DETERMINATION OF RELATIONS BETWEEN ELASTIC PROPERTIES OF CEMENT MORTARS BY USING DESTRUCTIVE AND NONDESTRUCTIVE METHODS

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ABSTRACT

DETERMINATION OF RELATIONS BETWEEN ELASTIC PROPERTIES OF CEMENT MORTARS BY USING DESTRUCTIVE AND NONDESTRUCTIVE METHODS

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The measurement and monitoring of the elastic properties of cement-based materials is very important for assessing their quality, integrity and performance. Due to the nonhomogeneous and time-dependent characteristics of these materials, it is difficult to observe the developments in elastic properties with traditional destructive methods.

The aim of this thesis is to determine and monitor elastic properties of mortar specimens made with different cements by using resonant frequency and ultrasonic pulse velocity test methods, and to obtain relationships between these elastic properties.

For this purpose, eight different cement mortar mixtures were prepared with different constituent CEM I cements. Dynamic elastic moduli, static elastic moduli, dynamic Poisson’s ratio and strength of these mixtures were observed for different ages. The relationships between these elastic properties are determined and the results obtained from two different nondestructive test methods are compared.

Although nondestructive tests made it possible to obtain elastic properties of mortar mixtures, the results revealed that it is very difficult to develop a single relationship between different elastic properties of mortars with varying mixture proportions. This situation is mainly due to the anisotropy and nonlinear behavior of the mortar and the difficulty of describing the actual behavior of mortar by formulations defined for perfectly elastic materials.

Keywords: Portland Cement Mortars, Ultrasonic Pulse Velocity Test, Resonant Frequency Test, Nondestructive Testing, Elastic Properties

ÖZ

ÇİMENTO HARÇLARININ ELASTİK ÖZELİKLERİ ARASINDAKİ İLİŞKİLERİN TAHRİBATLI VE TAHRİBATSIZ YÖNTEMLERLE BELİRLENMESİ

Deniz, Saygın
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Çimento esaslı malzemelerin kalitesinin, bütünlüğünün ve performansının değerlendirilmesinde bu malzemelerin elastik özeliklerinin ölçülmesi ve gözlemlenmesi önemli yer tutar. Fakat bu malzemelerin homojen olmayan ve zamana bağlı değişen yapısı, elastik özeliklerinin geleneksel tahribatlı yöntemlerle belirlenmesini zor kılar.

Bu tezin amacı, rezonans frekansı ve ultrasonik dalga hızı metotlarını kullanarak çimento harcı numunelerinin elastik özeliklerini saptamak, bu özeliklerin zaman içindeki değişimini gözlemlemek ve bulunan farklı elastik özelikler arasında bağıntı kurmaktır.

Bu amaçla, farklı CEM I çimentoları kullanılarak sekiz farklı harç numunesi hazırlanmıştır. Farklı yaşlardaki dinamik elastisite modülü, statik elastisite modülü, dinamik Poisson oranı ve dayanım özelikleri her bir karışım için gözlemlenmiştir. Elde edilen elastik özeliklerin birbirleriyle olan ilişkileri belirlenmiş ve iki farklı tahribatsız yöntemle elde edilen sonuçlar karşılaştırılmıştır.

Tahribatsız yöntemler harç karışımlarının elastik özeliklerinin saptanmasına olanak tanısalar da, test sonuçları farklı karışımların farklı elastik özelikleri arasında tek bir bağıntı kurulmasının çok zor olacağını açığa çıkarmıştır. Bu durum genel olarak harcın anizotropik ve lineer olmayan davranışına ve harcın gerçek davranışının tamamen elastik malzemeler için tanımlı formüller ile açıklanmasının zorluğuna bağlanabilir.

Anahtar Kelimeler: Portland Çimentolu Harçlar, Ultrasonik Dalga Hızı Metodu, Rezonans Frekansı Metodu, Tahribatsız Deneyler, Elastik Özelikler

To My Family...

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LIST OF ABBREVIATIONS

E_D	Dynamic Modulus of Elasticity (Dynamic Young’s Modulus)
E_S	Static Modulus of Elasticity
G_D	Dynamic Modulus of Rigidity (Dynamic Shear Modulus)
R.F.M.	Resonant Frequency Method
S.M.	Static Method
U.P.V.	Ultrasonic Pulse Velocity
U.P.V.M.	Ultrasonic Pulse Velocity Method
V_L	Longitudinal Wave Velocity
V_T	Shear Wave Velocity
υ	Poisson’s Ratio
f	Frequency
λ	Wavelength
ρ	Density
δ	Maximum Deflection at Beam Midpoint
σ	Standard Deviation

CHAPTER 1

INTRODUCTION

1.1 General

Cement-based materials such as mortar and concrete are the most commonly used fundamental materials in the construction industry. These composite materials consist of cement and water with fine and coarse aggregates. Various types of chemical and/or mineral admixtures are generally used in production of these materials to improve their properties. Types and amount of components along with production methods directly affect the characteristics of cement-based materials.

The popularity and wide spread use of concrete as a construction material derive from its advantages over other construction materials (Erdoğan, 2002). Since the use of concrete is extremely wide all over the world, the performance of this material is very significant, and has direct and indirect influences on people’s lives. As the performance of concrete govern the performance of infrastructure, measurement and monitoring performance of this material is very important for assessing its quality and for safety evaluation of structures.

Different techniques have been developed for observing the characteristics of cement-based materials up till now. However, techniques used in civil engineering for examining cement-based materials are generally destructive and expensive. Since these techniques are destructive, the tested specimens cannot be reused for repeat testing at later ages as a result (Hasar, 2009). Thus, developments or variations in material cannot be observed with time. Moreover, while evaluating the quality of these materials in buildings or structures, test results cannot be obtained immediately and generally these tests are time consuming.

Due to the reasons mentioned above, several nondestructive techniques have been proposed and applied for quality assessment, mixture content evaluation, and for monitoring the internal integrity of cement-based materials (Malhotra and Carino, 2004). Among these techniques, for new structures, the principal applications of nondestructive testing are likely to be for quality control or the resolution of doubts about the quality of construction or materials. The testing of existing structures is usually related to an assessment of structural adequacy (International Atomic Energy Agency, 2002).

The most important properties of cement-based materials are generally considered to be their elastic characteristics since they are mostly related with engineering design and give a direct idea about the existing structures. However, it is usually very grueling to obtain and monitor these time dependent characteristics of materials with traditional destructive methods.

On the other hand, resonant frequency and ultrasonic pulse velocity tests are the two major nondestructive tests which enable the determination of elastic properties of concrete, and the monitoring of developments in elastic properties over the time. Further, the results of these tests can be used to construct generalized correlations between several properties of concrete.

1.2 Objective and Scope

In this study, an experimental research program has been implemented on cement mortar specimens to initially obtain dynamic elastic moduli of specimens from resonant frequency and ultrasonic pulse velocity tests, and then to generate generalized and satisfactory relations between dynamic elastic moduli, static elastic moduli and strength of cement mortars. Since cement mortar is a time-dependent material, the development of its elastic characteristics is also aimed to be monitored.

For this purpose, mortar specimens using eight different CEM I type cements were prepared with the same water/cement ratio of 0.5. The experimental set–up was arranged for two nondestructive test methods according to the specification for each test. Dynamic elastic moduli, static elastic moduli and strength of each mixture were measured for different ages and corresponding results were used for establishing relationships between these elastic properties.

In this context, following this introduction, a detailed explanation of the theories related to the resonant frequency and ultrasonic pulse velocity test methods are compiled in Chapter 2. Then in Chapter 3, properties of the different mixtures prepared and details of the experimental studies performed are explained. In Chapter 4, results obtained from all tests and comparisons of these results with detailed discussions are provided. Finally, in Chapter 5, major research findings and the conclusions about the study are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 General Knowledge

A general definition of nondestructive testing is an examination test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or discontinuities that may have an effect on the usefulness or serviceability of that object (Hellier, 2003). Modern nondestructive testing history begins in the early 19th century with the first thermography observations. Despite its 200 year history, as a technology, there has been significant growth and unique improvement over the past 30 years.

With advances in technology; for metals and homogeneous materials, nondestructive techniques are routinely used to determine characteristics of these materials and there are accepted national and international standards on the use of these tests (Malhotra and Carino, 2004). However, for concrete, the use of nondestructive testing is comparatively new. The slow advance of nondestructive testing techniques for concrete is due to the nature of concrete. Unlike metals, concrete is a heterogeneous composite material with varying composition and properties. Moreover, the imperfect and varied production of concrete makes these tests harder to get a relation for it with.

Although concrete is not like metals and there are many drawbacks about its composition and nature, there has been progress in the development of nondestructive methods for testing concrete, and several nondestructive methods have been standardized by some organizations such as; American Society for Testing and Materials (ASTM), American Concrete Institute (ACI), Canadian Standards Association (CSA), International Standards Organization (ISO) and British Standards Institute (BSI) (Malhotra and Carino, 2004).

Nondestructive testing methods for concrete and cement mortar are generally used for measuring the properties directly related with the material's mechanical and physical characteristics. Methods are generally based on several formulations and the aim of these tests is to make accurate measurements for exploring material characteristics more easily, quickly and cheaply. In Table 2.1, the most common nondestructive tests used for concrete structures are shown with their major principles.

Table 2.1 Commonly-used nondestructive test methods and their principles

Nondestructive Test Method	**Major Principles**
Half Cell Electrical Potential Method	Detect corrosion potential of reinforcing bars in concrete
Schmidt Hammer Test	Calculate the surface hardness of concrete
Carbonation Depth Measurement Test	Determine the moisture depth in concrete
Permeability Test	Measure the flow of water through concrete
Penetration/Windsor Probe Test	Measure the surface hardness of concrete
Covermeter Testing	Measure the distance of reinforcing bars beneath surface of concrete
Radiographic Testing	Detect voids in concrete and the position of stressing ducts
Ultrasonic Pulse Velocity Testing	Measure the sound velocity of concrete, hence elastic properties
Resonant Frequency Tests	Measure the frequency of concrete, hence elastic properties
Tomography	Detect voids in concrete
Impact Echo Testing	Detect voids, delamination and other anomalies in concrete
Ground Penetrating Radar Testing	Detect the position of reinforcing bars
Infrared Thermography	Detect voids, delamination and other anomalies in concrete

Since concrete is a nonlinear, inelastic and nonhomogeneous structural material, its behavior under loads is different than other widely used engineering materials in that it is time dependent. Structural design using this material is generally related with its mechanical properties which are mainly considered to be as compressive and flexural strength and elastic modulus. Since structural design requires knowledge of mechanical characteristics of concrete, studies conducted on concrete are generally related to these properties.

For nondestructive testing, the situation is also similar in that several nondestructive tests are carried out to obtain strength and elastic moduli of concrete. According to ASTM C 215, resonant frequency of concrete and according to ASTM C 597, ultrasonic pulse velocity through concrete are directly related with its dynamic modulus of elasticity. Hence, by applying resonant frequency tests and ultrasonic pulse velocity tests on concrete, dynamic elastic modulus of this material can be easily obtained. Until now, a considerable amount of work about these test methods and dynamic elastic modulus has been carried out by various investigators. Usually, the aim of these investigations is to get generalized correlations between dynamic and static elastic moduli, and between dynamic elastic modulus and strength of the material. More detailed information about these nondestructive test methods and studies regarding elastic properties of concrete will be presented in the following sections.

2.2 Ultrasonic Pulse Velocity Test Method

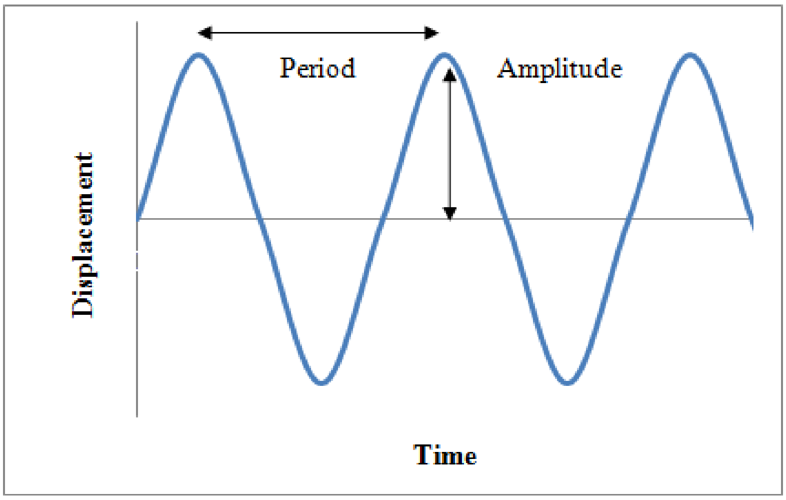
The ultrasonic pulse velocity test method is a nondestructive test method, as the technique covers the determination of the propagation of mechanical (stress) waves through concrete. According to Malhotra and Carino (2004), the ultrasonic pulse velocity method has been successfully used to evaluate the quality of concrete for more than 65 years, and can be used for detecting internal cracking and other defects as well as changes in concrete such as deterioration due to aggressive chemical environment or freezing and thawing, and also for estimating the strength of concrete test specimens.

2.2.1 Theory of Wave Propagation

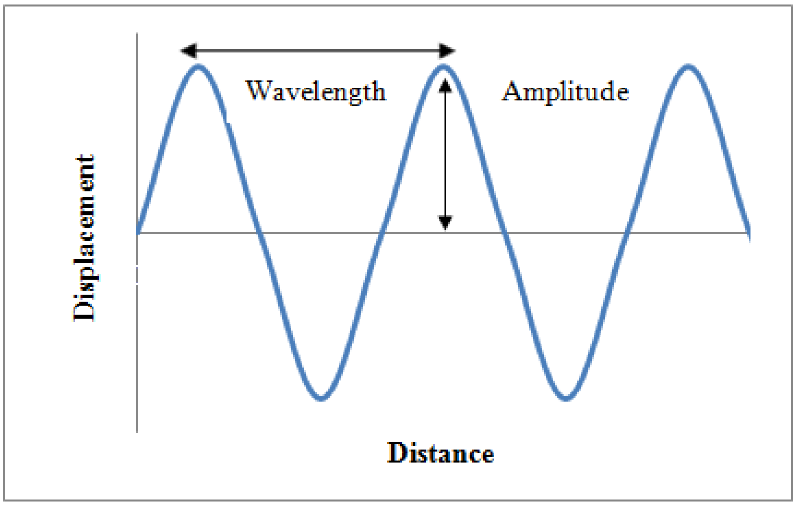
According to Wikipedia (2009), a wave is defined as a disturbance that propagates through space and time, usually with transference of energy where a mechanical wave (or stress wave) is a wave that propagates or travels through a medium due to the restoring forces it produces upon deformation. The wave parameters, generally embodied by amplitude, wavelength, period and frequency, are defined in Wikipedia (2009) as follows:

Amplitude is defined as the magnitude of change in the oscillating variable, with each oscillation, within an oscillating system. The wavelength is the distance over which the wave's shape repeats and period is defined as the duration of one cycle in a repeating event. Period is also described as the reciprocal of the frequency since frequency is the number of occurrences of a repeating event per unit time. These major parameters of wave for constant amplitude are shown in Figure 2.1.

There are three different types of waves created when the surface of a large solid elastic medium is disturbed by a dynamic or vibratory load. These waves are; the compressional waves (longitudinal or P-waves), the shear waves (transverse or S-waves), and the surface waves (Rayleigh or R-waves) (Malhotra and Carino, 2004). The P-wave is associated with the propagation of normal stress and particle motion is parallel to the propagation direction. The S-wave is associated with shear stress and particle motion is perpendicular to the propagation direction. Lastly, R-wave travels away from the disturbance along the surface (ACI Committee 228, 1998). Among these three types of waves, for concrete, it has been noted that longitudinal wave has the highest velocity and the velocity of shear and surface waves are typically 60 and 55 percent of the longitudinal wave velocity, respectively (Malhotra and Carino, 2004).



(a) Time domain



(b) Space domain

Figure 2.1 Wave parameters

For a homogeneous medium, the frequency f and wavelength λ of propagating wave motion are related by the velocity of propagation as follows (Malhotra and Carino, 2004);

$$V = f \times \lambda \tag{2.1}$$

Moreover, ACI Committee 228 (1998) has stated that the velocity of stress wave propagation in an elastic solid is also a function of the modulus of elasticity, Poisson's ratio, the density, and the geometry of the solid. Thus, this relationship between the properties of a solid and the resultant stress wave propagation behavior permits assumptions about the characteristics of the solid by monitoring the propagation of stress waves.

For elastic, homogeneous and isotropic media, longitudinal wave velocity V_L is related to the dynamic modulus of elasticity E_D; Poisson's ratio ν; and the density ρ as follows (Krautkrämer and Krautkrämer, 1990);

$$V_L = \sqrt{\frac{E_D(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \tag{2.2}$$

On the other hand, shear wave velocity V_T is related to dynamic modulus of rigidity $G_{D;}$ and the density ρ of solid as follows (Krautkrämer and Krautkrämer, 1990);

$$V_T = \sqrt{\frac{G_D}{\rho}} \tag{2.3}$$

2.2.2 The Pulse Velocity Method for Concrete

Since the velocity of a pulse of longitudinal waves through a medium depends on the elastic properties and density of the medium, as shown in equation 2.2, ultrasonic test methods can be used to assess and estimate many different characteristics of concrete such as uniformity, quality, deterioration and cracking properties, strength, elastic modulus etc. Furthermore, as mechanical waves result in no damage to the concrete element being tested, this method gives the chance to monitor changes in concrete over long periods of time since the test specimen can be tested again and again at the same location. Due to these opportunities about the test, numerous studies about this method have been evaluated by various investigators and the test method is standardized as ASTM C 597 “Standard Test Method for Pulse Velocity through Concrete”.

According to ASTM C 597, the fundamental principle of ultrasonic testing depends on measuring the velocity of longitudinal waves propagating through concrete. To measure the wave velocity, the test instrument produces a wave pulse from one surface of the concrete and then senses the arrival of the pulse at the other surface of the concrete. It is important for the test instrument to measure the time taken by the pulse to travel through the concrete accurately. An instrument of ultrasonic pulse velocity test, a schematic representation of which can be seen in Figure 2.2, consists of a pulse generator, a pair of transducers (transmitter and receiver), an amplifier, a time measuring circuit, a time display unit, connecting cables and an optional display device. The transmitter sends the pulse wave into the concrete and the receiver, at a distance L, receives the pulse through the concrete at another point. The transit time of pulse between transmitter and receiver, Δt, is measured and displayed in time display units. The equipment may also be connected to an oscilloscope, or other display device, to survey the nature of the received pulse. By measuring travel distance and getting transit time from the test instrument, it is easy to obtain ultrasonic pulse velocity (UPV) using Equation 2.4. Since accuracy of this method depends on accuracy of transit time and travel distance measurement, ASTM C 597 recommends coupling agents such as oil, grease, moldable rubber, water soluble jelly and petroleum jelly for eliminating air between the contact surfaces of the concrete and transducers and so for ensuring the efficient transfer of energy between the concrete and the transducers.

$$UPV = \frac{L}{\Delta t} \tag{2.4}$$

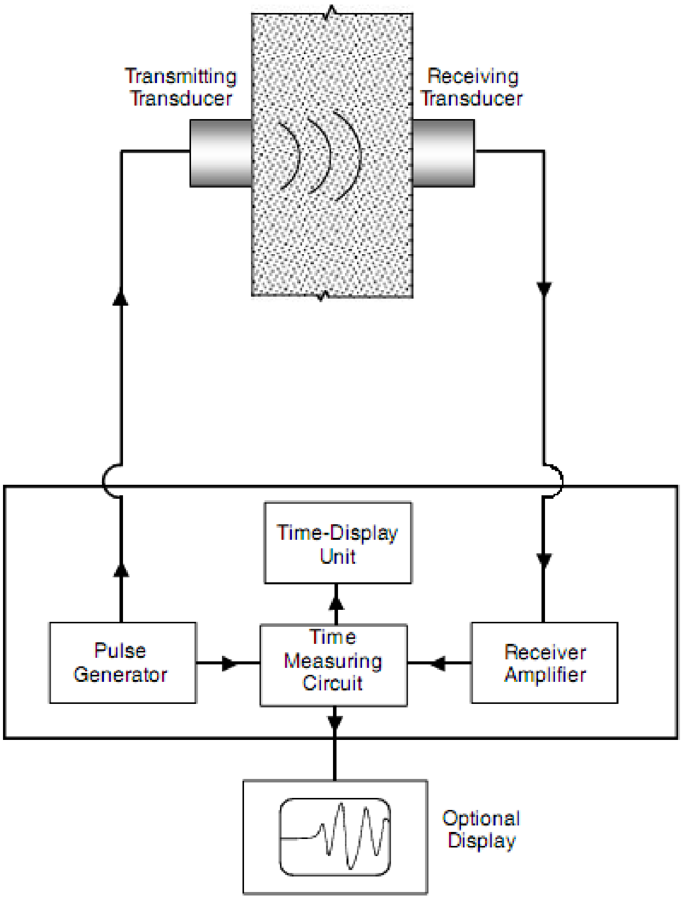


Figure 2.2 Schematic representation of pulse velocity test circuit (ASTM C 597, 2002)

While performing ultrasonic pulse velocity tests, three different configurations of transducer arrangements, shown in Figure 2.3, can be used. These are direct transmission, semidirect transmission and indirect transmission.

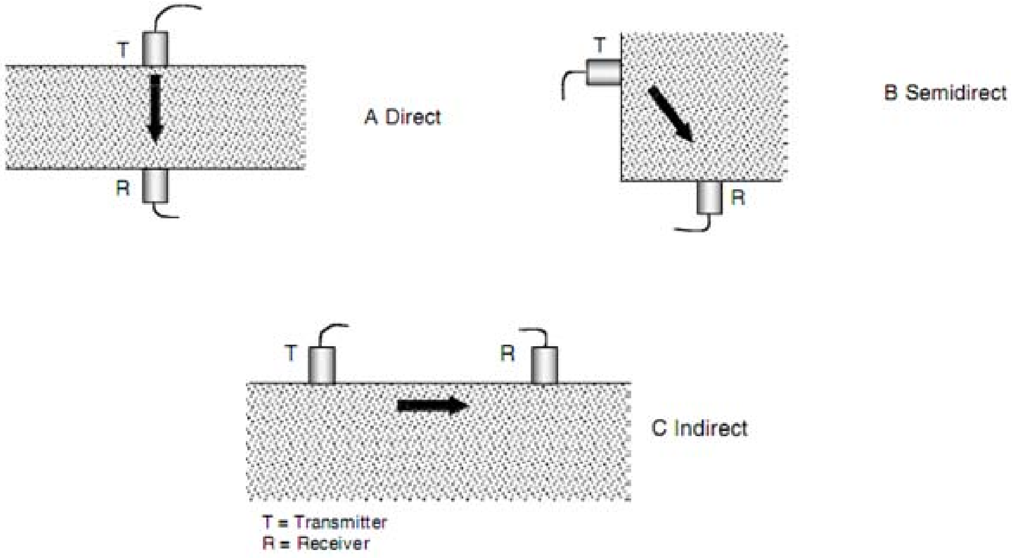


Figure 2.3 Pulse velocity measurement configurations (Malhotra and Carino, 2004)

Among these three types of configurations, direct transmission method is the most desirable, most satisfactory and the most preferred arrangement because maximum energy of the pulse is transmitted and received with this arrangement (Malhotra and Carino, 2004). Semidirect transmission method can also be used quite satisfactorily. But, special care should be taken that; the transducers should not be too far apart. Otherwise, there might be attenuation and the pulse signal might not be detected by the receiver. On the other hand, the indirect transmission method is the least satisfactory and sensitive method since the amplitude of received signal is lower than in the other methods. This method is also more prone to errors and gives information only about the surface layer (ASTM C 597, 2002).

2.2.3 Factors Influencing Pulse Velocity Measurements

Although the ultrasonic pulse velocity test seems to be an easy test, there are various factors affecting test measurements. Thus, special care should be taken to obtain accurate test results. These factors affecting pulse velocity results are not only due to the properties of concrete, but also depend on the test conditions. These factors influencing measurements are briefly discussed below:

2.2.3.1 Aggregate Type and Content

It has been observed from the studies by Bullock and Whitehurst (1959), Anderson and Seals (1981), Popovics et. al (1990) and Jones (1954) that the aggregate content has a significant effect on the pulse velocity of concrete. According to these studies, the pulse velocity of aggregate was generally higher than that of cement paste. Thus, concretes having higher aggregate contents gave higher pulse velocities. Regarding aggregate type, Jones (1954) reported that for the same concrete mixture and at the same compressive strength level, concrete with rounded gravel had the lowest pulse velocity, crushed limestone resulted in the highest pulse velocity, and crushed granite gave a velocity that was between these two. Therefore, it can be stated that aggregate type, content, and shape directly influence ultrasonic pulse velocity measurements.

2.2.3.2 Cement Type

Although Jones (1954) reported that the type of cement used did not have a significant effect on the pulse velocity, the rate of hydration, which is directly affected by cement type, influences modulus of elasticity and ultrasonic pulse velocity. As it is expected, when the degree of hydration increases, both the modulus of elasticity and the pulse velocity will also increase.

2.2.3.3 Water - Cement Ratio

Water/cement ratio, which is related with the porosity of concrete, has a direct effect on ultrasonic pulse velocity. Regarding this issue, Kaplan's (1959a) studies show that assuming no other changes in the composition of concrete, as the water/cement ratio increases, the strength and the ultrasonic pulse velocity of concrete will decrease.

2.2.3.4 Age of Concrete

The influence of age of concrete on pulse velocity is similar to its influence on the strength development of concrete. As hydration proceeds, the porosity of concrete decreases hence the pulse velocity increases. Jones (1954) has reported that pulse velocity, like strength, increases rapidly initially at early ages, but soon it flattens after reaching a limiting value.

2.2.3.5 Temperature of Concrete

Jones and Facaoaru (1969) show that temperature variations between 5 °C and 30 °C do not have a significant effect on pulse velocity. However, for temperatures beyond this range, corrections may be necessary to get accurate results. Regarding this situation, correction values proposed in British Standard BS 1881 (1986), are shown in Table 2.2 below.

Table 2.2 Corrections for pulse velocity due to temperature changes (British Standard BS 1881 - 203, 1986)

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

2.2.3.6 Moisture Content

The moisture content of a specimen can affect the pulse velocity in two ways; chemically and physically. The chemical way is related to the hydration of cement and the physical way is related with the presence of free water in the voids in concrete. Ultrasonic pulse velocity will be relatively higher when the voids in concrete are filled with water. If concrete is in dry condition, the wave propagation will be slow due to the increased path length. However, if the concrete is saturated, mechanical waves will propagate through the water present in the voids and the pulse velocity will be higher.

2.2.3.7 Shape and Size of Specimen

According to Malhotra and Carino (2004), the pulse velocity is not dependent on the size and the shape of a specimen unless its smallest lateral dimension is less than a certain minimum value. Below this value, the pulse velocity may be reduced appreciably. If the minimum lateral dimension is less than the wavelength or if the indirect transmission arrangement is used, the mode of propagation changes and therefore the measured velocity will be different (International Atomic Energy Agency, 2002). This is extremely important in cases where concrete elements of significantly different sizes are being compared.

2.2.3.8 Path Length

In theory path length does not have an influence on propagation time and pulse velocity but Jones (1962) has stated that shorter path lengths tend to give more variable and slightly higher pulse velocity because of the heterogeneous nature of concrete. Thus, the path length over which the pulse velocity is measured should be long enough not to be significantly influenced by the nature of concrete. On the other hand, very long path lengths should not be used to prevent energy loss during propagation.

2.2.3.9 Transducer Contact

It is very important to make proper transducer contact for eliminating air between contact surfaces and for ensuring efficient energy transfer between the concrete and the transducers. Otherwise, incorrect pulse velocity readings, and incorrect estimations about the concrete specimens tested may result.

2.2.3.10 Effect of Reinforcing Bars

According to Malhotra and Carino (2004), the pulse velocity of steel is higher than that of concrete and the pulse velocity measured in reinforced concrete in the environs of reinforcing bars is usually higher than in plain concrete of the same composition. Thus, if there are reinforcing bars in the concrete, they have to be taken into account while performing ultrasonic pulse velocity testing.

2.3 Resonant Frequency Test Method

The resonant frequency test method is a nondestructive test method which has been in use for homogeneous and isotropic solids for more than 60 years and, as a technique, covers the determination of the fundamental transverse, longitudinal and torsional resonant frequencies of a system for the purpose of calculating dynamic modulus of elasticity, dynamic modulus of rigidity, and dynamic Poisson’s ratio. In addition to calculation of dynamic properties, several investigations for estimating strength of concrete and for monitoring durability characteristics of concrete from resonant frequencies have been also undertaken by various researchers.

2.3.1 Theory of the Resonant Frequency Test Method

“Resonance” is defined as the tendency of a system to oscillate at maximum amplitude at certain frequencies which are known as the system's resonant frequencies. At these frequencies, even small periodic driving forces can generate large amplitude oscillations (Wikipedia, 2009).

According to Wikipedia (2009), resonances occur when a system is able to store and easily transfer energy between two or more different storage modes. However, there are some losses in amplitude from cycle to cycle as a function of time which is called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is the frequency of unforced vibrations.

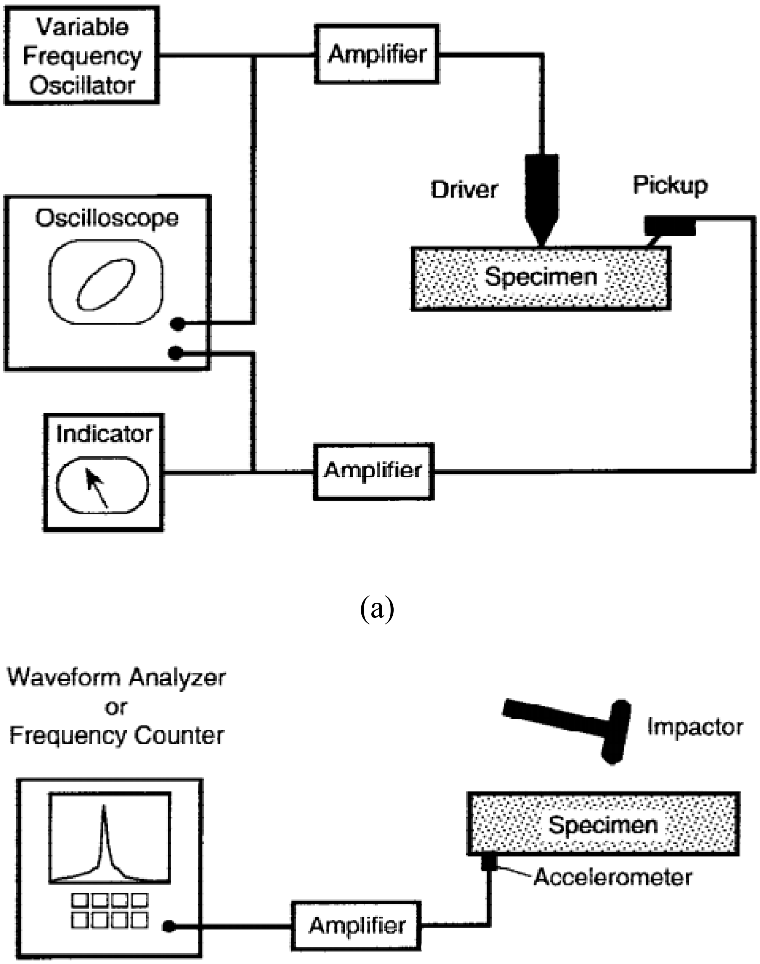
For perfectly elastic, homogeneous and isotropic systems, the natural frequency of vibration is directly related with the dynamic elastic modulus hence the mechanical integrity of the system. So, the dynamic elastic modulus of a system can be determined by the measurement of natural frequency of that system. Although this relationship between natural frequency and dynamic elastic modulus is mostly considered for homogeneous and perfectly elastic systems, it may be applied to heterogeneous systems, such as concrete, when the dimensions of the specimens are large in relation to the size of the constituents of the material (Malhotra and Carino, 2004).

2.3.2 Resonant Frequency Method for Concrete

Since resonant frequency is one of the most important properties for determining the dynamic properties of solid bodies, the test method for measuring resonant frequency of concrete is standardized in ASTM C 215 as "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens."

According to ASTM C 215, there are two different methods for determining the fundamental resonant frequencies of concrete. The first method is the forced resonance method, by which the supported specimen is forced to vibrate by an electro–mechanical driving unit and the specimen response is monitored by a pickup unit on the specimen. Then the value of the frequency causing maximum amplitude is recorded as the resonant frequency of the specimen. Test equipment for this method, which can be seen in Figure 2.4-a, consists of a driving circuit and a pickup circuit. The driving circuit consist of a variable frequency audio oscillator, an amplifier and a driving unit. The combined oscillator and amplifier shall be capable of delivering sufficient power output to induce vibrations in the test specimen at frequencies other than the fundamental ones. It is recommended in ASTM C 215 that the audio oscillator calibration should be checked periodically and it is important for the driving unit to be in full contact with the test specimen.

The second method is the impact resonance method, by which the supported specimen is struck with a small impactor and the specimen response is measured by an accelerometer on the specimen. Then the output of the accelerometer is recorded and the fundamental frequency of vibration is determined by using digital signal processing methods or counting zero crossings in the recorded waveform. Test equipment for this method, which can be seen in Figure 2.4-b, consists of an impactor, an amplifier, a sensor (accelerometer) and a waveform analyzer. According to ASTM C 215, the striking end of the impactor shall have a spherical shape and the waveform analyzer shall have a sampling rate of at least 20 kHz and shall record at least 1024 points of the waveform to get accurate results.



(a)

(b)

Figure 2.4 Schematic representation of test apparatus for (a) forced resonance test (b) impact resonance test (ASTM C 215, 2002)

Transverse, longitudinal and torsional frequencies are the three different types of fundamental resonant frequencies which can be obtained using the forced or impact resonance methods. The location of impact or driver placement and pickup or accelerometer placement are arranged according to the type of frequency to be determined. Different arrangements of these units to measure different frequency types can be seen in Figure 2.5.

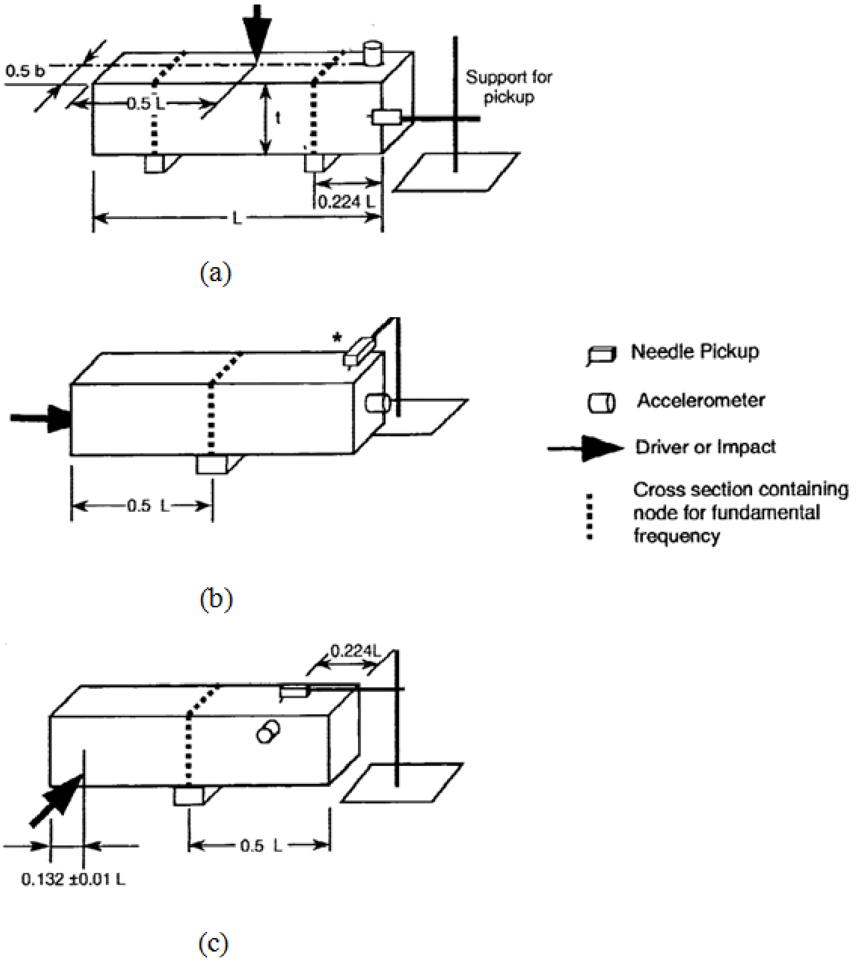


Figure 2.5 Locations of driver (or impact) and needle pickup (or accelerometer) for different frequencies. (a) Transverse frequency. (b) Longitudinal frequency. (c) Torsional frequency. (ASTM C 215, 2002)

Determination of fundamental transverse, longitudinal and torsional resonant frequencies allow the calculation of dynamic modulus of elasticity, dynamic modulus of rigidity and dynamic Poisson’s ratio. The relationships between frequencies and these dynamic parameters are formulized in ASTM C 215 as follows;

$$E_D = CMn^2 \tag{2.5}$$

$$E_D = DMn'^2 \tag{2.6}$$

$$G_D = BMn''^2 \tag{2.7}$$

$$\upsilon_D = \left(\frac{E_D}{2G_D} \right) - 1 \tag{2.8}$$

Where;

E_D: Dynamic modulus of elasticity (Pa)

G_D: Dynamic modulus of rigidity (Pa)

υ_D: Dynamic Poisson's ratio

n: Fundamental transverse frequency (Hz)

n′: Fundamental longitudinal frequency (Hz)

n″: Fundamental torsional frequency (Hz)

M: Mass of the specimen (kg)

C: 1.6067 (L^3T/d^4) ($N.s^2$ ($kg.m^2$)) for cylinder specimens

0.9464 (L^3T/bt^3) ($N.s^2$ ($kg.m^2$)) for prism specimens

D: 5.093 (L/d^2) ($N.s^2$ ($kg.m^2$)) for cylinder specimens

4 (L/bt) ($N.s^2$ ($kg.m^2$)) for prism specimens

B: (4LR/A) ($N.s^2$ ($kg.m^2$))

L: Length of specimen (m)

d: Diameter of cylinder specimen (m)

t and b: Dimensions of cross section of prism specimen (m)

T: Correction factor which depends on the ratio of radius of gyration, specimen length and Poisson's ratio.

R: Shape factor which is 1 for a circular cylinder and 1.183 for a square cross – section prism.

A: Cross sectional area of test specimen (m^2)

As can be seen from Equations 2.5 and 2.6, the dynamic elastic modulus of concrete can be determined from both the transverse and the longitudinal frequencies. Practically, there should not be any differences between the dynamic elastic modulus values calculated from these two methods. Regarding this condition, studies by Batchelder and Lewis (1953), Jones (1962) and Swamy (1971) have shown that there was no appreciable difference between dynamic elastic modulus calculated by these two methods especially for wet specimens, but it has been observed that after the specimens were allowed to dry, the dynamic elastic modulus calculated from the transverse vibrations was lower than that calculated from longitudinal vibrations. This was attributed to the moisture gradients within the concrete specimens.

In addition to the dynamic elastic modulus, dynamic shear modulus and dynamic Poisson's ratio can also be determined by using the resonant frequency test by finding the fundamental torsional frequency and using Equations 2.7 and 2.8. Even though the test method seems to be easy and straightforward, special care should be taken to get dependable test results since there are several factors affecting both the resonant frequency test and the dynamic properties calculated from this test. The factors, which can influence the test results, are discussed in the following section.

2.3.3 Factors Influencing Resonant Frequency Measurements

2.3.3.1 Mix Properties and Properties of Aggregates

It has been stated by Swamy and Rigby (1971), Malhotra and Carino (2004) and Jones (1962) that the resonant frequency and the dynamic elastic modulus of concrete are significantly affected by the elastic moduli of its constituent materials, their particular properties and their relative proportions. According to Jones (1962), for a given composition of cement paste with same water/cement ratio and same cement type, the dynamic elastic modulus of hardened concrete increases with an increase in the percentage of total aggregate. Jones (1962) also stated that an increase in the amount of mixing water or in the volume of entrapped air reduces the dynamic modulus of elasticity.

2.3.3.2 Specimen – Size Effect

The size of the specimen directly affects the resonant frequency test results and hence the dynamic elastic modulus calculations. According to Obert and Duvall (1941), the value of the dynamic modulus of elasticity varies depending on the size of specimen used in the measurements and larger specimens will have lower resonant frequencies due to their dimensions and greater weight. It has been pointed out in ASTM C 215 that specimens having either small or large ratios of length to maximum transverse direction are frequently difficult to excite in the fundamental mode of vibration, so it is suggested that this ratio be between 3 and 5. ASTM C 215 has also recommended against comparing test results from specimens of different sizes or shapes since different computed values for the dynamic modulus of elasticity may result from widely different resonant frequencies of specimens of different sizes and shapes of the same concrete.

2.3.3.3 Influence of Moisture and Curing Conditions

It was previously mentioned that the dynamic elastic modulus of concrete depends on the moisture content of the specimen and there can be a difference between the values of dynamic elastic modulus calculated from transverse and longitidunal vibrations due to drying. According to Jones (1962), this difference is caused by the loss of moisture resulting in gradients for moisture content, elastic modulus, and density in each dimension of the specimen. Then, these gradients would affect the transverse and longitudinal modes of vibration in different ways.

On the other hand, Obert and Duvall (1941) stated that the change in the elastic modulus with drying is rather small after about 3 or 4 days of air drying. Moreover, it has been shown that a large decrease in the dynamic modulus of elasticity occurs over the first 48 hours of oven drying but the subsequent change is small. Further, it has been observed that oven drying, even at as low a temperature as 34 ˚C, causes an irreversible decrease in the elastic modulus. According to Malhotra and Carino (2004), a possible explanation for this situation is that shrinkage results in micro-cracking of paste with subsequent reduction in its stiffness thus affecting the value of the dynamic modulus of elasticity.

Curing conditions may also have an influence on the resonant frequency and dynamic elastic modulus of concrete. According to Malhotra and Carino (2004), to achieve more reproducible results, water-curing shall be preferred and the specimen shall be in a water-saturated or saturated-surface-dry condition at the time of test.

2.4 Studies Regarding Dynamic Properties of Concrete Found by Ultrasonic Pulse Velocity and Resonant Frequency Tests

Various methods of nondestructive testing can offer the opportunity to get concrete dynamic characteristics such as dynamic elastic modulus and dynamic Poisson's ratio, or to estimate concrete strength, quality and integrity. In particular, the ultrasonic pulse velocity test and the resonant frequency test can be performed continuously and the standardized straightforward procedures of these tests make them favorable over other tests. Thus, several studies about these two test methods have been performed and important results have been obtained. In the following sections, the studies regarding these test methods and the results obtained from these studies are discussed.

2.4.1 Comparison of Resonant Frequency and Ultrasonic Pulse Velocity Test Results

Practically, dynamic elastic modulus can be found both from ultrasonic pulse velocity and resonant frequency tests using standardized methods. Moreover, in theory, the dynamic elastic modulus found from these techniques shall be the same. However, due to nature of concrete, and drawbacks in the test methods, differences between test results may be observed.

If the Poisson's ratio and density of concrete are known or assumed, by using Equation 2.2, the dynamic elastic modulus of concrete can be easily found by ultrasonic pulse velocity method. This approach also has an advantage over the resonant frequency method since the testing is not restricted to specially-shaped laboratory specimens. However, according to Malhotra and Carino

(2004), the determination of the dynamic modulus of elasticity in concrete from ultrasonic pulse velocity measurements may not recommended for the reasons of inaccurate estimation of Poisson's ratio and nonhomogeneous structure of concrete.

On the other hand, the structure of concrete is also a disadvantage for the resonant frequency tests and the accuracy of results obtained from these tests are also doubtful. However, there is a major advantage of the resonant frequency test over ultrasonic pulse velocity test, which is the lack of need to make assumptions for determining dynamic elastic modulus since Poisson's ratio can also be found using the standardized torsional frequency method. Thus, the studies about dynamic elastic modulus of concrete have generally used vibration methods rather than ultrasonic pulse velocity methods.

Despite the disadvantages above, several studies have been employed for determining dynamic elastic modulus with ultrasonic testing. It has been stated by Philleo (1955) that even if the value of Poisson's ratio is known, the dynamic modulus of elasticity estimated from pulse velocity measurements is higher than that obtained from vibration measurements.

2.4.2 Comparison of the Dynamic and Static Moduli of Concrete

Since concrete is not a linearly elastic material, it is very difficult to justify any definition of static modulus of elasticity for concrete. Young's modulus, also called the modulus of elasticity can be defined as the slope of the stress-strain curve (Ersoy et al., 2004). However, the slope of this curve is affected by many variables. Thus, it is complicated to obtain the instantaneous modulus of elasticity. As it is comparatively easier to obtain the strength of concrete by destructive methods, several correlations between static modulus of elasticity and strength have been made by different researchers. Today, many designers of structures use estimated elastic modulus values in their calculations for different concrete classes.

On the other hand, the dynamic elastic modulus is relatively easier, quicker and cheaper to find compared to the static elastic modulus. Thus, a considerable amount of work for correlating and comparing static and dynamic modulus of elasticity has been performed. However, current studies for generating correlations between dynamic and static elastic modulus show that it is almost impossible to obtain a general formulation between these properties of concrete. Due to the varying composition and time-dependent properties of concrete, correlations can be only made for a particular type of concrete and differs according to the age of concrete. Nonetheless, there are some similarities between different test results. Regarding the relationship between dynamic and static elastic modulus, the following observations can be made from the studies by Han and Kim (2004), Klieger (1957), Powers (1938), Sharma and Gupta (1960), Stanton (1944), Swamy and Rigby (1971) and Wright (1954);

i. The differences between static and dynamic modulus of concrete can depend upon the size and shape of the specimen, the type of static test, age of the concrete and type and elastic modulus of the aggregate used.

ii. The dynamic modulus of elasticity is usually a bit higher than the static elastic modulus.

iii. There is no single ratio between static and dynamic elastic modulus. As can be seen in Figure 2.6, the values may vary between 0.6 and 1.0 and increase to approach 1.0 with increasing age and static elastic modulus.

iv. The values for both dynamic and static modulus of elasticity show close agreement for higher static modulus of elasticity.

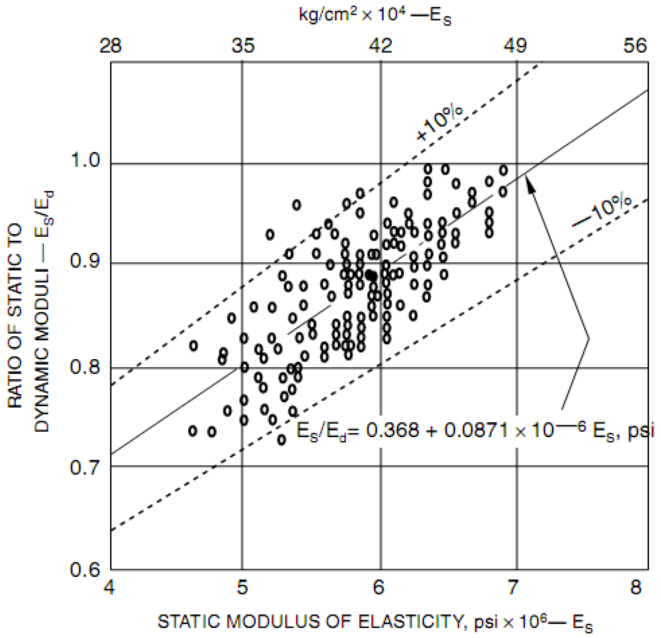


Figure 2.6 Ratio of static to dynamic moduli which has observed for high strength concrete (Sharma and Gupta, 1960)

2.4.3 Correlation between Dynamic Modulus of Elasticity and Strength Properties of Concrete

Numerous empirical relations or correlations have been also established between the dynamic elastic modulus of concrete and its compressive or flexural strength. But generally these relations and correlations seem to be done for the particular type of concrete investigated. Thus, there appears to be no generalized or unique relationship between these properties of concrete. The existing studies done by Takabayashi (1953), Kameda et. al (1953), Preece (1946), Han and Kim (2004), Swamy and Rigby (1971), Shrivastava and Sen (1963), Sharma and Gupta (1960), Kaplan (1959b) and Malhotra and Berwanger (1970) show that such relations depend upon the composition of concrete (mix proportions, type of aggregate, type of cement, cement content, etc.) and the curing conditions. And for that reason, for a given variable (such as cement type), changes in strength do not strictly follow changes in dynamic elastic modulus. In the same manner, it can be observed from these existing studies that limited correlation between strength and dynamic modulus can be obtained when only one variable is varied such as the age of concrete, the degree of compaction, water/cement ratio or the deterioration characteristics. Three relations reported by various investigators, are shown in Figure 2.7, Figure 2.8 and Figure 2.9. In all of these figures, the pattern of relations is similar but as can be noticed from Figure 2.8 and Figure 2.9, as the number of variables (water/cement ratio and moisture content for these examples) increases, the results show deviations and it is hard to establish a unique relationship.

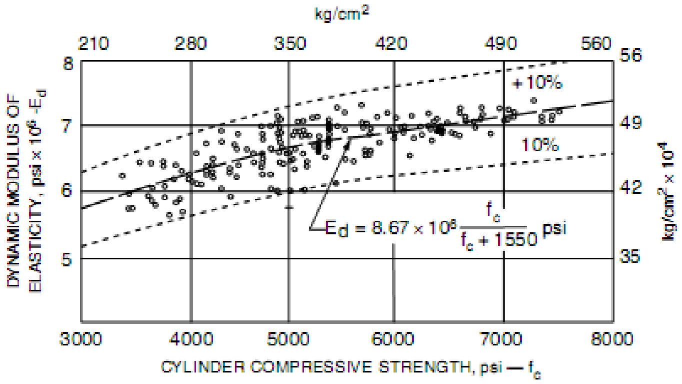


Figure 2.7 Relationship between dynamic modulus of elasticity and compressive strength of concrete (Sharma and Gupta, 1960)

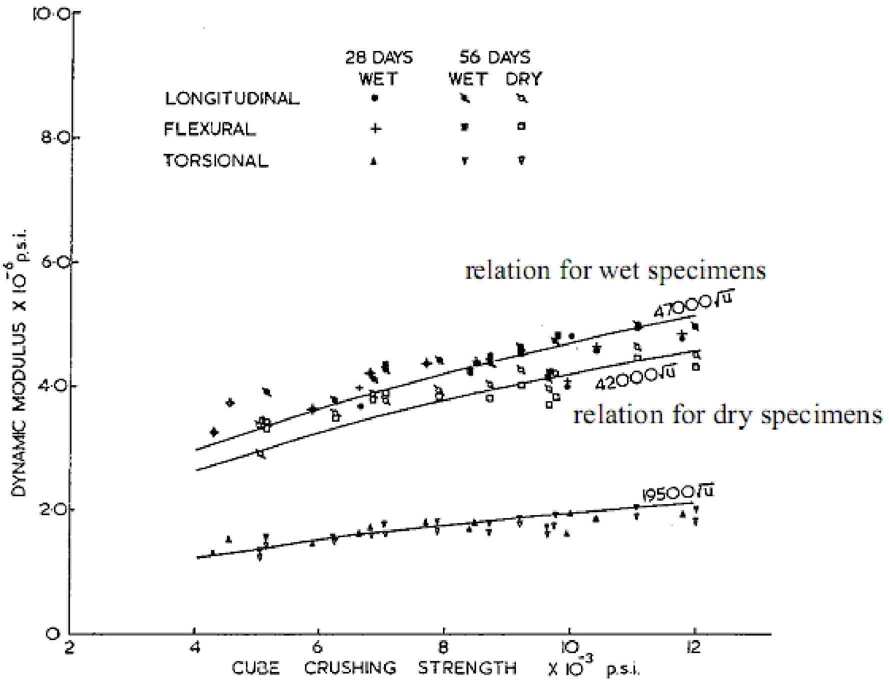


Figure 2.8 Relation between dynamic elastic modulus and cube compressive strength of mortar for different moisture contents (Swamy and Rigby, 1971)

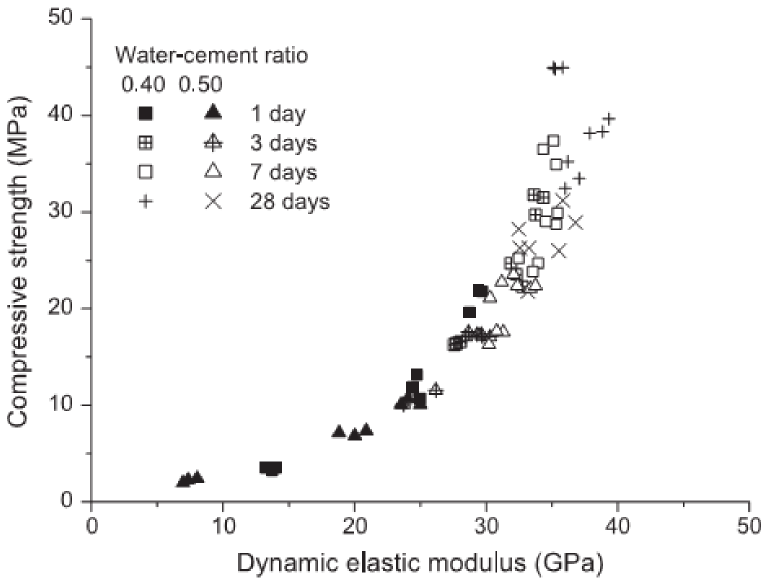


Figure 2.9 Relation between dynamic elastic modulus and compressive strength for different test ages and water/cement ratios (Han and Kim, 2004)

2.4.4 Studies Regarding Dynamic Poisson’s Ratio of Concrete

Another important elastic property for concrete is the Poisson’s ratio. According to Ersoy et. al (2004), Poisson’s ratio is defined as the ratio of transverse strain to longitudinal strain. The difference in the values of Poisson’s ratio from one concrete to another is usually very small and its value is normally not critical in engineering design and is neglected. Numerous tests have revealed that the Poisson’s ratio changes significantly with the load level. For concrete, Poisson’s ratio is generally between 0.15 and 0.25 and practically taken as 0.20 for engineering design.

Although Poisson’s ratio seems to be relatively less critical in engineering design, a precise assessment of its value is, however, necessary for multiaxial creep computations and knowledge of Poisson’s ratio is also necessary to assess spalling effects due to thermal movements (Swamy, 1971). Investigations by Robinson (1968) have also shown that Poisson’s ratio plays a significant role in the study of the formation and propagation of microcracks, and in studying the fracture mechanism of concrete.

In general, Poisson’s ratio is found by the help of strain gauges. Longitudinal and transverse strains are found by loading the specimens and strain curves are plotted. By nondestructive methods, on the other hand, it is also possible to evaluate dynamic Poisson’s ratio with the help of vibrations in the longitudinal and torsional modes. For cylindrical specimens empirical equations have been also developed by Subramaniam et. al (2000) in which the first two resonance frequencies are used.

Various studies made by Chefdeville (1953), Swamy (1971) and Jones (1962) have shown that dynamic Poisson's ratio, like dynamic elastic modulus, also varies with the varying composition of concrete. According to these investigations, Poisson's ratio depends on the aggregate content, type of aggregate, the Poisson's ratio of the aggregate, water/cement ratio and type of cement used. As can be seen in Figure 2.10, degree of wetness and age of the specimen have also remarkable effects on Poisson's ratio. Regarding this issue, Swamy (1971) observed that Poisson's ratio of mortar and concrete increased with water/cement ratio and decreased with the drying process. Although Pickett (1945) has reported that Poisson's ratio increased as hydration proceed, Jones (1962), Chefdeville (1953) and Swamy (1971) have stated that the Poisson's ratio was initially high and decreased greatly between first and seven days and continued to decrease with age and ongoing hydration.

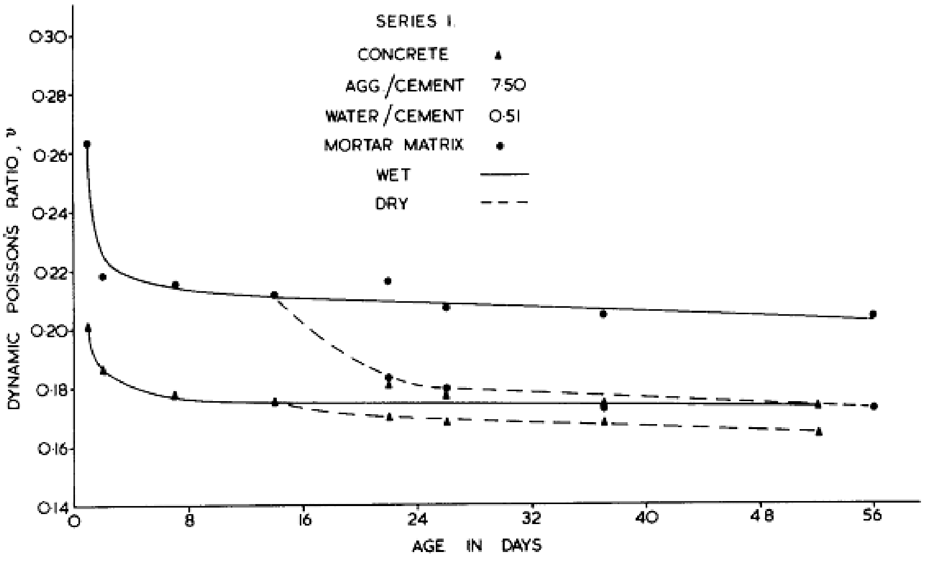


Figure 2.10 Typical variation of dynamic Poisson's ratio with age of wet and dry concrete and its corresponding mortar matrix (Swamy, 1971).

It can be inferred from the investigations mentioned above that any factor that increases the strength of concrete or elastic modulus is likely to decrease its Poisson’s ratio, but there may appear different relationships for different mix proportions. It is then unlikely to be able to formulate one unique relationship between Poisson’s ratio and either water/cement ratio, compressive strength or dynamic elastic modulus for all types of concrete.

2.4.5 Studies Regarding the Dynamic Modulus of Rigidity of Concrete

Modulus of rigidity is defined as the ratio of unit shearing stress to the corresponding unit shearing strain. The value of modulus of rigidity for a concrete is generally about 40 to 45 % of its elastic modulus. Dynamic modulus of rigidity, like dynamic elastic modulus, can also be determined with the help of forced vibrations in concrete. Various studies conducted by Swamy and Rigby (1971) have shown that factors which influence dynamic elastic modulus also influence dynamic modulus of rigidity. Thus, it is again unlikely to formulate a unique relationship between dynamic modulus of rigidity and other mechanical characteristics of concrete.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

This study is mainly focused on the determination of dynamic elastic modulus, static elastic modulus, and strength characteristics of different cement mortar specimens. Hence, the aim of study can be described as to establish relations and correlations between these time-dependent properties of mortar mixtures, and to observe the effects of cement characteristics on the results. For this purpose, eight different mortar mixtures, which had the same water/cement ratios, were prepared using different types of CEM I cements. Two nondestructive test methods, the ultrasonic pulse velocity method and the resonant frequency method, were carried out to acquire the dynamic elastic moduli of specimens. Strength properties of corresponding specimens were determined and static elastic moduli of the mortar mixtures were estimated by non-standard methods. As a result of all these tests, several relationships between different properties of mortars were obtained for different ages. This chapter is devoted to introduce the details of these test methods carried out, material and mixture properties used in the tests, the software used, and the numerical calculations made in the study presented.

3.2 Materials

3.2.1 Cements

As has been mentioned, eight different mortar mixtures with identical water/cement ratios were prepared for the tests performed. The only difference in the constituents of these eight mixtures was cement type. According to TS EN 197 - 1, cements, which consist of 95 to 100 % of portland cement clinker without any major additives, are defined as portland cement and designated CEM I type cement. Although this definition characterizes CEM I as a unique type, in fact there are a wide range of cements with different constituents and related properties within the CEM I type. Thus, to observe the effects of cement composition and cement properties on the elastic properties investigated, as many different CEM I types of cement as possible were used in the mixtures. The main physical properties of these cements, their density and fineness values, were measured as described in ASTM C 188 and ASTM C 204, respectively. The chemical analyses of the cements, on the other hand, were performed at The Turkish General Directorate of Mineral Research and Exploration laboratories by X-Ray Fluorescence (XRF) spectroscopy analysis method. The corresponding chemical and physical properties of these cements are given in Table 3.1.

As can be noticed from Table 3.1, three of the eight cements are marked (with asterisks) since their properties are wholly different from those of the others. One of these cements is a sulphate resistant cement (recognizable by its low Al_2O_3 content), one is a white portland cement CEM I 52.5 N (discernible by its very low Fe_2O_3 content), and the other is a CEM I 42.5 N type cement. The unmarked cements are all portland cements of type CEM I 42.5 R obtained from five different sources.

Table 3.1 Chemical and physical properties of cements

Cement Type	Chemical Analysis									Physical Analysis	
	Component (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Free CaO	Specific Gravity (g/cm^3)	Blaine Fineness (cm^2/g)
1	19.56	5.00	3.68	64.55	1.57	2.41	0.66	0.77	1.00	3.09	3370
2*	18.60	3.80	5.00	62.90	0.90	2.20	0.60	0.10	0.84	3.12	3790
3	18.30	4.80	3.10	63.00	1.50	2.30	0.70	0.10	0.80	3.12	3870
4	22.70	6.50	3.10	56.70	2.00	3.10	1.40	0.30	0.80	3.10	3800
5	18.30	4.60	3.20	61.50	2.50	2.30	0.90	0.30	1.20	3.12	3853
6**	21.56	4.08	0.21	65.46	1.07	3.62	0.45	0.20	1.30	3.05	4600
7	19.80	5.38	3.27	63.43	1.87	3.20	0.32	0.00	0.80	3.09	3731
8***	20.00	4.50	5.60	62.00	1.30	2.30	0.50	0.15	0.95	3.15	3800
*Sulphate Resistant Cement (S.R.C 32.5)											
**White Portland Cement (CEM I 52.5 N)											
***CEM I 42.5 N											

3.2.2 Aggregates

Natural silica sand was used as the fine aggregate in preparing the mortar mixtures. The gradation of the sand, which is defined by TS EN 196 – 1, can be seen below from Table 3.2.

Table 3.2 Gradation of the aggregate (TS EN 196 – 1)

Sieve Size (mm)	Cumulative Retained on Sieve (%)
2.00	0 ± 5
1.60	7 ± 5
1.00	33 ± 5
0.50	67 ± 5
0.16	87 ± 5
0.08	99 ± 5

3.2.3 Water

Pure (distilled) water was used for the preparation of all mortar mixtures.

3.3 Mortar Mixtures

Mortar mixture preparation was performed according to the procedures described in TS EN 196 – 1. The constituents of mixtures were prepared according to the water/cement ratio of 0.5, and they were mixed with a mechanical mortar mixer. Then, the mixtures were placed in the molds with appropriate compaction and placing methods described in the standard. Subsequently, to prevent sudden moisture loss and related crack formations, the mixtures placed in the molds were covered with wet blankets. After 24 hours, the mixtures were taken out of the molds and put in water for curing. The curing conditions of all specimens were identical and all of the specimens were kept at the same temperature throughout the tests.

Several tests were performed on the mixtures for the purpose of obtaining dynamic elastic modulus, static elastic modulus and strength. Tests for obtaining dynamic elastic modulus and strength were done according to specified standards and prism specimens which had the approximate dimensions 160 mm length, 40 mm width, and 40 mm thickness were prepared for these tests. On the other hand, static elastic modulus tests were carried out by using a non-standard method. Although the constituents and preparation methods for these mixtures were the same as the other mixtures prepared for dynamic elastic modulus and strength determination, the dimensions of the molds and hence the specimens were totally different. For obtaining static elastic modulus, specimens which had the approximate dimensions 500 mm length, 50 mm width, and 15 mm thickness were prepared. The reasons for selecting these dimensions will be explained in the following sections.

3.4 Tests Performed

Resonant frequency tests, ultrasonic pulse velocity tests, static elastic modulus tests and strength tests were performed on the mortar mixtures prepared. Since mortar is a naturally time-dependent material, the tests were performed on different days for observing the development and variation of its characteristics over time. The development of mass and density of mortar mixtures for each test day were also observed and are given in Figure A.1 and Figure A.2, in Appendix A. While applying all tests, the specimens were in saturated condition and no observations for the effects of drying were made. The procedures and the application details of the tests will be discussed in the forthcoming sections.

3.4.1 Resonant Frequency Test

The dynamic elastic modulus and the dynamic Poisson’s ratio are two important properties of engineering materials obtained from vibrational methods of testing. As has been stated, the great advantage of these tests, apart from their nondestructive nature, is that the dynamic values are obtained from temporary loads far from the elastic limit, so that the results are free from time–dependent inelastic strains and directly related to the internal structure of the material. Thus, the development of the dynamic characteristics of mortar mixtures with time can be obtained by finding the fundamental modes of vibrations.

In this study, the fundamental longitudinal and torsional resonant frequencies of 4×4×16 cm^3 prismatic mortar specimens were found at the ages of 1, 3, 7, 28 and 56 days. While performing the tests, the impact resonance method, which is described in ASTM C 215, was used. As the equipment; an impactor, a specimen support, a sensor, an amplifier and software for waveform analysis and for obtaining frequency were used. The schematic representation of the test set up can be seen below in Figure 3.1.

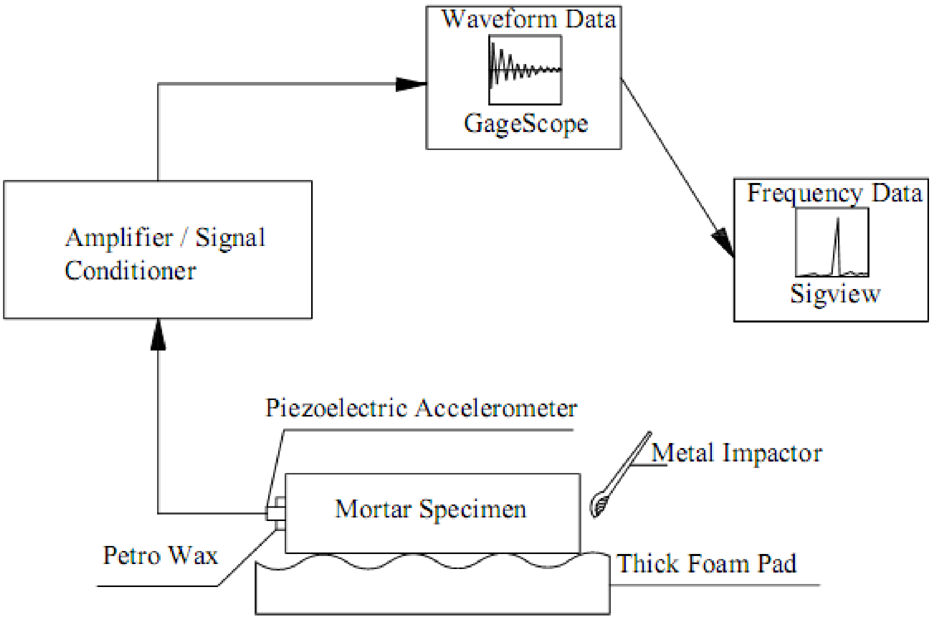


Figure 3.1 The schematic representation of resonant frequency test set up.

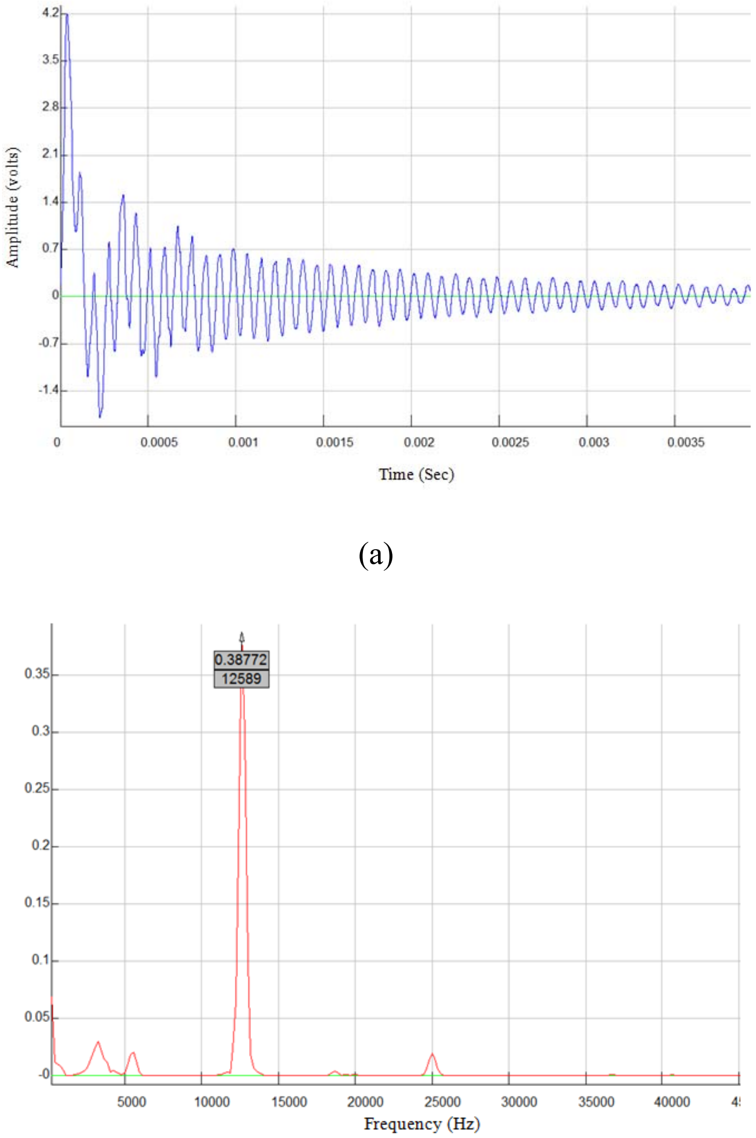
The impactor was selected as a metal tea spoon whose striking end had a spherical shape which yields easy to analyze waveforms. A thick pad of soft foam was used as the specimen support which allowed the specimen to vibrate freely in the longitudinal and torsional modes. The sensor was a piezoelectric accelerometer which was attached to the mortar specimens with petro wax.

While performing the experiment, the locations of impact and accelerometer were determined using Figure 2.5 according to the type of frequency that was going to be determined. Then the wave was generated by striking with the impactor on the defined point of the mortar specimen. The program, “GageScope for Windows”, was used as the waveform analyzer which recorded the voltage–time response of the mortar prism specimens and displayed them on the computer screen. While recording and analyzing the waves, a sampling rate of 25 MS/s was selected and the program recorded 100000 points of the waveform. Thus, 25000000 samples could be collected in one second and 100000 points correspond roughly to a time period of 4000 microseconds in real time.

To observe the frequency of specimens, time–domain response data which had been found, needed to be converted to the frequency domain response data. For this process, a Fast–Fourier Transform (FFT) operation was needed to be done. Another software, “Sigview”, was used for performing FFT analysis and obtaining frequency of the specimen. While vibrations were being recorded, some undesired disturbance or error could occur due to electrical noise. For eliminating the noise, filtering and smoothening methods were executed whenever plausible frequency values had not been found. The time domain and frequency domain data of a sample wave taken from mortar specimen can be seen in Figure 3.2.

After the FFT operation and obtaining the frequency domain response data, the resonant frequency could easily be recognized since the software also gives the maximum peak results as can be seen in Figure 3.2. Then the principal peaks of frequency were analyzed to determine the resonant frequency and subsequently the dynamic modulus of elasticity, dynamic modulus of rigidity and dynamic

Poisson’s ratio were calculated by using Equations 2.6, 2.7 and 2.8, respectively.



(a)

(b)

Figure 3.2 The time domain (a) and the frequency domain (b) response of a wave taken from a mortar specimen.

According to ASTM C 215, the precision statements of the impact resonance tests have not yet been determined. In this study, to obtain more accurate results, three control specimens from each mixture have been selected. For each control specimen, resonant frequency measurement was carried out three times and the averages of these measurements were determined. Thus, for one mixture, for every test day, three average results were found. Then the averages of these results were also determined for a final average result. In other words, as a result of these applications; for each mixture, one result was obtained as an average of nine results for every test day. In order to reduce uncertainties, the measurements, which deviated greater than ± 10 % from the average, were discarded before implementing the calculations.

3.4.2 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test is another important nondestructive test method which can be used to monitor concrete undergoing internal structural changes over a period of time. Although the test is mainly used to evaluate and detect durability characteristics of concrete, it can be used also for estimating dynamic elastic modulus of concrete as has been mentioned before. For ultrasonic pulse velocity tests performed in this study, 4×4×16 cm^3 prismatic control specimens, which had been also tested for resonant frequency tests, were used. Thus, another set of dynamic elastic moduli values were found for the same specimens, for the ages of 1, 3, 7, 28 and 56 days. As such, the dynamic elastic modulus values found from two different nondestructive test methods could be compared.

Ultrasonic pulse velocity tests were carried out according to ASTM C 597. Since small laboratory specimens were tested, transducers capable of producing higher frequency (150 kHz) pulses were used during the tests. A pulse of longitudinal vibration was produced with the transmitting transducer from one side of the mortar specimen, and the receiving transmitter sensed the arrival of the pulse from the other side of the specimen. The travel time taken by the pulse through the concrete was displayed on the pulse velocity test instrument "Pundit Plus" as seen in Figure 3.3. By measuring the travel distance, which was the length of specimen, and by using Equation 2.4, the pulse velocity was calculated.

Figure 3.3 Pulse velocity instrument

While calculating the pulse velocity, to obtain more satisfactory and desirable results, the direct transmission method was preferred since the maximum energy of the pulse was transmitted and received with this method. Thus, the transducers were located directly opposite each other at the middle of the square cross sections of the mortar specimens.

The accuracy of pulse velocity measurements depended upon the precise determination of the travel distance and the accurate measurement of the transit time. Thus, a digital vernier caliper was used to measure the travel distance and petroleum jelly was used as a coupling agent to ensure stable transit times. Moreover, before starting the measurement of pulse velocity, for verifying the proper operation of the equipment, “zero–time adjustment” was also made. For this application, the coupling agent was applied to the faces of both transducers and then the faces of transducers were pressed together. Since no specimen was placed in between transducers, it was verified that the instrument displayed zero as the transit time.

As has been stated before, the results obtained by the use of ultrasonic pulse velocity tests will not be adequate for establishing the modulus of elasticity of concrete since the value of Poisson’s ratio cannot be found by using these test. Further, in this method, generally an estimated value of Poisson’s ratio is used for finding dynamic elastic modulus which can lead to errors. In this study, however, the Poisson’s ratio was not assumed. Since the resonant frequency method was also implemented, the results from those tests were used to calculate the dynamic elastic modulus. In other words, the Poisson’s ratio results found by resonant frequency testing were used with the pulse velocity results found by ultrasonic testing to calculate the dynamic elastic modulus by Equation 2.2.

In order to obtain more consistent results from pulse velocity measurements, like had been also performed in resonant frequency testing; three control specimens were measured for each mixture and a representative result, which was obtained from the average of the control specimen results, were used in calculations. For increasing the accuracy, the measurements, which deviated greater than ± 10 % from average, were discarded before performing the calculations.

3.4.3 Static Elastic Modulus Test

Static elastic modulus is generally obtained by conventional stress–strain relationship tests conducted at low levels of loading which is described in ASTM C 469. In this study, however, non-standard methods were used for determining the static elastic modulus due to the difficulty of applying conventional methods to small mortar specimens.

Since deflection of a statically loaded beam is related to the geometric properties of the beam and the elastic modulus of the material used, it is possible to obtain the static elastic modulus of a mortar specimen by using this relationship. For this purpose, an experimental set–up, shown schematically in Figure 3.4, was devised. Two roller supports were placed at the ends of a beam and the beam was loaded from its center with pseudo point load. A dial gauge of 0.0001 inches graduation was used in the tests to determine the maximum deflection at the midpoint of beam.

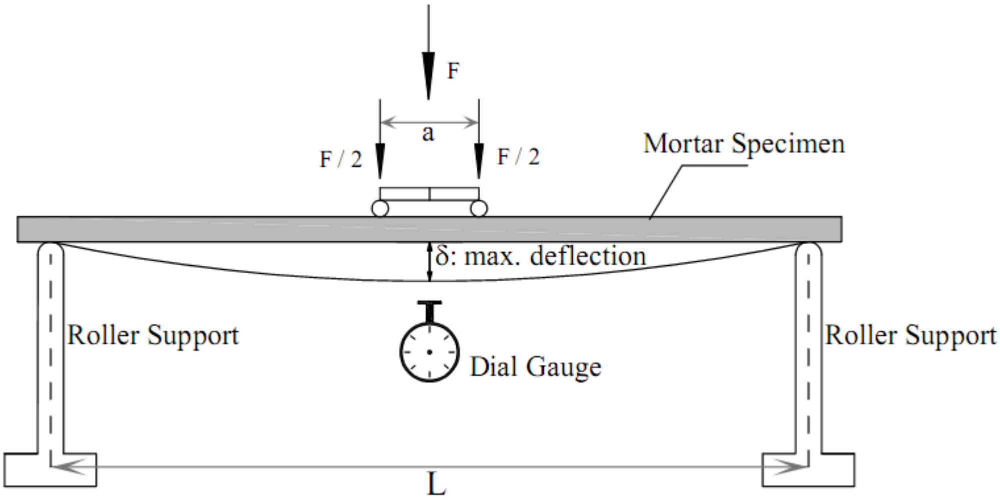


Figure 3.4 Schematic representation of the experimental set–up used for determining static elastic modulus.

The maximum deflection of a beam loaded as in Figure 3.4 can be found by using Equation 3.1 below;

$$\delta = \frac{\mathrm{F(L\text{-}a)}^2 (L + 2a)}{48 E_s I} \tag{3.1}$$

Where;

δ: Maximum deflection at beam midpoint

F: Force acting on the beam

L: The length of beam in between supports (48 cm in this study)

a: Distance between two half forces (4 cm in this study)

E_S: Static elastic modulus of material

I: Moment of inertia of the beam

By using the inverse operation of Equation 3.1; with known values of force and deflection, and with properly measured geometric data, the static modulus of eight different mortar mixtures were calculated. The beam dimensions used in these tests were different than the beam dimensions used in other tests. While prism specimens which had the approximate dimensions 160 mm length, 40 mm width, and 40 mm thickness were used for strength and dynamic elastic modulus measurements; prism specimens which had the approximate dimensions 500 mm length, 50 mm width, and 15 mm thickness were used for static elastic modulus determination. The main reason for selecting these dimensions was to decrease the percentage of error which could accumulate due to imprecise dial gauge readings. If shorter and thicker specimens had been used, the deflection of beams would have decreased and hence, any wrong reading from the dial gauge would have caused relatively larger percentage errors. By using thinner and longer beams, on the other hand, the deflection of beams increased and the possible errors occurring from dial gauge readings were minimized. One other important point about the dimensions of the specimen was to select its thickness properly. Thinner specimens would have had lower bending strengths which would require very careful loading to prevent cracking or failure. On the other hand, thicker specimens would have shown smaller deflections relatively and the errors could have increased. Thus, the most appropriate thickness and length were calculated according to loading conditions and the strength of the specimens. As a result, the dimensions given above were chosen.

The static elastic modulus tests were carried out at the ages of 3, 7, 28 and 56 days. The tests were not implemented on the first day considering the risk of crack formation on that day. On each test day, all specimens were loaded with three different weights to obtain three different deflections and hence three elastic modulus values. The loads used in the measurements were determined after preliminary calculations since they needed to be neither too large nor too small. After computations, three load values for each day were determined which were not large enough to cause any crack formation, but were large enough to deflect the beam midpoint sufficiently.

For each mixture, two specimens were prepared and tested to obtain more data. Then the averages of results from each mixture were computed to obtain a representative result. Although the results deviating more than ± 10 % from the average were discarded as outliers during calculations, the measurements and results might include some percentage of error since the method used was not a standard one.

3.4.4 Strength Test

Flexural and compressive strength determination of mortar mixtures were performed according to TS EN 196 – 1. Prismatic specimens having 40 mm, 40 mm and 160 mm dimensions were used in order to determine the flexural and compressive strength of mortar mixtures. The prisms were first tested for flexural strength by mid–point loading as shown in Figure 3.5-a.

After the prisms were divided into two pieces, the compressive strength could be determined from those two pieces by applying load on a cross sectional area of 40 mm × 40 mm, as shown in Figure 3.5-b.

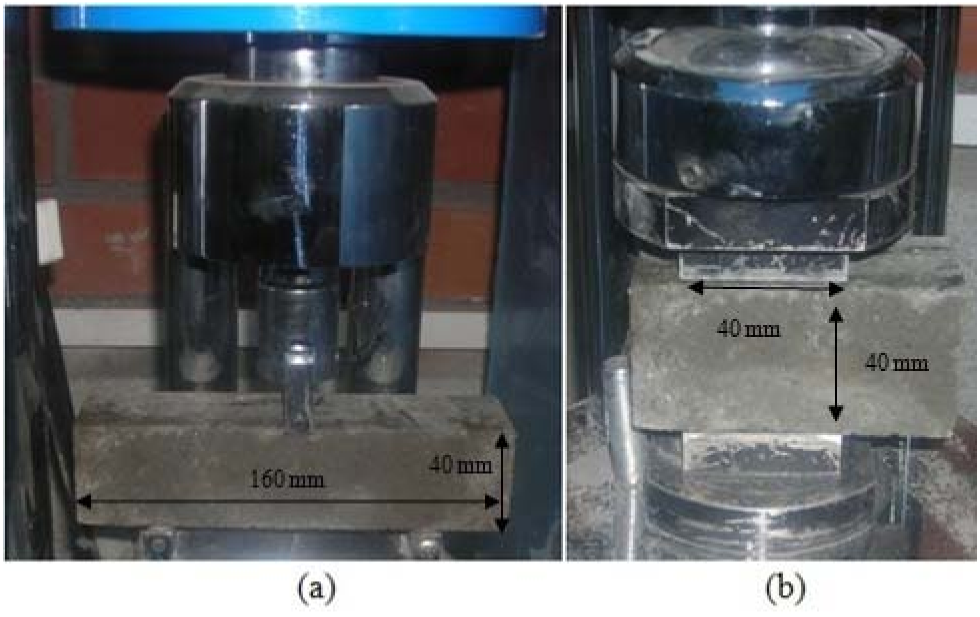


Figure 3.5 Determination of (a) flexural and (b) compressive strength of prism specimens

The flexural and compressive strength tests were performed at the ages of 3, 7, 28 and 56 days. For each mixture, on each test day, 3 prisms were tested to determine the flexural strength and the 6 pieces obtained from flexural testing were tested to determine the compressive strength. Then the averages of these tests from each mixture were used to obtain a representative result for that mixture. The measurements, which deviated more than ± 10 % from the average, were not used in the calculations.

CHAPTER 4

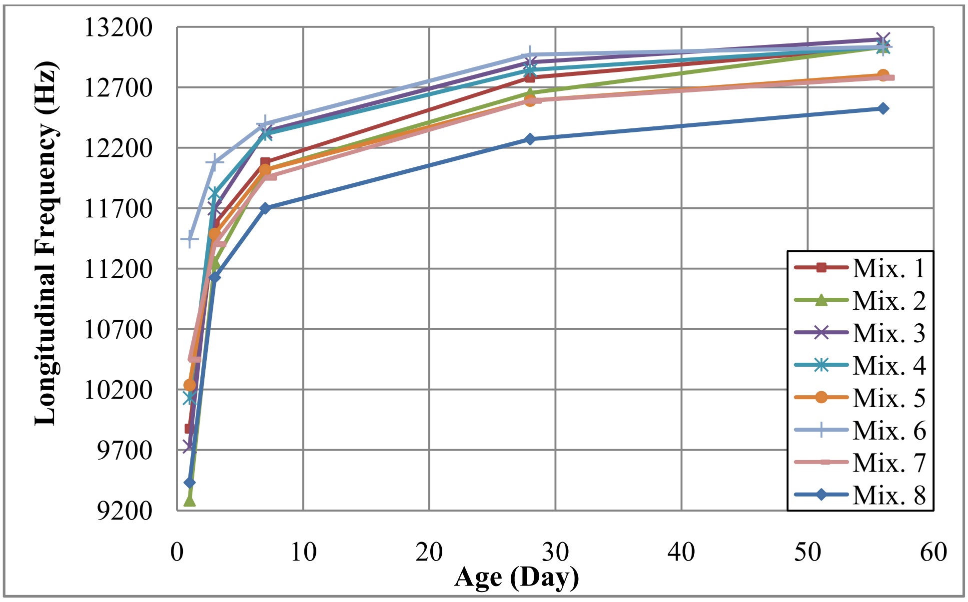
TEST RESULTS AND DISCUSSION

4.1 Introduction

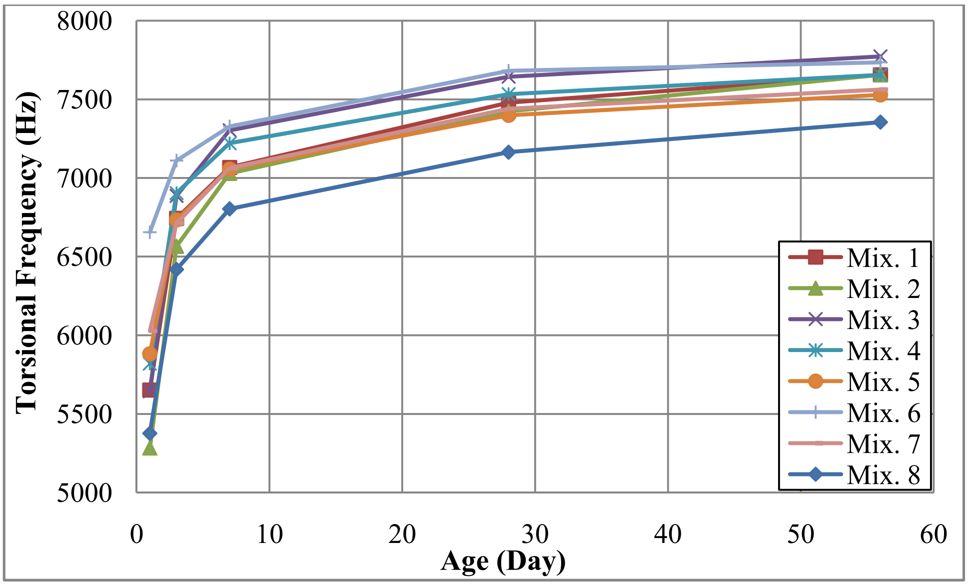
This chapter is mainly devoted to the presentation of the results which were obtained from the experiments performed. A comparison of dynamic elastic modulus values obtained from ultrasonic pulse velocity testing and resonant frequency testing is also made. A detailed discussion of the influence of cement type on dynamic elastic modulus, dynamic Poisson's ratio, static elastic modulus and strength is presented. Furthermore, the relations between dynamic elastic modulus, static elastic modulus and strength for different types of mixtures are discussed.

4.2 Resonant Frequency Test Results

As has been mentioned in Chapter 3, the fundamental longitudinal and torsional frequencies of prismatic mortar specimens were determined using resonant frequency testing to evaluate the dynamic characteristics of mortar mixtures, and to observe changes in dynamic characteristics over the time. Below, in Figure 4.1, the development and variation of longitudinal and torsional frequencies, which were determined for different mixtures, are presented.



(a)



(b)

Figure 4.1 Development of (a) longitudinal and (b) torsional frequencies over time for different mixtures.

As can be observed from Figure 4.1; for all mixtures, torsional frequency of a prismatic specimen is around 60 percent of its corresponding longitudinal frequency. While longitudinal resonant frequencies range generally between the values of 9000 Hz and 13000 Hz, the corresponding torsional resonant frequency values lie between 5000 Hz and 8000 Hz. Another remarkable point seen in Figure 4.1; both longitudinal and torsional frequencies increase rapidly in the first 7 days but later developments for frequencies slow down and they reach asymptotic values. The exact longitudinal and torsional frequency values for each mixture and for each age are also provided in Table A.1 and Table A.2, in Appendix A.

Since eight different cements were used for the preparation of mixtures, different resonant frequencies were expected for every individual mixture. According to the data presented in Figure 4.1; it can be stated that mixture 8 has the lowest resonant frequencies on all test days except the first day. On the first day, mixture 2 has the lowest frequency but it seems after the third day that its frequencies near those of the other mixtures. On the other hand, mixture 6 has the highest resonant frequencies, especially for early ages. After the seventh day, however, the frequencies of other mixtures approach that of the 6th mixture and no big difference remains between their values. Regarding the other five mixtures, it can be reported that although their resonant frequencies are not strictly the same, the values are very close to each other for all ages.

4.2.1 Dynamic Elastic Modulus Results Obtained by Resonant Frequency Testing

Using the data presented in Figure 4.1; dynamic elastic modulus, dynamic shear modulus and dynamic Poisson’s ratio values for the mortar mixtures were determined using the well established equations given in Chapter 2. In Figure 4.2 below, the development of dynamic elastic modulus values over time, found using longitudinal resonant frequencies, are presented. Additionally, the exact dynamic elastic modulus values for each mixture can be seen in Table A.3, in Appendix A.

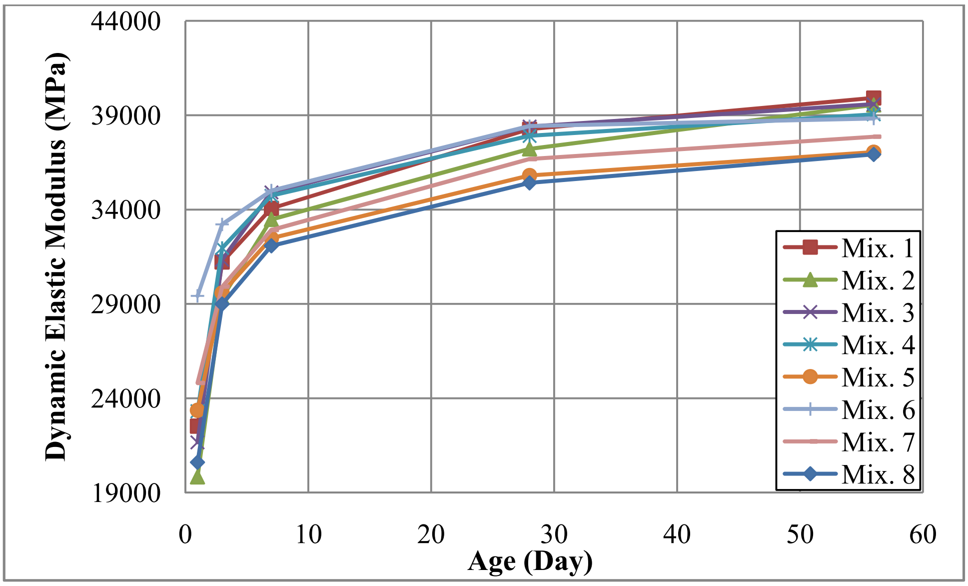


Figure 4.2 Dynamic elastic modulus developments for different mortar mixtures.

Since the dynamic elastic modulus of a specimen is directly related with its geometric properties, mass and longitudinal resonant frequency; it can be expected to observe that the development tendencies for dynamic elastic modulus and longitudinal frequency are similar for a particular mixture. Further, among the eight different mixtures, it can be expected to see the same order for longitudinal frequencies and dynamic elastic modulus values. As an example, it can be estimated that the mixture with the highest frequency will also have the highest elastic modulus. Regarding these issues, it is observed that although the development trends of frequencies and elastic modulus values are very similar, little variations in the sequencing can be noticed by comparing Figure 4.1-a and Figure 4.2. These variations may be mainly due to the differences in mass and geometric properties of the specimens from different mixtures. Regarding the relation between the longitudinal resonant frequency and dynamic modulus of elasticity, a correlation curve is presented in Figure A.3, in Appendix A.

On the other hand, observations similar to those made for the frequency results can be made for dynamic elastic modulus regarding the influence of cement type. A more detailed and comprehensive discussion about cement type influence will be given in the following sections.

4.2.2 Dynamic Shear Modulus Results Obtained by Resonant Frequency Testing

Using the relationships between dynamic shear modulus and torsional resonant frequency, the shear modulus values of mortar specimens for the eight mixtures were determined and the development of the values for each mixture are presented in Figure 4.3 below. The exact dynamic shear modulus values for each mixture on each day are presented in Table A.4, in Appendix A.

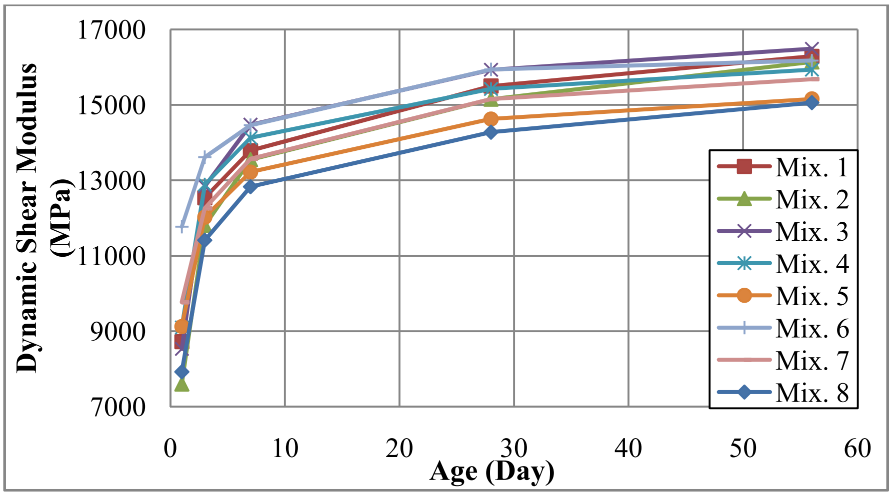


Figure 4.3 Dynamic shear modulus development for different mortar mixtures

Figure 4.2 and Figure 4.3 can be compared to observe that the dynamic elastic modulus values of the specimens are between 19000 MPa and 40000 MPa where the corresponding shear modulus values range between 7500 MPa and 17000 MPa. Therefore, it may be inferred from these results that the dynamic shear modulus of a mortar specimen is nearly 40 to 45 percent of its corresponding dynamic elastic modulus, for all ages.

4.2.3 Dynamic Poisson’s Ratio Results Obtained by Resonant Frequency Testing

Using the dynamic elastic modulus and dynamic shear modulus test results obtained from resonant frequency testing, dynamic Poisson’s ratios, presented in Figure 4.4, were obtained.

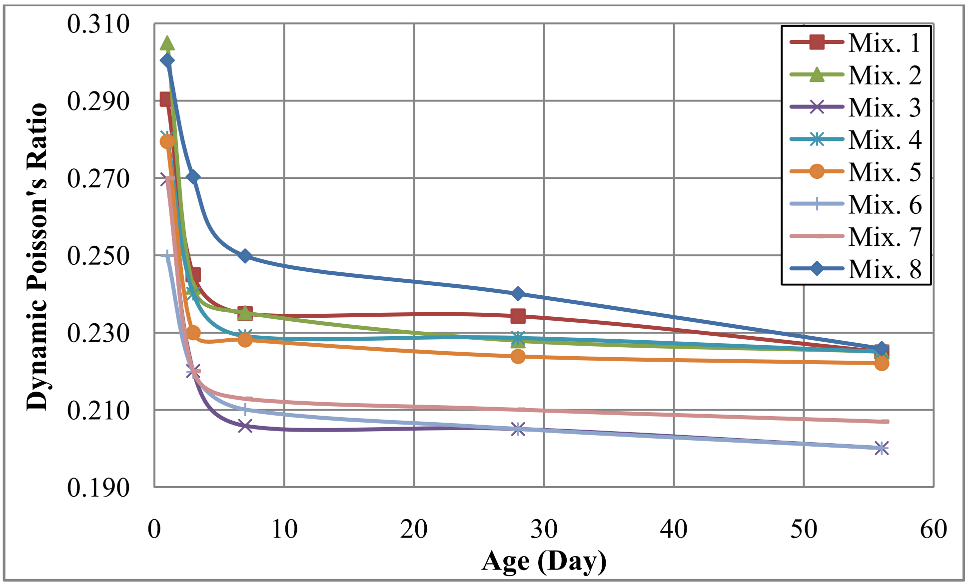


Figure 4.4 Variation of dynamic Poisson’s ratio with age of mortar

As can be observed from Figure 4.4, the dynamic Poisson’s ratios of mortar mixtures are initially high and decrease mainly between the first and seventh days, by about 10 to 20 percent. After 7 days, however, reductions seen in the Poisson’s ratio are gradual. This situation may be related to the non-rigid, semi-solid state of the mortars in the first few days. With ongoing hydration and strength gain, the mortars become more rigid and Poisson’s ratio values reach asymptotic values.

Regarding the relationship between dynamic elastic modulus and Poisson’s ratio, it can be noticed from Figure 4.2 and Figure 4.4 that the dynamic elastic modulus increases with age while the Poisson’s ratio decreases. And it may be guessed from the results that any factor that decreases dynamic elastic modulus increases Poisson’s ratio. In order to portray this issue more satisfactorily, Figure 4.5 below is plotted.

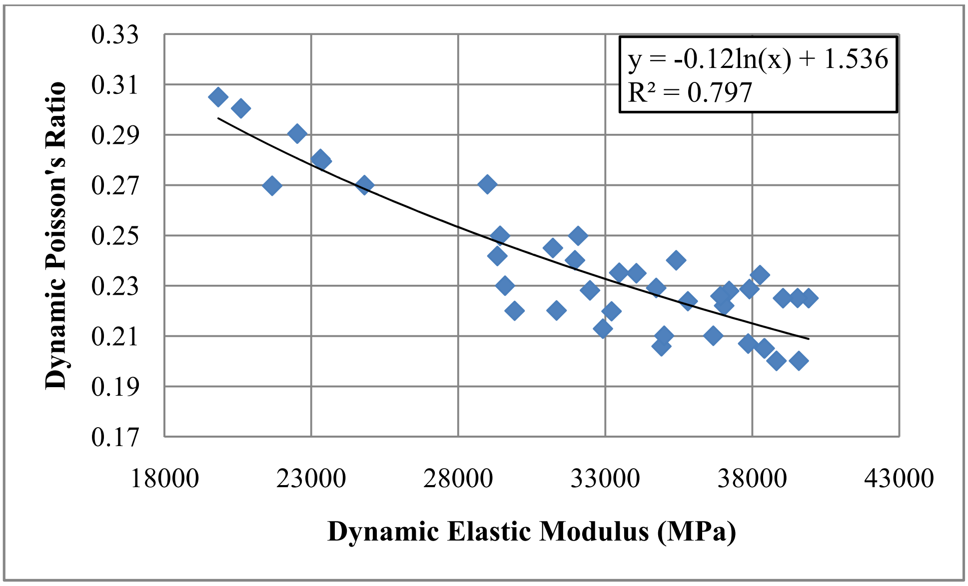


Figure 4.5 Variation of dynamic Poisson’s ratio with dynamic elastic modulus of test specimens

From Figure 4.5; it seems that Poisson’s ratio tends to decrease with an increase in dynamic modulus of mortar. An empirical equation, which seems to best fit for higher values of Poisson’s ratio, is also developed regarding this relation. However, the cement type is the only variable for preparation of different mixture types in this study and the scattered data seen in Figure 4.5 reveals that it may be difficult to make any definite comment if more variables existed for the mixtures.

4.3 Ultrasonic Pulse Velocity Test Results

It is generally not recommended to use the results obtained from ultrasonic pulse velocity tests for elastic modulus determination due to the risk of inaccurately estimating Poisson’s ratio. In this study, however, the Poisson’s ratio values for the test specimens had been previously determined using resonant frequency tests. Thus, by combining the pulse velocity test results, which are presented in Figure 4.6, with resonant frequency test results; it could be possible to obtain dynamic elastic modulus values without making any assumptions about Poisson's ratio. The dynamic elastic moduli obtained using the pulse velocity method are presented in Figure 4.7. The exact pulse velocity and dynamic elastic modulus values for each mixture and for each day are also provided in Table A.5 and Table A.6, in Appendix A.

In general, the typical pulse velocity for ordinary concrete is 3700 m/s to 4200 m/s (Malhotra and Carino, 2004). In this study, for different mortar mixtures, the results ranged between 3600 m/s and 4700 m/s. The same development trend observed for resonant frequency and dynamic elastic modulus over time is also reported for pulse velocity. It can be noticed from Figure 4.6 that the most remarkable increase in velocities for different specimens occurs between the first day and the seventh day. The velocity also increases between the seventh and twenty-eighth days but beyond one month, large changes in pulse velocities are not seen.

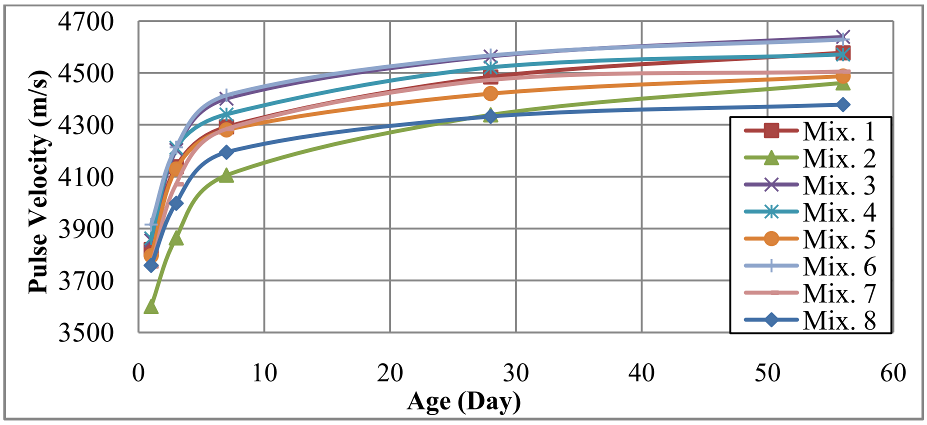


Figure 4.6 Pulse velocity development over time for different mixtures

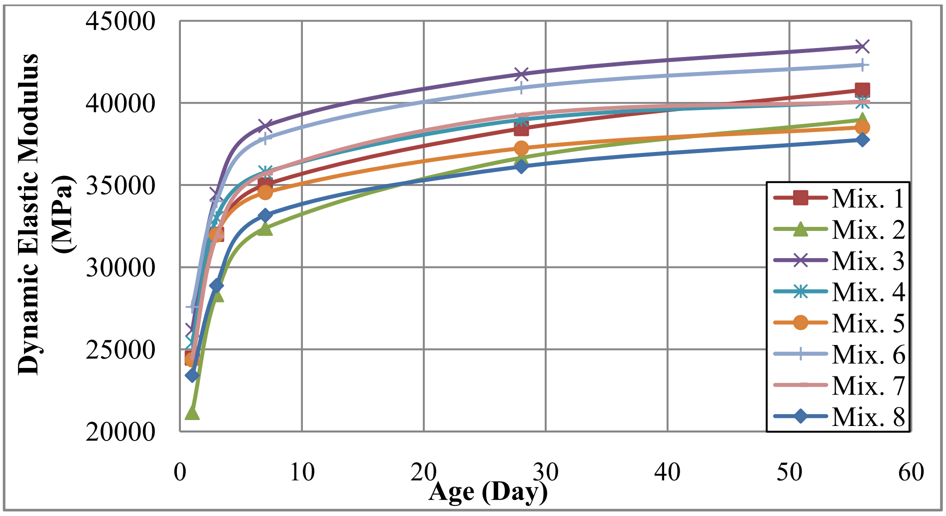


Figure 4.7 Dynamic elastic modulus variations determined by ultrasonic pulse velocity testing

By examining the pulse velocities and dynamic elastic modulus values given in Figure 4.6 and Figure 4.7, respectively, it can be noticed that there is little difference in the development trends. This difference may be related with different geometric properties, masses and Poisson's ratio values for different specimens. Regarding the relationship between pulse velocity and dynamic elastic modulus, a correlation curve is also presented in Figure A.4, in Appendix A.

Another point of interest is the relation of elastic moduli results obtained by the two different nondestructive methods. A detailed discussion about their relations is presented in the following sections.

4.4 Static Elastic Modulus Test Results

As has been mentioned in Chapter 3, midpoint deflection values of different mortar beam specimens under static loading were measured using a non-standard method to obtain the static elastic moduli. While performing static elastic modulus tests, no measurements were made at age one due to possibility of microcrack formation on the specimens. Static elastic moduli at 3, 7, 28, and 56 days are reported in Figure 4.8, and the exact values of the results for each mixture can be seen in Table A.7, in Appendix A.

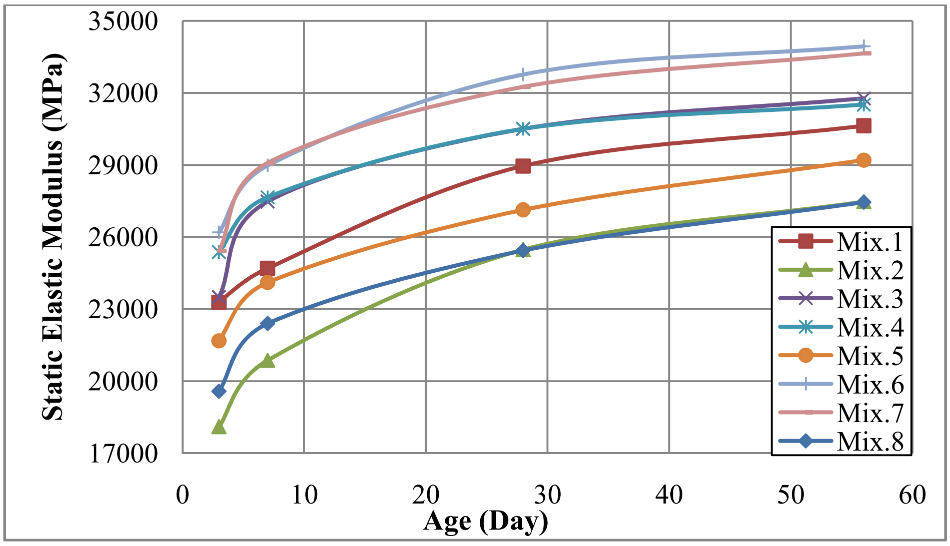


Figure 4.8 Static elastic modulus development for different mixtures

Analyzing the data presented in Figure 4.8, it can be seen that the static elastic moduli range between 17000 MPa and 35000 MPa. The values naturally increase rapidly between the third and seventh days and continue to increase up to the twenty-eighth day. After this age, however, large changes in the elasticity moduli are not observed, similarly to previous test results. It can be noticed from Figure 4.2, Figure 4.7 and Figure 4.8 that dynamic elastic moduli of specimens are slightly higher than the static elastic moduli. Their relation is very important since static elastic modulus is mainly used for the engineering design of structures. Thus, a detailed discussion about their relation will be covered in the following sections.

4.5 Strength Test Results

For determining the strength of mortar mixtures, the prismatic test specimens were initially divided into two pieces by applying flexural loads and the corresponding flexural strengths were recorded. Then compressive loads were applied to those two pieces for obtaining compressive strength values. The average resultant test results for each mixture are presented below in Figure 4.9 and Figure 4.10 while the statistical descriptors for the results can be seen in Table A.8 and Table A.9, in Appendix A.

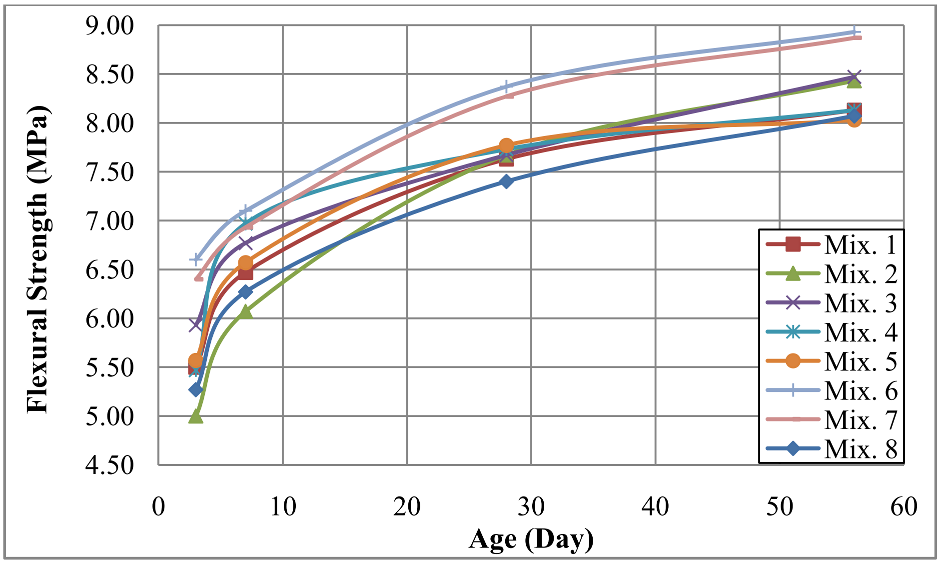


Figure 4.9 Development of flexural strength of the mortar specimens

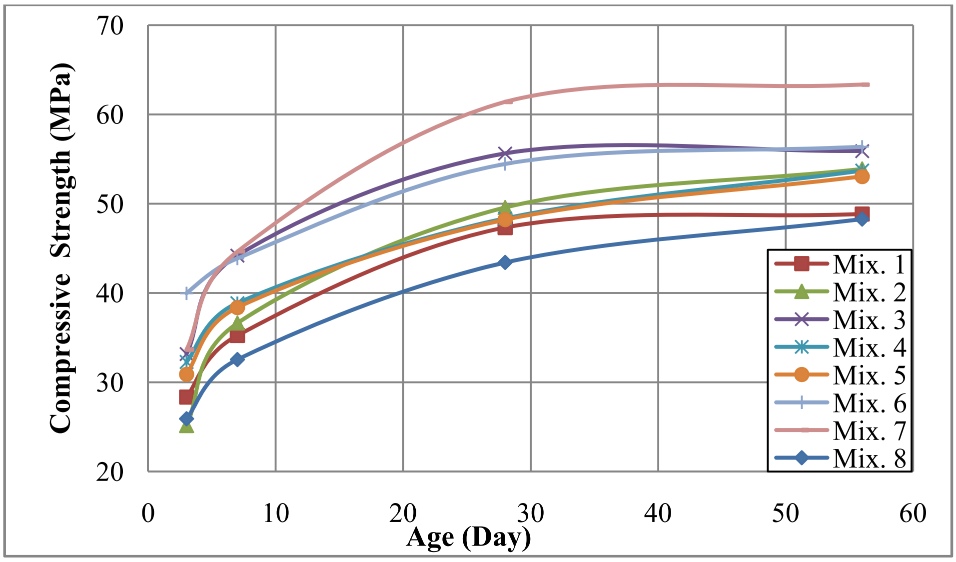


Figure 4.10 Development of compressive strength of the mortar specimens

As can be seen in Figure 4.9 and Figure 4.10, compressive strengths of specimens are much higher than the flexural strengths, as expected. The flexural strength of a specimen is approximately 15 to 20 percent of its corresponding compressive strength. Examining the development curves over the time, it can be inferred that both compressive and flexural strength increase greatly in the first 28 days and continue to increase more gradually as hydration continues. Moreover, it can be noticed from Figure 4.9 and Figure 4.10 that the specimens which have the higher compressive strength do not always have the higher flexural strengths. This situation may be due to the nonhomogeneous nature of the material, or due to measurement errors arising from the test machine. The relationship between flexural and compressive strength observed for the different mixtures is presented in Figure A.5 and Figure A.6, in Appendix A.

On the other hand, variations up to 40 percent at early ages, and 25 percent at later ages apparent in the strength data of different mixtures indicate that cement type has a great influence on strength results as well. As such, the influence of cement type on strength and other test results will be discussed in the following section in detail.

4.6 Influence of Cement Type on Test Results

Eight different mixtures were prepared for this study and the only difference between these mixtures was cement type. Although one variable was used for preparation of different mixtures, great variation in the results was found. In this section, the remarkable effects of cement type are discussed in detail.

It can be observed from Figure 4.2, Figure 4.7, Figure 4.8 and Figure 4.10 that the 2nd and the 8th mixtures, which were prepared using CEM I 42.5 N and SRC 32.5 cements respectively, have relatively low early strength with low early static and dynamic moduli. On the other hand, the highest early strength and dynamic moduli were recorded for the 6th mixture, prepared by using the white cement CEM I 52.5 N. Actually, it was expected to obtain relatively low early strengths and dynamic moduli for the 2nd and 8th mixtures due to chemical compositions of the constituent cements but this much higher early strengths and dynamic moduli for the 6th mixture were not expected. However, it is observed from Table 3.1 that the Blaine fineness value of 6th cement is significantly higher than that of the other cements. As is known, increasing the fineness of cement mostly decreases the setting time and increases the early strength of mixtures. Thus, the early strength gain of the 6th mixture might be related to its fineness. On the other hand, it seems that as time passes and hydration of cements continue, the strength and elasticity moduli results obtained for these three mixtures get closer to those of the other five mixtures.

Regarding the other five mixtures prepared with five different CEM I 42.5 R type cements; it can be stated that although the results show little variation, no remarkable differences between their results develop. The results are generally close due to their similar chemical compositions. Only the 7th mixture has, curiously, very high compressive strength at later ages despite its dynamic elastic modulus not being very high. There are also some scattered data for other mixtures but other than 7th mixture it appears that as hydration continues and as mixtures gain strength, the results of different mixtures near one another and do not differ greatly.

By observing the Poisson’s ratio data in Figure 4.4, there are once again noteworthy points among the early age results. The 2nd, 6th and 8th mixtures have greatly higher or lower Poisson’s ratio values, especially for the first test day when compared to the average values. As can be seen from Figure 4.4; the 6th mixture has the lowest Poisson’s ratio for the early ages where the 2nd and 8th mixtures have the highest values. This situation may again be related to chemical composition and fineness of the cements. As time passes, the differences between results decrease and less scattered data for later ages are obtained. Regarding the other five mixtures, little differences in the results due to different chemical or physical properties of the cements are also seen but these differences appear not to be remarkable when they are compared to the 2nd, 6th and 8th mixtures.

After evaluating all results, it can be claimed that chemical composition and physical properties of cements have a direct influence on strength, static elastic modulus and dynamic elastic modulus of mortars.

4.7 Comparison of Resonant Frequency Test Results with Ultrasonic Pulse Velocity Test Results

Both the resonant frequency and pulse velocity methods were derived for solid media which is considered to be homogeneous, isotropic and perfectly elastic. In theory, the dynamic elastic modulus results determined by these test methods should be the same. However, the elastic properties of cement mortar obtained by using these different tests may not exactly be the same and may differ from each other due to the heterogeneous, nonlinear and inelastic nature of cement-based materials. Regarding this issue, differences between the dynamic elastic modulus results of mortar specimens obtained using these two test methods are observed and have been presented in Figure 4.11 below.

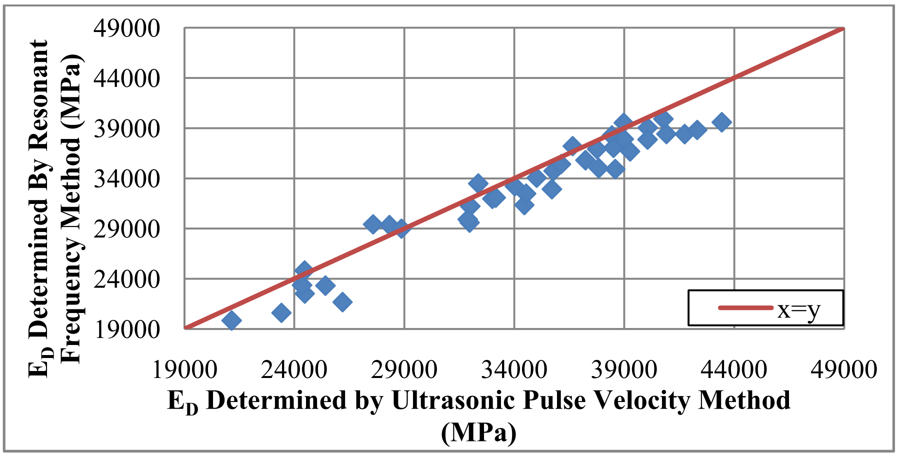


Figure 4.11 Comparison of dynamic elastic modulus results obtained from two nondestructive methods

Examining the data in Figure 4.11, it can be claimed that the dynamic elastic modulus values determined from ultrasonic pulse velocity testing are generally slightly higher than those obtained from resonant frequency testing although not strictly. This is investigated individually for each mixture in Figure 4.12.

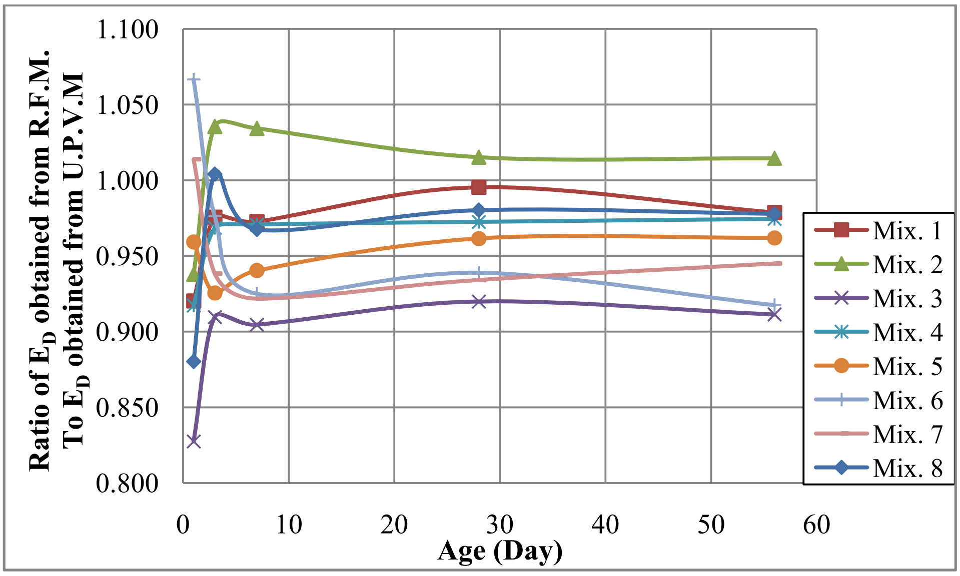


Figure 4.12 The variation in the ratios of E_D obtained from resonant frequency testing to E_D obtained from ultrasonic pulse velocity testing

It can simply be stated that the ratios of dynamic elastic moduli obtained from resonant frequency testing to those obtained from ultrasonic pulse velocity testing show variations for each mixture. Although the results generally seem to be in the ranges of 0.90 to 1.05, the 1-day measurements show great deviations. This may be related to Poisson's ratio values obtained from resonant frequency testing. Since Poisson's ratio values are very high on the first day relative to the other days, dynamic elastic moduli obtained from ultrasonic testing may be different due to this reason. On the other hand, the nearly plastic and non-rigid state of mortar specimens at this early age may also cause these deviations.

After the first day, more uniform and linear relationships are seen in Figure 4.12. For these days, the results of dynamic elastic moduli obtained from ultrasonic testing are higher than those obtained from resonant frequency testing except for the 2nd mixture. By observing the ratios, it can be seen that the 3rd, 6th and 7th mixtures have relatively lower ratios which are between 0.90 and 0.95. On the other hand the 1st, 4th, 5th and 8th mixtures have relatively higher ratios which are between 0.95 and 1.00. Investigating the strengths of these mixtures, the 3rd, 6th and 7th mixtures have also comparatively higher compressive strength values than the other mixtures. Thus it may be claimed that the ratio of resonant to ultrasonic dynamic elastic moduli tends to decrease for the mixtures which have higher strength values and tends to increase for the mixtures which have lower strength values.

Among the eight mixtures, mixture 2 differs from the other mixtures since the dynamic elastic modulus values determined from resonant frequency testing for this mixture are higher than that obtained from ultrasonic pulse velocity testing. This situation may be related to its constituent cement. Since the cement used for preparing mixture 2 was the sulphate resistant one, its properties differ greatly from those of the others.

After evaluating all results, it appears that the dynamic elastic moduli obtained from two nondestructive test methods differ by a maximum of 10 percent and the results are close. However, it is difficult to claim that this trend will be same for any mixture with more variables. Increasing the variables may increase the differences in the results.

4.8 Comparison of Dynamic and Static Moduli of Elasticity

Since the static elastic modulus is commonly used for engineering design and since dynamic elastic modulus is easier to obtain, it is important to establish a relationship between dynamic and static elastic moduli. In this study, two different dynamic elastic modulus results found by different nondestructive methods are compared with the static elastic modulus results found by nonstandard deflection methods. The regarding results are presented below in Figure 4.13 and Figure 4.14.

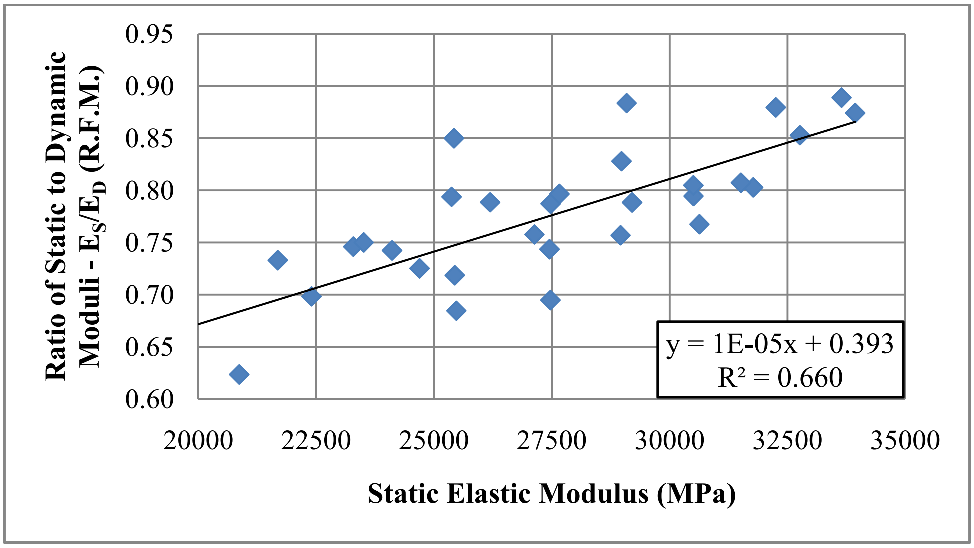


Figure 4.13 Relationship between ratio of static to vibrational dynamic moduli and static elastic modulus

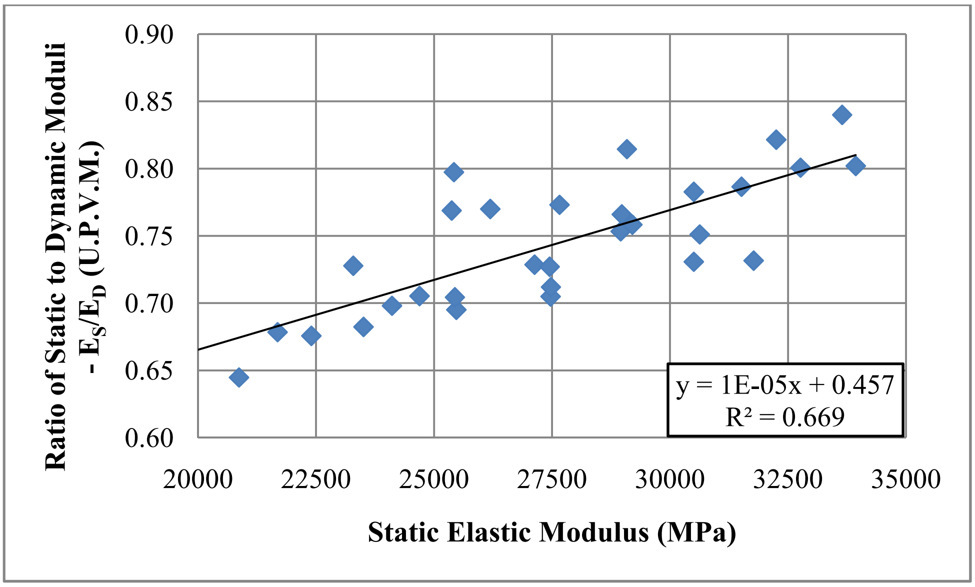


Figure 4.14 Relationship between ratio of static to pulse velocity dynamic moduli and static elastic modulus

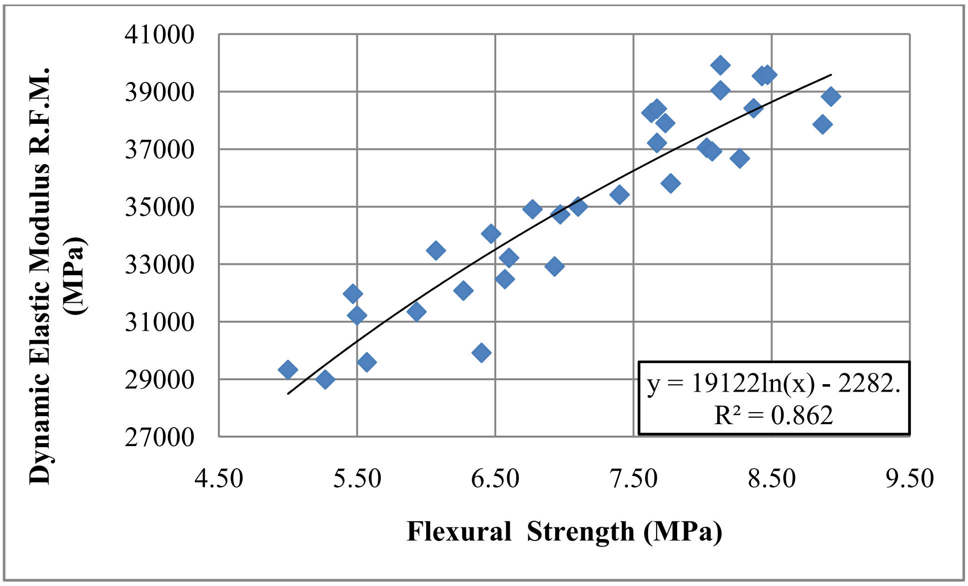
As can be observed from Figure 4.13 and Figure 4.14, dynamic elastic moduli of mortar specimens obtained from both nondestructive methods are always higher than the static elastic moduli. However, there is no single ratio between static and dynamic elastic modulus. The values vary between 0.6 and 0.9 and increase with increasing specimen age.

The behaviour corresponding to each mixture was also investigated and is presented in Figure A.7 - Figure A.16, in Appendix A. It can be observed from Figure A.15 and Figure A.16 that the ratios between static and dynamic moduli are relatively smaller for the specimens which have lower static elastic moduli, and relatively higher for the specimens which have higher static elastic moduli. As an example, the ratios, at age 28 days, for the 4th, 6th and 7th mixtures are around 0.85 while those for the 2nd and 8th mixtures are around 0.7. Thus, it can be stated that the static and dynamic elastic modulus results are closer for higher static elastic modulus values. The results obtained separately for each mixture also reveal that there is more than 15 percent difference between the ratios for different types of mixtures. Thus, it is not likely to attain one comprehensive relationship between static and dynamic elastic modulus which represents all different types of mixtures.

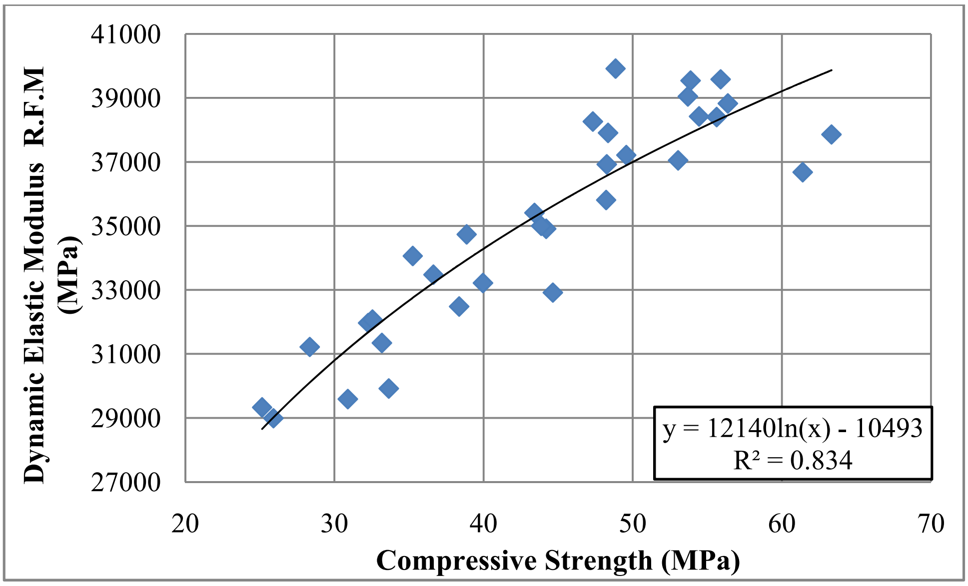
Moreover, although the common tendency shows that the ratios of static to dynamic moduli increase with increasing specimen age, this is contradicted for a couple of mixtures, particularly for the mixture 1. This situation may be related with the different shaped and sized mortar specimens used in the static tests, or with the test technique used for determining static elastic modulus. It may then be claimed that the size and mass of specimens with their constituents and the test techniques used for obtaining both static and dynamic elastic modulus have an influence on test results.

4.9 Relation between Dynamic Elastic Modulus and Strength of the Cement Mortars

Since strength is used in almost all areas of engineering design, it is generally considered to be the most important property for materials. For concrete and mortar, the situation is no different. Thus, correlations between strength and dynamic modulus were generated for the different mixtures. Corresponding correlations, which were formed for both compressive and flexural strength, are presented below in Figure 4.15 and Figure 4.16.

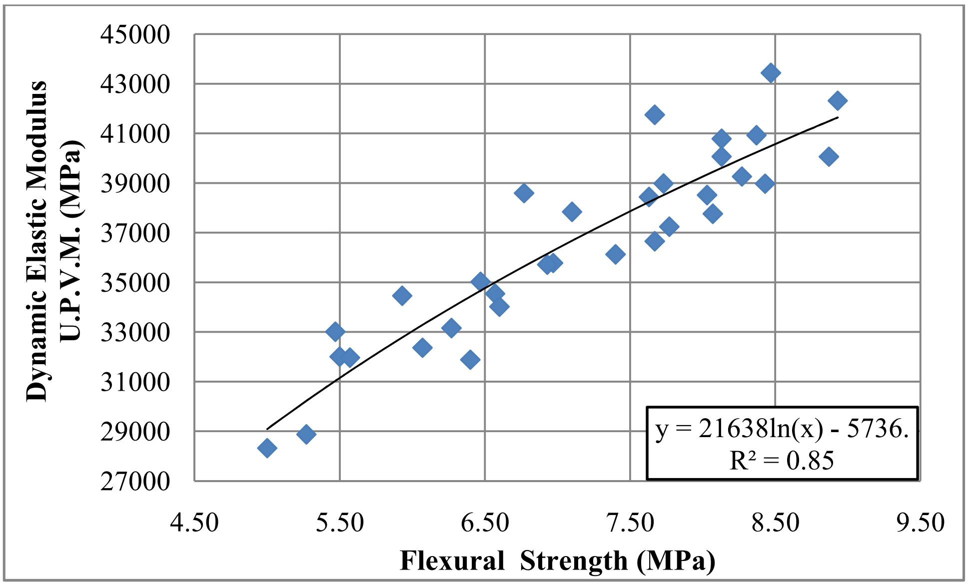


(a)

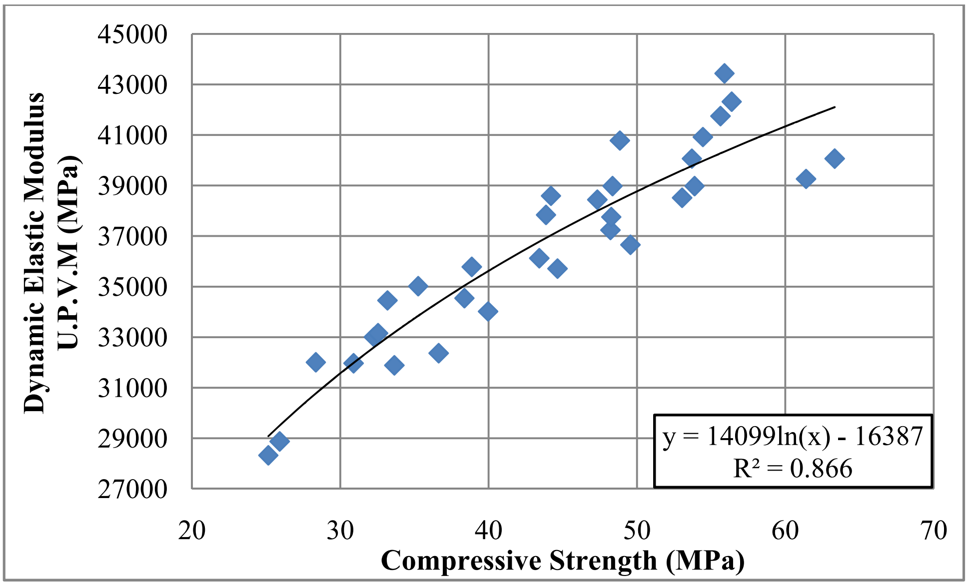


(b)

Figure 4.15 Relationship between dynamic elastic modulus found using the resonant frequency method and (a) flexural strength, (b) compressive strength



(a)



(b)

Figure 4.16 Relationship between dynamic elastic modulus found using the ultrasonic method and (a) flexural strength, (b) compressive strength

As has been mentioned in Chapter 2, numerous empirical equations have been established between the dynamic elastic modulus of a mortar and its compressive or flexural strength by various researchers. However, no unique relationship has been obtained up to now.

Nevertheless, the dynamic tests and strength tests were performed on prismatic specimens to obtain relationships and to develop correlations between these elastic characteristics of cement mortars. In Figure 4.15, the developed correlations between resonant frequency results and strength values are shown. It can be seen from the results that although the data shows some scatter, empirical equations for both compressive and flexural strengths could be generated with reasonable accuracy to predict the modulus of elasticity from strength values. The same deductions can be made for the test results presented in Figure 4.16. Again slightly satisfactory empirical equations between strength and dynamic modulus are formed for the results obtained from ultrasonic pulse velocity testing. The correlations generated from the results of both nondestructive test methods are similar and do not differ much since the dynamic elastic moduli obtained from these methods are also similar.

On the other hand, more satisfactory correlations can be obtained for individual mixture studies. As an example, the correlation curve which includes the data of only first mixture has the coefficient of determination (r^2) value of 0.96. However, by increasing the variables such as including the data of second mixture to existing data, the coefficient of determination value decreases to 0.86. This situation may be another great example showing the influence of cement type on test results. Moreover, the water/cement ratio, wetness (moisture condition), degree of compaction and constituents of mixtures other than cement were all identical for the specimens tested in this study. It appears that if the test conditions stated were not same, and more of the parameters were varied, the variations seen in Figure 4.15 and Figure 4.16 could increase. Then it might be impossible to obtain a single relationship between strength and dynamic elastic modulus which include all types of mixtures with a desired accuracy. Regarding the relationship between dynamic elastic modulus and compressive strength observed for each mixture, Figure A.17 and Figure A.18 are presented in Appendix A.

CHAPTER 5

CONCLUSIONS

An experimental study has been carried out to establish relations and correlations between dynamic elastic modulus, static elastic modulus, and strength characteristics of mortar specimens made using different CEM I cements. Different nondestructive and destructive tests have been performed in order to obtain these characteristics, and monitor their developments over the time. The corresponding results have been presented within the limitations of tests and variables. A detailed evaluation and discussion of results has also been supplied with comparisons.

As a result of these studies, the following conclusions can be drawn:

- For all mixtures, the torsional frequency of a 4 × 4 × 16 cm^3 prismatic mortar specimen is around 60 percent of its corresponding longitudinal frequency, for all ages. The torsional frequencies for specimens developed approximately from 5000 Hz to 8000 Hz whereas the corresponding longitudinal frequencies increased from approximately 9000 Hz to 13000 Hz.
- Dynamic shear moduli of all specimens are about 40 to 45 percent of their corresponding dynamic elastic moduli for all ages. Dynamic elastic moduli of specimens lie between 19000 MPa and 40000 MPa

whereas the corresponding dynamic shear moduli range between 7500 MPa and 17000 MPa.

- The results confirm that dynamic Poisson’s ratios of all mortar mixtures are initially high and decrease mainly between the first and seventh days, by about 10 to 20 percent, with increases in the strength and maturity of mortars. After 7 days, however, no large changes appear and more gradual decreases occur.
- Although considerable scatter exists in the data, using Figure 4.5, the dynamic Poisson’s ratio of mortar mixtures can be predicted from known dynamic elastic modulus values.
- Although no unique ratio exists, the flexural strengths of all specimens are approximately 15 to 20 percent of their corresponding compressive strengths for all ages.
- Increases in the values of dynamic elastic modulus, static elastic modulus and strength of mortar specimens are all high in the first seven days. For later ages, more steady developments are observed.
- The chemical and physical properties of cements have a direct influence on both destructive and nondestructive test results.
- The Blaine fineness value of a cement is especially important for the early age development of elastic properties of mortar mixture. The white portland cement used has a nearly 20 percent higher Blaine fineness value than the other cements and the mixture made with this cement has noticeably higher strength, dynamic elastic modulus and static elastic modulus at early ages.
- Chemical composition of cement has a direct influence on the elastic properties of mortar mixture. Mixtures which include CEM I 42.5 R type cements have relatively higher strengths and elasticity moduli than

mixtures including CEM I 42.5 N and SRC 32.5 type cements, especially at early ages due compositional differences.

- Dynamic elastic moduli obtained from resonant frequency and ultrasonic pulse velocity methods do not differ excessively and the results are close for all ages except the first day.
- The dynamic elastic moduli determined from ultrasonic pulse velocity testing are higher than those obtained from resonant frequency testing for all mixtures except the second mixture which uses SRC 32.5 type cement.
- The ratio of dynamic elastic moduli found using the resonant frequency method to that obtained from ultrasonic pulse velocity method tends to decrease for the mixtures which have higher strength values and tends to increase for the mixtures which have lower strength values.
- The discrepancies between dynamic elastic moduli of mortar specimens obtained from the two nondestructive test methods can be attributed to the formulations used in these methods since they are inadequate to describe nonhomogeneous, inelastic and nonlinear behaviour of cement-based materials.
- Dynamic elastic moduli of mortar specimens obtained from both nondestructive methods are always higher than static elastic moduli. However, there is no unique ratio between static and dynamic elastic moduli. The values vary in between 0.6 to 0.9 and increase with ongoing hydration.
- The ratios between static and dynamic moduli are relatively smaller for the specimens which have lower static moduli and strength, and relatively higher for the specimens which have higher static elastic moduli and strength.

- The differences between the static and dynamic modulus of concrete can depend on types of destructive and nondestructive tests used and their corresponding drawbacks, and on the geometry of the tested specimens.
- Using Figure 4.15 and Figure 4.16, the dynamic elastic moduli of mortar specimens can be predicted with known values of flexural or compressive strength values.
- Although several relations are obtained between different elastic properties of cement mortar specimens within test and material limitations, results have revealed that it is very difficult to obtain unique relationships between elastic properties of cement-based materials for a wide range of mix proportions and compositions. This situation is mainly related with the time-dependent and nonhomogeneous structure of cement-based materials and the difficulty of describing the actual behavior of these materials with formulas defined for perfectly elastic materials.

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APPENDIX A

SUPPLEMENTARY TEST RESULTS

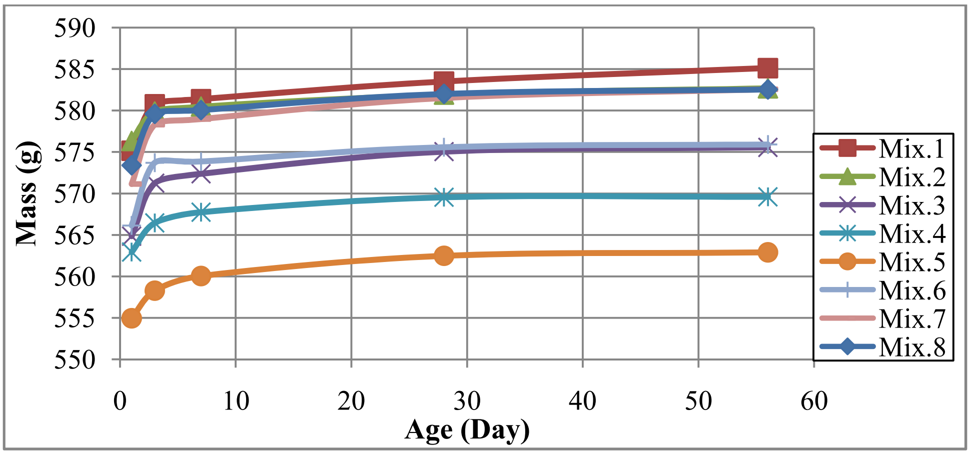

Figure A.1 Mass development of eight mixtures over time

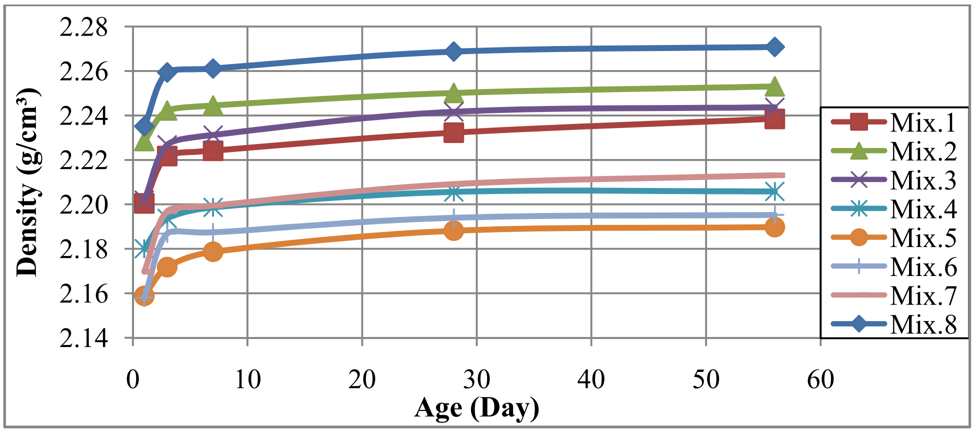

Figure A.2 Density development of eight mixtures over time

Table A.1 Exact longitudinal frequency values for each mixture

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
1	1	9728	10300	229	9876
	3	11444	11826	191	11571
	7	11826	12398	252	12080
	28	12589	12970	165	12779
	56	12970	13161	96	13034

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
5	1	10109	10300	96	10236
	3	11444	11635	84	11486
	7	12016	12016	0	12016
	28	12589	12589	0	12589
	56	12779	12970	64	12800

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
2	1	9155	9346	95	9282
	3	11253	11253	0	11253
	7	12016	12016	0	12016
	28	12589	12779	95	12652
	56	12970	13161	96	13034

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
6	1	11444	11444	0	11444
	3	12016	12207	96	12080
	7	12398	12398	0	12398
	28	12970	12970	0	12970
	56	12970	13161	96	13034

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
3	1	9728	9728	0	9728
	3	11635	11826	96	11699
	7	12207	12398	96	12334
	28	12779	12970	96	12906
	56	12970	13161	96	13097

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
7	1	10300	10490	84	10448
	3	11253	11444	84	11402
	7	11826	12016	95	11953
	28	12589	12589	0	12589
	56	12779	12779	0	12779

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
4	1	10109	10300	64	10130
	3	11826	11826	0	11826
	7	12207	12398	101	12313
	28	12779	12970	96	12843
	56	12970	13161	96	13034

Mix.	Age (Day)	Longitudinal Frequency (Hz)			
		Min.	Max.	σ*	Mean
8	1	9155	9728	216	9431
	3	10872	11253	191	11126
	7	11444	11826	191	11699
	28	12016	12398	191	12271
	56	12207	12779	252	12525

* σ denotes standard deviation

Table A.2 Exact torsional frequency values for each mixture

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
1	1	5568	5820	126	5652
	3	6668	6890	111	6742
	7	6974	7253	140	7067
	28	7253	7603	137	7478
	56	7618	7731	57	7656

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
2	1	5210	5319	55	5283
	3	6565	6565	0	6565
	7	7029	7029	0	7029
	28	7386	7497	56	7423
	56	7618	7730	56	7655

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
3	1	5605	5722	59	5644
	3	6848	6960	56	6885
	7	7253	7327	37	7302
	28	7568	7681	57	7643
	56	7697	7810	57	7772

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
4	1	5820	5820	0	5820
	3	6904	6904	0	6904
	7	6960	7253	98	7220
	28	7497	7603	53	7532
	56	7618	7731	57	7656

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
5	1	5810	5920	55	5883
	3	6710	6780	35	6733
	7	7057	7057	0	7057
	28	7398	7398	0	7398
	56	7515	7553	19	7528

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
6	1	6655	6655	0	6655
	3	7073	7185	56	7110
	7	7327	7327	0	7327
	28	7681	7681	0	7681
	56	7697	7810	57	7735

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
7	1	5978	6052	37	6027
	3	6698	6736	19	6711
	7	6974	7185	54	7062
	28	7440	7440	0	7440
	56	7562	7562	0	7562

Mixture	Age (Day)	Torsional Frequency (Hz)			
		Min.	Max.	σ*	Mean
8	1	5220	5455	118	5377
	3	6271	6491	110	6418
	7	6655	6877	111	6803
	28	7015	7238	112	7164
	56	7135	7562	175	7354

* σ denotes standard deviation

Table A.3 Exact dynamic elastic modulus values obtained from resonant frequency test method

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
1	1	22105	23208	598	22522
	3	30969	31545	295	31219
	7	33295	34699	710	34059
	28	37862	38808	490	38262
	56	39354	40310	499	39915

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
2	1	19189	20281	574	19837
	3	29148	29571	218	29329
	7	33277	33745	242	33475
	28	36610	38252	904	37213
	56	38912	40622	941	39541

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
3	1	21133	22466	703	21672
	3	30678	32308	855	31343
	7	33831	35594	945	34910
	28	37264	39109	995	38401
	56	38420	40305	1016	39582

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
4	1	23115	23427	170	23311
	3	31788	32296	285	31968
	7	34486	35019	268	34733
	28	37353	38451	549	37906
	56	38482	39595	557	39045

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
5	1	22478	23829	766	23363
	3	29065	30205	576	29589
	7	32172	32653	268	32480
	28	35464	36011	299	35807
	56	36939	37129	97	37045

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
6	1	29011	29757	379	29422
	3	32978	33399	216	33216
	7	34468	35421	487	35002
	28	37826	38898	546	38422
	56	37851	39706	931	38825

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
7	1	24301	25161	451	24811
	3	29687	30114	216	29917
	7	32442	33237	420	32918
	28	36528	36864	171	36676
	56	37702	38064	185	37859

Mixture	Age (Day)	Dynamic Elastic Modulus - R.F.M (MPa)			
		Min.	Max.	σ*	Mean
8	1	20049	21400	705	20607
	3	28571	29738	648	28991
	7	31666	32880	695	32078
	28	34946	36254	732	35411
	56	36190	37414	646	36921

* σ denotes standard deviation

Table A.4 Exact dynamic shear modulus values for each mixture

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
1	1	8568	8987	227	8727
	3	12438	12667	117	12538
	7	13623	14048	227	13790
	28	15203	15801	299	15499
	56	16065	16451	202	16291

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
5	1	8784	9312	300	9130
	3	11821	12268	225	12028
	7	13098	13294	109	13223
	28	14488	14712	122	14629
	56	15115	15190	39	15157

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
2	1	7352	7771	221	7601
	3	11736	11906	88	11809
	7	13471	13660	98	13551
	28	14908	15575	367	15153
	56	15881	16578	383	16137

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
6	1	11606	11905	152	11771
	3	13517	13689	88	13614
	7	14241	14635	201	14462
	28	15694	16139	226	15941
	56	15770	16541	387	16175

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
3	1	8300	8846	281	8534
	3	12572	13238	350	12844
	7	14129	14707	305	14474
	28	15461	16226	412	15933
	56	16007	16790	423	16490

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
7	1	9566	9907	179	9769
	3	12165	12342	89	12261
	7	13395	13706	159	13570
	28	15093	15232	71	15154
	56	15618	15768	77	15683

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
4	1	9057	9186	72	9102
	3	12817	13021	115	12889
	7	14018	14191	97	14129
	28	15209	15631	211	15425
	56	15705	16163	229	15936

Mixture	Age (Day)	Dynamic Shear Modulus (MPa)			
		Min.	Max.	σ*	Mean
8	1	7710	8174	234	7923
	3	11245	11705	255	11411
	7	12668	13153	278	12833
	28	14090	14618	295	14278
	56	14626	15355	383	15059

* σ denotes standard deviation

Table A.5 Exact pulse velocity values for each mixture

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
1	1	3807	3829	12	3820
	3	4120	4151	16	4138
	7	4240	4320	45	4292
	28	4474	4503	16	4485
	56	4528	4605	43	4578

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
2	1	3555	3681	71	3599
	3	3815	3949	74	3864
	7	4050	4149	51	4106
	28	4313	4379	36	4338
	56	4447	4481	17	4461

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
3	1	3849	3861	6	3854
	3	4188	4226	20	4203
	7	4376	4416	22	4401
	28	4545	4591	24	4564
	56	4620	4662	22	4638

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
4	1	3821	3940	67	3863
	3	4160	4299	76	4211
	7	4297	4416	65	4340
	28	4485	4573	46	4521
	56	4522	4621	49	4571

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
5	1	3730	3830	56	3795
	3	4030	4185	87	4130
	7	4185	4336	83	4280
	28	4324	4476	83	4420
	56	4392	4535	83	4487

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
6	1	3880	3969	47	3915
	3	4171	4286	63	4213
	7	4407	4426	11	4413
	28	4557	4585	15	4567
	56	4613	4651	20	4629

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
7	1	3724	3770	26	3754
	3	4035	4099	33	4071
	7	4265	4320	31	4284
	28	4449	4515	36	4473
	56	4486	4540	31	4505

Mixture	Age (Day)	Pulse Velocity (m/s)			
		Min.	Max.	σ*	Mean
8	1	3741	3774	16	3758
	3	3976	4019	22	3997
	7	4179	4216	20	4194
	28	4288	4390	52	4332
	56	4334	4433	51	4378

* σ denotes standard deviation

Table A.6 Exact dynamic elastic modulus values obtained from ultrasonic pulse velocity test method

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
1	1	24138	24685	294	24473
	3	31438	32429	509	32002
	7	33916	36796	1556	35016
	28	38269	38729	254	38437
	56	39561	41472	1060	40782

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
5	1	23398	24845	827	24353
	3	30395	32854	1365	31966
	7	32968	35473	1370	34540
	28	35586	38241	1443	37239
	56	36839	39380	1449	38512

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
2	1	20507	22232	940	21153
	3	27330	29711	1239	28322
	7	31657	33200	779	32366
	28	35862	37485	813	36653
	56	38498	39464	483	38974

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
6	1	26719	28775	1066	27583
	3	32716	35763	1571	34019
	7	37170	38337	602	37838
	28	40261	41480	616	40921
	56	41719	42732	530	42315

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
3	1	25688	26599	463	26191
	3	34002	34836	421	34455
	7	38337	38847	255	38593
	28	41169	42262	549	41745
	56	42836	43890	542	43435

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
7	1	24209	24757	274	24471
	3	31521	32111	317	31883
	7	35532	35850	163	35712
	28	38956	39634	343	39264
	56	39838	40328	247	40062

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
4	1	24289	26754	1246	25415
	3	32215	34395	1207	33005
	7	34718	36981	1138	35780
	28	38248	39927	862	38975
	56	39209	40951	871	40068

Mixture	Age (Day)	Dynamic Elastic Modulus - U.P.V.M (MPa)			
		Min.	Max.	σ*	Mean
8	1	23214	23624	205	23411
	3	28431	29445	519	28873
	7	32526	33809	642	33155
	28	34841	37318	1241	36123
	56	36642	38338	967	37758

* σ denotes standard deviation

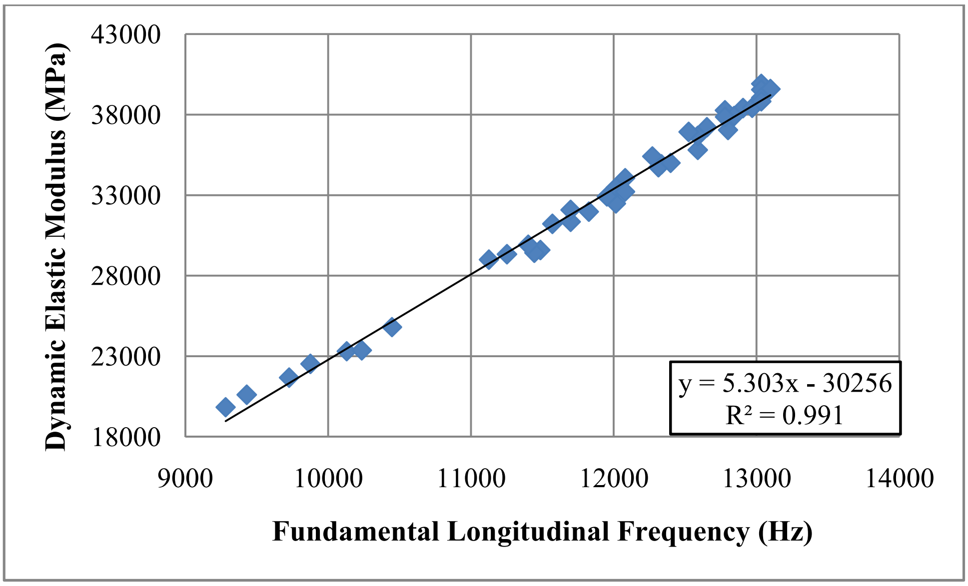

Figure A.3 Relationship between longitudinal frequency and dynamic elastic modulus

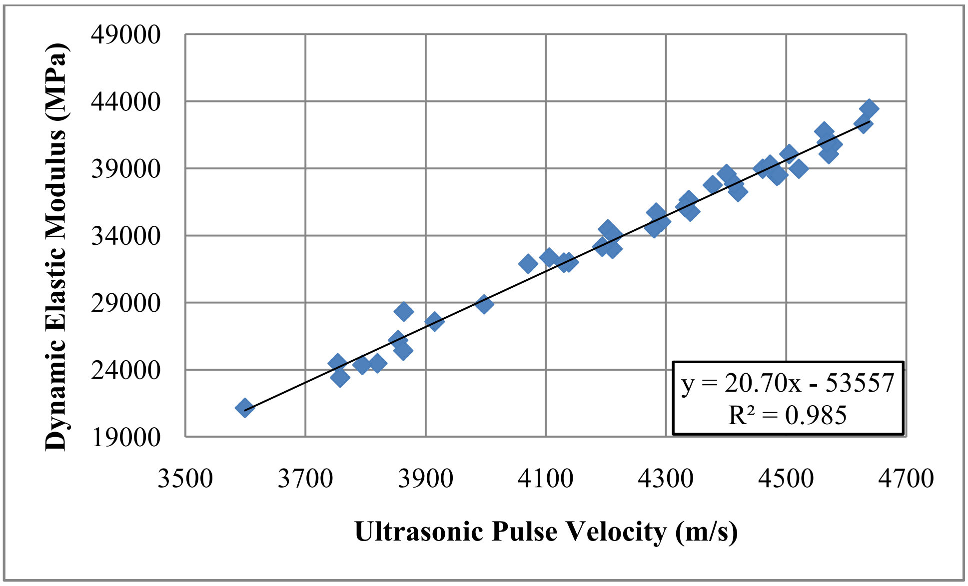

Figure A.4 Relationship between ultrasonic pulse velocity and dynamic elastic modulus

Table A.7 Exact static elastic modulus values for each mixture

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
1	3	23001	23989	388	23288
	7	24185	25311	420	24694
	28	27196	31375	1372	28957
	56	29326	31838	1115	30631

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
2	3	17090	18714	756	18103
	7	20126	21515	581	20867
	28	24949	26029	498	25473
	56	26262	28552	988	27471

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
3	3	22491	24306	699	23506
	7	25033	29632	1664	27476
	28	29033	31917	1363	30506
	56	30238	32987	954	31772

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
4	3	24562	25857	550	25373
	7	25324	28604	1295	27661
	28	28646	31936	1530	30504
	56	29195	34865	2031	31514

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
5	3	20814	23553	1020	21686
	7	22444	25875	1176	24110
	28	24772	29092	1477	27130
	56	27883	30992	1194	29202

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
6	3	23548	28350	1761	26192
	7	27875	30522	1081	28980
	28	29724	35524	2174	32766
	56	31788	35722	1442	33936

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
7	3	21954	28136	2619	25423
	7	28155	30731	1041	29087
	28	31301	33131	738	32252
	56	32805	34542	705	33646

Mixture	Age (Day)	Static Elastic Modulus (MPa)			
		Min.	Max.	σ*	Mean
8	3	17800	21741	1757	19582
	7	20384	24989	2076	22400
	28	23807	27896	1665	25441
	56	25984	28770	1289	27450

* σ denotes standard deviation

Table A.8 Exact flexural strength values for each mixture

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
1	3	5.30	5.70	0.20	5.50
	7	6.20	6.70	0.25	6.47
	28	7.60	7.70	0.06	7.63
	56	8.10	8.20	0.06	8.13

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
2	3	4.90	5.10	0.10	5.00
	7	6.00	6.10	0.06	6.07
	28	7.60	7.70	0.06	7.67
	56	8.40	8.50	0.06	8.43

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
3	3	5.80	6.10	0.15	5.93
	7	6.50	7.00	0.25	6.77
	28	7.60	7.70	0.06	7.67
	56	8.40	8.50	0.06	8.47

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
4	3	5.20	5.60	0.23	5.47
	7	6.70	7.30	0.31	6.97
	28	7.80	7.90	0.06	7.83
	56	8.10	8.20	0.06	8.13

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
5	3	5.40	5.70	0.15	5.57
	7	6.50	6.60	0.06	6.57
	28	7.70	7.80	0.06	7.77
	56	8.00	8.10	0.06	8.03

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
6	3	6.50	6.70	0.10	6.60
	7	7.00	7.20	0.10	7.10
	28	8.30	8.40	0.06	8.37
	56	8.80	9.10	0.15	8.93

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
7	3	6.30	6.50	0.10	6.40
	7	6.90	7.00	0.06	6.93
	28	8.20	8.30	0.06	8.27
	56	8.80	8.90	0.06	8.87

Mixture	Age (Day)	Flexural Strength (MPa)			
		Min.	Max.	σ*	Mean
8	3	5.10	5.50	0.21	5.27
	7	6.10	6.40	0.15	6.27
	28	7.30	7.50	0.10	7.40
	56	8.00	8.10	0.06	8.07

* σ denotes standard deviation

Table A.9 Exact compressive strength values for each mixture

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
1	3	26.40	29.90	1.40	28.35
	7	32.60	36.90	1.67	35.25
	28	46.00	48.60	1.09	47.33
	56	48.20	49.40	0.49	48.85

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
2	3	23.90	27.00	1.16	25.15
	7	34.50	39.10	1.89	36.63
	28	47.50	51.70	1.83	49.57
	56	51.10	56.60	2.24	53.88

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
3	3	31.70	34.90	1.16	33.18
	7	41.80	45.90	1.47	44.20
	28	53.50	58.90	1.96	55.63
	56	53.60	59.50	2.28	55.90

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
4	3	29.20	33.90	1.86	32.27
	7	37.30	41.20	1.66	38.87
	28	46.10	51.10	2.08	48.35
	56	51.40	55.40	1.86	53.70

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
5	3	29.10	32.90	1.69	30.90
	7	37.40	40.00	1.06	38.37
	28	43.80	49.60	2.20	48.22
	56	50.80	55.10	1.69	53.05

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
6	3	38.40	41.50	1.14	39.97
	7	41.60	47.60	2.22	43.87
	28	51.40	56.00	1.81	54.45
	56	55.00	58.80	1.56	56.38

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
7	3	31.20	35.20	1.59	33.65
	7	41.10	46.40	2.13	44.65
	28	58.50	63.50	2.28	61.40
	56	63.00	63.80	0.31	63.33

Mixture	Age (Day)	Compressive Strength (MPa)			
		Min.	Max.	σ*	Mean
8	3	24.80	27.50	0.95	25.92
	7	31.00	33.80	1.13	32.55
	28	41.90	44.10	0.85	43.42
	56	47.00	49.90	1.08	48.27

* σ denotes standard deviation

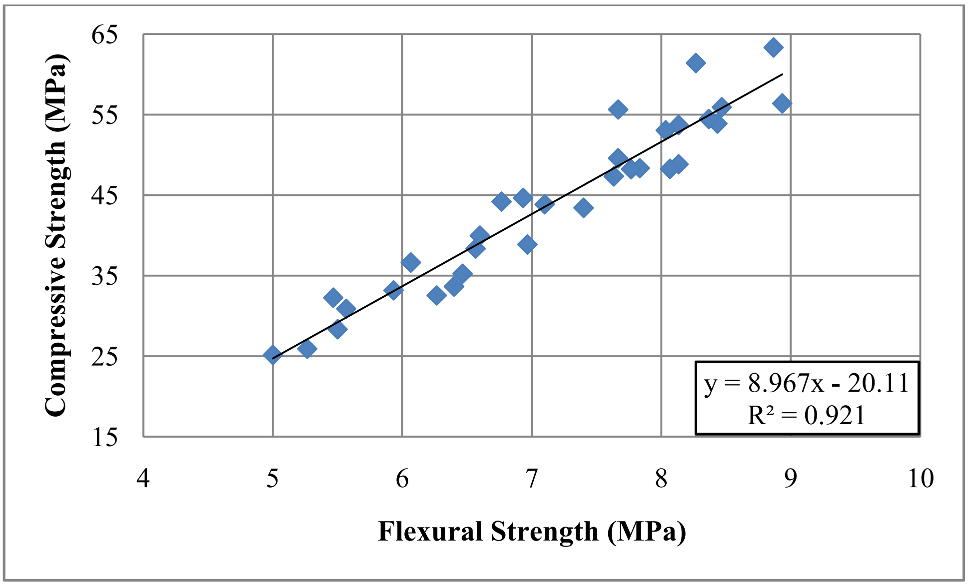

Figure A.5 Relationship between flexural strength and compressive strength

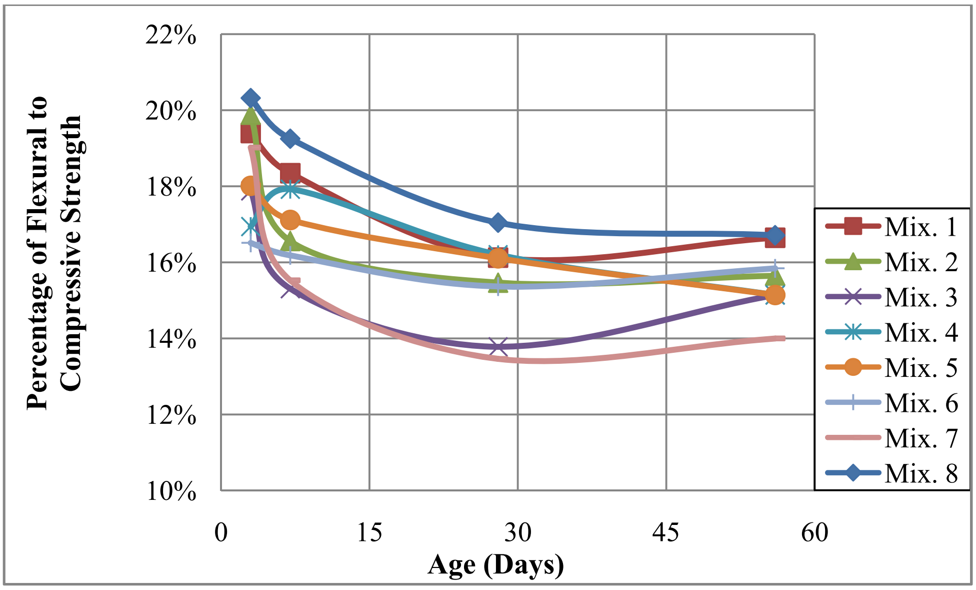

Figure A.6 Percentage of flexural to compressive strength for different ages

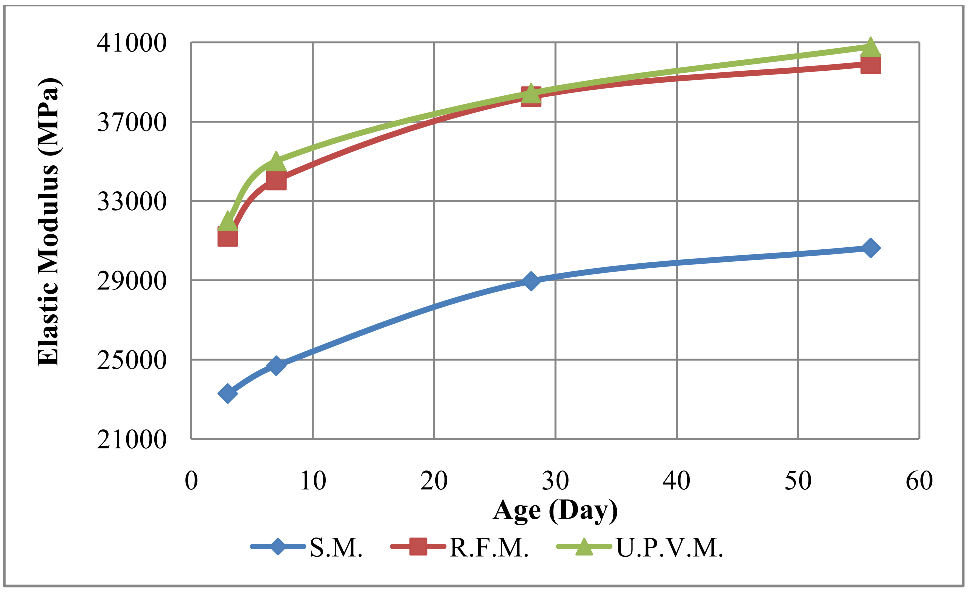

Figure A.7 Mixture 1 elastic modulus values found using the three different methods

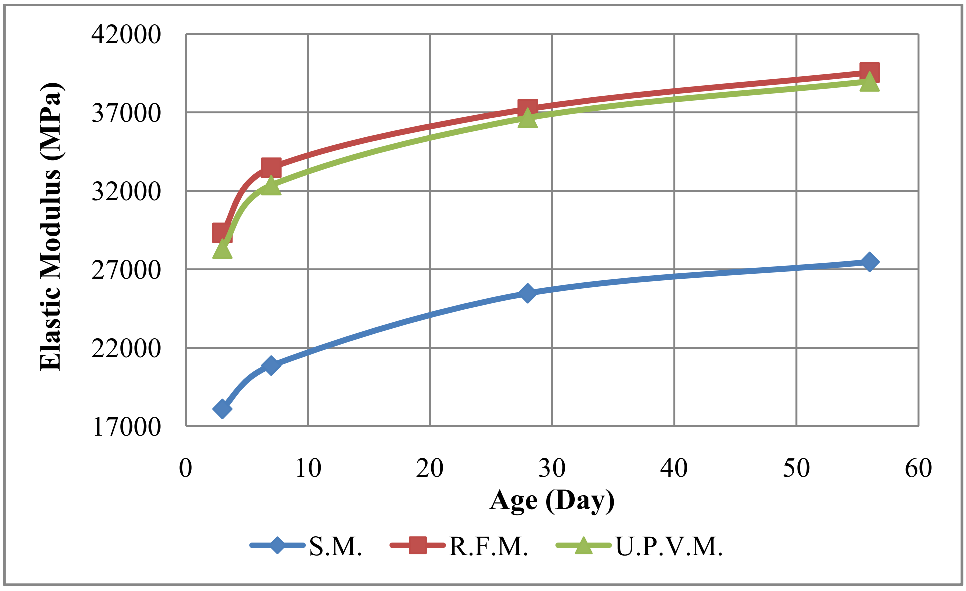

Figure A.8 Mixture 2 elastic modulus values found using the three different methods

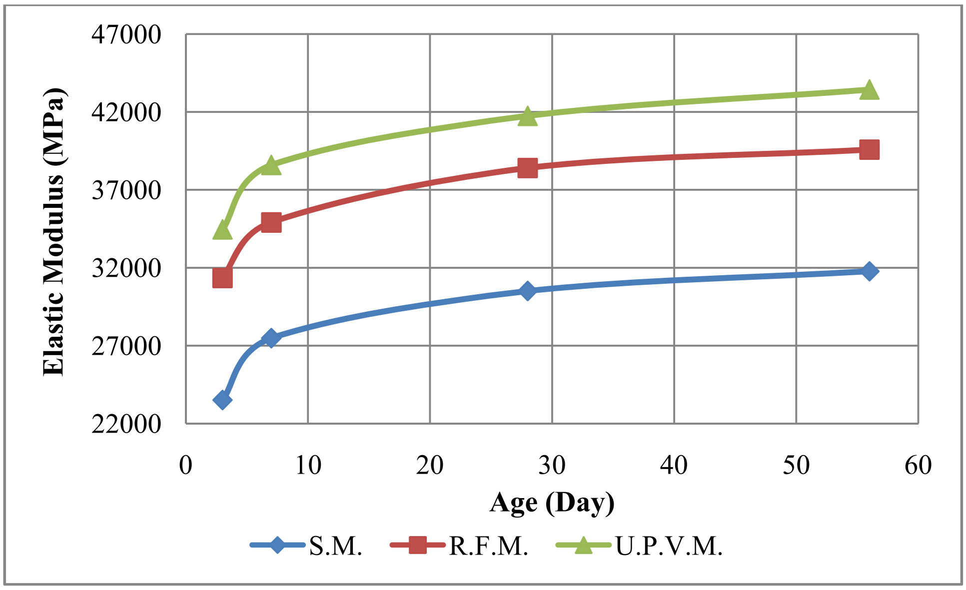

Figure A.9 Mixture 3 elastic modulus values found using the three different methods

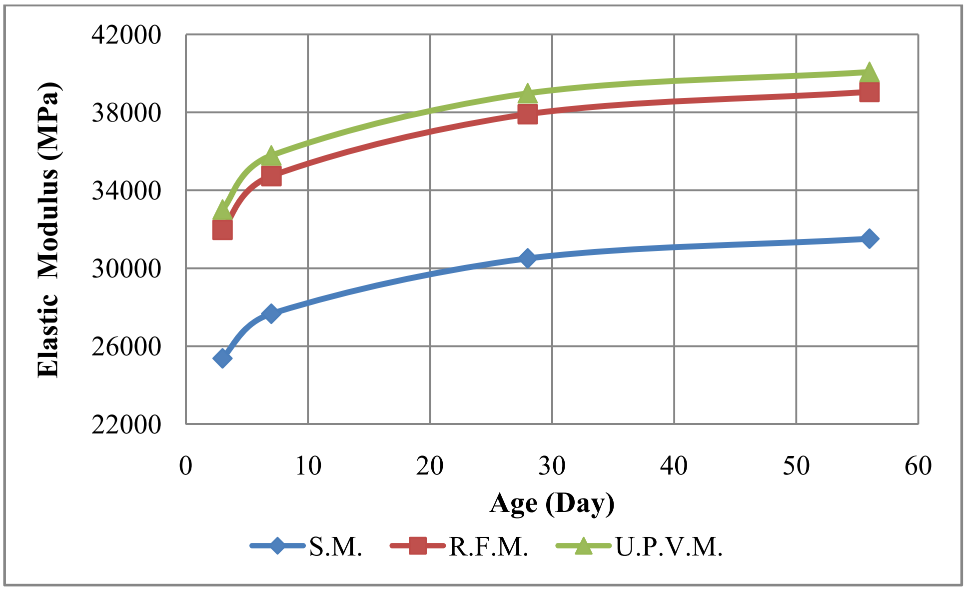

Figure A.10 Mixture 4 elastic modulus values found using the three different methods

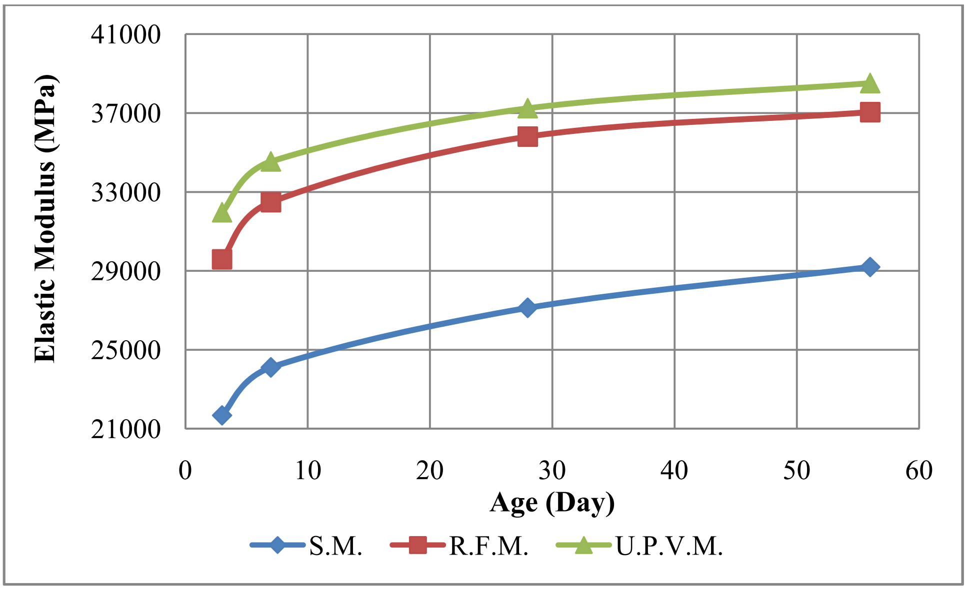

Figure A.11 Mixture 5 elastic modulus values found using the three different methods

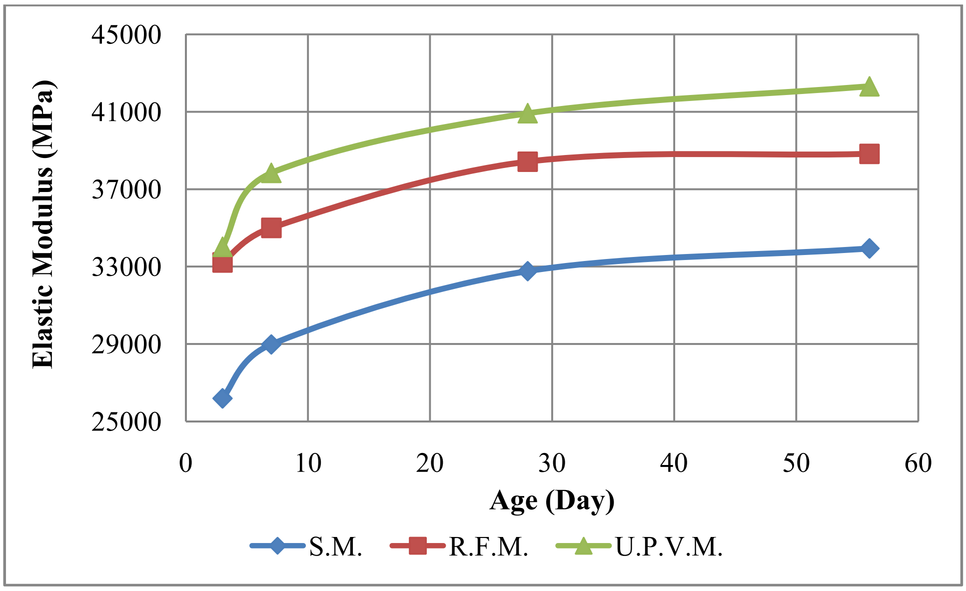

Figure A.12 Mixture 6 elastic modulus values found using the three different methods

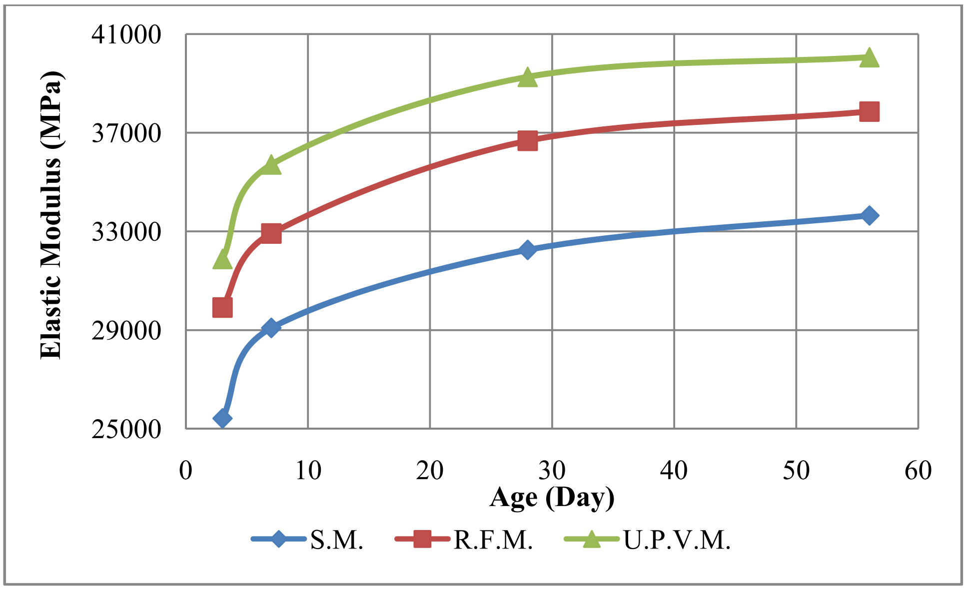

Figure A.13 Mixture 7 elastic modulus values found using the three different methods

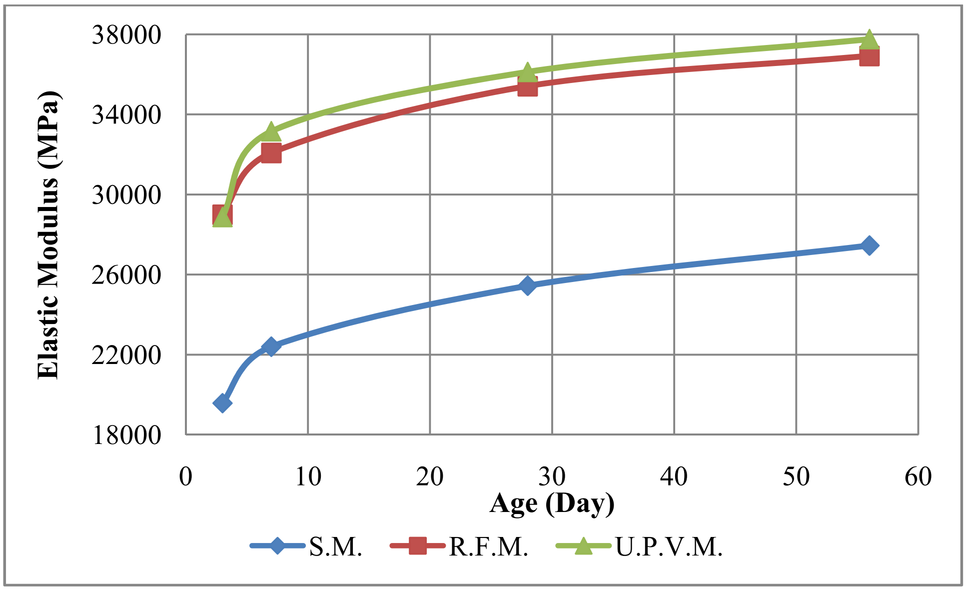

Figure A.14 Mixture 8 elastic modulus values found using the three different methods

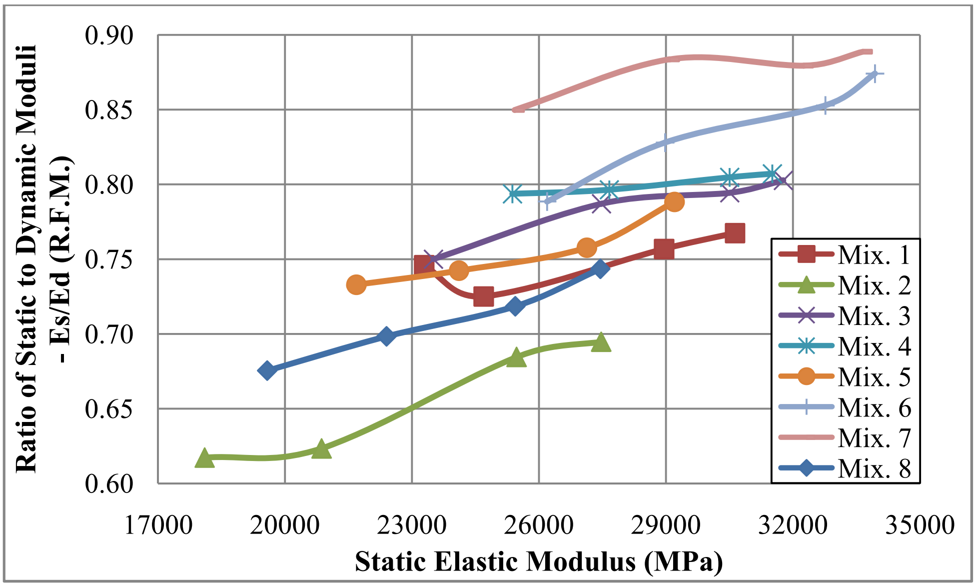

Figure A.15 Relationship between static modulus of elasticity and ratio of static to vibrational dynamic moduli for the eight different mixtures

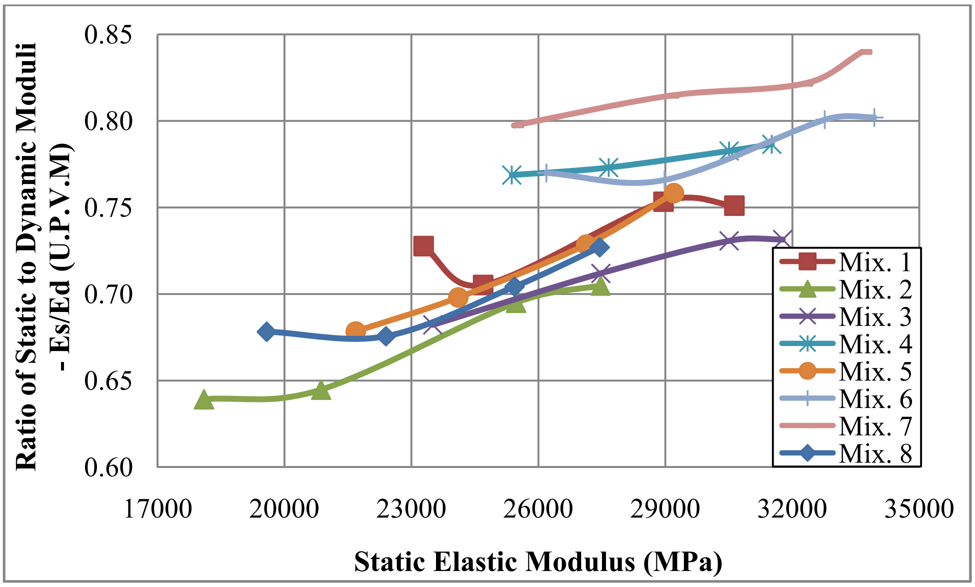

Figure A.16 Relationship between static modulus of elasticity and ratio of static to pulse velocity dynamic moduli for the eight different mixtures

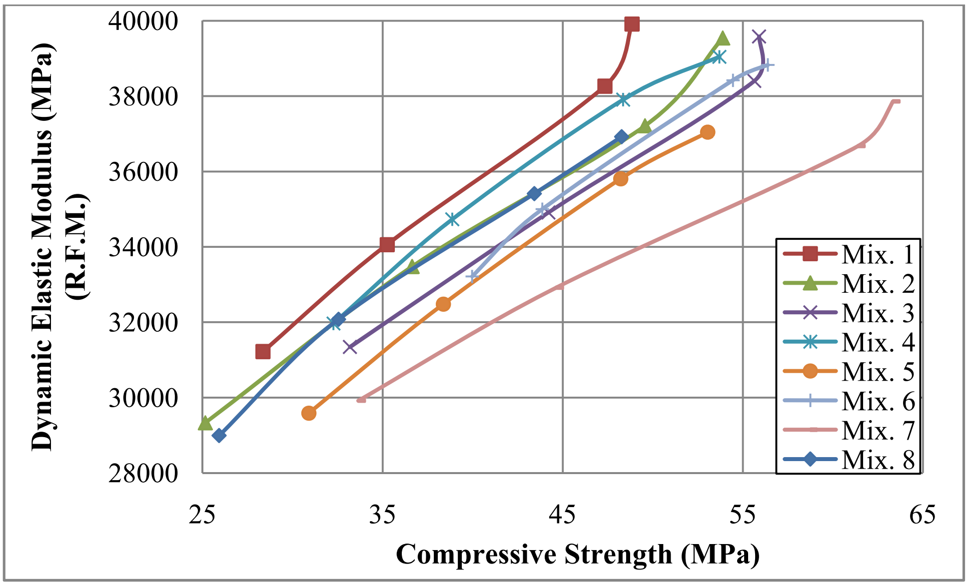

Figure A.17 Relationship between dynamic elastic modulus found using the resonant frequency method and compressive strength for the eight different mixtures

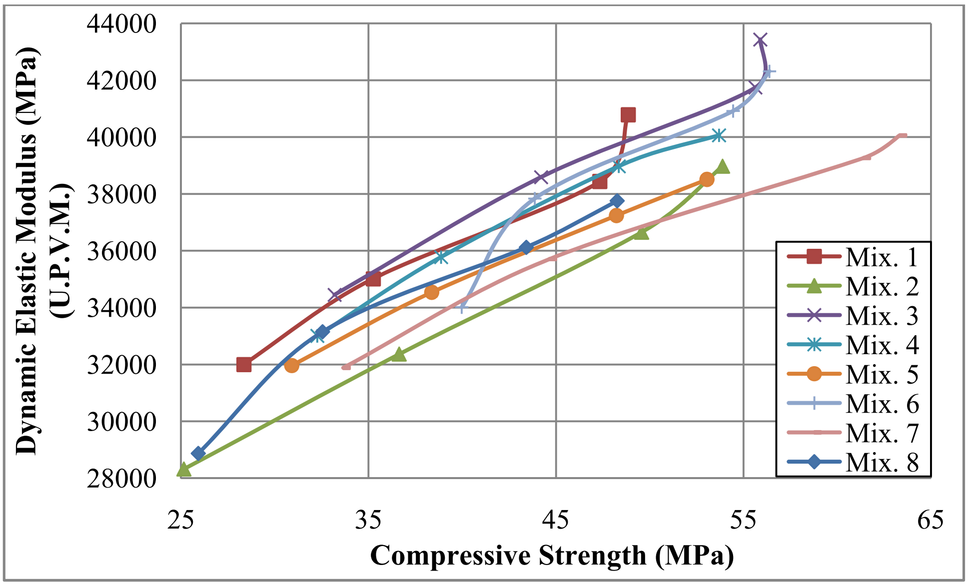

Figure A.18 Relationship between dynamic elastic modulus found using the ultrasonic method and compressive strength for the eight different mixtures