggregate content and pulse velocity was observed by (Berriman et al., 2005), they used in their investigation two testing systems; traditional ultrasonic equipment (PUNDIT) as contact system and air-coupled ultrasonic equipment as a non-contact system. However, the contact system gave high values for the pulse velocity and a strong dependence on the aggregate content than the non-contact system. The researchers hypothesised that this discrepancy was due to the effect of preferential coupling between the ultrasound wave and the constituent materials of concrete.

The results of these experiments also showed differences in UPV measurements between the conventional test and the coupling tests, where the coupling system returned lower values, which is in accordance with the results obtained in chapter 4. It is thought these differences can confirm the original hypothesis of preferential coupling that occurs between the ultrasound wave and the constituent materials of concrete. When the liquid couplants are used, the acoustic energy would initially transmit to the cement paste returning lower values for the pulse velocity. Conversely, with the rubber couplant, it is assumed that the acoustic energy would couple into the aggregate initially and hence returning a closer measured value of the pulse velocity to that of the conventional test. Thus for these experiments, it was reasonable to presume that the liquid couplant tests will not be affected by the change of the aggregate content while the rubber test and the conventional test will be sensitive to that change. To determine if the differences between UPV measurements of mixes with different coarse aggregate contents and constant w/c are statistically significant, one-way ANOVA was applied for the UPV measurements of these mixes for each of the conventional test and the coupling tests.

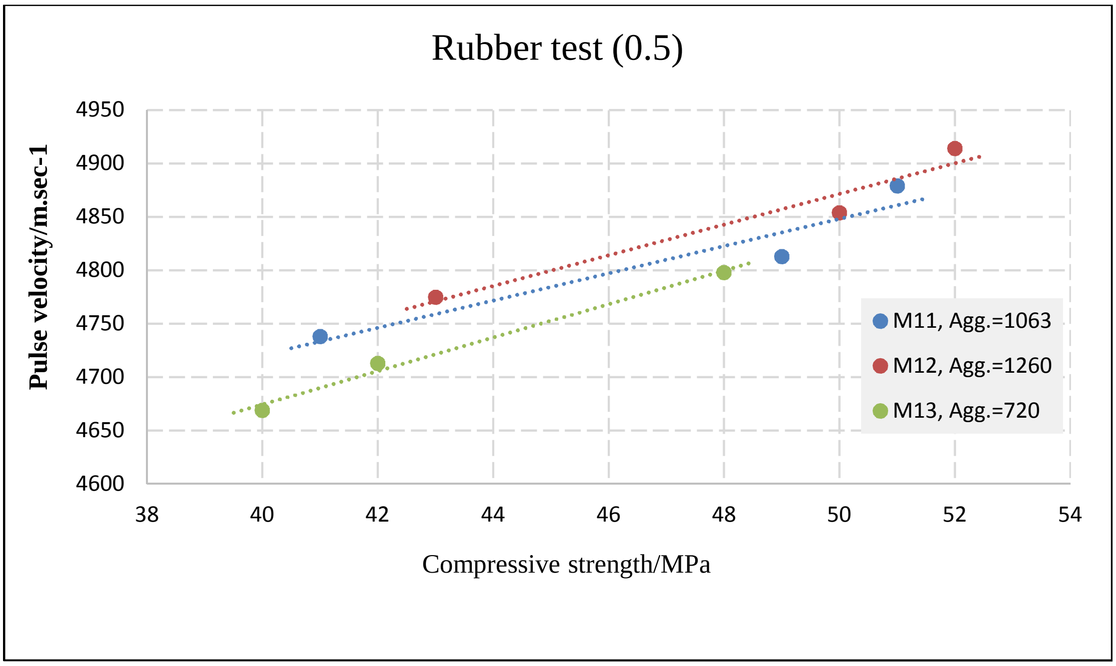


Figure 5-2 Pulse velocity vs compressive strength of the rubber test for different coarse aggregate content and a constant w/c of 0.5

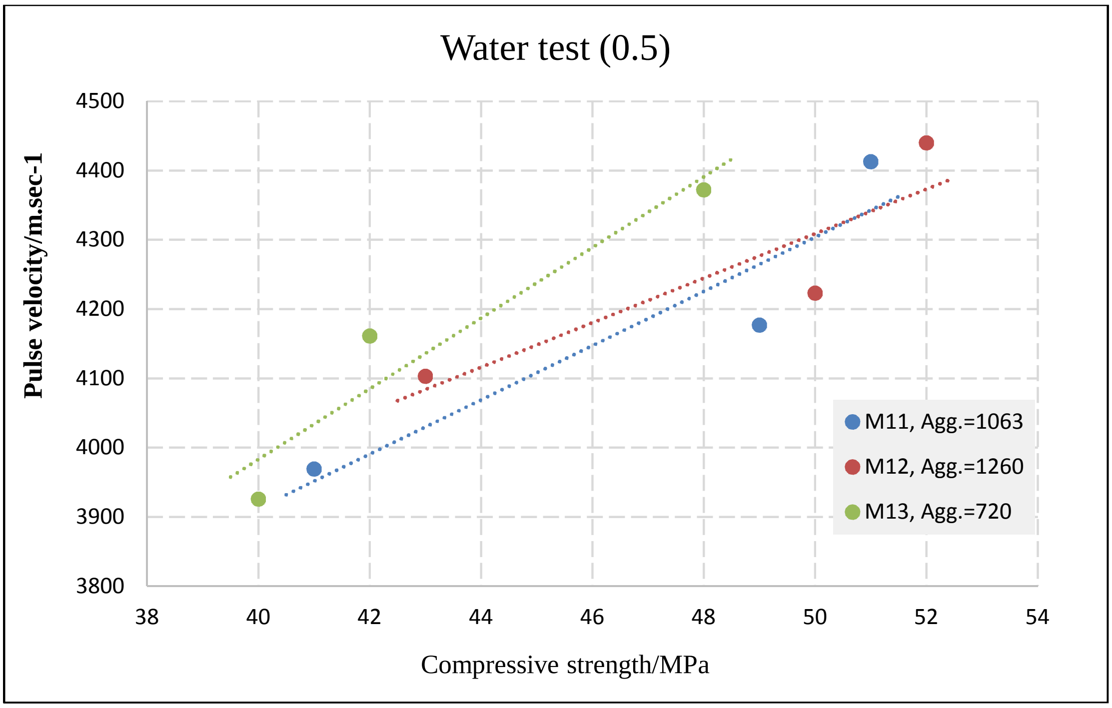


Figure 5-3 Pulse velocity vs compressive strength of the water test for different coarse aggregate content and a constant w/c of 0.5

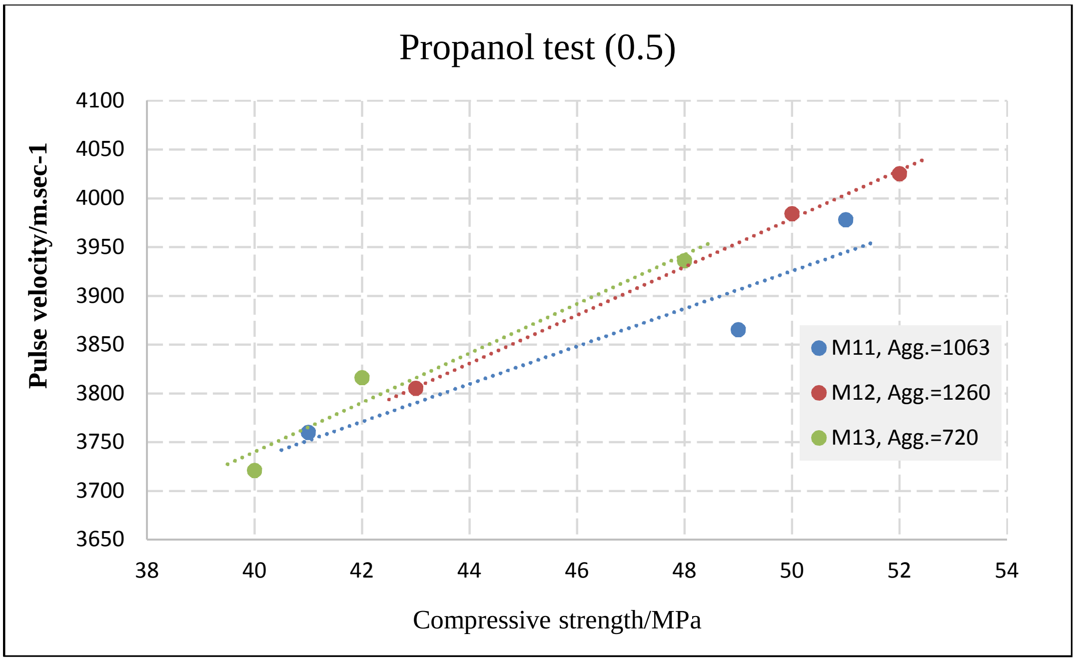


Figure 5-4 Pulse velocity vs compressive strength of the propanol test for different coarse aggregate content and a constant w/c of 0.5

5.3 ANOVA test

The one-way ANOVA test was conducted to determine if the differences in the UPV measurements due to change the coarse aggregate content of mixes with constant w/c are statistically significant for each of the conventional test and the coupling tests. It tests the null hypothesis which stated there are no differences between the means of the pulse velocity measurements of mixes with different coarse aggregate contents. The alternative hypothesis stated that at least one mix has a different mean from that of the other mixes.

The one-way ANOVA was conducted separately for each of the conventional test and coupling tests. The test assumptions: independence of the measurements, normality distribution of the measurements and homogeneity of variance among the groups of the measurements were checked for each ANOVA test. The results of one-way ANOVA for the conventional and rubber tests were significant while for the liquid couplants tests were not significant. As the ANOVA tests of the conventional and rubber couplants were statistically significant it can be concluded that at least one mix of the three mixes has different mean measurements from the other mixes. To determine which mix or mixes are/are different, the Games-Howell post hoc test was used to test the significance of the mean differences of all possible combinations of pairwise comparison between the mixes at the 5% level of significance.

The results of pairwise comparisons for mixes with different coarse aggregate contents and a constant w/c of the conventional and rubber measurements showed that when the aggregate content change from 720 to 1063 kg/m^3 the differences in mean measurements were statistically significant but when the coarse aggregate content change from 1063 to 1260 comparisons of the difference in mean measurements were statistically found not significant.

As mentioned above with the liquid couplants, the differences in the measurements of the mixes due to a change in the coarse aggregate content were found statistically not significant. Thus, it can be concluded the pulse velocity measurements were not sensitive to the change of the coarse aggregate content when the liquid couplant are used. The results of the one way ANOVA are presented in Tables (5-1) to (5-7).

In order to verify that behaviour another set of three mixes was cast with different coarse aggregate contents but with lower w/c ratio of 0.36. The aggregate contents were 626, 950 and 1095 kg/m^3 as shown in Table (3-7).The mixes showed a similar behaviour to that of mixes with w/c ratio of 0.5, the UPV increased as the aggregate content increased and the highest values were recorded by the mix with the highest aggregate content of 1095 kg/m^3. Generally, the couplants returned lower values for UPV than that of the conventional test and the lowest discrepancy was recorded by the rubber test. When the aggregate content change from 626 to 950 kg/m^3, the mean differences between the UPV measurements of conventional and rubber tests were found significant while for the liquid couplants, they were found not significant as assessed by the one-way ANOVA and post-hoc tests. As the aggregate content changed from 950 to 1095 kg/m^3, the means differences between the UPV measurements of the conventional test were not significant as well as for the couplant tests with accordance to the results of the one-way ANOVA and post-hoc tests. The results of the one way ANOVA are presented in Tables (5-8) to (5-14).

Comparison between the measurements of M12 and M15 mixes which they have the highest aggregate contents of 1260 and 1095 kg/m^3 and w/c ratios of 0.5 and 0.36 respectively revealed that, there are two different behaviours: conventional and rubber tests recorded a higher UPV for M12 than for M15 i.e. higher UPV for the highest coarse aggregate content. Conversely, the liquids couplants recorded higher UPV for M15 than for M12 i.e. higher UPV for the lowest w/c ratio. It can be noted that the with the conventional and rubber tests, UPV is more sensitive to the aggregate phase and when the liquids couplants are used, UPV is more sensitive to the paste phase.

Lin et al. (2007) investigate the effect of mix proportion on the UPV and compressive strength of concrete. The concrete samples were assorted into three groups based on the coarse aggregate content (666, 915 and 1961 kg/m^3) and each group contained five mixes with w/c ratios of (0.3, 0.4, 0.5, 0.6 and

0.7). The results of the investigated mixes showed that for a specific w/c ratio, the effect of changes in aggregate content on the pulse velocity will depend if the concrete had a high or low w/c ratio. The UPV of concrete with a high w/c (0.7) was not significantly affected as the aggregate content changed while the UPV of the concrete having a low w/c (0.3) showed a noticeable increase as the aggregate content increased. It also revealed that for a given aggregate content, UPV and compressive strength of concrete increased as the w/c ratio decreased.

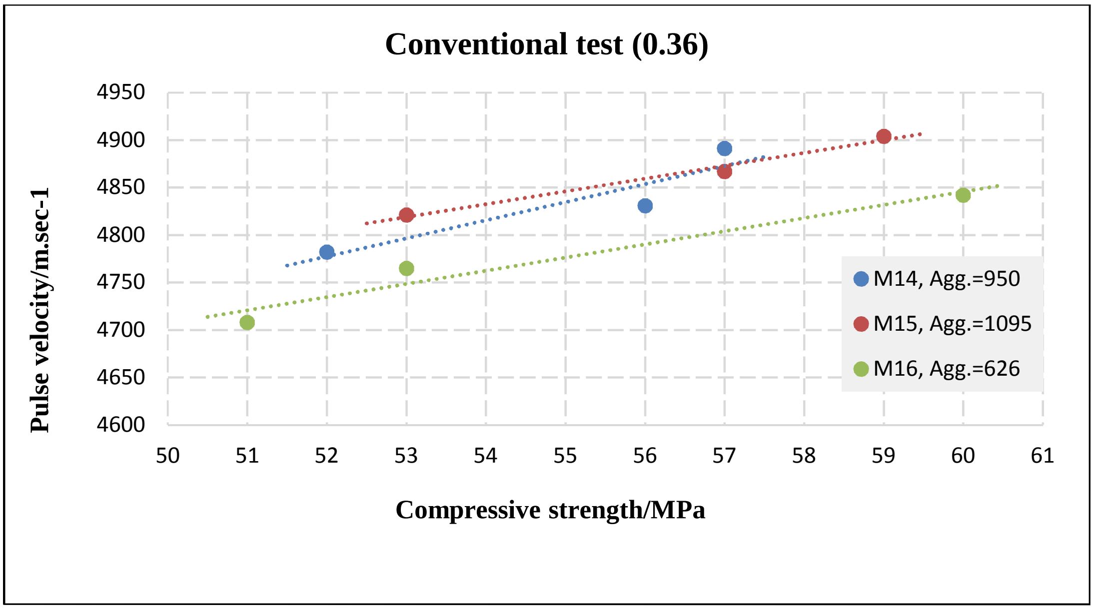


Figure 5-5 Pulse velocity vs compressive strength of the conventional test for different coarse aggregate content and a constant w/c of 0.36.

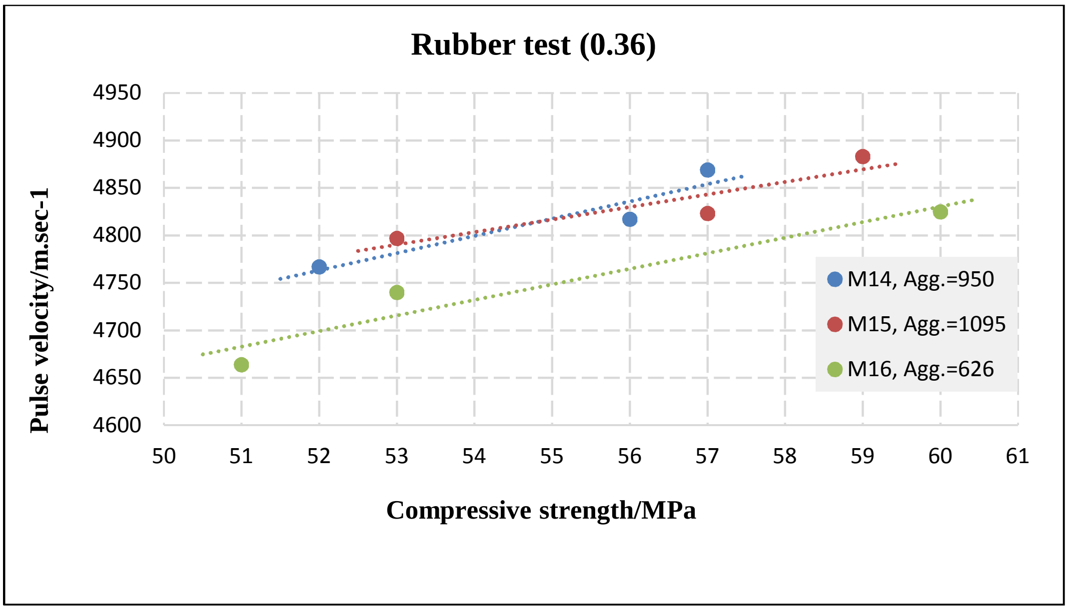


Figure 5-6 Pulse velocity vs compressive strength of the rubber test for different coarse aggregate content and a constant w/c of 0.36.

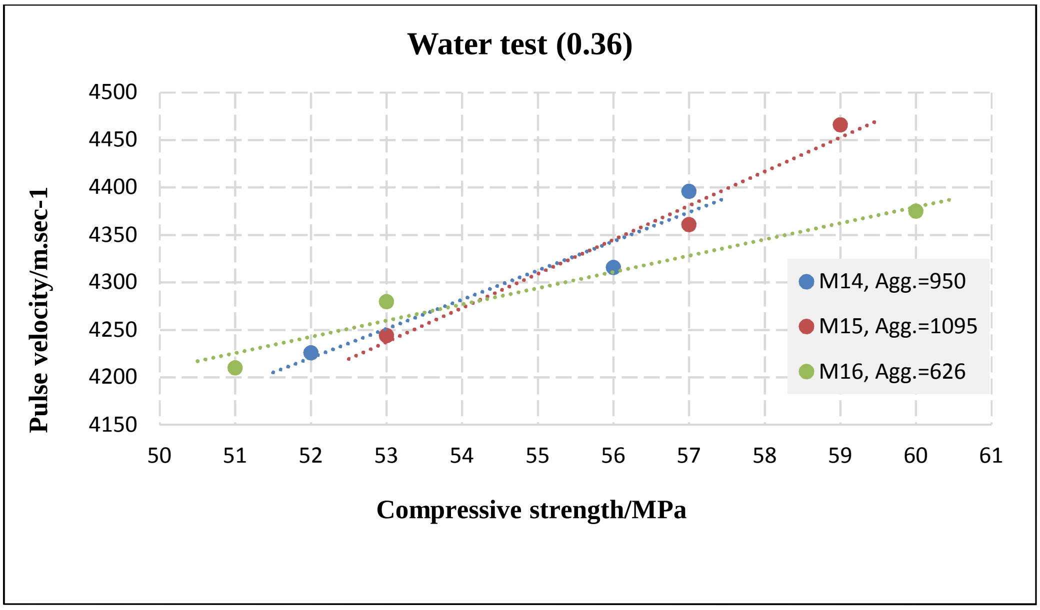


Figure 5-7 Pulse velocity vs compressive strength of the water test for different coarse aggregate content and a constant w/c of 0.36

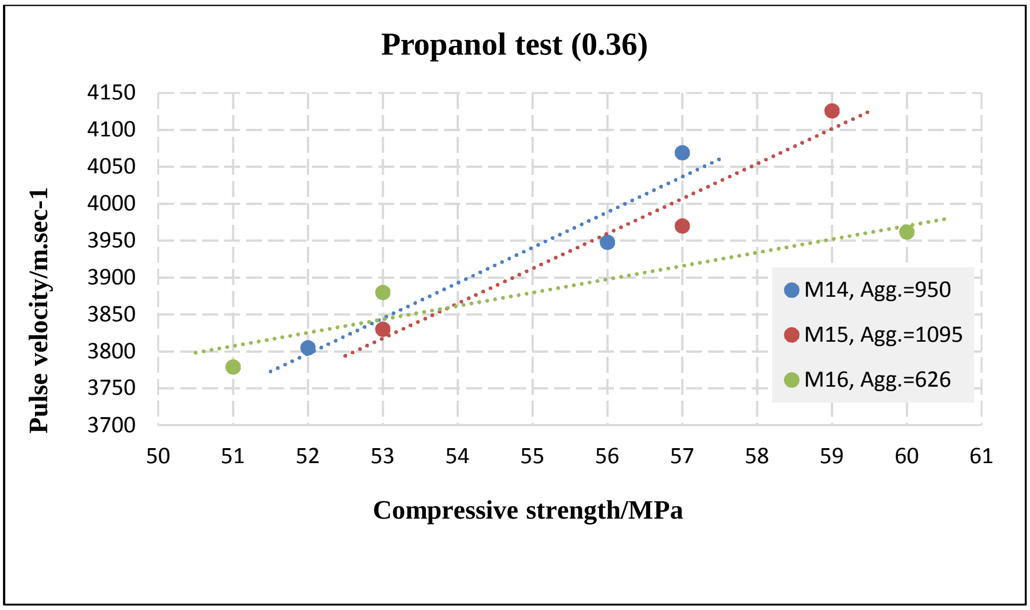


Figure 5-8 Pulse velocity vs compressive strength of the propanol test for different coarse aggregate content and a constant w/c of 0.36

Table 5-1 Second moment statistics of the one way ANOVA for the conventional tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Conventional M11	28	4865.4643	83.59137	15.79728	4833.0509	4897.8776
Conventional M12	27	4905.1481	70.88816	13.64243	4877.1057	4933.1906
Conventional M13	26	4777.6923	93.44250	18.32558	4739.9501	4815.4346
Total	81	4850.5185	97.61738	10.84638	4828.9335	4872.1035

Table 5-2 Second moment statistics of the one way ANOVA for the rubber tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Rubber M11	26	4809.7692	84.80769	16.63216	4775.5147	4844.0238
Rubber M12	22	4841.7273	93.26214	19.88356	4800.3772	4883.0774
Rubber M13	24	4726.2500	133.84067	27.32011	4669.7340	4782.7660
Total	72	4791.6944	115.11337	13.56624	4764.6441	4818.7448

Table 5-3 Second moment statistics of the one way ANOVA for the water tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Water M11	21	4196.1429	252.46590	55.09258	4081.2218	4311.0640
Water M12	25	4262.5600	252.16349	50.43270	4158.4720	4366.6480
Water M13	23	4163.0000	268.14294	55.91167	4047.0463	4278.9537
Total	69	4209.1594	257.43426	30.99144	4147.3170	4271.0019

Table 5-4 Second moment statistics of the one way ANOVA for the propanol tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Propanol M11	26	3840.1538	159.56834	31.29393	3775.7028	3904.6049
Propanol M12	24	3930.8750	158.44744	32.34295	3863.9685	3997.7815
Propanol M13	23	3824.6087	179.19257	37.36423	3747.1200	3902.0974
Total	73	3865.0822	169.89055	19.88418	3825.4438	3904.7206

Table 5-5 Test of homogeneity of variance of the one way ANOVA for the coupling tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

	Levene Statistic	df1	df2	P-value
Conventional	1.549	2	78	0.219
Rubber	0.492	2	69	0.613
Water	0.185	2	66	0.831
Propanol	0.351	2	70	0.705

Table 5-6 One way ANOVA for the coupling tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

Welch	Statistic	df1	df2	P-value	Test significant
Conventional	15.406	2	51.041	0.000	sig.
Rubber	5.812	2	43.812	0.006	sig
Water	0.913	2	43.434	0.409	not sig
Propanol	2.917	2	45.974	0.064	not sig

Table 5-7 Games-Howell post hoc test of the one way ANOVA for the conventional and rubber tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.5

Coupling Material	Mix (I)	mix(J)	Mean Difference (I-J)	Std. Error	P-value	Comparison results
Conventional	M11	M12	-39.68386	20.87271	0.148	not sig.
		M13	87.77198*	24.19465	0.002	sig.
	M12	M11l	39.68386	20.87271	0.148	not sig.
		M13	127.45584*	22.84607	0.000	sig.
	M13	M11	-87.77198*	24.19465	0.002	not sig.
		M12	-127.45584*	22.84607	0.000	sig.
Rubber	M11	M12	-31.95804	25.92266	0.441	not sig.
		M13	83.51923*	31.98464	0.034	sig.
	M12	M11	31.95804	25.92266	0.441	not sig.
		M13	115.47727*	33.78971	0.004	sig.
	M13	M11	-83.51923*	31.98464	0.034	not sig.
		M12	-115.47727*	33.78971	0.004	sig.

Table 5-8 Second moment statistics of the one way ANOVA for the conventional tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Conventional M14	18	4836.6744	74.66484	17.59867	4799.5445	4873.8044
Conventional M15	18	4862.1976	70.65479	16.65349	4827.0618	4897.3334
Conventional M16	16	4774.9879	85.72519	21.43130	4729.3082	4820.6676
Total	52	4826.5289	83.68088	11.60445	4803.2320	4849.8258

Table 5-9 Second moment statistics of the one way ANOVA for the rubber tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Rubber M14	16	4818.3129	156.06230	39.01557	4735.1532	4901.4726
Rubber M15	16	4840.1110	75.23981	18.80995	4800.0185	4880.2034
Rubber M16	16	4744.5372	112.41005	28.10251	4684.6381	4804.4362
Total	48	4800.9870	123.77628	17.86557	4765.0461	4836.9279

Table 5-10 Second moment statistics of the one way ANOVA for the water tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Water M14	18	4311.1870	172.80440	40.73039	4225.2534	4397.1206
Water M15	18	4354.9474	183.26458	43.19588	4263.8121	4446.0828
Water M16	16	4292.4559	184.20196	46.05049	4194.3016	4390.6102
Total	52	4320.5714	178.39495	24.73893	4270.9059	4370.2369

Table 5-11 Second moment statistics of the one way ANOVA for the propanol tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Propanol M14	16	3937.2824	154.91171	38.72793	3854.7358	4019.8290
Propanol M15	16	3977.9862	220.31829	55.07957	3860.5869	4095.3855
Propanol M16	16	3870.6089	130.87805	32.71951	3800.8689	3940.3489
Total	48	3928.6259	174.97965	25.25614	3877.8171	3979.4346

Table 5-12 Test of homogeneity of variance One way ANOVA for the coupling tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

	Levene Statistic	df1	df2	P-value
Conventional	0.749	2	49	0.478
Rubber	1.064	2	45	0.354
Water	0.020	2	49	0.980
Propanol	0.601	2	45	0.553

Table 5-13 One way ANOVA for the coupling tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

Welch	Statistic	df1	df2	P-value	Test significant
Conventional	5.111	2	31.846	0.012	sig.
Rubber	3.917	2	27.694	0.032	sig
Water	0.519	2	32.304	0.600	not sig
Propanol	1.692	2	28.932	0.202	not sig

Table 5-14 Games-Howell post hoc test of the one way ANOVA for the conventional and rubber tests with mixes of different aggregate content and MAS of 20mm and w/c of 0.36

Coupling Material	Mix (I)	mix(J)	Mean Difference (I-J)	Std. Error	P-value	Comparison results
Conventional	M14	M15	-25.52315	24.22916	0.549	not sig.
		M16	61.68653	27.73110	0.083	sig.
	M15	M14	25.52315	24.22916	0.549	not sig.
		M16	87.20968*	27.14110	0.009	sig.
	M16	M14	-61.68653	27.73110	0.083	not sig.
		M15	-87.20968*	27.14110	0.009	sig.
Rubber	M14	M15	-21.79806	43.31315	0.871	not sig.
		M16	73.77575	48.08291	0.291	sig.
	M15	M14	21.79806	43.31315	0.871	not sig.
		M16	95.57381*	33.81665	0.023	sig.
	M16	M14	-73.77575	48.08291	0.291	not sig.
		M15	-95.57381*	33.81665	0.023	sig.

5.4 Effect of maximum size of aggregate

To investigate the effect of aggregate maximum size (MAS), another set of five mixes (M6-M10) of concrete test prisms were cast using coarse aggregate with MAS of 10mm and constant content as the same as that of mixes with MAS of 20mm (M1-M5) as listed in Table (3-7). Figure 5-9 showed the relationship between the pulse velocity and the corresponding compressive strength for the conventional test and coupling tests for these mixes. As can be observed, these mixes also returned an approximately linear relationship for the conventional test as well as the coupling tests but with greater $\Delta c/\Delta S$ of about 7 m/Mpa.sec comparing to that of mixes with MAS of 20mm ($\Delta c/\Delta S$ about 4 m/Mpa.sec). The coupling tests returned similar values for $\Delta c/\Delta S$; i.e., the c/S lines are simply "shifted down vertically" with respect to that of the conventional test.

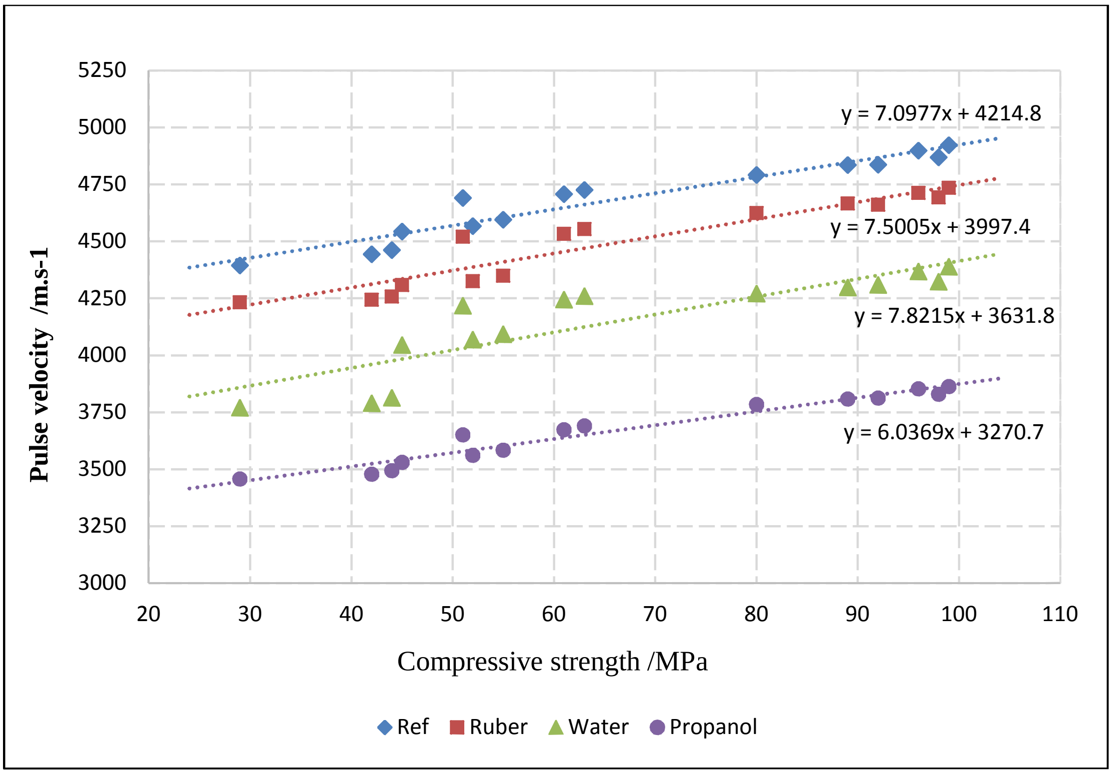


Figure 5-9 Pulse velocity vs compressive strength: conventional test, rubber, water and propanol tests

To have a clear comparison between mixes of the two MAS (10 and 20mm), UPV measurements have been plotted against compressive strength for each of the conventional test and coupling tests, the measurements were taken at age of 7, 28 and 90 days as shown in Figures 5-10 through 5-13. Generally, mixes with MAS of 10mm returned lower values for the pulse velocity than that of mixes with MAS of 20mm at all compressive strength levels. The difference in UPV measurements between the normal strength groups (≤ 60 MPa) and the high strength groups (> 60 MPa) was larger in mixes with MAS of 10mm.

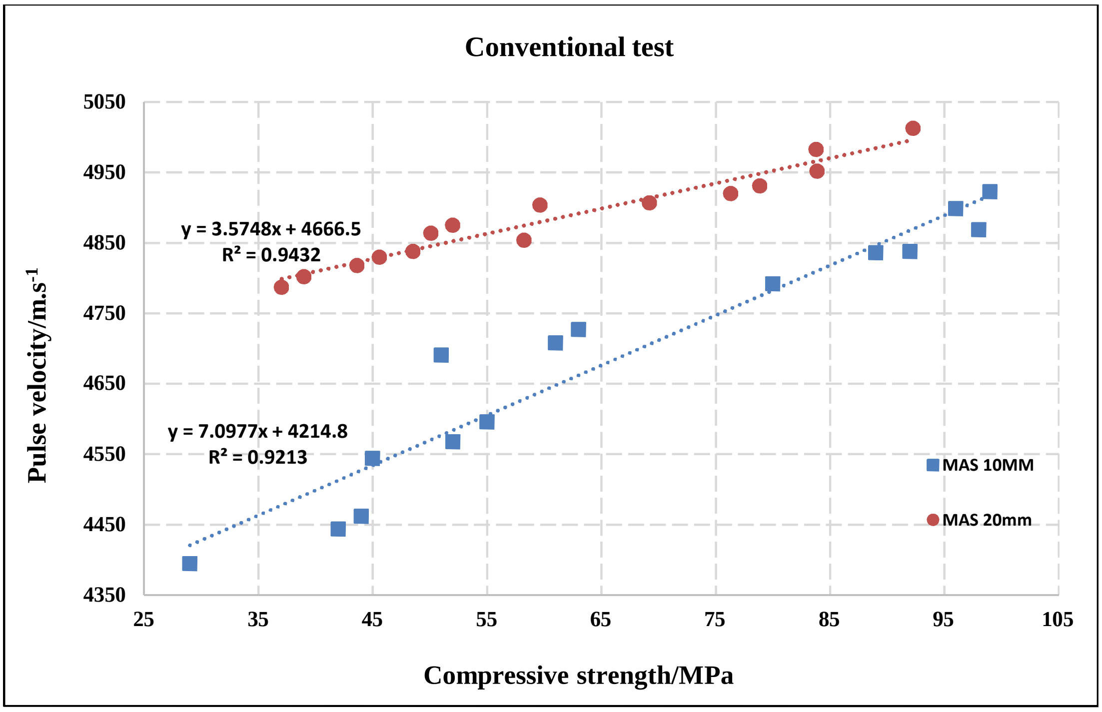


Figure 5-10 Pulse velocity vs compressive strength of the conventional test for mixes with MAS 10 and 20mm.

From the conventional test results, it can be clearly seen that mixes with MAS of 10mm returned much lower values for UPV than those with MAS of 20mm and the effect of MAS on the UPV was more noticeable in mixes with compressive strength (≤ 60MPa) than high compressive strength. The difference in average means of UPV between the two sizes was 271 m/sec for normal group strength and 91.5 m/sec for high strength group.

This behaviour is consistent with what was found by (Mohammed and Mahmood, 2016) for the brick aggregate concrete that made with a variation of MAS (12.5, 19, 25, 37.5 and 50 mm) and w/c ratio of (0.45, 0.5 and 0.55), that the UPV increased with an increase of the maximum size of coarse aggregate. They demonstrated that at a given aggregate content with smaller MAS, the propagating wave will need to across larger number of aggregate particles through its way from the transmitter to receiver transducers which means more transition zones comparing to greater MAS resulting an increase the transit time of the wave. They also proposed two sets of simulation curves for the UPV-strength relationship and of UPV- Young's modulus relationship for the concrete mixes with different MAS of brick aggregate, the MAS was treated as the main dominant factor governing this relationship.

A contrary behaviour was reported by (Abo-Qudais, 2005); the UPV decreased as the MAS of aggregate was increased and the magnitude of reduction was depended on the w/c ratio of the mix, the effect was more clearly with higher w/c ratio. He pointed out that the reduction in UVP could be attributed to weaker transition zone caused by using larger coarse aggregate, for the same w/c ratio, concrete with larger MAS will consume less mixing water leaving more amount in the transition zone which will lead to forming more capillary voids and microcracks. The tested samples were combination for each MAS (4.75, 12.5, 19.3 and 25mm) with w/c ratio of (0.4, .0.45, 0.5 and 0.55).

For the coupling tests, it seems the UPV measurements is more affected by the couplant used than the change in MAS of the mix. Rubber couplant has roughly the same trend as the conventional test, the UPV increased with an increase in MAS; the differences in UPV measurements due to a change in MAS were greater in low strength concrete (≤60 MPa), as the compressive strength increases the difference become smaller. However, UPV measurements of the concrete mixes were lower than of the conventional test for both MAS sizes.

Water couplant test showed that at high strength concretes both MAS mixes returned approximately similar values for UPV but returned different values for low strength concrete. For the high strength group, the average means of UPV measurements of both sizes ranged between 4327 and 4359 m/sec. while for the normal strength group, the average means of UPV measurements of both sizes varied between 4034 and 4217 m/sec.

The propanol test showed that mixes of both MAS sizes recorded approximately similar values for the UPV at all compressive strength levels; the plotted points of UPV measurements for both MAS sizes clustered very closely from each other showing that the measurements were not so sensitive to the change in MAS of aggregate. The UPV measurements of mixes with MAS of 20mm ranged between 3537 to 3885 m/sec. while mixes with MAS of 10 mm the UPV recorded varied between 3458 and 3863 m/sec.

To investigate if the differences between the measurements of mixes of the two MAS (10 and 20mm) are really significant, a t-test was performed for each of the conventional and the coupling tests.

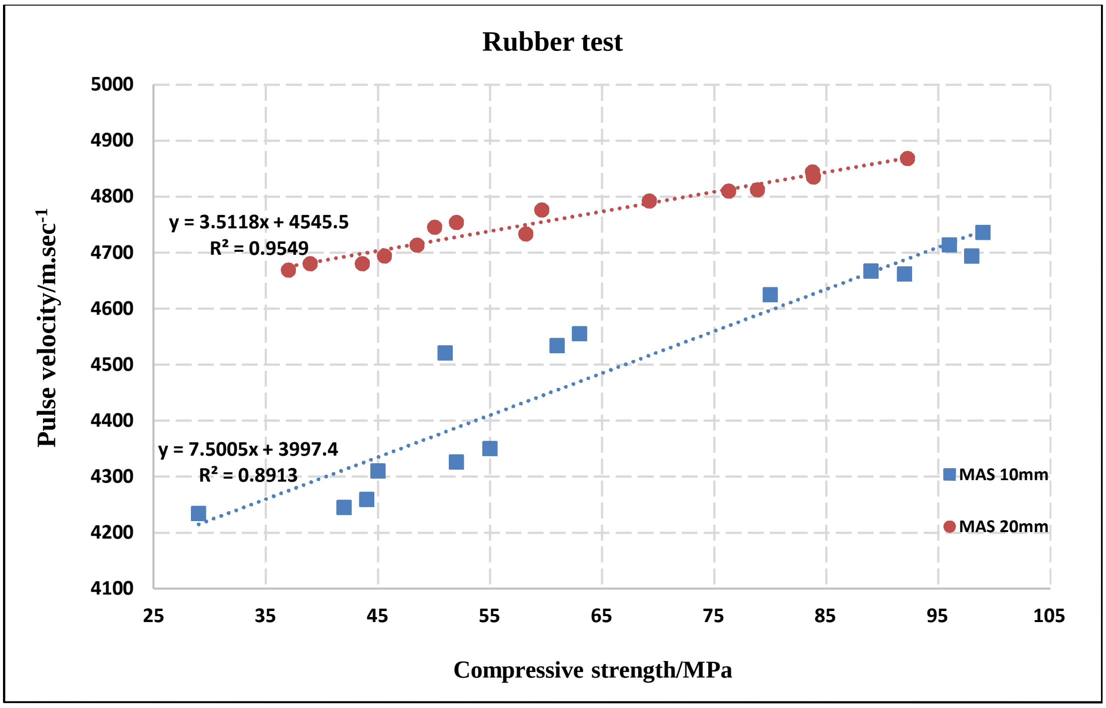


Figure 5-11 Pulse velocity vs compressive strength of the rubber test for mixes with MAS 10 and 20mm.

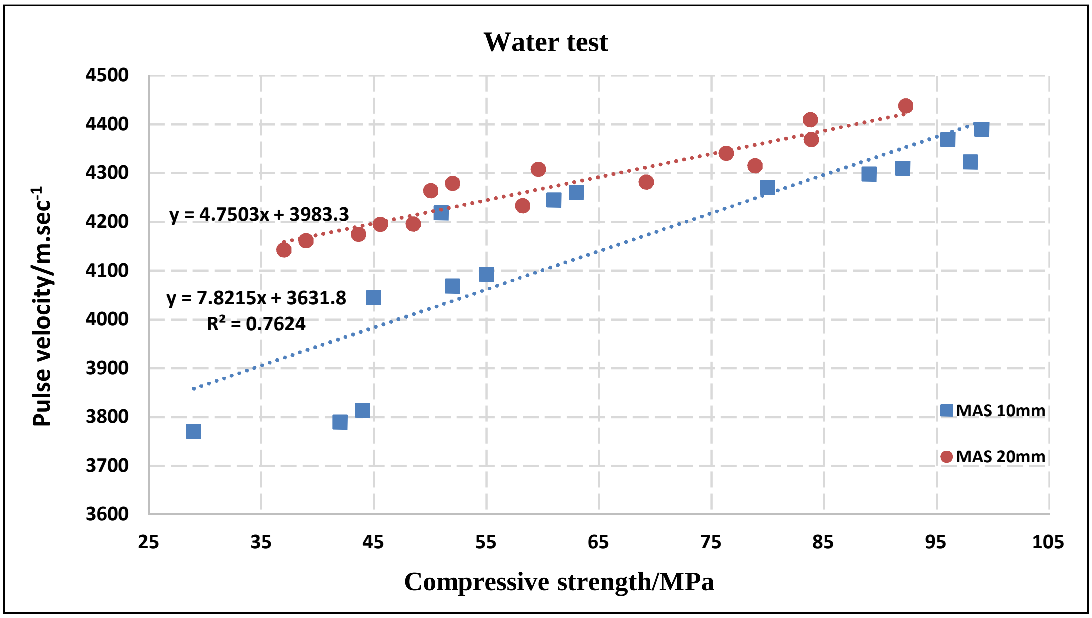


Figure 5-12 Pulse velocity vs compressive strength of the water test for mixes with MAS 10 and 20mm.

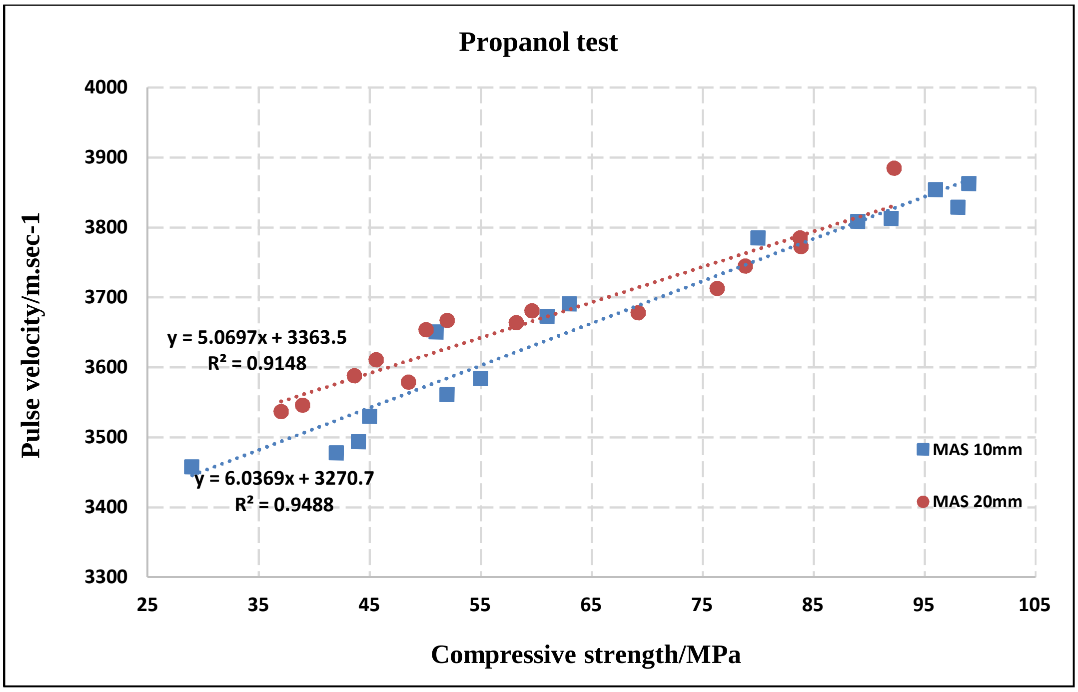


Figure 5-13 Pulse velocity vs compressive strength of the propanol test for mixes with MAS 10 and 20mm.

5.5 t- Test

The t-test was performed to compare the measurements of mixes with MAS of 20mm and 10mm and different strength levels. The test was applied for each of the conventional test and the coupling materials. The test results were significant for the conventional and rubber tests at each strength level, where the mean difference was decreased as the level of the compressive strength increased. For the water test, there are two different results regarding the compressive strength level. For normal strength group (≤ 60 MPa), the differences between the means of measurements were significant while for high strength group (>60 MPa) were found not significant. For the propanol test, at each compressive level, the comparison between the means of measurements was found not significant. Results of the t-test are presented in Tables (5-15) to (5-20).

The difference in the degree of influence of aggregate MAS on the pulse velocity measurements between normal and high strength concrete mixes with a specific aggregate content can be explained that the smaller MAS the larger surface area of aggregate and consequently more interfacial transition zones between the cement paste and aggregate. As the transition zone is the weakest phase in concrete, i.e. containing higher capillary voids and microcracks comparing to cement paste, resulting in an increase in the flight time of the crossed pulse through the concrete and thus, lower UPV will be recorded. At high strength concretes the MAS of aggregate has a less noticeable effect on UPV compared to concretes with a compressive strength of (≤ 60MPa), this could be attributed to the significant improvements in the structures of cement paste and the transition zones which accompanied with low w/c ratio. As a result, the pulse velocity will not be so sensitive to the changes in MAS of aggregate.

In the coupling tests, it seems the UPV measurements are more affected by the couplant used than the change in MAS of the mix. This behaviour may confirm the original hypothesis of preferential coupling (Purnell et al., 2004), between the ultrasound wave and the constituent materials of concrete on two counts. Firstly, the coupling tests return a lower value for the pulse velocity than the conventional test. Secondly, the measured value of the pulse velocity is depended on the couplant used; the rubber couplant recorded a closer value of the measured pulse velocity to that the conventional test in both MAS mixes as it assumed the acoustic energy would couple into the aggregate initially and thus will be very sensitive to the change in MAS of aggregate. Conversely, when the liquid couplants are used, the acoustic coupling would initially transmit to the cement paste and thus the measurements were not significantly affected by the change in MAS of aggregate.

In terms of theoretical consideration, the velocity of a wave propagating through a solid medium is a function of its density and elastic properties. Only an alteration in the properties of that medium will cause a change in the velocity. As the energy that imparted to the wave through the couplant layer is not affecting the wavelength or the frequency of the wave, it would be also expected that the velocity of the wave will not be changed it's only the amplitude of that wave will change depending on the type of couplant. However, when ultrasonic wave normally incident into the couplant layer from the transducer generates reflected wave and transmitted wave into that layer. The transmitted wave into the layer is reflected again at the rear interface between the couplant layer and the concrete and then transmitted into the concrete.

As the concrete is a composite material which consists of three different phases, the transmitted wave will subject again to reflection as it encounters with the boundaries between the different phases which they have different acoustic impedances causes reflection, refraction, attenuation, and mode conversion. It is most likely the longitudinal wave would subject to a mode conversion while propagating through concrete and that shear waves are expected to be generated within the sample. In general, the velocity of the shear wave through a solid medium is less than that of the longitudinal wave. Also, the scattering that the wave subject to it while propagating through the concrete will result in redirecting the wave energy to a new pattern of angles and a change in its direction away from the original wave pathway.

It is thus thought that the discrepancy in the pulse velocity measurements between the conventional test and coupling tests cannot be explained simply by preferential coupling as it was suggested by previous studies using 'non-contact' apparatus. It is thought these discrepancies could be explained by preferential mode conversion between compression and shear waves and/or attenuation. The combination of those processes will result in redirecting the wave energy to a new pattern of angles that differs from the initial direction and a change in the pathway of the wave and hence increase transit time corresponding to propagation distance.

Table 5-15 Second moment statistics of the t-test for the conventional test with mixes of constant aggregate content and MAS of 20 and 10mm

	N	Mean	Std. Deviation	Std. Error
Conventional 20mm	15	4885.2000	66.75135	17.23512
Conventional 10mm	15	4686.1333	175.18678	45.23303

Table 5-16 Second moment statistics of the t-test for the rubber test with mixes of constant aggregate content and MAS of 20 and 10mm

	N	Mean	Std. Deviation	Std. Error
Rubber 20mm	15	4760.3333	65.17193	16.82732
Rubber 10mm	15	4495.4667	188.21297	48.59638

Table 5-17 Second moment statistics of the t-test for the water test with mixes of constant aggregate content and MAS of 20 and 10mm

	N	Mean	Std. Deviation	Std. Error
Water 20mm	15	4274.0000	90.80749	23.44639
Water 10mm	15	4151.1333	212.21178	54.79285

Table 5-18 Second moment statistics of the t-test for the propanol test with mixes of constant aggregate content and MAS of 20 and 10mm

	N	Mean	Std. Deviation	Std. Error
Propanol 20mm	15	3665.0000	81.76884	21.11262
Propanol 10mm	15	3679.1333	158.14138	40.83193

Table 5-19 t-test for coupling tests with mixes of constant aggregate content and MAS of 20 and 10mm

	T Statistic	df1	P-value	Mean difference	Std. Error of difference	Test significant
Conventional	4.112	17.981	0.001	199.0666	48.40534	sig.
Rubber	5.150	17.310	0.000	264.866	51.427	sig
Water	2.062	18.961	0.053	122.8664	59.598	not sig
Propanol	-0.307	20.986	0.762	-14.1333	45.967	not sig

Table 5-20 t-test for coupling tests with mixes of constant aggregate content and MAS of 20 and 10mm at each strength level

	Target 28-day compressive strength	t Statistic	df1	P-value	Mean difference	Std. Error of difference	Test significant
conventional	30 MPa	11.198	17	0.000	278.998	24.915	sig.
	40 MPa	13.754	27	0.000	261.874	19.039	sig.
	60 MPa	22.0202	31	0.000	370.557	16.690	sig.
	80 MPa	9.0409	34	0.000	100.736	10.706	sig.
	100 MPa	9.846	33	0.000	89.980	9.229	sig.
Rubber	30 MPa	20.992	30	0.000	342.053	16.294	sig
	40 MPa	18.243	26	0.000	324.650	17.796	sig.
	60 MPa	21.221	29	0.000	348.469	16.421	sig.
	80 MPa	11.668	27	0.000	141.329	12.113	sig.
	100 MPa	12.417	29	0.000	141.334	11.299	sig.
Water	30 MPa	4.095	28	0.000	178.386	43.233	sig.
	40 MPa	3.584	31	0.000	155.820	43.505	sig.
	60 MPa	3.144	27	0.000	181.416	56.177	sig.
	80 MPa	0.758	26	0.458	33.082	43.665	not sig.
	100 MPa	0.623	25	0.539	28.899	46.391	not sig.
Propanol	30 MPa	1.934	29	0.71	39.287	20.689	not sig.
	40 MPa	2.513	22	0.108	38.777	23.606	not sig.
	60 MPa	1.973	15	0.055	67.368	34.142	not sig.
	80 MPa	1.533	23	0.088	98.951	12.344	not sig.
	100 MPa	1.902	27	0.065	33.512	17.620	not sig.

5.6 Conclusion

A number of concrete samples were cast, some of them prepared with different aggregate contents and constant w/c ratio and the other samples prepared with constant aggregate content and different maximum aggregate size. The pulse velocity therein measured using the conventional test and the coupling materials tests at age of 7, 28 and 90 days. It was shown that the coupling tests return lower values for the pulse velocity than that of the conventional test. For concrete with a specific w/c, the pulse velocity increased as the aggregate content increased. The conventional and rubber tests showed more sensitivity to the changes in aggregate content than the liquids tests. When the aggregate content is constant, concretes with larger MAS generally yielded higher pulse velocities than those with smaller MAS. It should also point out that, as the compressive strength increased the differences between pulses velocities of concretes with different MAS are decreased.

In the coupling tests, the UPV measurements were more affected by the couplant used than the change in MAS of the mix. While the rubber test showed significant differences between the measurements of the two MAS at each strength level, the propanol test recorded approximately similar values for both MAS at all compressive strength levels.

Concrete is considered as a composite material where large aggregate (5 to 30mm) are embedded in a mortar matrix, while the mortar consist of small aggregate (0.1 to 5mm) dispersed in a cement paste medium. This description reveals that concrete is a highly non-homogenous material with a complex microstructure containing random inhomogeneity over a wide range of length scales.

The content of inhomogeneity and the typical size leave their signature on the velocity and attenuation versus frequency curves. In the cases of bulk materials, this is attributed to scattering on the inhomogeneities which are responsible for redirecting the energy to a pattern of angles that differs from the initial direction. Therefore, ultrasonic wave propagation in cement-based materials is a complicated process and understanding of how a stress wave propagates through such a medium is of paramount importance for the aforementioned non-destructive testing techniques. Thus, the discrepancy in the pulse velocity measurements between the conventional test and coupling test could be explained by a combination of preferential mode conversion between compression and shear mode and the differences between the attenuation of both modes in concrete.

Chapter 6 Conclusions and Recommendations for the Future Works

6.1 Conclusion

This work examined the effect of coupling media on the pulse velocity of concrete. In conclusion, the following points were highlighted in relation to the objective of the study.

- Using coupling materials has an effect on the pulse velocity measured in a given concrete, the effect varies depending on the material used. This was attributed to a presentational coupling occur between the ultrasound wave and the constituent materials of the concrete there.
- Solid couplants return higher values of the pulse velocity than the liquid couplants.
- The coupling effect in this study is different to that of the non-contact system (air coupling) in that the slope of the strength-pulse velocity relationship curves stays the same (i.e. curves are parallel) but the offset changes.
- The magnitude of the coupling effect changes with mix proportions of the concrete under test, for example, when the rubber test showed significant differences between the measurements of the two MAS at each strength level, the propanol test recorded approximately similar values for both MAS at all compressive strength levels.
- Although there are variations in the acoustic impedances of the three couplants and thus in the amount of energy that are transmitted through the couplant-concrete interface, it seems that these differences were not

sufficient to cause such marked difference in the measurements of the UPV when the liquid couplants are used comparing to the rubber couplant.

- The discrepancy in the pulse velocity measurements between the conventional test and coupling tests cannot be explained by simple preferential coupling. It is required more research as the propagation of the ultrasonic wave in concrete is clearly complex.
- The discrepancy in the pulse velocity measurements between the conventional and the coupling tests could be explained by preferential mode conversion between compression and shear waves and/or attenuation.
- The sensitivity of the technique can be marginally improved by using a liquid couplant but probably not by a practical amount.
- The variation in speed of sound with couplant demonstrates that the mechanism by which sound travels through concrete is more complex than previously thought and throws further doubt on the established relationships between the speed of sound and strength for concrete.

6.2 Recommendations for the Future Works

Based on the experimental work carried out in this thesis the following future investigations are proposed:

1. More experimental tests can conduct to investigate the effect of degree of saturation of the concrete on the pulse velocity.
2. Further to the current research, measuring the velocity of shear waves in concrete is recommended.
3. Effect of the thickness solid coupling layer on the pulse velocity is also recommended.

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