EVALUATION OF CEMENT MORTARS BY ULTRASOUND

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Prof Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Erdal Çokça
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst.Prof.Dr. İsmail Özgür Yaman
Supervisor

Examining Committee Members

Prof.Dr. Turhan Y. Erdoğan	(METU,CE)	
Asst.Prof.Dr. İ. Özgür Yaman	(METU,CE)	
Prof.Dr. Mustafa Tokyay	(METU,CE)	
Prof.Dr. Erdal Çokça	(METU,CE)	
M.Sc. Abdulkadir Başkoca	(CHRYSO)	

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Name, Surname: Paksoy, Nesibe Gözde

Signature :

ABSTRACT

EVALUATION OF CEMENT MORTARS BY ULTRASOUND

Paksoy, Nesibe Gözde
M.Sc., Department of Civil Engineering
Supervisor: Asst. Prof. Dr. İsmail Özgür Yaman

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Ultrasonic testing of concrete is often used for the assessment of its uniformity, strength, modulus of elasticity, durability and etc. Therefore, the related parameters of testing such as the transducer frequency, the specimen geometry and etc. are well-known. On the other hand, most of the concrete properties are affected by the cement and the mechanical as well as some durability properties of cements are determined through cement mortars. Applications of ultrasound on determining the properties of cement mortars are quite limited. Therefore, the required specimen dimensions, transducer frequencies have not yet been established for cement mortars.

In this study, ultrasonic pulse velocity (UPV) of mortars was determined with different transducers of different frequencies for different size and shape of specimens. Within the scope of the experimental program, three different ultrasonic frequencies (54 kHz, 82 kHz, and 150 kHz) were utilized and the relation between ultrasonic testing frequency and specimen shape was experimentally investigated.

It was concluded that the mechanical properties of mortar was adversely affected by water-to-cement ratio. It was also observed that, when the length/wavelength ratio increases, the measured UPV with different transducer frequencies tends to converge to a single value. Finally, it was also concluded that an increase in moisture content of the mortar mixtures causes an increase in UPV and a decrease in compressive strength.

Keywords: Ultrasonic pulse velocity, cement mortar, testing frequency, specimen size and shape.

ÖZ

ÇİMENTO HARÇLARININ ULTRASES İLE İNCELENMESİ

Paksoy, Nesibe Gözde
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Ultrasonik test kullanarak, betonun homojenliğini, dayanımını, elastiklik modülünü ve dayanıklılığını belirlemek oldukça yaygın olarak kullanılmaktadır. Bu yüzden bu testlerle ilgili parametrelerden transduser frekansı, numune geometrisi gibi özellikler bilinmektedir. Öte yandan betonun birçok özelliği çimento tarafından etkilenmekte ve çimentoların mekanik özeliklerinin yanısıra dayanıklılık özellikleri çimento harçları kullanılarak belirlenmektedir. Betondan farklı olarak çimento harçlarında iri agrega parçacıkları bulunmamakta ve ultrasesin harçlar üzerinde kullanımını uygun kılmaktadır.

Bu çalışmada, farklı şekil ve boyutlara sahip harç numunelerinde farklı frekansa sahip transduserler ile ultrases hızları belirlenmiştir. Bu çalışma kapsamında üç farklı ultrases frekansı (54 kHz, 82 kHz ve 150 kHz) kullanılmış ve ultrasonik test frekansı ile numune boyutu arasındaki ilişki deneysel olarak incelenmiştir.

Sonuç olarak harçların mekanik özelliklerinin su-çimento oranıyla ters orantılı olarak etkilendiği tespit edilmiştir. Ayrıca, numune boyu ile dalgaboyu oranı arttıkça ve ultrases hızında transduser frekansı değiştikçe ultrases hızının sabit olarak ölçülebildiği görülmüştür. Son olarak, harçlardaki nem miktarı arttıkça ultrases hızının arttığı ve basınç dayanımlarının azaldığı belirlenmiştir.

Anahtar Kelimeler: Ultrases hızı, çimento harcı, test frekansı, numune geometrisi ve boyutu

To My Fiancée, **M. Kemal Özerkan**

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LIST OF SYMBOLS

V : Velocity of Sound
E : Modulus of Elasticity
ρ : Density
G : Shear Modulus
λ : Wavelength
f : Frequency
N : Near Field Length
A : Amplitude
A_0 : Incident Amplitude
α : Amplitude Attenuation Coefficient
f'_c : Compressive Strength
f_t : Flexural Strength
R : Modulus of Rupture

LIST OF ABBREVIATIONS

ASNT : The American Society for Non-destructive Testing
UPV : Ultrasonic Pulse Velocity
ASTM : American Society for Testing and Materials
NDT : Nondestructive Testing
UPA : Ultrasonic Pulse Attenuation
TS : Turkish Standards
EN : European Norms

CHAPTER 1

INTRODUCTION

1.1. General

The mechanical properties of a given material can be determined through destructive or nondestructive testing methods. In destructive testing, the material being tested is permanently altered or deformed and the test can be performed only once on the same material. Therefore, many test substrates are needed through destructive testing to obtain convenient measure. On the other hand, a nondestructive test can be performed over and over on the same material without negative impact on the material itself, and also the future usefulness of the material is not affected.

There are numerous ways to classify the nondestructive testing methods that are applied to concrete. One of these classifications is made with respect to the property that is being determined [Malhotra 1984]. In this classification Malhotra listed various types of pullout methods, surface hardness methods, penetration resistance, break-off techniques and maturity concept as the methods that measure strength. The second type which does not measure strength directly but measure some other property of concrete from which an estimate of strength can be made includes magnetic methods, electrical methods, radioactive methods, ultrasonic pulse velocity (UPV) and pulse echo techniques, acoustic emission methods, nuclear methods, and infrared thermography. Another classification can be made again according to whether estimating the strength or estimating the other properties of concrete like uniformity, modulus of elasticity, density, thickness, pulse velocity and durability [Yaman 2000]. In this classification; surface hardness tests, rebound tests, pullout tests and penetration are in the first type, and dynamic or vibration techniques, radioactive and nuclear methods, magnetic and electrical methods, and acoustic emission methods are in the second type. Prassianakis and co-workers also listed the nondestructive testing methods used for the evaluation of concrete as ultrasound, industrial radiography, acoustic emission, the rebound (Schmidt) hammer test, the penetration resistance test and the pull-off test [Prassianakis et.al. 2002].

Among the above mentioned nondestructive test methods, ultrasonic inspection has been used on concrete since the end of 1940s with UPV being the most widely used parameter [Yaman 2000]. Ultrasonic attenuation is another but rather less frequently measured parameter as the solid aggregate particles makes its determination more difficult. Main UPV applications in concrete can be categorized as, determining uniformity, determination of dynamic (pulse) modulus of elasticity, strength estimation, determining hardening characteristics, durability assessment, crack detection, appraisal of the effect of fire exposure, and establishing an acceptance criteria. According to ASTM C 597, the UPV can be used for the assessment of the uniformity and relative quality of concrete, the indication of the presence of voids and cracks, estimating the depth of cracks, and evaluating the effectiveness of crack repairs, to indicate changes in the properties of concrete, in the survey of structures, and to estimate the severity of deterioration or cracking [ASTM C 597]. However, among these applications determining the uniformity of concrete is the most widely used test method.

On the other hand, most of the concrete properties are affected by the cement and the mechanical as well as some durability properties of cements are determined through cement mortars. Unlike concrete, cement mortar does not contain the solid aggregate particles and makes the use of ultrasound on cement mortar more feasible. However, applications of ultrasound on determining the properties of cement mortars are quite limited. Therefore, the required specimen dimensions, transducer frequencies are not established for cement mortars. In this study, UPV is used as a nondestructive testing method to evaluate the effects of ultrasonic testing parameters such as transducer frequency and specimen geometry on cement mortars. In addition, relations between UPV and various properties of cement mortars are also determined.

1.2. Objective

The objective of this study is to determine the ultrasonic pulse velocity of mortars, to investigate the relationship between the UPV of mortars and their strength characteristics as evaluated during destructive testing at different ages and to make an attempt to evaluate the effects of different specimen size and shape on ultrasonic pulse velocity. For this purpose, several mortar mixes were prepared with different water-to-cement ratios keeping cement content constant and their ultrasonic pulse velocities were determined at 2, 7, and 28 days of mortar age. Moreover, the compressive and the flexural strengths as well as capillary porosity were also determined.

1.3. Scope

This thesis consists of five Chapters. Chapter 2 presents a literature review and devotes a general background on UPV including information about the basic principles of ultrasound and equipments of ultrasonic testing. At the end of the chapter, a brief introduction to testing the strength properties of mortar and concrete is also provided.

In Chapter 3, details about the experimental program, material properties, and experimental procedures are given. At the end, a summary of experimental data is provided.

Chapter 4 presents the results of the test program. The effect of water-to cement ratio on UPV, compressive strength and flexural strength, and the effect of specimen geometry on UPV are explained. In that Chapter, determining the compressive strength of cement mortars via ASTM C 109/C and TS EN 196-1 standards is also compared. The relationship between the compressive strength and UPV is discussed in this Chapter. In addition, the relationship between the longitudinal pulse velocities and lateral pulse velocities is also investigated. Finally, the effect of moisture content on UPV and compressive strength is also determined in this Chapter.

Chapter 5 presents a summary of thesis and lists the findings of this research. Suggestions for future studies are also included in Chapter 5.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1. Historical Review of Ultrasonic Testing

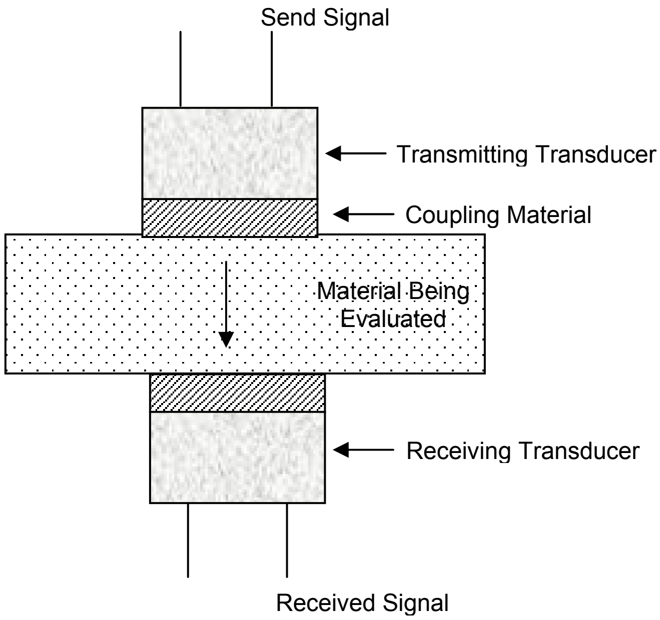
In 1883, Galton was aware of the existence of ultrasound, and used the whistle, which can be regarded as the first man-made ultrasonic transducers, to measure the upper frequency limit of response of the human ear. In the three decades following Galton's work, the development of ultrasonics was hampered because of the lack of progress in electrical technology [Blitz 1971]. During the 1914-18 war, Langevin made the first important use of ultrasonics for underwater soundings, and investigated the use of quartz transducers for transmitting and receiving ultrasonic waves. After the war, rapid developments took place in the field of electronics and, in 1925, Pierce used quartz and nickel transducers to generate and detect ultrasound at frequencies extending into the mega-hertz range. By this time, ultrasonic diffraction grating was discovered by Debye, Sears, Lucas and Biquard, working independently of one another [Blitz 1971; Blitz and Inst 1963]. The use of ultrasonic waves in detecting metal objects was first practiced by Sokolov in 1929 and 1935. Mulhauser used two transducers to detect flaws in solids and obtained a patent for using ultrasonic waves in 1931, and Firestone in 1940 and Simons in 1945 used a pulse-echo technique and developed pulsed ultrasonic testing [NDT Resource Center web site 2004]. After the 1939-45 war, the discovery of radar triggered the development of the pulse technique and it was used for the nondestructive testing of materials and for medical diagnosis [Blitz and Inst 1963]. After 1950, the ultrasound was used to detect gallstones, breast masses, and tumors in the international medical community of United States and Europe [NDT Resource Center web site 2004]. In the 1960s, microwave propagation was developed, and new materials and techniques were discovered, and also ultra-high frequencies, up to 100 GHz, were used to generate ultrasonic waves [Blitz 1971].

2.2. Basic Principles of Ultrasonic Pulse Velocity Testing

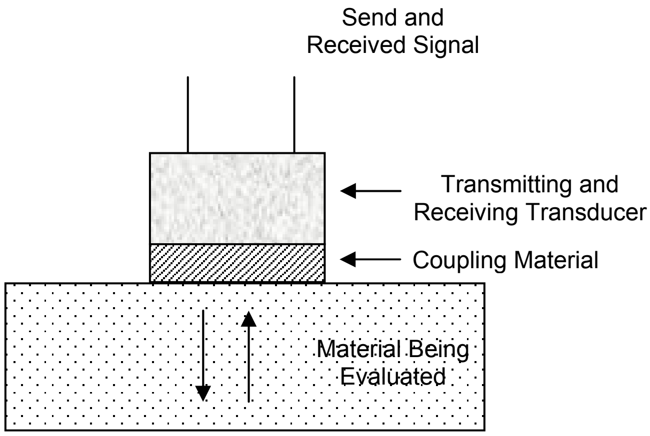
The theory of ultrasonic propagation and that of audible sound are exactly the same. The only difference between them is that ultrasound can not be detected by the human ear [Blitz 1971]. Ultrasonic testing uses high frequency sound energy above 20 kHz to make measurements. The measurement of ultrasonic velocities depends on propagating a dynamic pressure wave (pulse) through a material of known thickness and measuring the transit time of the emerging acoustic pressure wave [Brown 1997]. After measuring the transit time of wave, UPV is calculated by dividing the thickness of material to the transit time.

A typical ultrasonic testing system consists of a pulser/receiver, transducer, and display devices. High voltage electrical pulse is produced by the pulser/receiver which is an electronic device. The transducer, which can transform the mechanical energy into electrical energy and vice versa, generates high frequency ultrasonic energy. The sound energy propagates through the materials in the form of waves. If there is a discontinuity such as a crack in the wave path, part of the energy will be reflected back from the flaw surface. The transducer transforms the reflected wave signal into electrical signal and the signal is received by the display devices. The signal gives the information about the location of discontinuity, size, orientation, and other features [Yaman 2000; NDT Resource Center web site 2004].

The wave velocity of ultrasonic waves can be determined by two modes of measurements: through transmission and pulse echo. In through transmission, two transducers are used; one is the transmitter and the other one is the receiver (Figure 1a). On the other hand, in the pulse echo procedure, only one transducer is used which delivers the pulse and also receives the reflected signal (Figure 1b). Through transmission is preferred in concrete because of its highly attenuative nature. Attenuation is the reduction in the energy of the wave as it passes through the medium [Yaman et.al. 1998].



(a) Through Transmission



(b)Pulse Echo

Figure 1.Modes of Ultrasonic Testing

2.3. Physics of Ultrasound

2.3.1. Wave Propagation

Ultrasonic testing of materials makes use of mechanical waves which is composed of oscillations of discrete particles of materials. In solids, sound waves can propagate in four principle modes based on the way the particles oscillate. These modes are longitudinal waves, transverse waves, surface waves (Rayleigh waves) and plate waves (Lamb waves) in thin materials [Krautkrämer 1983; NDT Resource Center web site 2004].

In longitudinal waves, the particles in a medium oscillate parallel to the direction of wave propagation, i.e. the oscillations occur in the longitudinal direction as shown in Figure 2a. These waves are also called pressure or compression waves since compressional and dilatational forces are active in them [Krautkrämer 1983; Szilard 1982].

In transverse waves, the particles in a medium oscillate perpendicular and at a right angle or transverse to the direction of wave propagation as shown in Figure 2b. These waves can only propagate in solids because liquids and gases do not support shear stresses and, therefore they are also called shear waves [Krautkrämer 1983; Szilard 1982; Blitz 1971].

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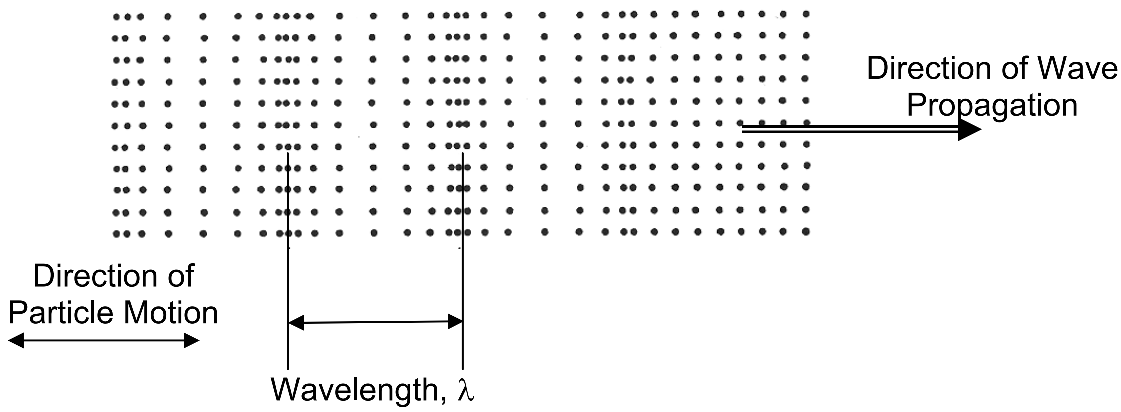
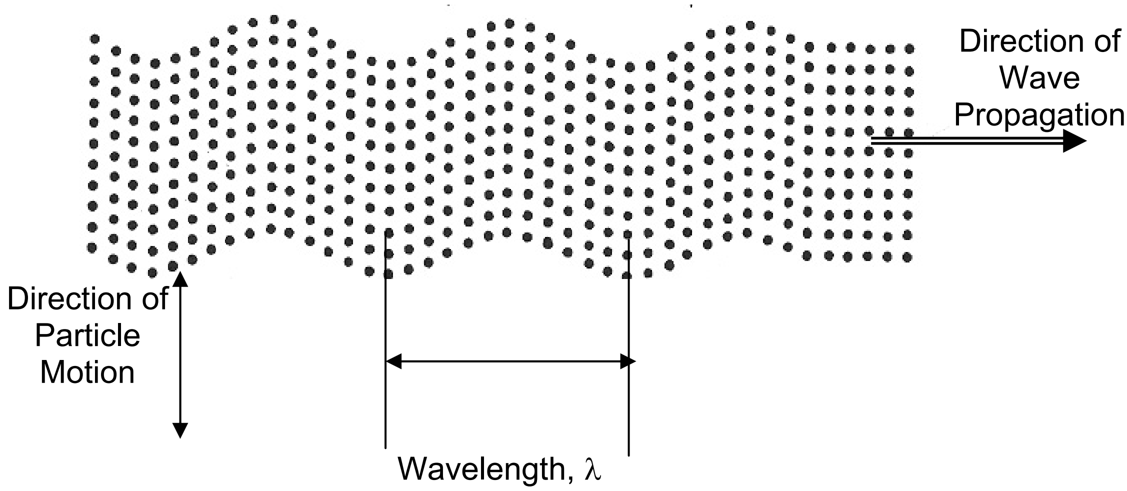


(a) Longitudinal Waves



(b) Transverse Waves

Figure 2.Waves in a Continuous Medium [Krautkrämer 1983]

Surface or Rayleigh waves have horizontal displacement and the motion of the particles in a medium is an ellipse. These waves occur on the interface between a liquid and a solid phase, and between two solid phases [Krautkrämer 1983].

Plate waves can propagate only in very thin metals. The most commonly used plate waves are Lamb waves which always contain components of the particle oscillation at right angles to the surface. Lamb waves occur in two different basic modes: the symmetrical or dilatational wave and the asymmetrical or bending wave. Lamb waves provide a useful tool for the detection of laminar defects just below the surfaces of solid materials [Krautkrämer 1983; NDT Resource Center web site 2004; Blitz 1971].

In the special case where the plate borders on one site on a different solid body, as in the case of a surface layer, the pure transverse waves are called Love Waves. Love waves are employed extensively by seismologists but have little application in the study of ultrasonics [Krautkrämer 1983; Blitz 1971].

Among the above mentioned waves, the most widely used modes of propagation that are used in ultrasonic testing are longitudinal and transverse waves. These waves travel through a uniform material at a constant velocity provided that the deformations produced by the action of the waves are purely elastic. This velocity depends on the density and the modulus of elasticity for longitudinal waves as shown by the following equation;

$$V_l = \sqrt{\frac{E}{\rho}} \tag{1}$$

where V_l is the velocity, E is the modulus of elasticity, and ρ is the density.

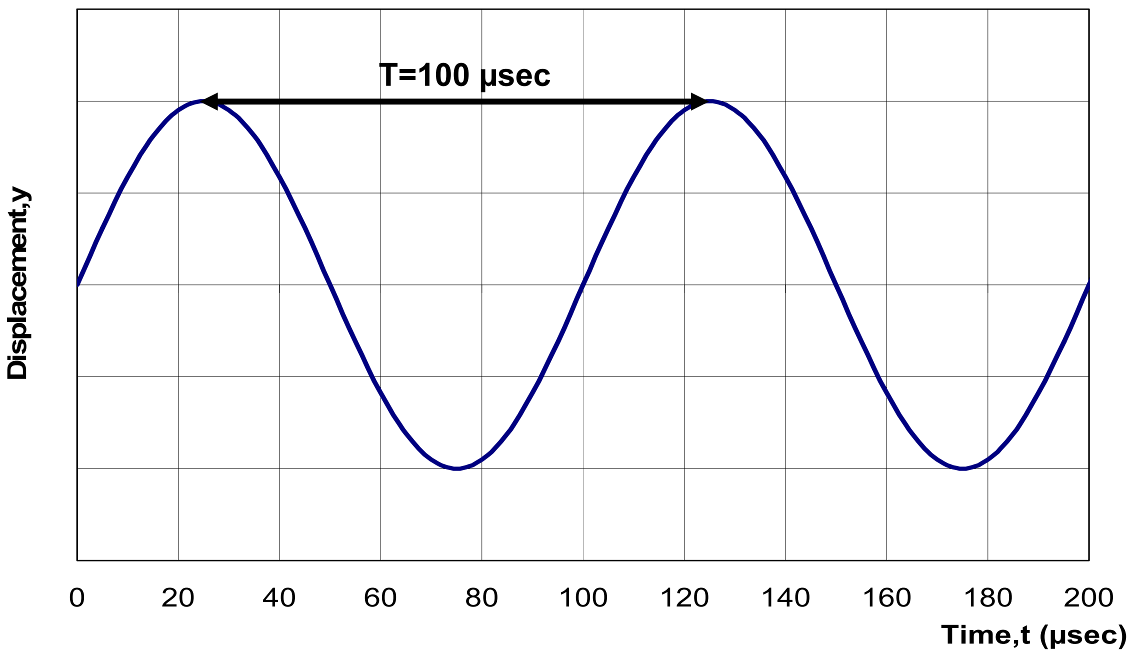
On the other hand, the shear wave velocity (V_s) is related to the shear modulus, G, in isotropic homogeneous materials as shown by the following equation;

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (2)$$

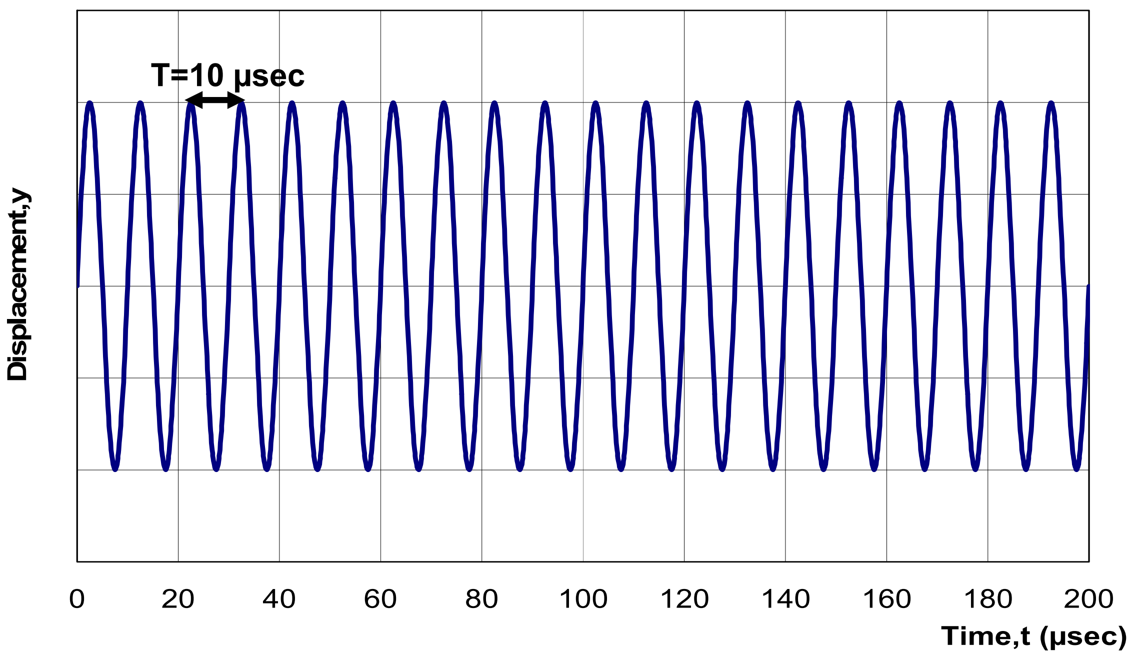
As seen from the above equations sound waves do travel at different speeds in different materials since the mass of the atomic particles related to the density of the material, and the spring constants related to the elastic constants of the material are different [Blitz 1971; Brown 1997].

2.3.2. Properties of Acoustic Plane Waves

The parameters of waves propagating in isotropic solid materials are wavelength, frequency, and velocity. The frequency of a wave is the number of oscillations of a given particle per second. Frequency is expressed in Hertz and determines the pitch of the sound. The reciprocal of the frequency is equal to the time period *T* which is defined as the time it takes for the source to execute one complete vibration as shown in Figure 3.



(a) Lower Frequency (f=10 kHz)



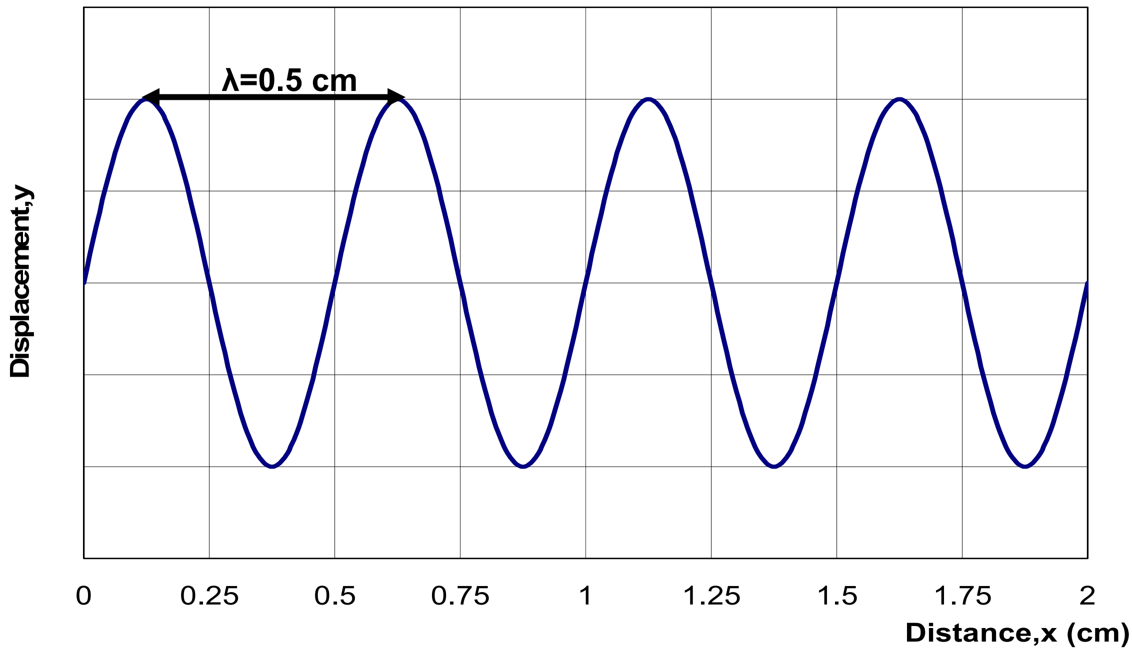
(b) Higher Frequency (f=100 kHz)

Figure 3.Waves in Time Domain

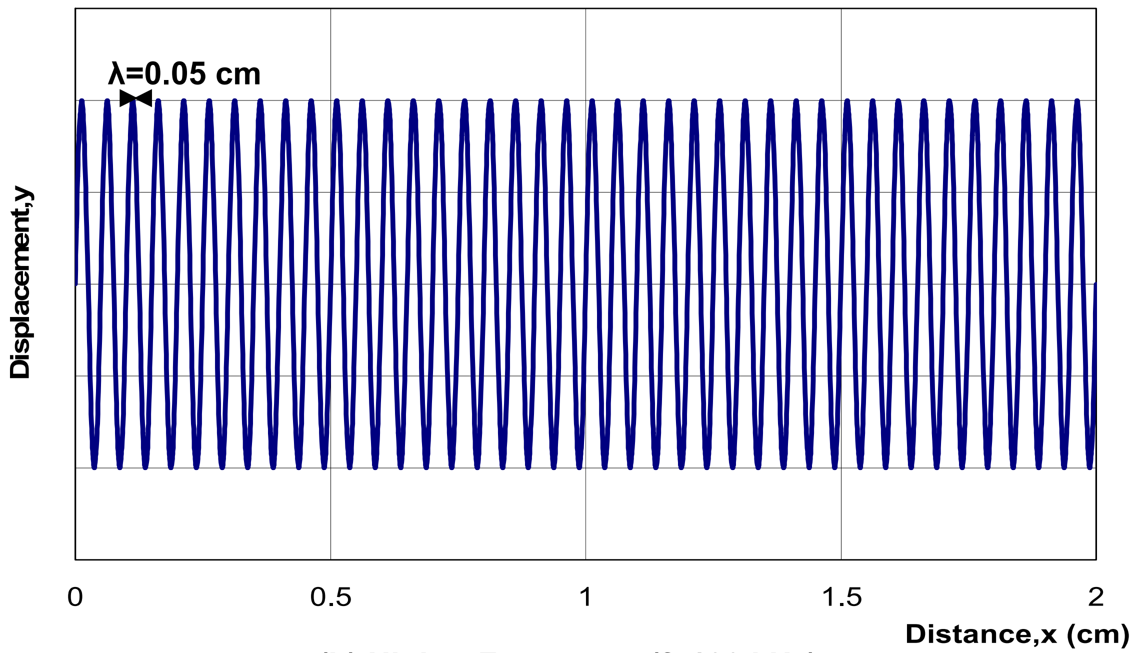
The wavelength is the distance between two planes in which the particles are in the same state of motion. It is inversely proportional to the frequency and directly proportional to the velocity of the wave. This relationship is shown by the following equation:

$$Wavelength(\lambda) = \frac{Velocity(v)}{Frequency(f)} \qquad (3)$$

In ultrasonic testing, an increase in frequency results in the shorter wavelength which can be used for the detection of smaller discontinuities (Figure 4). The grain structure, material thickness, size, type, and probable location of the discontinuity should be considered before selecting an inspection frequency. When frequency increases, sound will tend to scatter from large or coarse grain structure and from small imperfections within a material. Frequency also has an effect on the shape of the ultrasonic beam. The ability of ultrasound to locate defects is also affected by a number of other variables that include pulse length, type and voltage applied to the crystal, properties of the crystal, backing material, transducer diameter, and receiver circuitry of the instrument [Krautkrämer 1983; NDT Resource Center web site 2004].



(a) Lower Frequency (f=10 kHz)



(b) Higher Frequency (f=100 kHz)

Figure 4.Waves in Space Domain

2.3.3. Radiated Fields of Sound Waves

The area in which the waves travel before they merge represents the near field (Fresnel zone) and the area after that represents the far field (Fraunhofer zone) shown in Figure 5. The near field is the zone in the sound beam immediately in front of the crystal. The length of the near field changes depending on the frequency and cross-sectional area of the crystal surface. The far field is the zone beyond the near field in front of the transducer in which signal amplitude decreases monotonically in proportion to distance from the transducer [NDT Resource Center web site 2004; ASNT web site 2005].

Beam spread occurs because the vibrating particle of the material does not always transfer all of the energy in the direction of wave propagation. It is determined by the frequency and diameter of the transducer as shown by the following equation [NDT Resource Center web site 2004].

$$N = \frac{D^2 F}{4V} \tag{4}$$

where N is the near field length, D is the diameter of the transducer, F is the frequency of the transducer and V is the velocity of sound in the material [NDT Resource Center web site 2004].

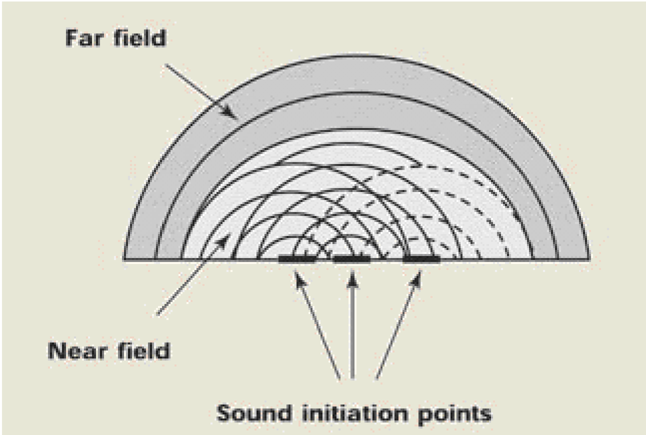


Figure 5.Near Field Zone in Ultrasonic Testing [ASNT web site 2005]

2.3.4. Attenuation of Sound Waves

Attenuation is the loss of the energy of the wave as it propagates through the medium. In ideal materials, the sound pressure is attenuated only by the virtue of the spreading of the wave. Attenuation results from two basic causes; scattering and absorption, which can both be combined in the concept of attenuation [Krautkrämer 1983]. Absorption is mainly caused by the internal friction (viscosity) and the elastic hysteresis. The scattering results from the fact that the material is not strictly homogeneous and it is affected by the differences between the elastic constants (anisotropy) and the densities of the inhomogeneities and the surrounding medium, and by the kind of wave [Szilard 1982]. As a result, the amplitude and the intensity of ultrasonic waves decrease with distance. Ultrasonic attenuation is the decay rate of mechanical radiation at ultrasonic frequency as it propagates through material. A decaying plane wave is expressed by following equation;

$$A = A_0 e^{-\alpha r} \qquad (5)$$

where A is the amplitude, A_0 is the incident amplitude, r is the traveling distance, and α is the amplitude attenuation coefficient. This rate of decay is described by the damping coefficient or logarithmic decrement as shown in

Figure 6 [Krautkrämer 1983; NDT Resource Center web site 2004; Szilard 1982; Blitz 1971].

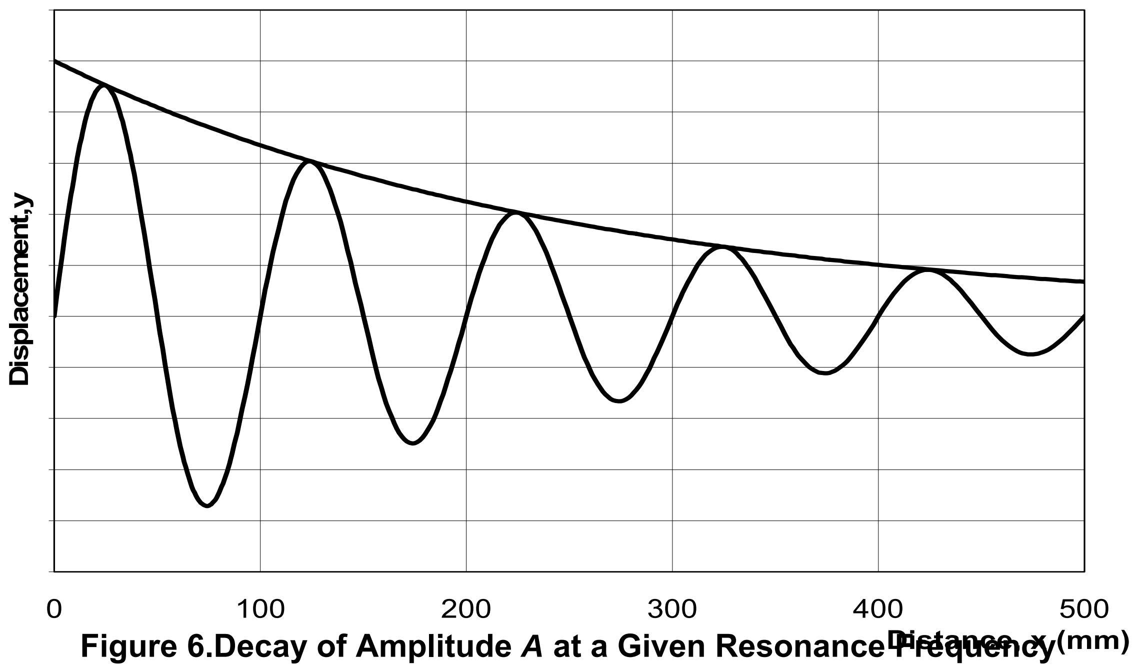


Figure 6.Decay of Amplitude *A* at a Given Resonance Frequency

Concrete has attenuation characteristics because of the scattering of the waves at the aggregate-matrix boundaries and the absorption of some of the wave energy. Therefore, through transmission and low frequency ultrasonic transducers (between 50 and 100 kHz) are considered most suitable for concrete [Yaman et.al. 1998; Krautkrämer 1983].

2.3.5. Reflection and Refraction

An ultrasonic wave produces reflected and refracted waves, when it passes through an interface between two materials at an oblique angle as seen in Figure 7. In the figure, O represents the point of incidence on the boundary, AO the incident longitudinal beam, OB the reflected longitudinal beam, OC reflected transverse beam, and OD and OE the respective refracted longitudinal and transverse beams. When a beam of plane longitudinal ultrasonic waves travels in a material A directing at an angle *i* to the normal at a plane boundary separating A from another material B, at this boundary, longitudinal waves will be reflected back into A at an equal angle *i* to the normal but on its other side (OB beam). If the material A is solid, there will be an additional beam reflected at an angle *i'* to the normal (OC beam). This second beam consists of transverse waves produced as a result of mode conversion. Mode conversion occurs when a wave encounters an interface between materials of different acoustic impedance. The waves transmitted into material B are refracted at the surface and a beam of longitudinal waves emerges at an angle *r* to the normal. If B is solid, a beam of transverse waves will emerge at an angle *r'* to the normal as a result of mode conversion.

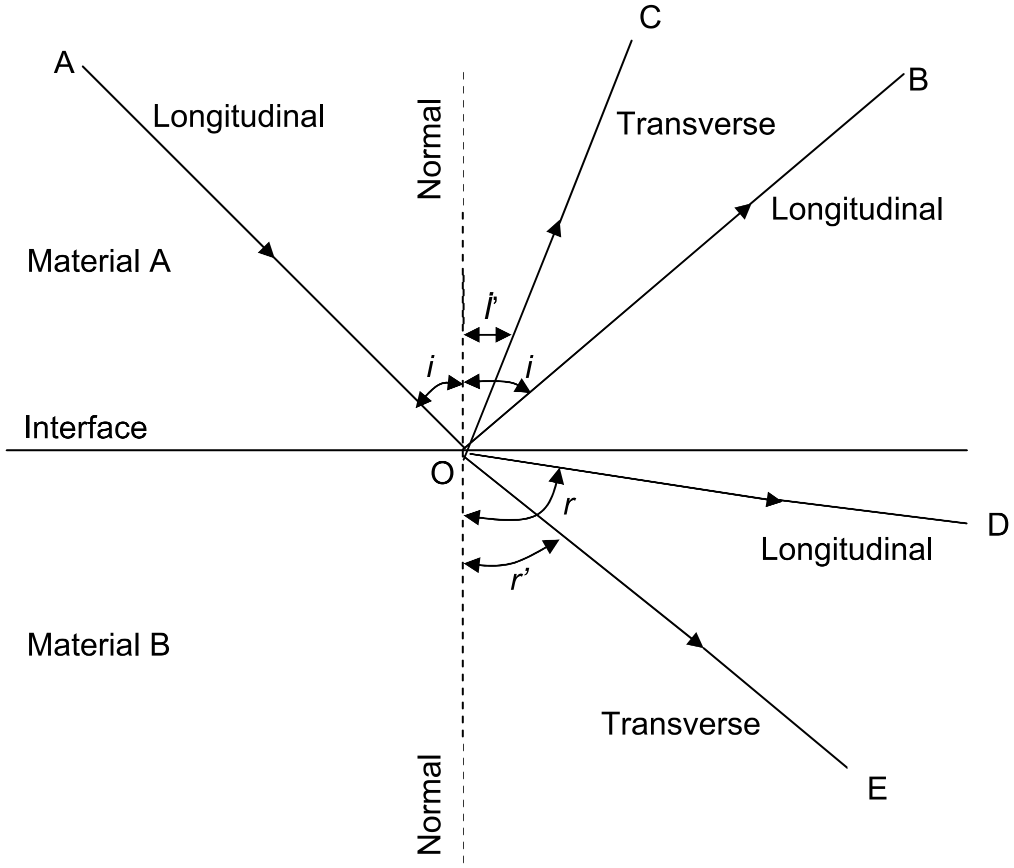


Figure 7.Reflection and Refraction of Ultrasound at a Boundary

Reflection of the ultrasonic wave occurs at the interface of two acoustic impedances which is defined for bulk materials where the sound propagation is normal to the transducer to specimen interface as ρV_L, where ρ is the mass density and V_L is the longitudinal velocity of sound in that medium [Krautkrämer 1983; Auld 1973; Blitz and Inst 1963; Brown 1997; Blitz 1971].

2.4. Test Equipment

The ultrasonic pulse velocity testing system consists of several functional units which are pulser/receiver, transducer and display devices as schematically described in Figure 8.

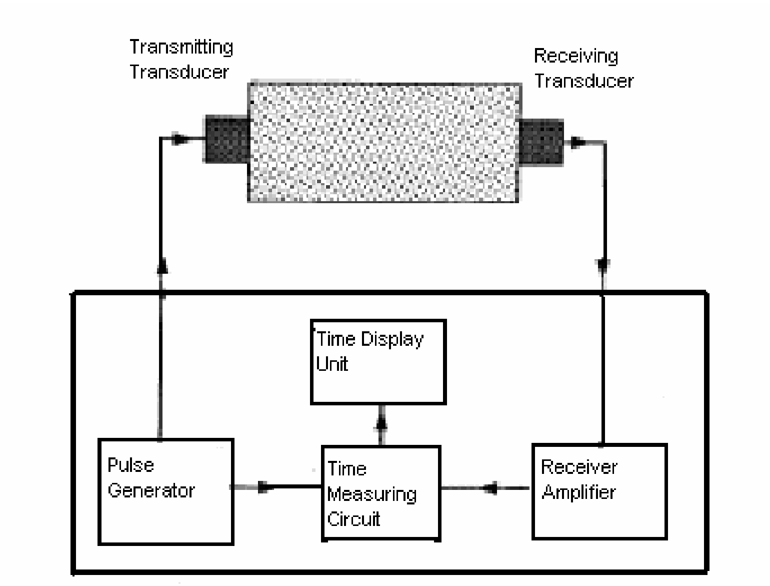


Figure 8.Schematic Description of Pulse Velocity Testing Unit [ASTM C 597]

2.4.1. Transducers

Transducer is a device that generates or receives sound waves; this converts energy from one form to another. Therefore, acoustic transducers are used to transfer acoustical energy to or from such forms of energy as electrical, mechanical, and thermal. There are various types of transducers such as:

- Piezoelectric Transducers,
- Magnetostrictive Transducers,
- Mechanical Transducers,
- Electromagnetic Transducers,
- Electrostatic Transducers.

Piezoelectric transducers are made from materials displaying the piezoelectric effect which is defined as the voltage produced between surfaces of a solid dielectric (nonconducting substances) when a mechanical stress is applied to it. Piezoelectric transducers, which can be cut in various ways to produce different wave modes, are the most widely used acoustic transducers today due to their good piezoelectric properties and their ease of manufacture into variety of shapes and sizes. They also operate at low voltage and are usable up to about 300 ˚C. The possible frequency range extends from 20 kHz to well over 10 GHz [Krautkrämer 1983; Auld 1973; Blitz and Inst 1963; Blitz 1971; Mattiat 1971]. In Figure 9, a schematic description of a typical piezoelectric transducer is presented.

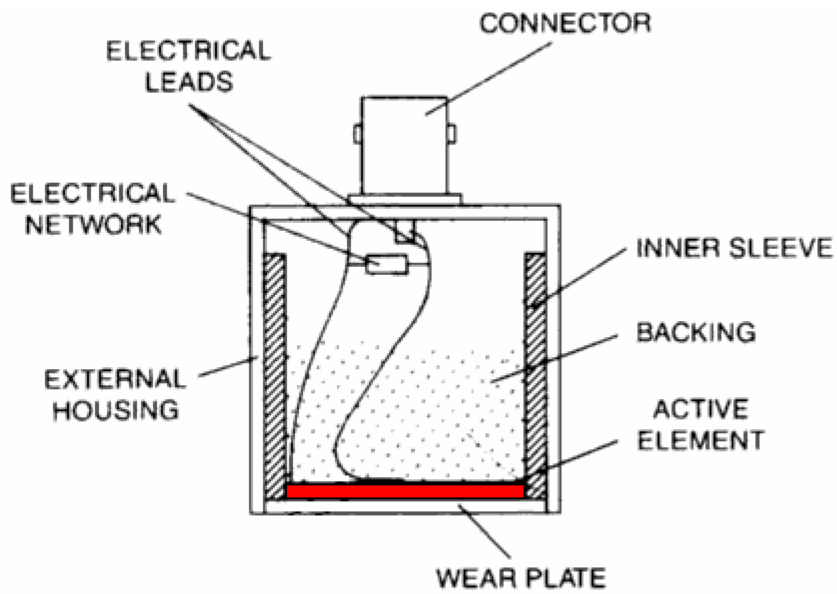


Figure 9.Schematic Description of Piezoelectric Transducers [NDT Resource Center web site 2004].

Magnetostrictive oscillators make use of the phenomenon of magnetostriction which is the changing of physical dimensions of a material in response to changing its magnetization. They are generally made of ferromagnetic materials which can be easily be magnetized and which display magnetostriction or the Joule effect. They are not often used in the design of ultrasonic transducers because of their poor mechanical properties. Mechanical transducers include purely mechanical oscillators (e.g. whistles and sirens) and radiometers. They are used mainly for high power applications, and the frequency range rarely extends beyond 50 kHz. Electromagnetic transducers are widely used as loudspeakers and microphones in the audio-frequency range but have very limited application at ultrasonic frequencies. Electrostatic transducers are used as generators at low intensities with an upper frequency limit of a few hundred kilo-hertz. They may be used as receivers at frequencies as high as 100 MHz [Krautkrämer 1983; Auld 1973; Blitz and Inst 1963; Blitz 1971; Mattiat 1971].

Another classification of transducers is made according to their application. This classification includes contact transducers and immersion transducers. A contact transducer is a single element longitudinal wave transducer which is generally hand manipulated and it is used for direct contact inspections. These transducers are used for straight beam flaw detection and thickness gaging, for detection and sizing of delaminations, for material characterization and sound velocity measurements, and also for inspection of plates, billets, bars, forgings, castings, extrusions, and a wide variety of other metallic and non-metallic components. On the other hand, immersion transducers do not contact the component. They are single element longitudinal wave transducers with a ¼ wavelength layer acoustically matched to water. Immersion transducers are used for automated scanning, for on-line thickness gaging, for high speed flaw detection in pipe, bar, tube, plate and other similar components, for time of flight and amplitude based imaging, for through transmission testing, and also for material analysis and velocity measurements [NDT Resource Center web site 2004; Panametrics-NDT web site 2005].

There is a variety of configurations of contact transducers to improve their usefulness for a variety of applications. These configurations are dual element transducers, delay line transducers, angle beam transducers, normal incidence shear wave transducers and paint brush transducers. Dual element transducers consist of two independently crystal elements in a single housing. One of the elements transmits longitudinal waves, and the other element receives. They are used for remaining wall thickness measurement and crack detection in bolts or other cylindrical objects. Delay line transducers are used for thickness measurements of very thin materials on commercially available thickness gauges and delamination checks in composite materials. Angle beam transducers are single element transducers used with a wedge to introduce a refracted shear wave or longitudinal wave into the test specimen. They are used for flaw detection and sizing, and for time of flight diffraction techniques. Normal incidence shear wave contact transducers introduce shear waves directly into the test piece without the use of refraction. They are used for shear wave velocity measurements, for calculation of Young's modulus of elasticity and shear modulus, and for characterization of material grain structure. Paint brush transducers are used to scan wide areas and they make it possible to scan a larger area more rapidly for discontinuities [NDT Resource Center web site 2004; Panametrics-NDT web site 2005].

2.4.2. Pulser-Receiver

Ultrasonic pulser-receivers generate the high voltage pulse that is required by the ultrasonic transducer. They can be used for flaw detection and thickness gauging in a wide variety of metals, plastics, ceramics and composites along with appropriate transducers and an oscilloscope.

The pulser section of the device generates short, large amplitude electric pulses of controlled energy, which are converted into short ultrasonic pulses when applied to an ultrasonic transducer. Control function associated with the pulser circuit includes pulse length or damping, and pulse energy.

In the receiver section the voltage signals produced by the transducer are amplified. Control functions associated with the receiver circuit include signal rectification, filtering to shape and smooth return signals, gain or signal amplification, and reject control (Figure 10) [NDT Resource Center web site 2004].

Figure 10.Pulser-Receiver and the Display Device used in This Study

2.5. Ultrasonic Testing of Mortar and Concrete

UPV was first used for concrete by Leslie and Cheesman in Canada and by Jones in England in 1949. Leslie and Cheesman presented a new apparatus named Soniscope for field laboratory testing of concrete and they reported that using this apparatus, the presence of internal cracks in a block of mass concrete, the depth of surface cracks and the dynamic modulus of concrete in any part of a structure regardless of the shape of the structure were obtained. In their study, UPV was measured using 20 kHz frequency transducers. Jones and his colleagues described an apparatus mainly used to determine the quality of concrete both in the laboratory and in the field in

1949. They reported that there is a measurable variation in UPV with changing water-to-cement (w/c) ratio and aggregate content, and a frost damage investigation using laboratory specimens. In these studies, 100 kHz frequency transducers were used [Jones 1962].

In 1952, Andersen and Nerenst used pulse velocity to observe the hardening of concrete specimens. Their testing technique was different from the early applications where an electrically operated hammer was used as the impact source and the wave velocity was determined using two pick-up (crystal transducers) readings [Malhotra 1984].

Kaplan, in 1958, investigated the compressive strength and UPV correlation both in the laboratory and on structural building columns; in 1959, reported the effects of w/c ratio and age, and concluded that, the relation between UPV and compressive strength can not be independent of age and w/c ratio; and in 1960, conducted to determine the effect of voids in specimens due to incomplete consolidation on the compressive strength, UPV, and dynamic modulus of elasticity of concrete. It was concluded that, voids due to incomplete consolidation had much less effect on pulse velocity than on compressive and flexural strength [Kaplan 1959].

In 1967, Galan used two acoustic characteristics, UPV and damping constant, to estimate concrete strength and concluded that, UPV expresses the elastic properties of concrete and damping constant represents the inelastic properties, therefore these two acoustic characteristics could be used to estimate concrete strength [Malhotra 1984].

One of the most recent studies on concrete strength and UPV was made by Sturrup, Vecchio and Caratin in 1982. In this study, strength-UPV relationships and the factors which affect this relationship was discussed, and it was concluded that the proportions and composition of the components, age, curing conditions and moisture content of the concrete have more effect than cement type, air-entrainment and curing temperature [Malhotra 1984].

The parameters affecting the transmission of sound waves in concrete are shown in Figure 11 [Sturrup et.al. 1982]. As seen from that figure, when compared to sound concrete, cracks and voids will reduce the UPV. Moreover the reinforcement may also affect the UPV measurements.

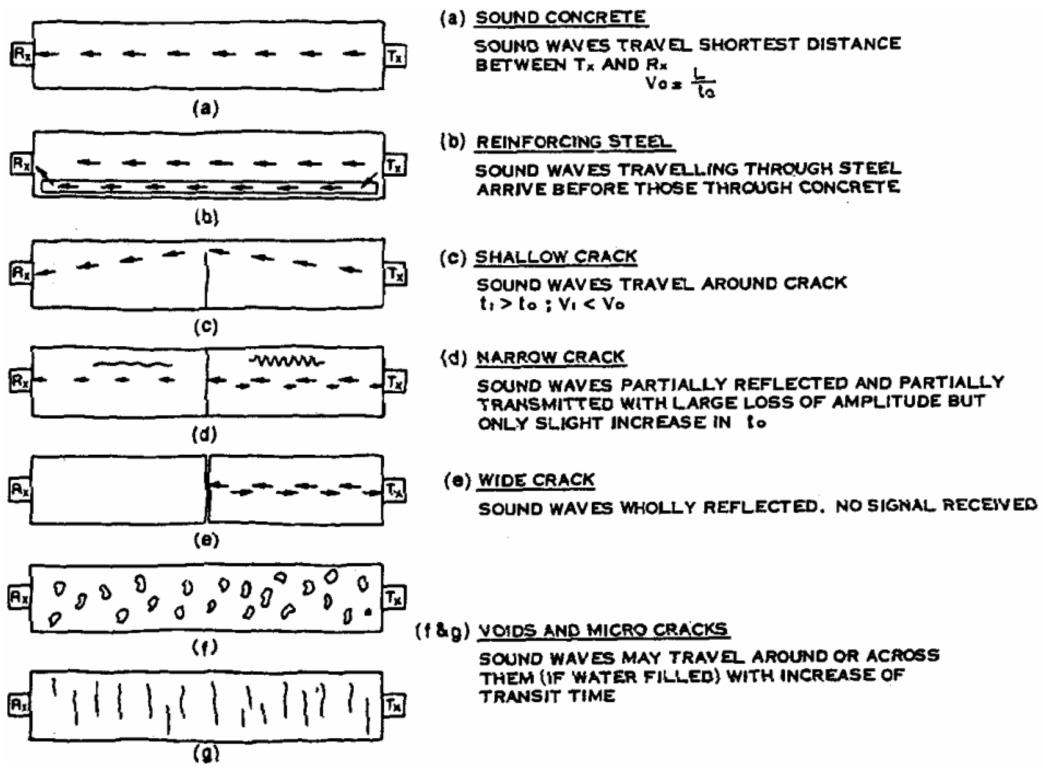


Figure 11.Conditions that Influence Transmission of Sound Waves in Concrete [Sturrup et.al. 1982]

In 1989, Popovics and Rose studied the difficulties of the estimation of concrete strength from pulse velocity measurement. In this study, the role of compositeness, and dispersion were discussed. They used three pairs of narrowband transducers with the nominal frequency of 24, 54, and 120 kHz. As a result of that study, they presented that the pulse velocity in the longitudinal direction of a concrete cylinder differs from the velocity in the lateral direction; more specifically, at low velocities the longitudinal velocities are greater, whereas at high velocities the lateral ones; this difference is more pronounced with lower frequencies; the dispersive nature of concrete decreases with age; and the pulse velocity is independent of the stresses in concrete to a large extent [Popovics et.al., 1990].

Another study was made by Gaydecki et.al., in 1992. In order to develop the attenuation equations which would determine the capabilities of any future system, they investigated a range of transducers, having centre frequencies ranging from 40 to 500 kHz. In this study, the manner in which medium-frequency ultrasonic pulses traveling concrete are generated, received, digitized and analysed was described and it was concluded that by a careful analysis of the attenuation characteristics it is possible to extract some information relating to the size distribution of the aggregate. They also demonstrated that it is possible to calculate the frequency-response characteristics of concrete, given suitable transducers and analysis equipment [Gaydecki et.al., 1992].

The relationship between permeability and UPV of concrete specimens was studied by Yaman et.al., in 1998. In their study, they used 50 kHz frequency transducers. Consequently, they concluded that UPV is a good estimator of RCPT (Rapid Test for Permeability to Chloride Ions) in the range of w/c ratio covered in their study and UPV is a good estimator of w/c ratio which means that compressive strength, elasticity modulus and other concrete properties dependent on w/c ratio can be estimated from UPV measurements [Yaman et.al., 1998].

In 2000, the influence of concrete porosity on its mechanical properties in saturated and dry states was investigated by Yaman et.al. In their study, the experimental data were compressive strength, entrained air content, porosity, saturated and dry static elasticity modulus, saturated and dry UPV, and saturated and dry density. In UPV measurements, they used 50 kHz frequency transducers. As a result of their studies, they concluded that the changes in the shape of capillary pores with moisture have significant influence on the mechanical properties of concrete [Yaman et.al., 2000].

The most recent study was made in 2004 by Río et.al., in Spain, to describe a technique which can be used to characterize some relevant properties of concrete, and they confirmed that there exists an exponential relationship between the compressive strength of the cylindrical specimens of concrete and the longitudinal speed of propagation of ultrasound in them. In their study, they used 40 kHz frequency transducers. From the data on the hardening of the concrete, they developed a time-dependent model with which it was found to be straightforward to predict the value of compressive strength at 28 days after fabrication of a specimen on the basis of the measurement of propagation velocity at only 2 and 5 days after fabrication [Río et.al., 2004].

In the literature, ultrasonic pulse velocity testing of cement mortars is very limited. One of the UPV testing of cement mortar was made by Tharmaratnam and Tan in 1989. They performed experiments to examine the relationship of the quality of cement mortar to pulse attenuation (UPA) and to pulse velocity, and also they evaluated the combined UPA and UPV method for strength estimation. They used two 50 kHz piezoelectric transducers as the transmitter and receiver of ultrasonic vibrations. They concluded that the attenuation of ultrasonic pulse is well correlated with the compressive strength of the cement mortar and the combined correlation of pulse attenuation and pulse velocity produced good estimation for strength of cement mortars [Tharmaratnam and Tan 1989].

The principal advantage of ultrasonic testing is that the test can be performed when only one surface is available [Malhotra 1984]. Other advantages of ultrasonic testing can be listed as follows;

a) It is sensitive to both surface and subsurface discontinuities.

b) The depth of penetration for flaw detection or measurement is superior to other nondestructive testing methods.

c) When the pulse echo technique is used, only single-sited access is needed.

d) Minimum part preparation is required.

e) Provides distance information.

f) Method can be used for much more than just flaw detection.

Ultrasonic testing has also some disadvantages which can be listed as follows [NDT Resource Center web site 2004];

a) Surface must be accessible to probe and couplant.

b) Skill and training required is more extensive than other technique.

c) Surface finish and roughness can interfere with inspection.

d) Thin parts may be difficult to inspect.

e) Linear defects oriented parallel to the sound beam can go undetected.

f) Reference standards are often needed.

CHAPTER 3

EXPERIMENTAL STUDY

3.1. Introduction

The objective of this study was to determine the ultrasonic pulse velocity of mortars, to investigate the relationship between the UPV of mortars and their strength characteristics as evaluated during destructive testing at different ages and to make an attempt to evaluate the effects of different specimen size and shape on ultrasonic pulse velocity. The mechanical properties determined included UPV, compressive and flexural strengths. Within the scope of the experimental program, three different ultrasonic frequencies 54, 82 and 150 kHz were utilized. A total of ten mortar mixes were prepared with ten different water-to-cement (w/c) ratios with a constant cement content. From each mortar mixture, cylindrical, cubical and prismatic specimens were prepared. On these specimens UPV was determined using all possible dimensions. In addition, compressive and flexural strengths were also determined on the appropriate specimens at 2, 7 and 28 days of age. Furthermore, the volume of voids in each mortar mix on six cube specimens was determined, and the effect of voids under dry and saturated conditions on UPV and compressive strength was investigated.

3.2. Material Properties

This section will provide information on the chemical and physical properties of all ingredients used in this study. For determining the properties of materials, ASTM (American Society for Testing and Materials) procedures were followed.

3.2.1. Portland Cement

An ordinary Turkish Portland Cement CEM I 42.5 N obtained from the Yibitaş Lafarge Yozgat plant was used throughout the tests. The physical properties and the chemical composition of the cement are given Tables 1 and 2, respectively.

Table 1.Physical Properties of Portland Cement

Physical Properties	Determined as	TS EN 197-1 Limits
Specific Gravity	3.06	–
Blaine Fineness (cm^2/g)	2888	≥ 2800
Setting Time		
Initial (min)	72	≥ 45
Final (hour)	4.5	–

Table 2.Chemical Composition of Portland Cement

Oxide	Determined as (%)	TS EN 197-1 Limits
SiO_2	19.11	–
Al_2O_3	5.24	–
Fe_2O_3	2.60	–
CaO	63.61	–
MgO	2.30	≤ 5%
K_2O	1.03	–
Na_2O	0.15	–
SO_3	2.78	≤ 3.5%

3.2.2. Fine Aggregate

Natural river sand was used as the fine aggregate in the experimental program. The specific gravity and absorption of the sand, and its gradation are shown in Table 3 and Table 4, respectively.

Table 3.Properties of Fine Aggregate

Property	Determined as
Apparent Specific Gravity	2.50
Dry Specific Gravity	2.36
SSD Specific Gravity	2.41
Absorption	2.41

Table 4.Sieve Analysis of Fine Aggregate

Sieve No	Cumulative Passsing (%)
3/8" (9.5 mm)	100
No.4 (4.75 mm)	96.71
No.8 (2.36 mm)	76.84
No.16 (1.18 mm)	51.45
No.30 (600 µm)	27.62
No.50 (300 µm)	7.45
No.100 (150 µm)	1.64

3.2.3. Water

In all the mortar mixes, tap water from the city water network of Ankara was used.

3.3. Experimental Procedures

3.3.1. Specimen Preparation

Mortars were prepared using an electrically driven mechanical mixer with a 200 kg capacity (Figure 12). From each mortar mixture, cylindrical, cubical and prismatic specimens with the geometrical dimensions provided in Table 5 were prepared. The tests performed on these specimens are also provided in that table. The molds that are used in this study are shown in Figure 13.

Figure 12.The Mechanical Mixer

Table 5.Number of Specimens Tested

Specimen Type	Dimensions (cm)			Number of Specimens	Tests Performed
	Length or Diameter	Width	Length		
Prismatic	4	4	16	9	Flexural Strength/UPV
	7	7	32	9	
Cubical	4	4	4	*	Compressive Strength/UPV
	5	5	5	24	
	7	7	7	*	
Cylindrical	5	−	10	15	Compressive Strength/UPV
	7	−	14	18	
	10	−	20	18	

* These specimens were obtained from the prismatic specimens.

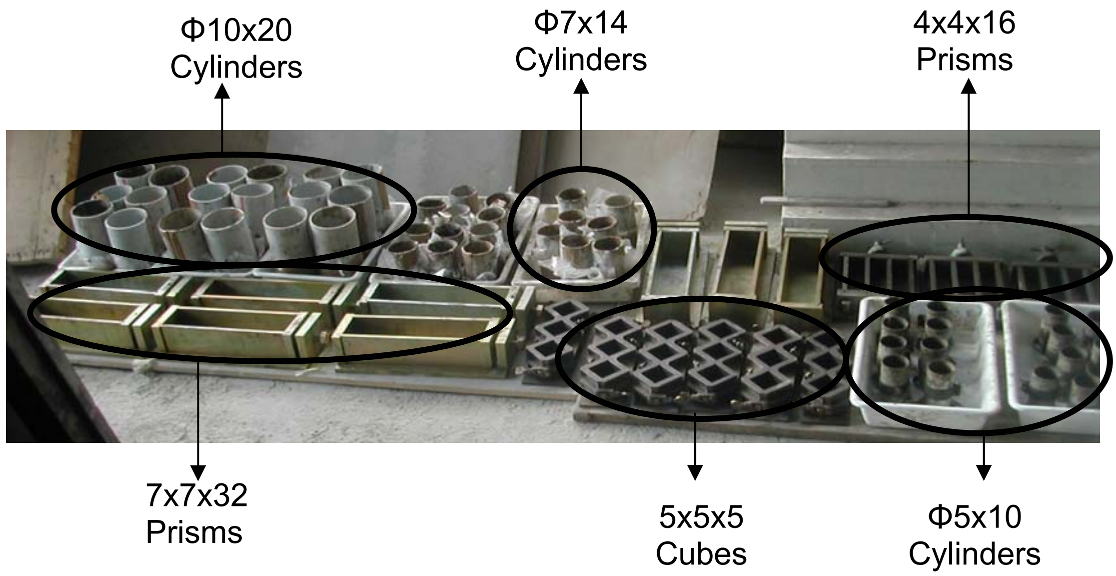


Figure 13.The Molds used in the Study

3.3.2. Determination of Compressive Strength

After demolding the next day, specimens were kept in lime saturated water at 23±2 °C. Later, compressive strength of cubical and cylindrical mortars was determined at 2, 7, and 28 days of mortar age using a universal testing machine (Figure 14).

The total maximum load indicated by the testing machine was recorded and the compressive strength values were calculated by dividing the total maximum load to loaded surface area as shown in equation 6.

$$f'_c = \frac{P}{A} \tag{6}$$

where f'_c is the compressive strength in kgf/cm^2, P is the total maximum load in kgf, A is the area of loaded surface in cm^2.

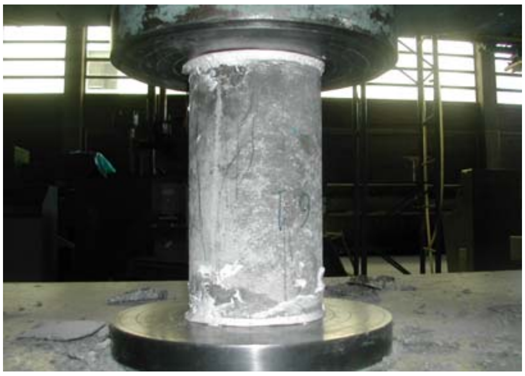
(a) 4x4x4 cubical

(b) 5x5x5 cubical

(c) 7x7x7 cubical

(d) 5x10 cylindrical

(e) 7x14 cylindrical



(f) 10x20 cylindrical

Figure 14.Typical Views of Compressive Strength Testing

3.3.3. Determination of Flexural Strength

Flexural strength of prism specimens was measured using a simple beam with center-point loading at 2, 7, and 28 days of mortar age. The test was conducted in accordance with ASTM C293-02 (Figure 15).

The flexural strength values of prism specimens were calculated using the following equation according to ASTM C293-02.

$$R = \frac{3PL}{2bd^2} \tag{7}$$

where R is the modulus of rupture in kgf/cm^2, P is the maximum applied load indicated by the testing machine in kgf, L is the span length in cm, b is the average width of specimen, in cm, d is the average depth of specimen in cm.

(a) 4x4x16 prismatic **(b) 7x7x32 prismatic**

Figure 15.Typical Views of Flexural Strength Testing

3.3.4. Determination of Density and Ultrasonic Pulse Velocity

All dimensions and the weights of the specimens were measured at ages 2, 7, and 28 days and using these data the density of the specimens was then calculated.

The UPV testing described in ASTM C597-97 was performed on each specimen at 2, 7, and 28 days. The testing system consists of a pulser-receiver unit with a built-in data acquisition system and two transducers. Three different transducers with 54 kHz, 82 kHz, and 150 kHz central frequencies were used. UPV measurements were conducted with the transducers firmly coupled to the opposite ends of the specimens using a viscous material that is petroleum jelly between the transducer and the specimen. UPV test gives the acquisition of the pulse arrival time which describes the elapsed time between the time of pulse application and arrival on the opposite face of the specimen. UPV was calculated by dividing the path length to the pulse arrival time.

(a) Through the length of a prismatic beam

(b) Through the cross section of a prismatic beam

(c) Through the length of a cubical specimen

(d) Through the length of a cylindrical beam

Figure 16.Typical Views of UPV Testing

3.3.5. Effects of Capillary Porosity and Saturation on the Properties of Mortar

In this part, effects of capillary porosity and degree of saturation on the mechanical properties of mortars were investigated. Within this scope, the test method described in ASTM C642-97 was performed to determine the volume of permeable pores (capillary porosity) in mortar on six cube specimens. The specimens were immersed in water at approximately 21 °C for 28 days and after drying, saturated mass and pulse velocities of specimens were measured. Afterwards, the apparent mass in water of the specimens were determined, and they were dried in an oven at a temperature of 50 °C for approximately 4 days, and the oven dry mass of the specimens were measured. The volume of the permeable pores was calculated using the values for mass and equation (8). Furthermore, after drying, the pulse velocities and compressive strengths of the specimens were also measured.

$$\textit{Volume of Permeable Pores (Voids)} = \frac{(C-A)}{(C-D)} x100 \qquad (8)$$

where C is the surface-dried mass, A is the oven-dry mass, D is the immersed apparent mass.

3.4. First Part of Experiments

3.4.1. Mixture Design (First Part)

In the first part of experiments, 5 mortar mixtures were prepared. All of the mixtures had a cement content of 500 kg and the w/c was changed from 0.5 to 0.7 with increments of 0.05. However, due to a computational error, it was realized that the dry sand weights were used in the mixture design.

Therefore, the w/c was recalculated with known moisture content of sand. The corrected mixture design is presented in Table 6.

Table 6.Mixture Design (First Part)

Mixture Number	w/c	w/c*	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)
1	0.50	0.43	215	500	1513
2	0.55	0.52	260	500	1404
3	0.60	0.53	265	500	1392
4	0.65	0.61	305	500	1296
5	0.70	0.68	340	500	1212

* Corrected w/c ratios

3.4.2. Test Data (First Part)

Table 7 presents the mean compressive strength of cubical and cylindrical specimens at 2, 7, and 28 days. Also included in that table are the coefficients of variations calculated from an average of six specimens.

The mean flexural strength at 2, 7, and 28 days for prismatic specimens and their coefficient of variations are provided in Table 8.

Table 9 presents the mean and the coefficient of variations (COV) of density of all the specimens tested. The mean UPV of all the specimens for 54 kHz, 82 kHz, and 150 kHz at 2, 7, and 28 days and coefficient of variations of UPV are shown in Table 10. However, as shown in the table some of the UPV measurements could not be obtained on time because of a technical problem in the UPV instrument.

Table 7.Compressive Strength of Cubical and Cylindrical Specimens (First Part)

Test Age	Specimen Type	Dimensions	Compressive Strength (kgf/cm^2)									
			w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
			Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Cubical	4x4x4	239	8.8	174	8.0	206	8.9	177	5.3	114	9.1
		5x5x5	247	9.5	188	6.3	219	8.9	162	1.9	109	5.6
		7x7x7	278	6.0	205	3.1	247	4.3	183	2.1	114	4.2
	Cylindrical	ϕ5x10	206	4.9	141	9.1	173	7.4	165	1.1	97	10.7
		ϕ7x14	201	9.1	153	3.6	211	9.4	184	3.9	97	9.2
		ϕ10x20	277	4.0	174	6.0	209	4.5	159	4.4	99	8.4
7 days	Cubical	4x4x4	319	5.8	343	6.6	320	9.0	276	8.9	194	7.4
		5x5x5	347	8.5	337	7.0	337	4.0	237	5.8	178	9.5
		7x7x7	370	3.7	338	6.4	337	6.6	251	3.3	220	5.8
	Cylindrical	ϕ5x10	289	4.1	283	6.9	229	11.6	209	2.6	175	5.6
		ϕ7x14	306	6.3	291	4.3	277	3.7	216	7.5	195	6.6
		ϕ10x20	343	5.4	270	5.1	287	4.8	223	5.6	183	5.4
28 days	Cubical	4x4x4	434	9.0	413	9.1	395	9.0	352	7.8	289	9.1
		5x5x5	434	6.9	393	8.6	368	7.6	245	8.6	209	6.0
		7x7x7	488	6.0	455	5.8	388	5.1	325	3.4	260	4.0
	Cylindrical	ϕ5x10	372	9.6	345	6.7	318	3.3	190	7.3	206	9.0
		ϕ7x14	372	5.9	347	8.9	344	5.8	263	8.2	205	9.0
		ϕ10x20	411	7.0	363	6.2	341	9.1	301	3.1	257	9.2

Table 8.Flexural Strength of Prismatic Specimens (First Part)

Test Age	Specimen Type	Dimensions	Flexural Strength (kgf/cm^2)									
			w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
			Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Prismatic	4x4x16	74	4.1	61	12.8	59	7.2	57	7.4	51	0.2
		7x7x32	65	4.7	68	5.4	63	4.4	36	86.7	*	*
7 days	Prismatic	4x4x16	86	2.0	79	1.3	89	6.2	81	6.9	66	1.9
		7x7x32	83	1.1	80	2.6	87	2.2	72	3.1	66	7.3
28 days	Prismatic	4x4x16	112	3.3	105	4.4	99	4.7	99	1.9	91	3.4
		7x7x32	99	2.1	96	3.6	93	4.3	88	6.6	59	43.8

* These specimens broke during demolding.

Table 9.Density of Specimens (First Part)

Test Age	Specimen Type	Dimensions	Density (g/cm^3)									
			w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
			Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Prism	4x4x16	2.27	1.6	2.10	1.6	2.19	1.5	2.14	2.2	2.21	1.0
		7x7x32	2.21	1.4	2.12	1.6	2.15	1.7	2.18	3.7	*	*
	Cube	5x5x5	2.33	0.6	2.17	0.7	1.98	3.6	2.13	0.9	2.28	1.2
		7x7x7	2.20	1.0	2.17	0.6	2.17	1.5	2.18	1.0	2.09	0.8
	Cylinder	ϕ5x10	2.37	1.6	2.19	0.7	2.15	2.9	2.19	1.0	2.13	2.3
		ϕ7x14	2.35	1.8	2.18	1.2	1.17	2.5	2.19	1.5	2.13	2.2
		ϕ10x20	2.40	4.3	2.22	4.3	2.20	0.9	2.27	2.4	2.15	1.1
7 days	Prism	4x4x16	2.21	2.5	2.19	0.4	2.20	1.2	2.16	2.0	2.11	1.4
		7x7x32	2.21	0.5	2.15	1.0	2.20	1.3	2.16	1.0	2.13	3.4
	Cube	5x5x5	2.26	1.3	2.24	1.4	2.21	1.1	2.22	0.5	2.16	4.7
		7x7x7	2.21	1.5	2.17	0.7	2.21	1.0	2.20	0.4	2.24	1.0
	Cylinder	ϕ5x10	2.27	0.4	2.26	0.7	2.27	0.7	2.24	0.8	2.19	0.7
		ϕ7x14	2.25	1.2	2.25	3.0	2.26	2.0	2.23	1.6	2.16	1.8
		ϕ10x20	2.32	3.2	2.36	1.5	2.22	1.9	2.30	1.0	2.18	1.2
28 days	Prism	4x4x16	2.23	0.1	2.26	0.8	2.15	1.2	2.24	0.1	2.13	3.3
		7x7x32	2.22	2.0	2.18	1.6	2.25	1.0	2.17	2.0	2.08	0.4
	Cube	5x5x5	2.26	1.1	2.26	0.9	2.21	1.6	2.20	0,7	2.14	0.9
		7x7x7	2.24	0.5	2.17	0.6	2.21	0.7	2.19	0.4	2.14	1.0
	Cylinder	ϕ5x10	2.29	0.9	2.24	1.5	2.24	1.1	2.22	0.6	2.19	1.4
		ϕ7x14	2.27	1.6	2.22	1.1	1.92	5.3	2.21	2.0	2.15	1.6
		ϕ10x20	2.35	2.6	2.36	2.4	2.35	1.8	2.30	1.7	2.30	2.4

* These specimens broke during demolding.

Table 10.UPV of Prismatic, Cubical and Cylindrical Specimens (First Part)

(a) 54 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 54 kHz									
				w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
				Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
2 days	Prism	4x4x16	L=4	4728	2.5	4179	2.1	*	2.2	4343	1.2	3697	0.8
			L=16	4085	0.1	3848	0.9	*	2.4	3650	0.7	3326	0.5
		7x7x32	L=7	4468	0.8	4177	0.7	*	0.1	3758	1.1	3532	1.0
			L=32	3959	0.2	3823	0.6	*	1.9	3424	0.3	3160	1.0
	Cube	5x5x5	L=5	4606	1.9	4207	0.8	*	1.6	4132	2.0	3603	2.3
	Cylinder	ϕ5x10	L=5	4137	1.9	4098	1.7	*	1.6	3842	0.9	3676	1.1
		ϕ7x14	L=7	4143	1.2	4117	1.2	*	0.7	3829	0.7	3545	1.4
		ϕ10x20	L=10	4039	1.0	3937	2.1	*	3.6	3643	1.3	3634	2.8
7 days	Prism	4x4x16	L=4	5303	2.6	5182	1.2	*	1.0	5374	1.0	4566	1.5
			L=16	4366	0.2	4268	0.3	*	0.3	4240	0.8	3823	0.5
		7x7x32	L=7	4637	1.8	4603	0.7	*	0.4	4237	0.6	3973	1.0
			L=32	4189	0.4	4138	0.3	*	0.1	3859	0.1	3588	1.0
	Cube	5x5x5	L=5	4976	1.6	4832	1.5	*	0.6	4665	0.7	4216	2.2
	Cylinder	ϕ5x10	L=5	4534	1.8	4436	0.8	*	1.3	4291	0.9	4072	1.1
		ϕ7x14	L=7	4337	1.2	4316	1.1	*	0.5	4172	0.8	3974	1.4
		ϕ10x20	L=10	4230	1.5	4162	1.2	*	0.8	4022	0.7	3930	1.2
28 days	Prism	4x4x16	L=4	5863	0.2	*	0.8	5376	0.8	*	0.6	5076	5.5
			L=16	4425	0.2	*	0.3	4470	0.5	*	1.1	4163	0.1
		7x7x32	L=7	5069	0.5	*	0.2	4632	0.4	*	1.0	4393	0.1
			L=32	4367	0.1	*	0.1	4291	0.2	*	0.1	3953	0.1
	Cube	5x5x5	L=5	5341	1.3	*	1.0	5176	1.1	*	1.5	4639	3.5
	Cylinder	ϕ5x10	L=5	4871	1.1	*	1.1	4650	0.8	*	0.9	4544	1.5
		ϕ7x14	L=7	4577	0.8	*	0.3	4751	6.8	*	0.8	4219	1.0
		ϕ10x20	L=10	4502	1.4	*	0.4	4302	0.5	*	0.3	4176	0.8

* Because of a technical problem in the UPV instrument, measurements could not be obtained.

(b) 82 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 82 kHz									
				w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
				Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
2 days	Prism	4x4x16	L=4	4502	0.7	4628	1.2	*	0.5	4429	2.3	*	*
			L=16	3954	0.3	3906	0.8	*	0.3	3670	0.5	*	*
		7x7x32	L=7	4097	1.6	4307	1.2	*	1.2	3785	0.8	*	*
			L=32	3897	0.4	3868	1.2	*	0.1	3433	0.4	*	*
	Cube	5x5x5	L=5	4583	0.8	4579	1.7	*	1.0	4203	1.0	*	*
	Cylinder	ϕ5x10	L=5	4102	1.0	4213	2.0	*	1.0	3851	1.1	*	*
		ϕ7x14	L=7	3989	1.0	4151	1.7	*	1.0	3841	0.8	*	*
		ϕ10x20	L=10	3958	1.7	3971	2.5	*	1.7	3654	1.4	*	*
7 days	Prism	4x4x16	L=4	4971	1.2	5513	0.6	*	1.1	5383	1.8	4758	1.1
			L=16	4314	0.3	4301	0.4	*	0.5	4234	0.8	3898	0.6
		7x7x32	L=7	4481	1.2	4664	0.4	*	1.0	4271	0.7	4103	0.4
			L=32	4213	0.2	4163	0.1	*	0.4	3862	0.1	3689	0.4
	Cube	5x5x5	L=5	4818	0.9	5003	0.3	*	1.5	4675	0.7	4567	2.3
	Cylinder	ϕ5x10	L=5	4496	1.1	4544	1.6	*	0.2	4320	1.0	4170	1.3
		ϕ7x14	L=7	4431	0.4	4406	1.1	*	1.7	4183	0.6	4012	1.2
		ϕ10x20	L=10	4290	1.2	4203	1.2	*	1.0	4025	0.7	4008	2.1
28 days	Prism	4x4x16	L=4	5818	2.3	*	1.0	5797	1.5	*	0.5	5113	5.8
			L=16	4438	0.1	*	1.2	4532	0.3	*	1.1	4169	0.1
		7x7x32	L=7	5084	0.2	*	0.8	4865	0.7	*	0.3	4454	0.9
			L=32	4361	0.1	*	0.2	4320	0.1	*	0.1	3958	0.4
	Cube	5x5x5	L=5	5405	2.1	*	1.2	5324	2.3	*	1.0	4699	2.8
	Cylinder	ϕ5x10	L=5	4862	0.9	*	0.9	4800	0.9	*	0.5	4581	1.2
		ϕ7x14	L=7	4577	1.4	*	7.0	4845	0.5	*	0.8	4242	1.0
		ϕ10x20	L=10	4513	1.2	*	0.5	4371	0.4	*	0.4	4189	0.6

* Because of a technical problem in the UPV instrument, measurements could not be obtained.

(c) 150 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 150 kHz									
				w/c=0.43		w/c=0.52		w/c=0.53		w/c=0.61		w/c=0.68	
				Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
2 days	Prism	4x4x16	L=4	4486	2.4	4642	2.5	*	2.0	4359	1.7	*	*
			L=16	3959	0.4	3838	0.3	*	1.4	3646	0.4	*	*
		7x7x32	L=7	4090	1.1	4179	0.5	*	6.1	3756	1.3	*	*
			L=32	3934	0.4	3827	0.4	*	1.4	3418	0.2	*	*
	Cube	5x5x5	L=5	4504	1.3	4281	0.6	*	2.1	4139	1.7	*	*
	Cylinder	ϕ5x10	L=5	4018	1.5	4060	1.3	*	3.4	3838	1.0	*	*
		ϕ7x14	L=7	3936	1.1	4047	1.3	*	0.9	3837	0.5	*	*
		ϕ10x20	L=10	3977	1.8	3911	1.7	*	1.0	3630	1.8	*	*
7 days	Prism	4x4x16	L=4	5429	1.0	5189	1.4	*	0.7	5358	0.4	4204	1.2
			L=16	4385	0.7	4258	0.4	*	0.5	4248	1.0	3774	0.9
		7x7x32	L=7	4672	0.7	4597	0.6	*	1.0	4245	0.3	4076	1.1
			L=32	4222	0.1	4136	0.3	*	1.0	3858	0.1	3655	0.5
	Cube	5x5x5	L=5	4993	1.9	4874	1.4	*	0.9	4647	1.3	4403	2.1
	Cylinder	ϕ5x10	L=5	4566	1.0	4425	0.3	*	1.5	4293	1.0	4070	1.3
		ϕ7x14	L=7	4372	0.6	4316	1.0	*	1.0	4171	0.8	3943	2.6
		ϕ10x20	L=10	4225	1.2	4154	1.0	*	1.4	4022	0.7	3922	1.7
28 days	Prism	4x4x16	L=4	5780	2.2	*	0.4	5760	1.0	*	1.1	5078	4.0
			L=16	4427	0.1	*	0.2	4491	0.1	*	0.7	4161	0.1
		7x7x32	L=7	5061	0.4	*	0.5	4654	0.6	*	0.4	4397	0.7
			L=32	4363	0.1	*	0.1	4293	0.1	*	0.2	3955	0.2
	Cube	5x5x5	L=5	5335	1.5	*	1.4	5141	1.6	*	1.6	4655	2.5
	Cylinder	ϕ5x10	L=5	4855	1.1	*	0.9	4646	1.0	*	0.6	4557	1.5
		ϕ7x14	L=7	4573	1.2	*	0.5	4764	6.5	*	0.8	4224	0.9
		ϕ10x20	L=10	4500	1.1	*	0.6	4310	0.4	*	0.4	4177	0.7

* Because of a technical problem in the UPV instrument, measurements could not be obtained.

3.5. Second Part of Experiments

As mentioned earlier in the first part, because of a technical problem within the UPV measurements some of the UPV measurements could not be obtained on time. Therefore, a second experimental program was designed with reduced number of specimens.

3.5.1. Mixture Design (Second Part)

In the second part of experiments, 5 mortar mixtures were prepared. The cement content was again fixed at 500 kg and the w/c ratios were changed from 0.40 to 0.60 with increments of 0.05. The mixture design of the second part of experiments is presented in Table 11.

Table 11.Mixture Design (Second Part)

Mix Number	w/c	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)
1	0.40	200	500	1525
2	0.45	225	500	1441
3	0.50	250	500	1380
4	0.55	275	500	1332
5	0.60	300	500	1284

3.5.2. Test Data (Second Part)

Table 12 includes the mean compressive strength of cubic specimens at 2, 7, and 28 days, together with its coefficient of variation.

The mean flexural strength at 2, 7, and 28 days for prismatic specimens and their coefficient of variations are provided in Table 13.

Table 14 presents the averages and the coefficient of variations of density of all the specimens tested. The mean UPV of all the specimens for 54 kHz, 82 kHz, and 150 kHz at 2, 7, and 28 days and coefficient of variations of UPV are shown in Table 15.

Table 12.Compressive Strength of Cubical Specimens (Second Part)

Test Age	Dimensions	Compressive Strength (kgf/cm²)									
		w/c=0.40		w/c=0.45		w/c=0.50		w/c=0.55		w/c=0.60	
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	4x4x4	245	14.0	269	11.7	219	9.9	182	8.9	145	9.1
	5x5x5	262	4.7	264	5.6	218	5.0	173	9.8	155	8.6
7 days	4x4x4	364	9.2	338	8.6	308	10.9	272	7.6	199	7.9
	5x5x5	323	9.7	379	7.3	380	2.5	276	7.6	247	9.4
28 days	4x4x4	424	5.1	442	7.0	398	7.3	344	8.4	342	5.4
	5x5x5	432	3.8	484	5.7	432	9.5	349	3.0	322	12.7

Table 13.Flexural Strength of Prismatic Specimens (Second Part)

Test Age	Dimensions	Flexural Strength (kgf/cm²)									
		w/c=0.40		w/c=0.45		w/c=0.50		w/c=0.55		w/c=0.60	
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	4x4x16	62	18.1	63	5.1	64	4.7	63	5.3	56	3.3
7 days	4x4x16	65	6.3	90	8.5	84	3.0	77	6.9	70	5.2
28 days	4x4x16	107	4.2	110	1.9	109	3.1	107	4.9	98	2.1
	7x7x32	86	9.0	116	4.3	115	2.9	108	3.6	107	4.2

Table 14.Density of Specimens (Second Part)

Test Age	Specimen Type	Dimensions	Density (gr/cm^3)									
			w/c=0.40		w/c=0.45		w/c=0.50		w/c=0.55		w/c=0.60	
			Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Prism	4x4x16	2.18	0.2	2.12	0.6	2.16	1.7	2.17	0.2	2.13	0.9
		7x7x32	2.14	1.8	2.20	0.7	2.17	1.6	2.14	1.1	2.16	1.3
	Cube	5x5x5	2.22	1.0	2.17	3.3	2.18	1.6	2.13	3.4	2.14	2.8
7 days	Prism	4x4x16	2.21	1.7	2.20	0.5	2.18	0.8	2.24	2.3	2.14	3.9
		7x7x32	2.18	1.4	2.23	0.5	2.23	0.8	2.19	1.2	2.19	1.0
	Cube	5x5x5	2.22	1.5	2.23	1.3	2.26	0.7	2.20	1.1	2.18	1.8
28 days	Prism	4x4x16	2.22	0.5	2.24	0.4	2.22	1.1	2.24	0.6	2.20	1.0
		7x7x32	2.20	1.3	2.21	0.4	2.22	1.0	2.19	0.5	2.20	1.4
	Cube	5x5x5	2.27	1.0	2.26	0.6	2.25	0.6	2.22	0.9	2.22	0.5

Table 15.UPV of Prismatic and Cubical Specimens (Second Part)

(a) 54 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 54 kHz									
				w/c=0.40		w/c=0.45		w/c=0.50		w/c=0.55		w/c=0.60	
				Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Prism	4x4x16	L=4	4579	2.0	4361	0.4	4170	1.8	3947	0.7	3737	1.1
			L=16	4185	0.5	3744	0.4	3682	0.6	3607	0.3	3492	0.3
		7x7x32	L=7	4398	1.1	4124	0.6	3954	0.5	3772	0.7	3610	0.2
			L=32	4088	0.1	3999	0.3	3811	0.2	3599	0.2	3460	0.2
	Cube	5x5x5	L=5	4544	1.9	4275	0.9	4102	0.9	3848	0.6	3632	0.7
7 days	Prism	4x4x16	L=4	5019	1.2	4740	0.3	4553	0.7	4345	0.5	4167	0.3
			L=16	4457	0.3	4219	0.6	4136	0.3	3971	0.5	3876	0.3
		7x7x32	L=7	4694	0.6	4451	0.2	4322	0.8	4131	0.3	3981	0.7
			L=32	4381	0.1	4186	0.4	4094	0.3	3953	0.1	3815	0.1
	Cube	5x5x5	L=5	4975	1.1	4536	0.8	4318	0.8	4154	0.8	3965	0.5
28 days	Prism	4x4x16	L=4	5466	0.5	5257	0.5	4961	1.1	4651	0.7	4447	0.9
			L=16	4638	0.5	4479	0.1	4370	0.2	4232	0.4	4129	0.2
		7x7x32	L=7	4906	1.0	4666	0.2	4542	0.4	4390	0.1	4274	0.7
			L=32	4546	0.1	4368	0.1	4278	0.2	4186	0.1	4103	0.1
	Cube	5x5x5	L=5	5293	1.3	4984	0.9	4695	0.7	4434	0.7	4370	1.1

(b) 82 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 82 kHz w/c=0.40 Mean	w/c=0.40 COV (%)	w/c=0.45 Mean	w/c=0.45 COV (%)	w/c=0.50 Mean	w/c=0.50 COV (%)	w/c=0.55 Mean	w/c=0.55 COV (%)	w/c=0.60 Mean	w/c=0.60 COV (%)
2 days	Prism	4x4x16	L=4	4591	2.0	4361	0.5	4190	2.1	3960	0.5	3729	0.4
			L=16	4178	0.3	3750	0.4	3678	0.9	3608	0.4	3495	0.1
		7x7x32	L=7	4418	1.0	4152	0.7	3989	1.0	3791	0.8	3621	0.5
			L=32	4090	0.1	3918	0.3	3819	0.1	3599	0.2	3461	0.1
	Cube	5x5x5	L=5	4571	1.7	4278	1.0	4108	1.3	3852	0.8	3645	0.5
7 days	Prism	4x4x16	L=4	5040	1.2	4765	0.2	4553	0.7	4350	0.5	4167	0.2
			L=16	4457	0.2	4225	0.6	4140	0.3	3972	0.5	3877	0.4
		7x7x32	L=7	4691	0.8	4457	0.2	4325	0.5	4136	0.4	3988	0.8
			L=32	4376	0.1	4187	0.5	4095	0.4	3954	0.1	3816	0.1
	Cube	5x5x5	L=5	4982	1.2	4548	1.1	4330	0.7	4163	0.8	3963	0.5
28 days	Prism	4x4x16	L=4	5475	0.8	5264	0.7	4955	1.0	4645	0.5	4441	0.8
			L=16	4640	0.3	4481	0.2	4379	0.1	4233	0.4	4129	0.2
		7x7x32	L=7	4906	0.9	4673	0.1	4542	0.6	4396	0.2	4279	0.6
			L=32	4547	0.1	4367	0.1	4276	0.1	4186	0.1	4104	0.1
	Cube	5x5x5	L=5	5299	1.3	5013	1.2	4704	0.7	4434	0.6	4375	1.1

(c) 150 kHz

Test Age	Specimen Type	Dimensions		UPV (m/s) 150 kHz									
				w/c=0.40		w/c=0.45		w/c=0.50		w/c=0.55		w/c=0.60	
				Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
2 days	Prism	4x4x16	L=4	4608	2.0	4361	0.5	4180	2.2	3947	0.7	3714	0.5
			L=16	4185	0.4	3744	0.3	3675	0.3	3598	0.4	3491	0.1
		7x7x32	L=7	4407	1.1	4144	0.9	3922	0.4	3774	0.9	3594	0.5
			L=32	4090	0.1	3915	0.3	3804	0.1	3598	0.3	3458	0.1
	Cube	5x5x5	L=5	4561	1.9	4279	1.2	4090	1.4	3838	0.8	3622	0.7
7 days	Prism	4x4x16	L=4	5033	1.4	4752	0.1	4541	0.6	4350	0.5	4157	0.4
			L=16	4457	0.2	4219	0.7	4133	0.1	3971	0.5	3872	0.3
		7x7x32	L=7	4688	0.7	4431	0.1	4311	0.8	4129	0.3	3979	0.6
			L=32	4375	0.1	4183	0.4	4091	0.3	3953	0.1	3814	0.1
	Cube	5x5x5	L=5	4973	1.2	4532	0.9	4317	0.8	4158	0.7	3960	0.6
28 days	Prism	4x4x16	L=4	5483	0.7	5264	0.7	4975	1.2	4645	0.5	4431	0.9
			L=16	4634	0.3	4479	0.2	4374	0.2	4232	0.4	4128	0.3
		7x7x32	L=7	4910	1.1	4666	0.2	4539	0.5	4387	0.2	4271	0.6
			L=32	4547	0.1	4367	0.1	4279	0.1	4185	0.1	4103	0.1
	Cube	5x5x5	L=5	5290	1.2	4981	1.0	4695	0.6	4433	0.7	4371	1.1

The volume of the voids of the six specimens is provided in Table 16. Furthermore, the compressive strength and UPV values of these specimens both saturated and dry conditions are also given in Table 17 and 18, respectively.

Table 16.Volume of Permeable Pores (Voids)

w/c	Volume of Permeable Pores (%)	
	Mean	COV(%)
0.40	6.4	10.7
0.45	7.6	7.8
0.50	8.3	5.8
0.55	8.4	12.5
0.60	9.5	1.8

Table 17.Effect of Capillary Water on Compressive Strength

w/c	Compressive Strength (kgf/cm^2)			
	Saturated	COV(%)	Dry	COV(%)
0.40	432	3.8	497	5.5
0.45	484	5.7	485	9.5
0.50	432	9.5	436	10.6
0.55	349	3.0	426	13.0
0.60	322	12.7	333	9.2

Table 18.Effect of Capillary Water on UPV

w/c	UPV (m/s)											
	54 kHz				82 kHz				150 kHz			
	Sat. Mean	COV (%)	Dry Mean	COV (%)	Sat. Mean	COV (%)	Dry Mean	COV (%)	Sat. Mean	COV (%)	Dry Mean	COV (%)
0.40	5503	1.3	4655	1.3	5501	1.2	4670	1.4	5280	0.8	4659	1.4
0.45	4929	1.4	4371	1.5	4983	1.2	4374	1.4	4950	1.2	4377	1.6
0.50	4594	1.6	4127	1.4	4622	1.4	4128	1.2	4614	1.1	4124	1.6
0.55	4441	0.6	4094	2.0	4443	0.6	4098	1.9	4438	0.7	4093	1.9
0.60	4364	0.9	3831	2.4	4366	0.9	3836	2.4	4364	0.9	3828	2.4

CHAPTER 4

DISCUSSION OF RESULTS

4.1. Effects of w/c ratio

4.1.1. Compressive and Flexural Strength

The strength of a properly cured concrete at a given age is assumed to depend primarily on the w/c ratio for the same cement content and the degree of compaction. The w/c ratio affects the total capillary porosity content in the cement paste [Erdoğan 2002]. By keeping the cement content constant, an increase in w/c ratio of the cement paste results in the increase in capillary porosity of the paste, and the decrease in the strength. However, at low w/c ratio where full compaction is difficult to achieve, the relationship between the w/c ratio and strength is invalid as seen in Figure 17.

The effect of w/c ratio on the compressive and flexural strength is shown using both parts (part one and two) of the experiments. When both parts are combined, a total of ten w/c ratios ranging from 0.40 to 0.68 could be used.

Figures 18 and 19 present the compressive strength test results of 4x4x4 and 5x5x5 cubical specimens, and the flexural strength test results of 4x4x16 prismatic specimens, respectively. At each age, as the w/c ratio increases there is a decrease in the strength.
As seen from Figure 18, at 28 days the compressive strength varies between 440 kgf/cm^2 and 290 kgf/cm^2 for 4x4x4 cubical specimens and between 460 kgf/cm^2 and 210 kgf/cm^2 for 5x5x5 cubical specimens.

In Figure 19, it is seen that at 28 days the flexural strength changes between 110 kgf/cm^2 and 90 kgf/cm^2 for 4x4x16 prismatic specimens.

In both figures, it can be concluded that the relationship between the strength and w/c ratio is linear, and the decrease in the strength at some low w/c ratios is due to the method of compaction.

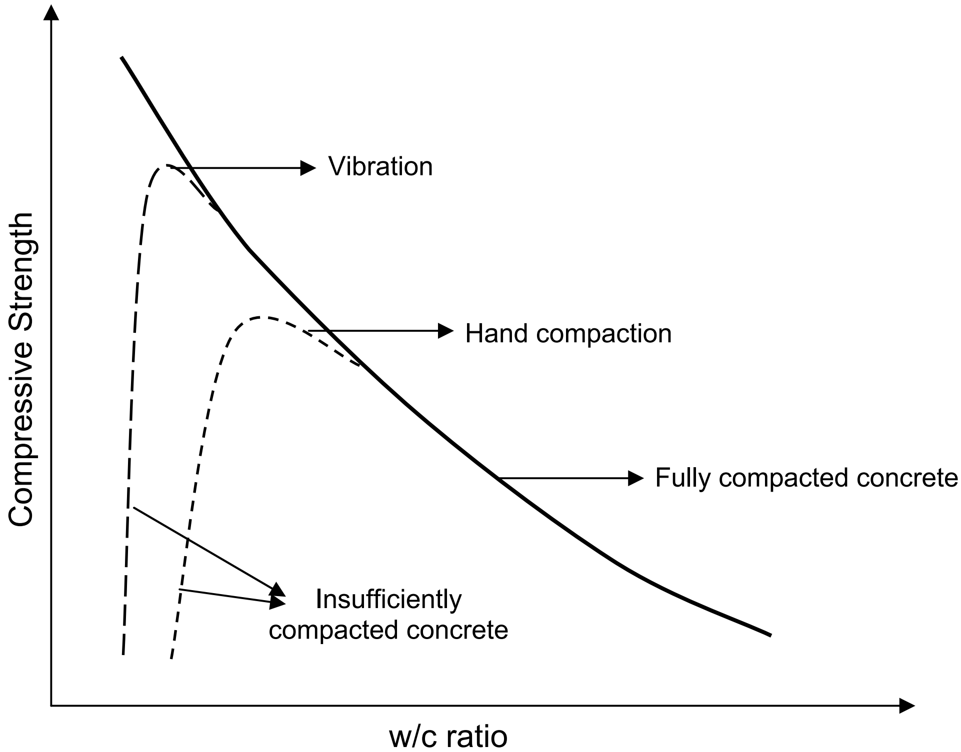
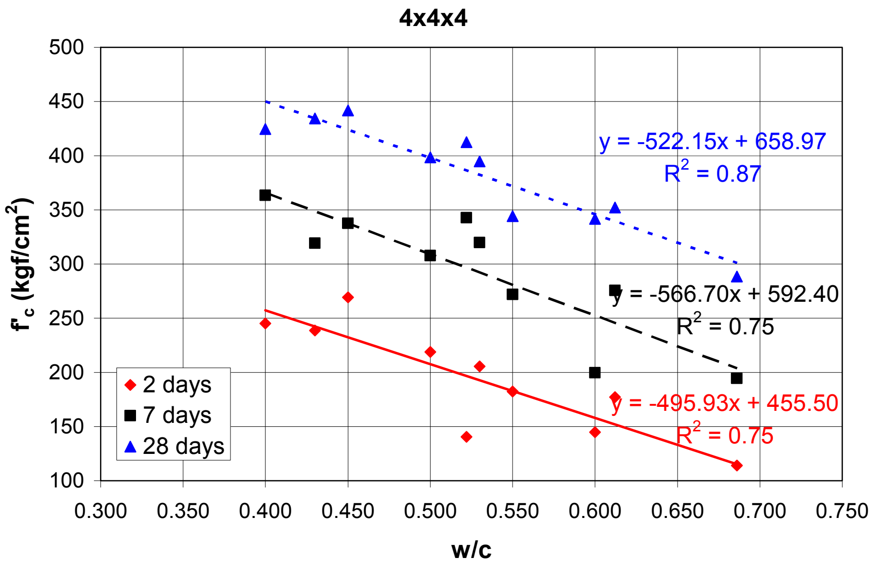


Figure 17.Relationship between the w/c Ratio and Strength [Erdoğan 2002]



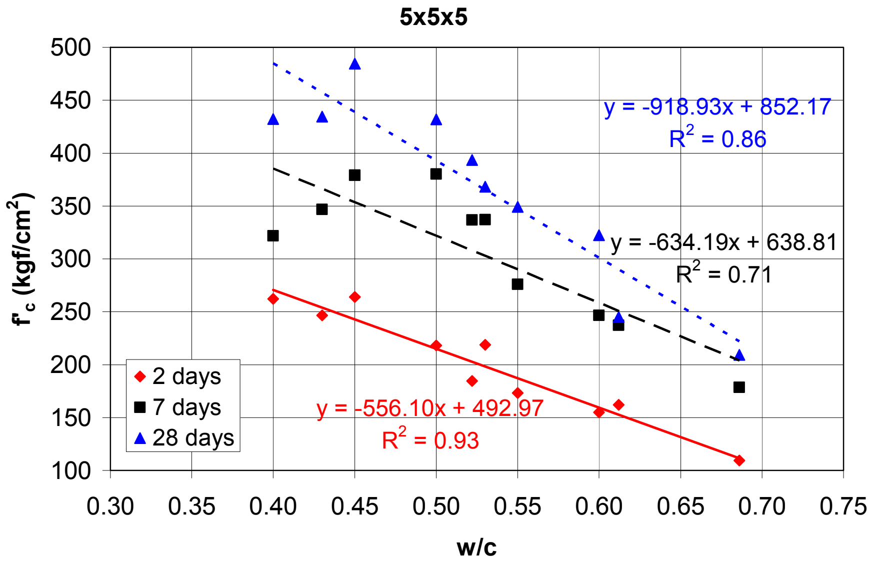


Figure 18.Effect of w/c ratio on Compressive Strength

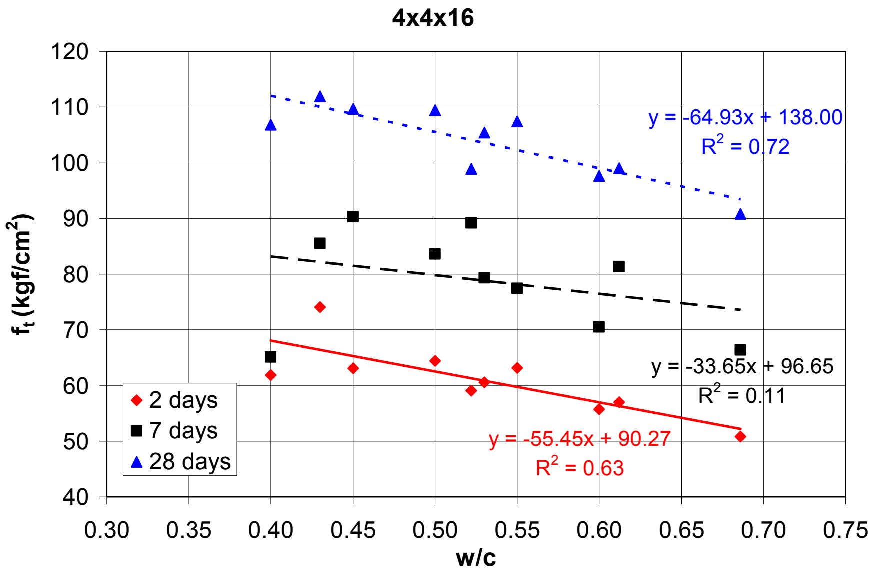
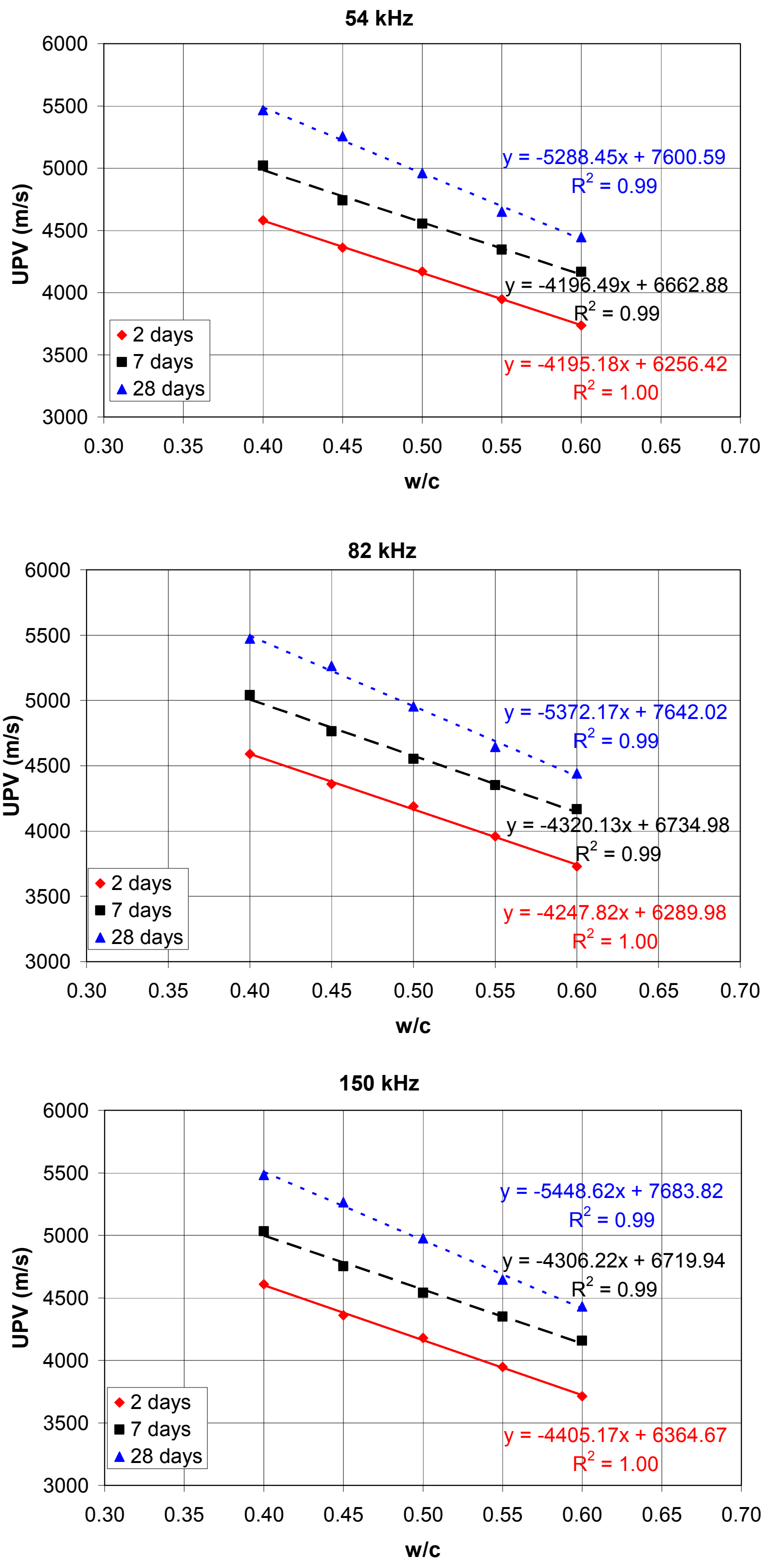


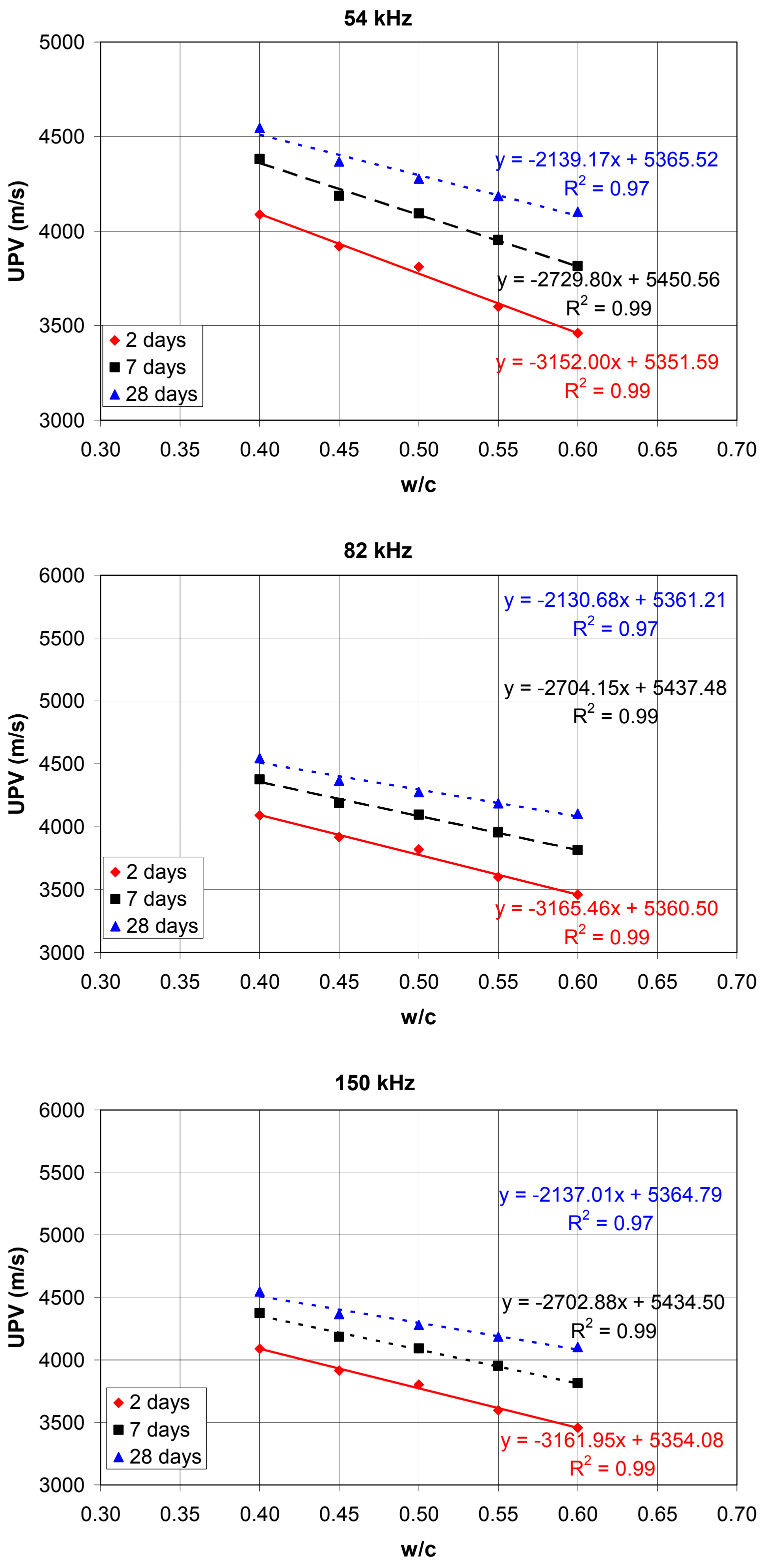
Figure 19.Effect of w/c ratio on Flexural Strength

4.1.2. UPV

The effect of w/c ratio on the UPV was investigated for all specimens and for each frequency (54, 82 and 150 kHz). Figure 20 presents the relationship between the UPV of the mortars determined at 2, 7, and 28 days of age, and w/c ratio for the minimum and maximum lengths used in the study. As it is seen from the graphs, there is a linear relationship between the w/c ratio and UPV, and the increase in w/c ratio results in a decrease in UPV. For specimens having lengths of 4 cm, UPV varies between the 5500 m/s and 4500 m/s, whereas for specimens having lengths of 32 cm, it varies between the 4500 m/s and 4100 m/s at age of 28 days. This reduction in UPV is due to the attenuation and will later be explained.


54 kHz
6000
5500
5000
4500
4000
3500
3000
UPV (m/s)
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
w/c
2 days
7 days
28 days
y = -5288.45x + 7600.59
R2 = 0.99
y = -4196.49x + 6662.88
R2 = 0.99
y = -4195.18x + 6256.42
R2 = 1.00
82 kHz
6000
5500
5000
4500
4000
3500
3000
UPV (m/s)
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
w/c
2 days
7 days
28 days
y = -5372.17x + 7642.02
R2 = 0.99
y = -4320.13x + 6734.98
R2 = 0.99
y = -4247.82x + 6289.98
R2 = 1.00
150 kHz
6000
5500
5000
4500
4000
3500
3000
UPV (m/s)
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
w/c
2 days
7 days
28 days
y = -5448.62x + 7683.82
R2 = 0.99
y = -4306.22x + 6719.94
R2 = 0.99
y = -4405.17x + 6364.67
R2 = 1.00

(a) For L = 4 cm



(b) For L = 32 cm

Figure 20.Effect of w/c ratio on UPV

4.2. Effect of Specimen Geometry

4.2.1. Compressive Strength

ASTM C 109/C and TS EN 196-1 are the standard test methods for determining the compressive strength of hydraulic cement mortars. In ASTM C 109/C, the compressive strength of hydraulic cement mortar is determined on 50 mm cube specimens. The mortar used consists of 1 part cement and 2.75 parts of sand proportioned by mass and w/c ratio is 0.485. 50 mm test cubes are compacted by tamping in two layers and cured one day in the molds and stripped and immersed in lime saturated water until tested. After removing the specimens from the lime saturated water, they are tested using a universal testing machine. The total maximum load is recorded and compressive strength is calculated by the equation shown in Table 19 [ASTM C109/C].

On the other hand, in TS EN 196-1, the cement mortar consists of 1 part cement, 3 parts standard sand and ½ part water, by weight. The cement mortar is placed in three molds that have 4 cm width, 4 cm height, and 16 cm length. The specimens are cured 24h in the molds and stripped and immersed in water until tested. After removing the specimens from water, they are first subjected to bending on the day the strength is tested. Each mortar bar is placed on two supports that are 10 mm apart and is loaded until the bar breaks, and flexural strength of each bar can be calculated. After the bending test, the compressive strength test is conducted on the broken halves of the mortar bars and the breaking load is found and the compressive strength is calculated using the equation as shown in Table 19 [TS EN 196-1].

Table 19.Standard Test Methods for Determining Compressive Strength of Hydraulic Cement Mortars

	ASTM C 109/C	TS EN 196-1
Specimen Geometry	Cube	Prism
Specimen Size	50 mm x 50 mm	40 mm x 40 mm x 160 mm
Number of Specimens	2 or 3	–
Curing Temperature	23±2 °C	20±1 °C
Mix Design	1 part of cement+ 2.75 parts of standard sand+ 0.485 w/c	1 part of cement+ 3 parts of standard sand+ 0.5 w/c
Compressive Strength	$f_m = P/A$	$R_c = F_c/1600$

$\mathbf{f_m}$ = compressive strength, MPa	$\mathbf{R_c}$ = compressive strength, N/mm2
P = total maximum load, N	$\mathbf{F_c}$ = maximum load, N
A = area of loaded surface, mm^2	**1600** = areas of plates, mm^2

In this study, both of the two test methods were used for determining the compressive strength and the relationship between them was shown by a graph (Figure 21). As seen from the graph, there is a linear relationship between the two standard test methods.

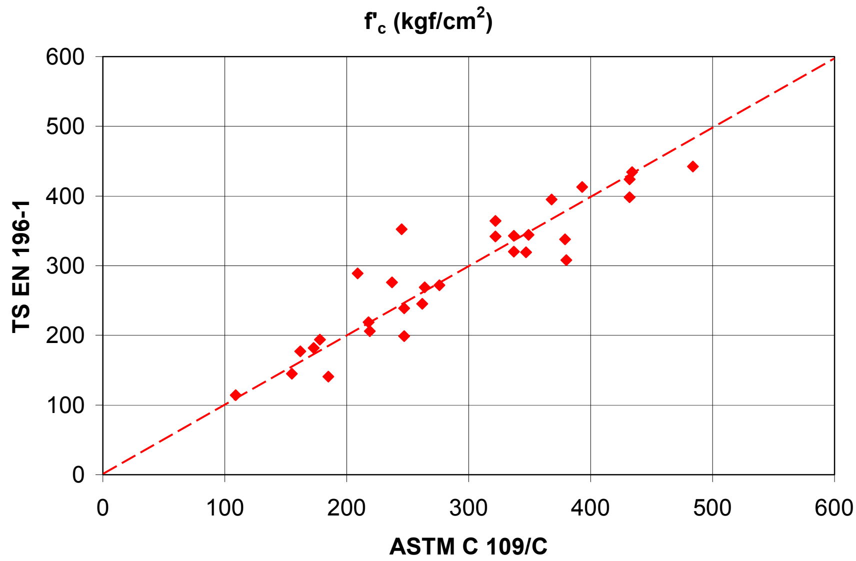


Figure 21.Comparisons of ASTM C 109/C and TS EN 196-1

4.2.2. UPV

4.2.2.1. Attenuation

The effect of specimen geometry on UPV could be investigated using the values in the Table 15. As an example, Figure 22 presents the UPV test results obtained at 28 days with 150 kHz frequency transducers with changing measurement length. As seen from this sample figure, the UPV decreases when the measurement length increases at all w/c ratios. The decrease in pulse velocity is attributed to the attenuation which is the loss of the wave energy as it propagates through the medium.

The UPV test results can be compiled as shown in Figure 23. In this figure the UPV measurements with a measurement length of 4 cm in x-axis is compared with all the other measurement lengths in y-axis for 2, 7 and 28 day measurements with 150 kHz frequency. As seen from this figure there is a constant decrease in the slope of the lines when the measurement length is increased.

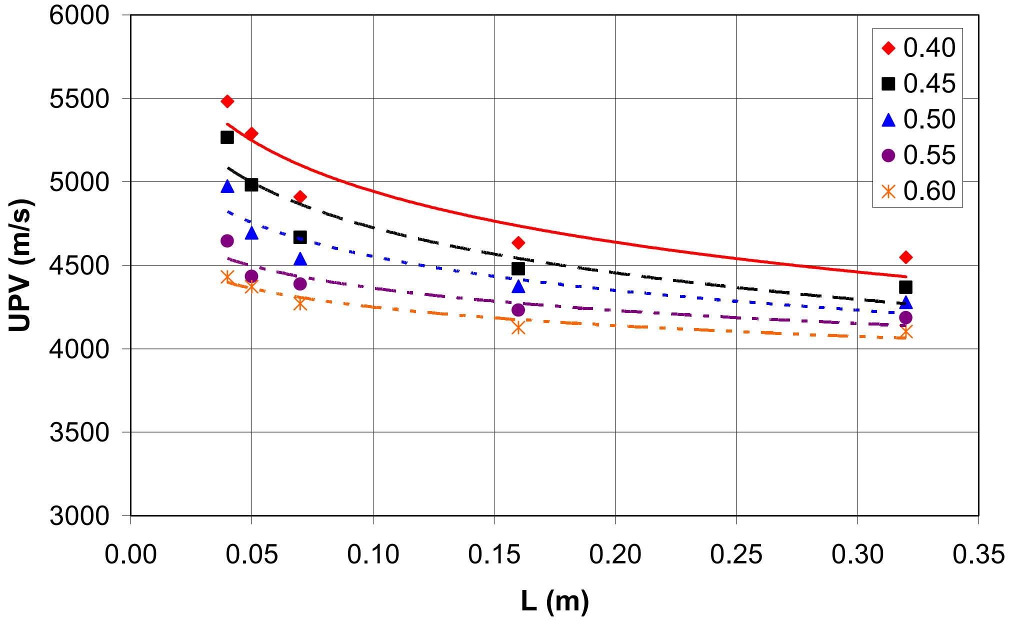


Figure 22.The relationship between UPV and Measurement Length (28 days and 150 kHz)

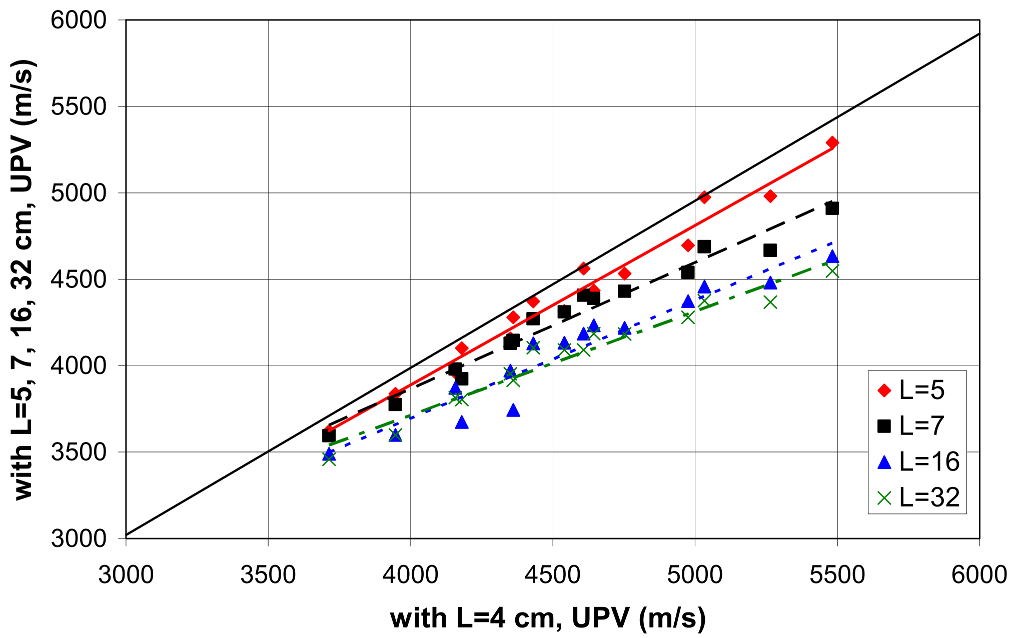
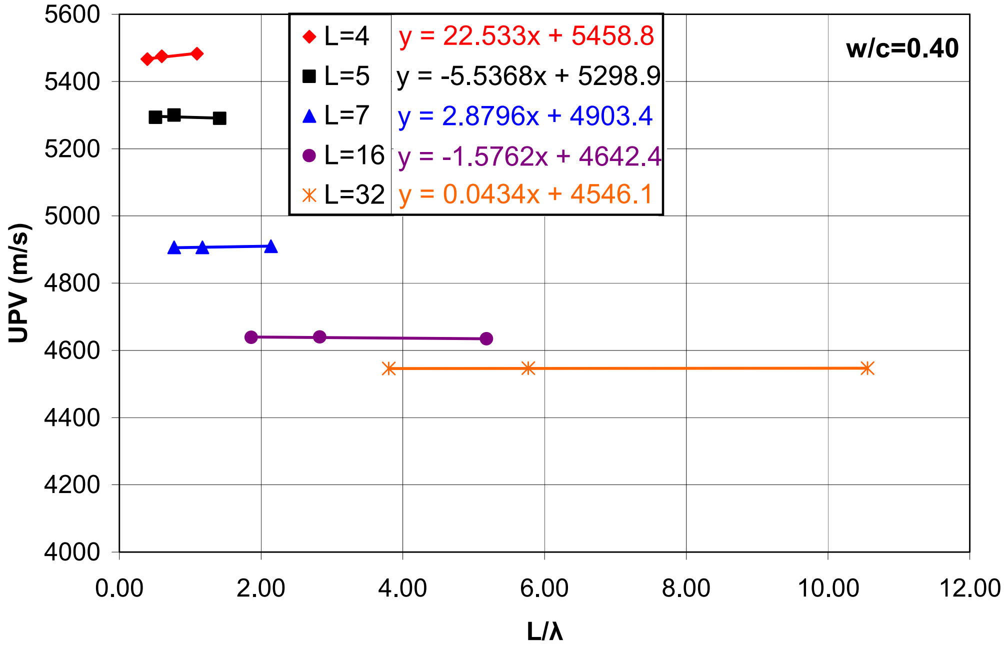


Figure 23.Reduction in UPV with Changing Measurement Length (150 kHz)

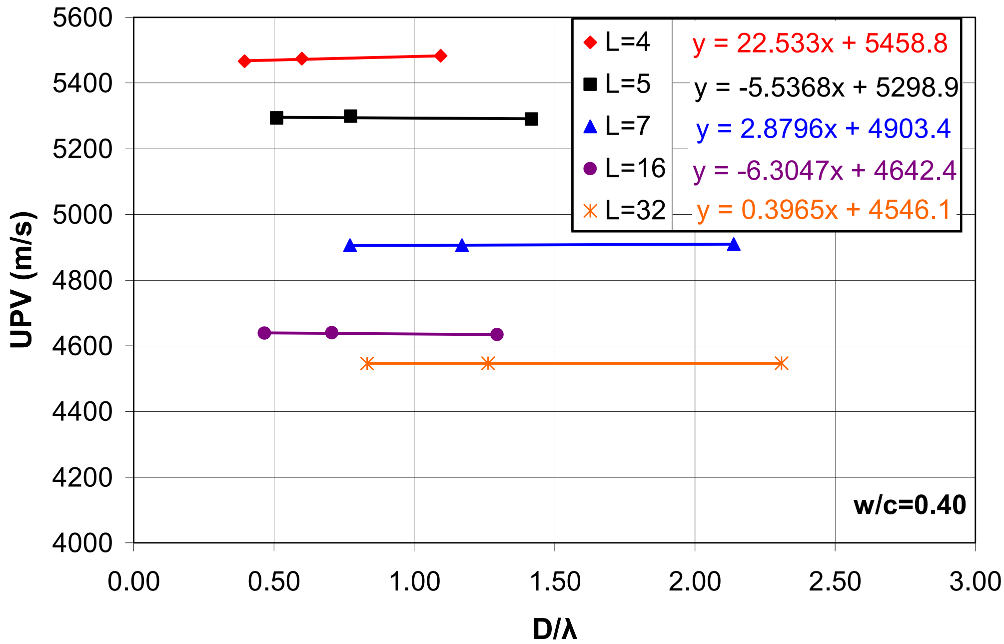
4.2.2.2. Testing Frequency

Figure 24 presents the effect of testing frequency on UPV of the mortars determined at 2, 7, and 28 days of age. In several standards there is conflicting information on the effects of transducer frequency on UPV. For example in the standard test method described for rocks, ASTM D 2845, it is stated that the natural resonance frequency of the transducers and the minimum lateral dimension of the specimen may affect the UPV test results. Therefore, it is recommended that the minimum lateral dimension of the test specimen will be at least five times greater than the wavelength of the traversed wave, and also recommended that the wavelength should be at least three times greater than the average grain size [ASTM D 2845]. However, when the standard test method for concrete, ASTM C 597, is examined, a requirement of the least dimension of the test object exceeding the wavelength of the ultrasonic vibrations is provided. Moreover, it is also stated in the standard that the pulse velocity is independent of the dimensions of the test object provided reflected waves from boundaries do not complicate the determination of the arrival time of the directly transmitted pulse [ASTM C 597].

To investigate the effect of transducer frequency and specimen geometry on the measured UPV, the test results are presented with respect to the length/wavelength (L/λ) and width/wavelength (D/λ) as shown in Figure 24 obtained for all w/c ratios. As seen from Figure 24, as the L/λ increases, measurement of UPV with three different transducers yields similar UPV results for each specimen length considered. For a L/λ smaller than one the slope of the fitted line increases which shows a higher variation in the measured UPV obtained from three different transducer frequencies.

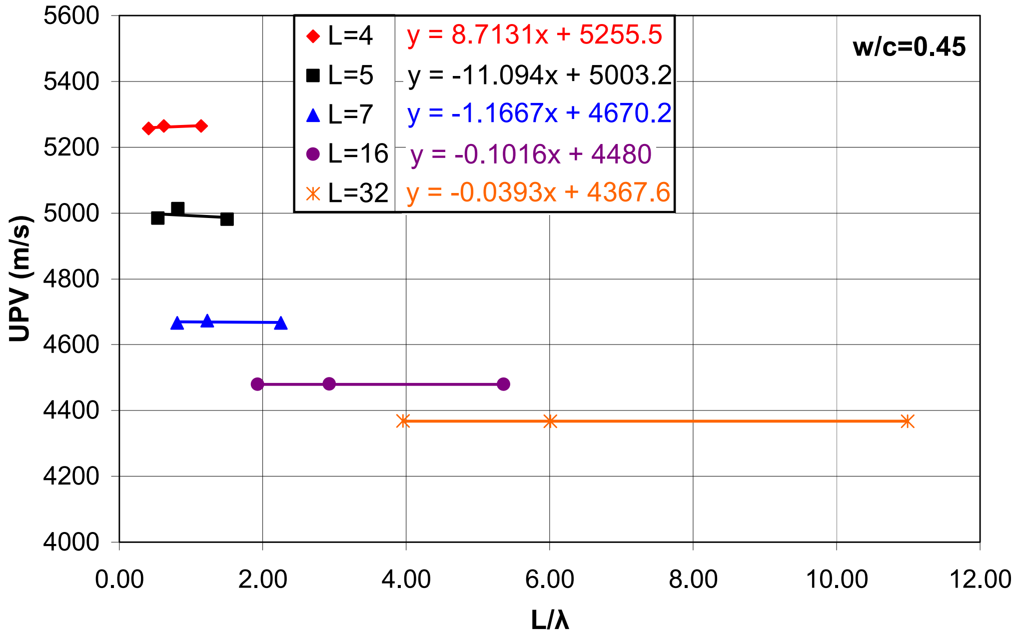


(i) Length

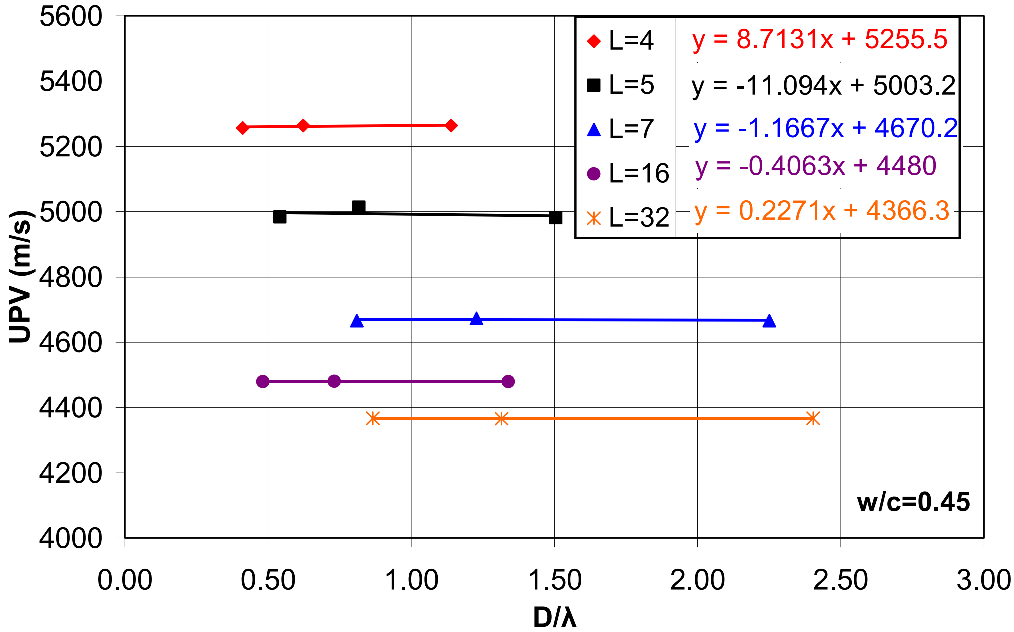


(ii) Width

(a) w/c=0.40

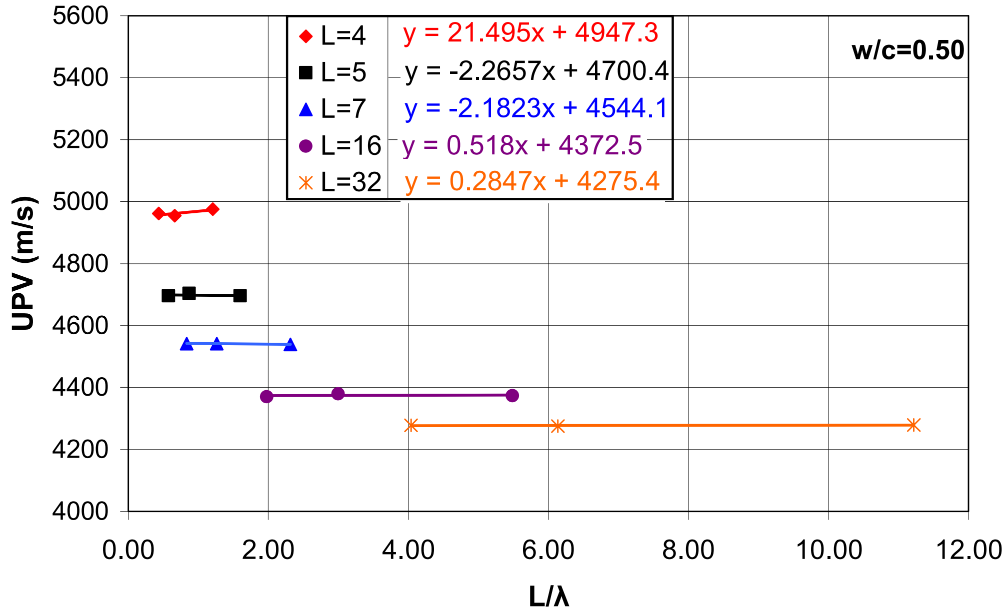


(i) Length

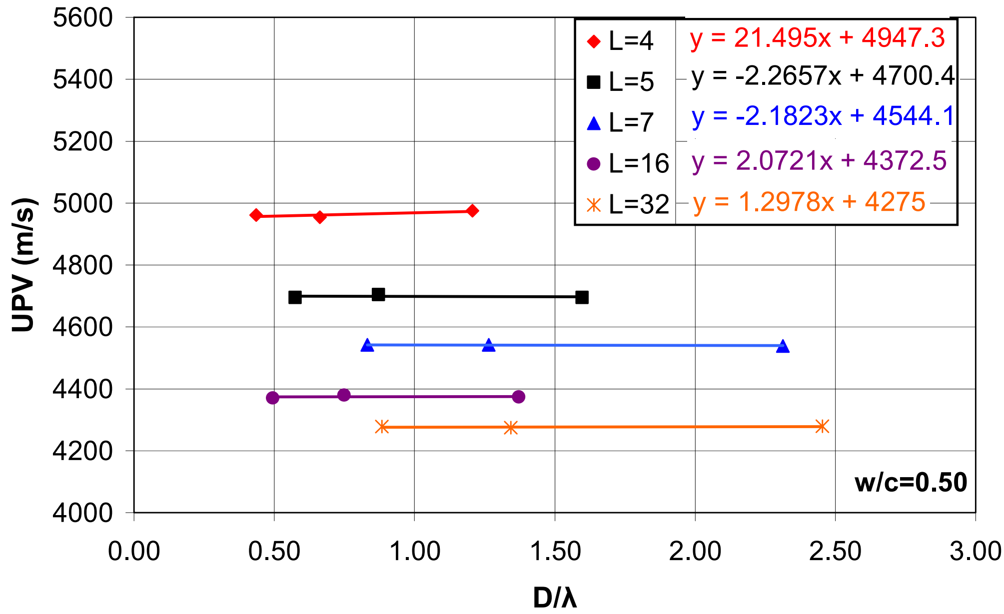


(ii) Width

(b) w/c=0.45

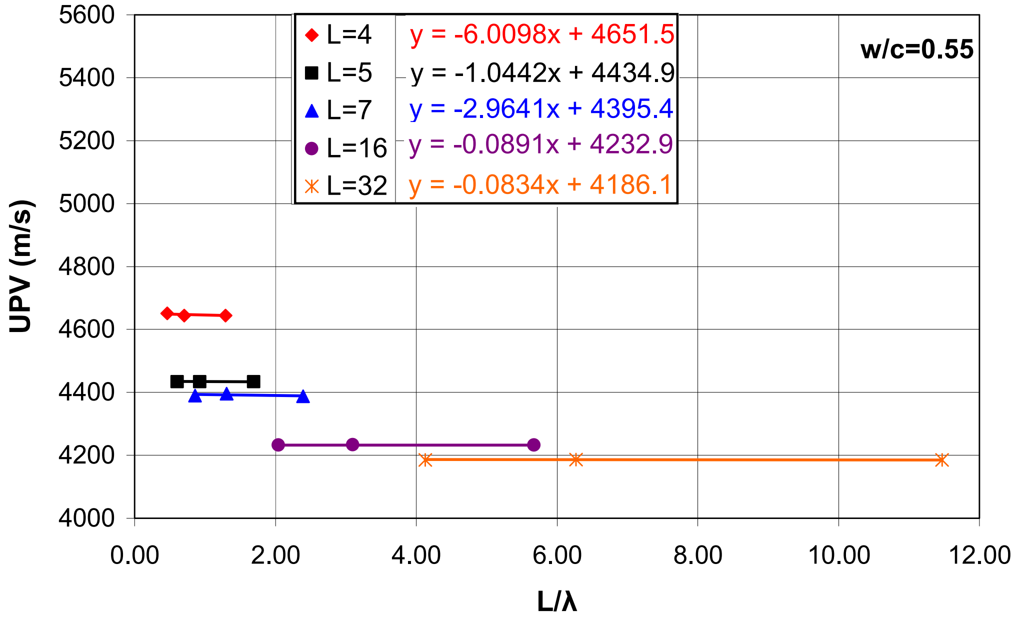


(i) Length

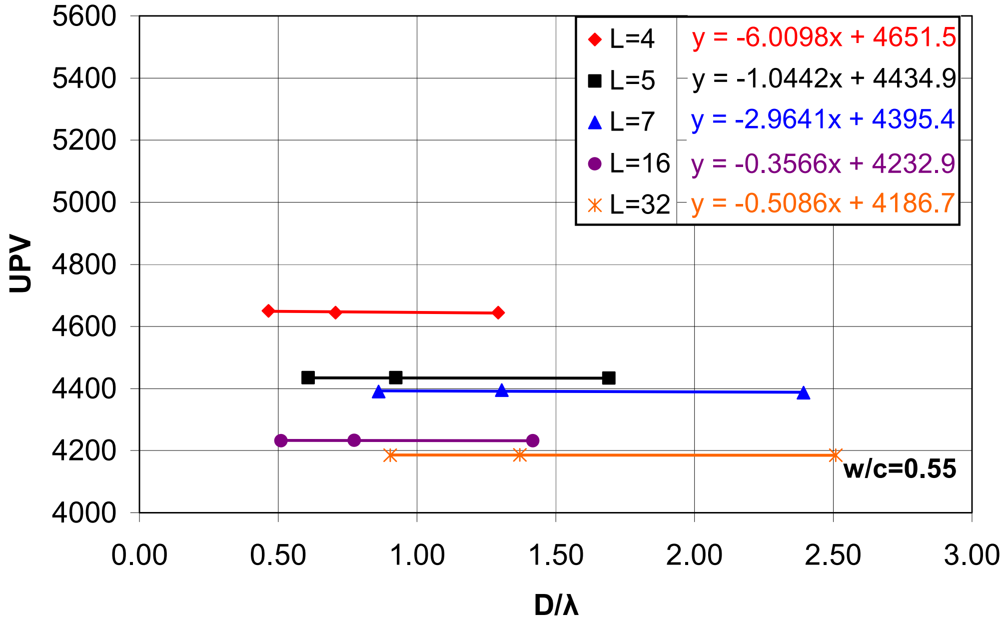


(ii) Width

(c) w/c=0.50

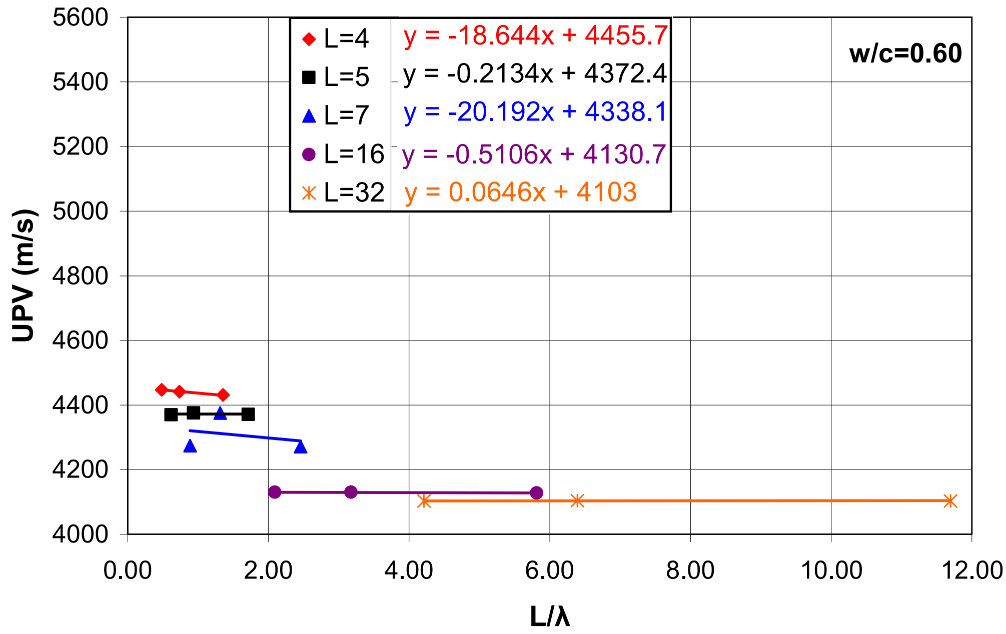


(i) Length

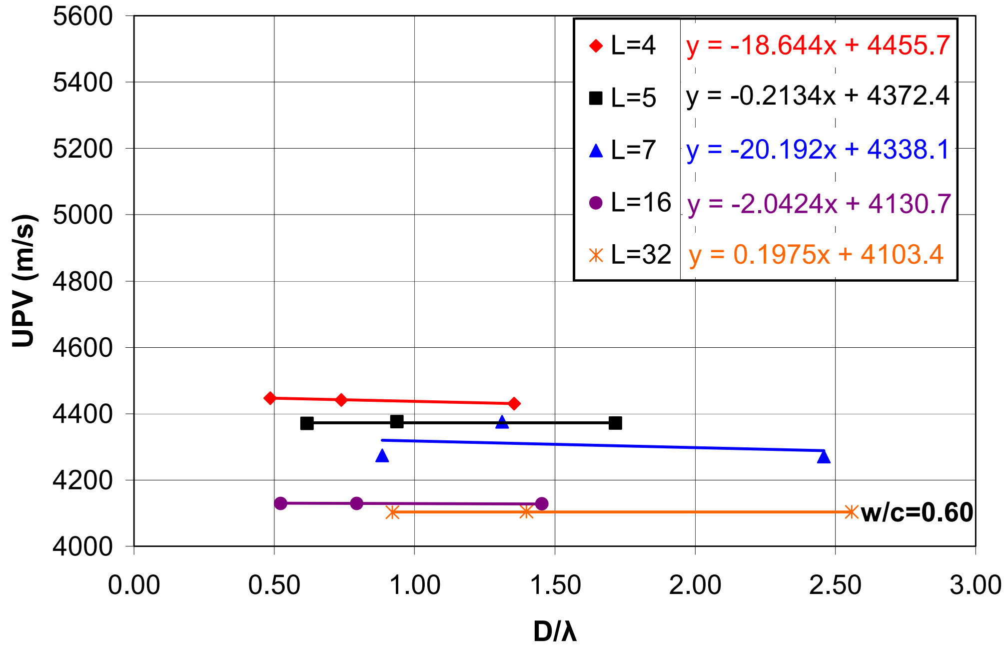


(ii) Width

(d) w/c=0.55



(i) Length



(ii) Width

(e) w/c=0.60

Figure 24.Effect of Testing Frequency and Specimen Geometry on UPV

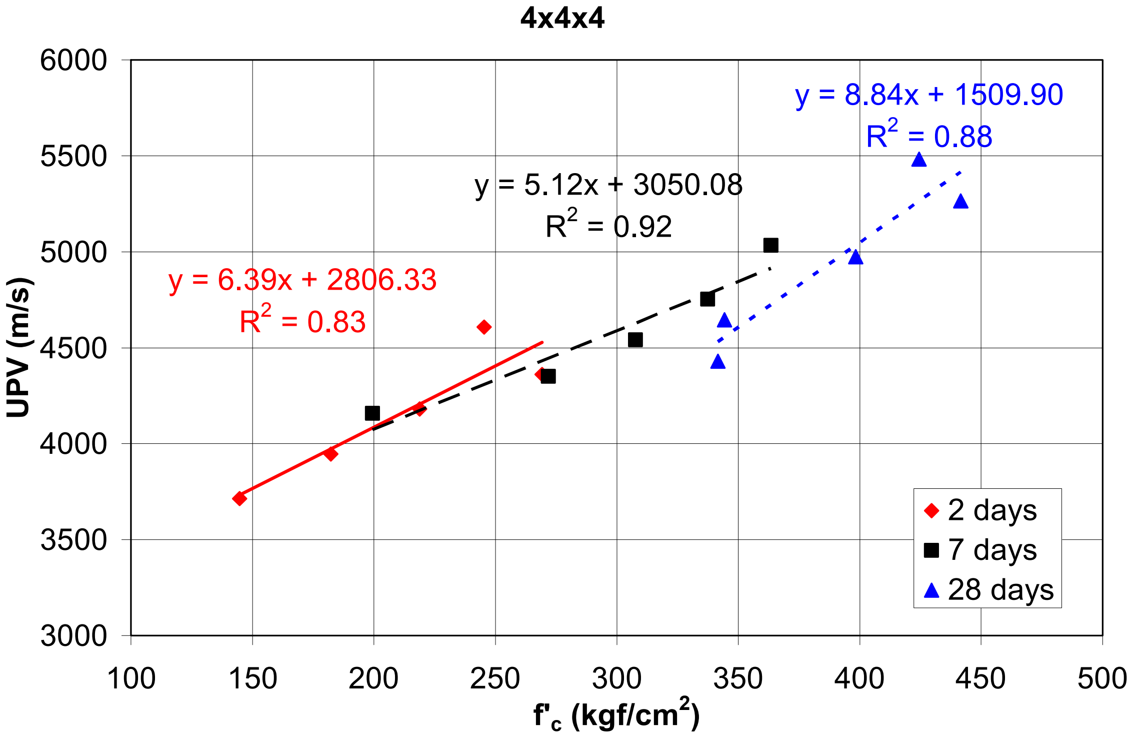
4.3. Relationship between Compressive Strength and UPV

Several studies have been made to investigate the relationship between the compressive strength and UPV for concrete. Their observation was also monitored in this investigation as presented in Figure 25. The linear relationship that exists between compressive strength and UPV varies, as the age of mortar increases.

There are several studies examining the relation between UPV and compressive strength of concrete, and such a relation for mortar has not yet been made. In those studies, the relation between compressive strength and UPV obtained using 150 kHz frequency of concrete is often considered as exponential as shown in the below equation [Popovics et.al., 1990, Río et.al. 2004].

$$f = ae^{-bv} \tag{9}$$

However, in this study, it was seen that a linear relationship between the UPV and compressive strength of mortar seems to best represent the data as presented in Figure 25. The graph in the figure was obtained for the two types of specimens, 4x4x4 and 5x5x5 cubical specimens, respectively. As seen from the two graphs the relation between compressive strength and UPV also changes with age. This was also mentioned by Sturrup et. al., as they concluded that a pulse velocity/compressive strength relationship developed at early ages is not applicable at later ages, and this relationship will be complicated by the presence of cracks or voids in the concrete due to improper consolidation [Malhotra 1984].



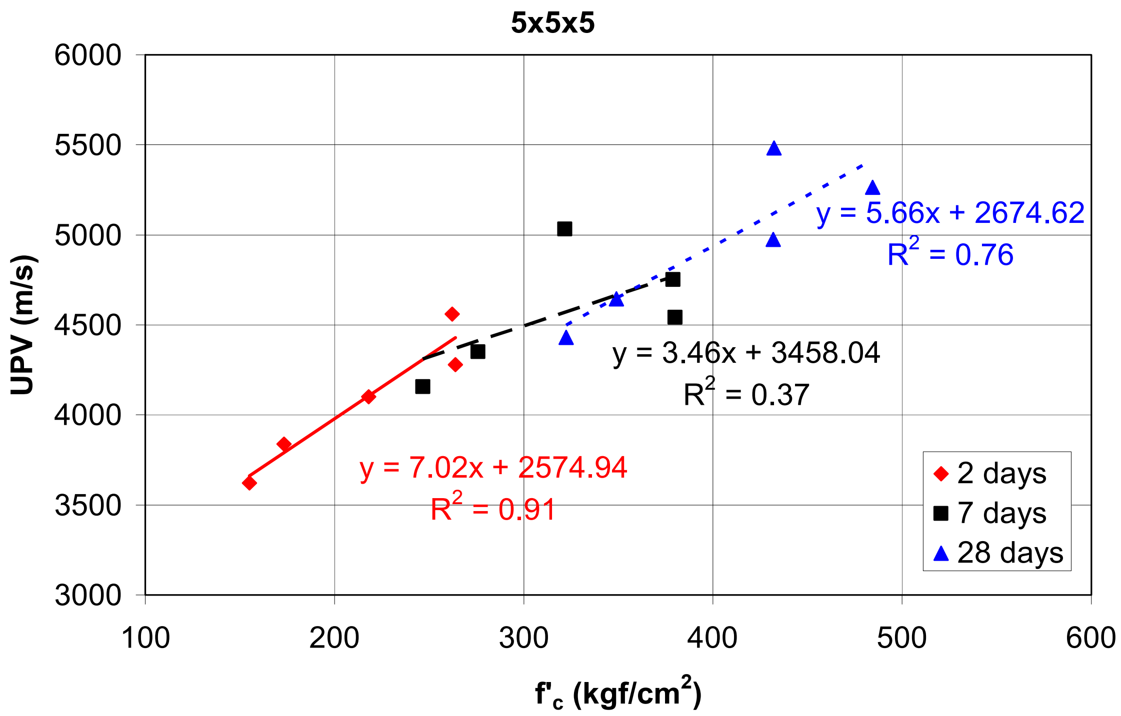
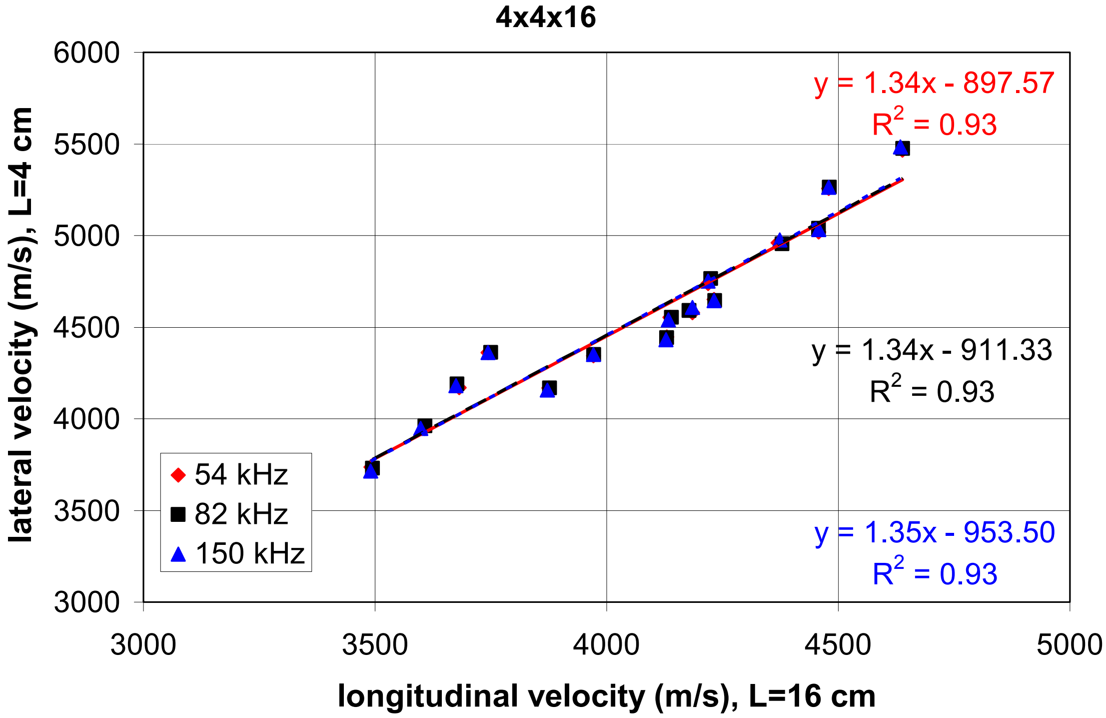


Figure 25.The relationship between Compressive Strength and UPV (150 kHz)

Moreover, Popovics and Rose also studied the estimation of concrete strength from pulse velocity measurement in 1989 by using concrete cylinder specimens, and as a result of their study, they concluded that the pulse velocity in the longitudinal direction of a concrete cylinder differs from the velocity in the lateral direction [Popovics et.al., 1990]. Their observation was also verified for mortars as presented in Figure 26. Moreover, according to Popovics and Rose, at low velocities the longitudinal velocities are greater, whereas at high velocities the lateral ones and, the pulse velocity in concrete increases with higher frequencies [Popovics et.al., 1990]. However, in this study, the lateral velocities are greater as attributed to the attenuation, and the pulse velocities in mortar will depend on the specimen geometry and wavelength as explained in the preceding section.



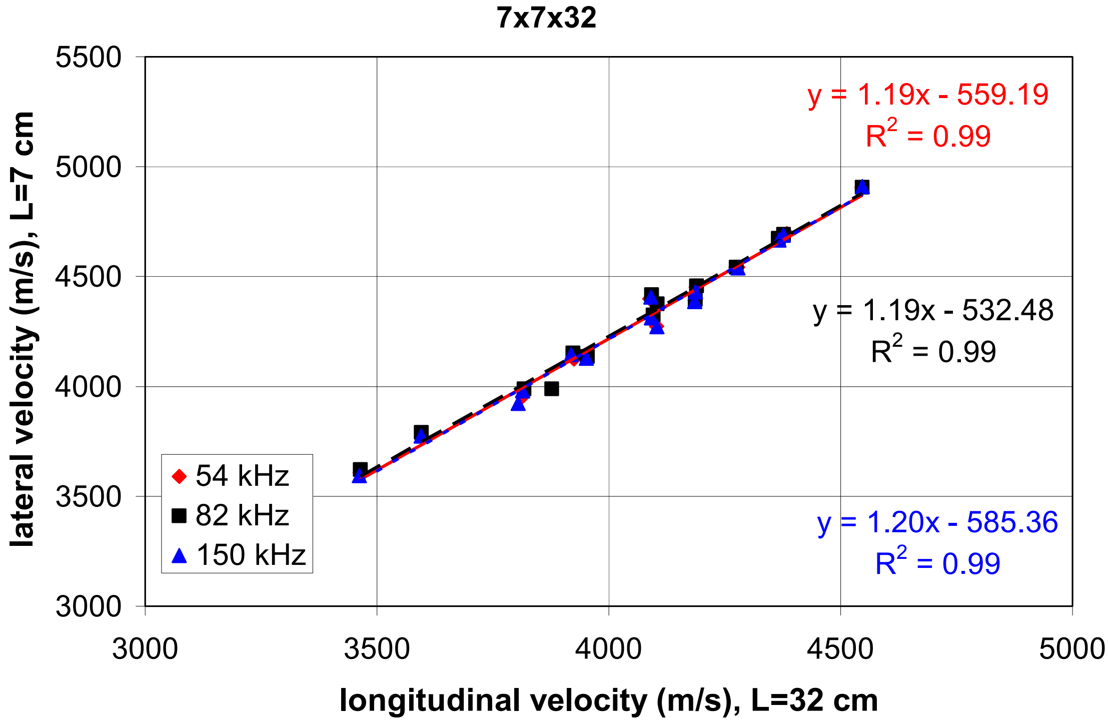


Figure 26.Longitudinal and Lateral Pulse Velocity of Mortars with different Frequencies at 28 days

4.4. Effect of Moisture Content on the Mechanical Properties of Mortars

Figure 27 presents the relationship between the w/c ratio and the volume of permeable pores or capillary porosity. As seen from that figure an exponential relationship between w/c ratio and capillary porosity exists. The effect of porosity and the moisture content of the concrete on its mechanical properties were discussed by Yaman and his colleagues [Yaman et. al. 2002]. Similar observations are also made for cement mortar and the effect of moisture content on UPV and compressive strength under dry and saturated conditions is demonstrated in Figure 28. As seen from these plots, an increase in moisture content results in an increase in UPV and a decrease in compressive strength. The increase in UPV resulting from an increase in moisture content can be explained as the waves being able to travel faster in the water filled pores. On the other hand, the decrease in compressive strength resulting from an increase in moisture content is due to swelling of the microstructure when water is absorbed [Yaman et. al. 2002b].

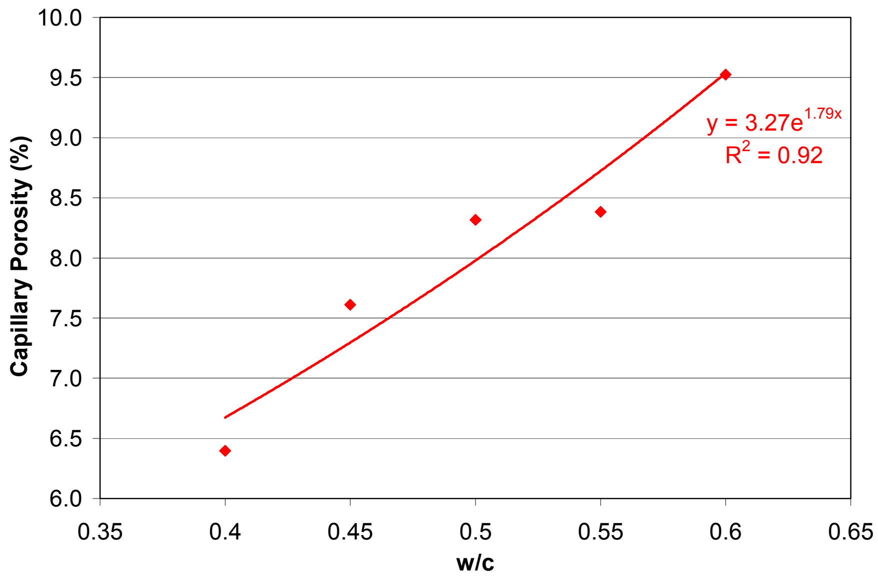
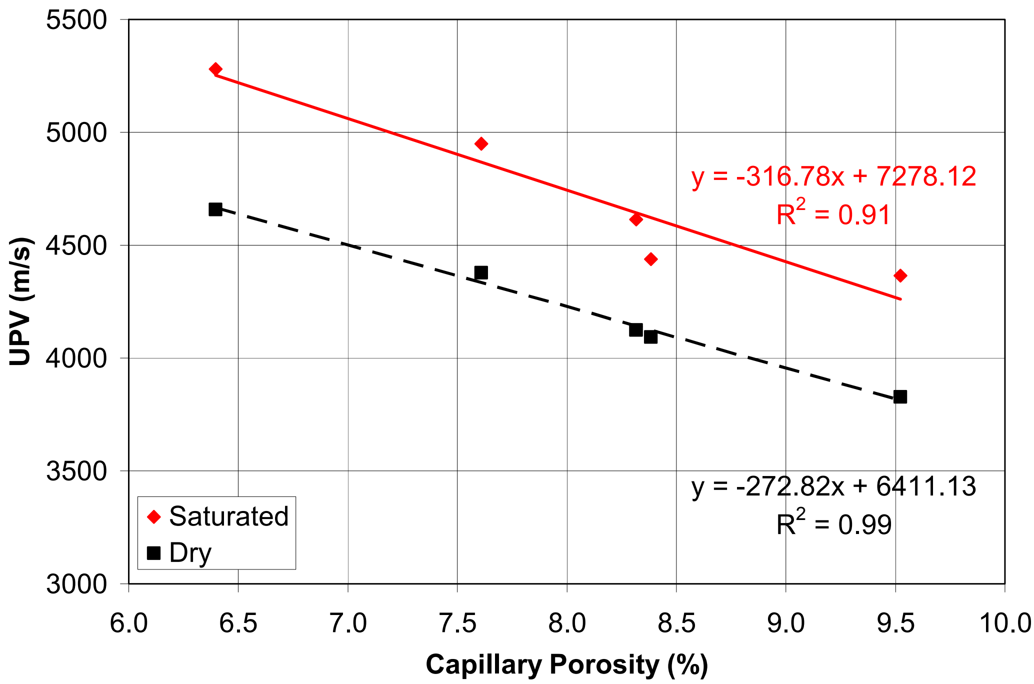
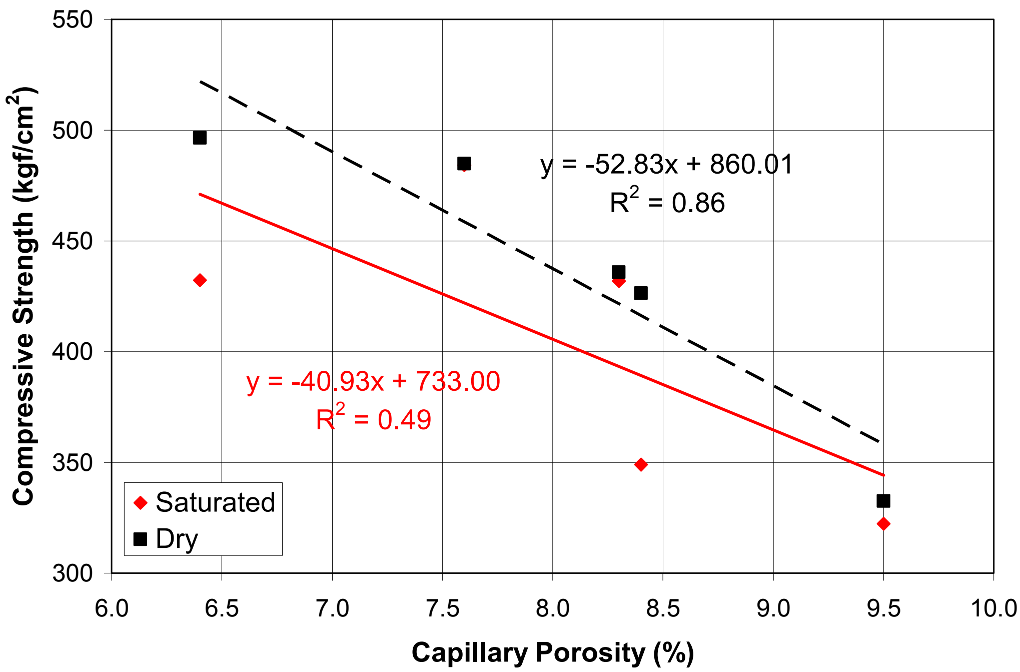


Figure 27.The relationship between the w/c ratio and capillary porosity



(a) UPV (150 kHz)



(b) Compressive Strength

Figure 28.Effect of Moisture Content on the Mechanical Properties of Mortars

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. Conclusions

In this study, ultrasonic pulse velocity (UPV) of mortars was determined with narrowband transducers of different central frequencies on different size and shape of specimens. Therefore, the relationship between ultrasonic testing frequency and specimen shape was experimentally investigated. Within the scope of the experimental study, mortar mixtures were prepared with various water-to-cement ratios and from each mortar mixture, cylindrical, cubical and prismatic specimens of various sizes were prepared. On these specimens UPV, compressive and flexural strengths were determined at 2, 7, and 28 days of mortar age. In addition, the total volume of permeable pores or capillary porosity of these mixtures was also determined, and the effect of capillary porosity and its saturation on the mechanical properties of mortar mixtures were determined.

The following conclusions could be drawn from the results of this study:

- The w/c ratio adversely affected the mechanical properties of mortars. An increase in w/c ratio caused a decrease in the compressive and flexural strength. Moreover, for lower w/c ratios compaction also became an issue and improper compaction caused reductions in the strength properties. The UPV of cement mortars was also adversely affected by the w/c. For the w/c ratios used in this study, a linear relationship exists between the w/c and the UPV.

- When the effect of specimen geometry on the compressive strength of mortars were considered, the two standard test methods ASTM C 109/C and TS EN 196-1 yielded similar compressive strengths for the mortar mixtures used in this study. However, when the effect of specimen geometry on the UPV of mortars were considered, it was observed that as the path length increases there is a significant decrease in the measured UPV. This was attributed to the attenuation of ultrasonic waves in the cement mortar.

- In ASTM D 2845 (pulse velocity testing of rocks), it is recommended that the minimum lateral dimension of the test specimen should be at least five times greater than the wavelength of the traversed wave. However, in ASTM C 597 (pulse velocity testing of concrete) that requirement is only one. As a result of this study, it can be concluded that, for cement mortars, as the traversed length (L or D) to wavelength (λ) ratio, L/λ or D/λ increases the results of the UPV test becomes more reliable, and the use of a 150 kHz transducer on a 4 or 5 cm length mortar specimen becomes more reliable as the wavelengths produced by the 150 kHz are, almost, three times smaller when compared to the 54 kHz transducers.

- The pulse velocity in the longitudinal direction of the mortar prismatic specimens is smaller when compared with the velocity in the lateral direction. This is attributed to the attenuation of the waves through the longer path.

- An exponential relationship between the volume of permeable pores or capillary porosity and w/c ratio exists. An increase in the moisture content results in an increase in UPV and a decrease in compressive strength.

5.2. Recommendations

The relationship between the compressive strength and UPV of mortars could be further studied with increased number of variables, such as cement content and mineral admixtures. Moreover, the attenuation characteristics of concrete and the frequency ingredient size relationship stated in standards could also be investigated.

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