NON-DESTRUCTIVE EVALUATION OF STRENGTH GAIN OF ORDINARY PORTLAND CEMENT MORTAR BY ULTRASONIC PULSE VELOCITY METHOD

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Degree of Master of Science

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Declaration

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

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Acknowledgement

I take this chance to forward my greatest gratitude to University of Moratuwa, for letting me to do the postgraduate degree in Materials Science & Engineering in the Department of Materials Science and Engineering.

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Abstract

This research is based on the results of the study of ultrasonic pulse velocity and compressive strength of ordinary Portland cement mortar. Objectives of this study are to determine correlations between ultrasonic pulse velocity and compressive strength of cement mortar and to predict strength of cement mortar at 28 days within 02 days using ultrasonic pulse velocity of cement mortar. Ten samples of ordinary Portland cement obtained from ten different sources were used to prepare thirty (30) specimens of cement mortar. Water/cement ratio, sand content, method of specimen preparation, curing conditions were kept constant throughout the experiment. Portable Ultrasonic Nondestructive Digital Indicating Tester with a transducer of 54 kHz frequency was used to measure ultrasonic pulse velocity.

Initially ultrasonic pulse velocity of ten samples of cement mortar was measured and compressive strength of same specimens was determined. Then the behavior of ultrasonic pulse velocity with cement hydration was studied. Graphs between ultrasonic pulse velocity and compressive strength of cement mortar, and graphs between ultrasonic pulse velocity and curing time were plotted for ten samples. Correlations obtained from above experiments were used to predict 28 days compressive strength of cement mortar within 02 days.

In this research it was found that the relationship between ultrasonic pulse velocity and compressive strength was linear and Lime Saturation Factor of cement also has an influence on this relationship. Further it was seen that, with the increase of curing period, ultrasonic pulse velocity of all samples increased. At the end it was possible to obtain an equation that can predict the cement strength and that equation was verified using another five (05) cement mortar samples.

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List of abbreviations

Abbreviation	Description
NDE	Non destructive evaluation
OPC	Ordinary Portland cement
SLSI	Sri Lanka Standards Institution
UPV	Ultrasonic Pulse Velocity
NDT	Non destructive testing
LSF	Lime saturation factor
UPA	Ultrasonic pulse attenuation
PUNDIT	Portable Ultrasonic Nondestructive Digital Indicating Tester

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1. INTRODUCTION

1.1 General

Evaluation of physical properties of materials can be done in destructive or non-destructive manner. In destructive evaluations the material being tested is damaged in order to determine mechanical properties such as strength, hardness, and toughness. In non-destructive evaluation properties of materials are being evaluated without causing damage to the material.

Non destructive evaluation (NDE) methods are used for almost all the types of materials such as metals, ceramics, cements, polymers and composites. Among these, NDE are widely used for evaluation of metals. However use of NDE for cement based materials is becoming popular in the recent past. Although many researches are available for NDE of concretes, researches on NDE of cement mortar are quite limited.

To test the compressive strength of cement, test specimens are casted using cement mortar which is prepared using cement, sand and water. After curing in water these test specimens are then used to check the compressive strength in destructive manner. After mixing with water, cement gains its strength over a period of time. Strength of a particular type of cement is considered as the strength of the cement mortar prepared using same type of cement at 28 days age. Therefore it is required to wait for 28 days to get an idea of the strength of cement.

In this study Ordinary Portland Cement (OPC) of 42.5N strength class, which is imported to Sri Lanka, was taken in to consideration. OPC manufactured or distributed in Sri Lanka compulsorily shall conform to the requirements given in Sri Lanka Standard 107 – Specification for Ordinary Portland Cement. As per SLS 107: 2008 two types of OPC are allowed to be used in Sri Lanka. These two types are defined based on strength of cement. The two strength classes are 32.5 N and 42.5 N

[1]. However the strength class of 32.5 N OPC is not imported to Sri Lanka at present.

Since OPC is a product which covered under Import Inspection scheme operated by Sri Lanka Standards Institution (SLSI), samples are drawn from cement consignments which are imported to Sri Lanka and checked for their conformity to Sri Lanka standard. In this process, compressive strength at 28 day is the main parameter on which the decision depends. Therefore, this process takes a minimum period of 30 days. Many researches have been carried out to predict the compressive strength of cement at 28 days within shorter time period with the knowledge of the composition of cement minerals. This research is an attempt to predict compressive strength at 28 days within 2 days, without the knowledge of cement mineral composition. For that purpose Ultrasonic Pulse Velocity (UPV) method was used in this study.

Among NDE methods, Ultrasonic Pulse Velocity (UPV) method is the most widely used method for testing of cement based materials, especially concrete. Unlike concrete, since cement mortar does not contain coarse aggregates, use of UPV method on cement mortar will be more feasible. In this study, relationship between UPV of cement mortar and curing time and relationship between UPV and compressive strength of cement mortar were studied.

1.2 Objectives

- Determine the ultrasonic pulse velocity of cement mortars, to investigate the relationship between the Ultrasonic pulse velocity (UPV) and compressive strength of cement mortar.
- Predict the compressive strength of cement mortar at 28 days within 02 days.

2. LITERATURE SURVEY

Non destructive testing is widely used in quality control method of finished products, semi-finished products and raw materials. The term "Non-destructive testing" is used to describe the material testing methods which, without damaging or influencing the usefulness of a material or component, give information about its properties [2]. The main non destructive testing methods are Visual inspection, Dye penetrant testing, Magnetic particle testing, Eddy current testing, Radiographic testing and ultrasonic testing. Each of these methods has its particular advantages and disadvantages and these must be taken in to consideration when selecting a method for a given material.
Among all these NDT methods, ultrasonic testing has been used in concrete testing for a long time and proved its suitability for testing such a heterogeneous material. Although concrete is not a subject in this research, principles of ultrasonic testing of concrete was reviewed because cement mortar is almost similar to concrete, unless the absence of coarse aggregates. Therefore ultrasonic testing method was selected to evaluate cement mortar which is a less heterogeneous material than concrete. The method, equipment and other factors effecting ultrasonic testing of concrete were reviewed and the same was applied in this research.

2.1 Ultrasonic Pulse Velocity (UPV) testing of concrete

The most common and popular method used for the determination of properties of concrete is UPV method. UPV method is useful for monitoring concrete hardening process, strength development of concrete, detection of voids, delaminations, and under compacted and honeycombed areas. In this method, the speed of travel of an ultrasonic pulse through concrete is measured. For this purpose it is required to have an electric pulse generator, a pair of transducers (transmitting and receiving), an amplifier and an electronic timing device. When two transducers are held in contact with the concrete under test, the transmitting transducer produces a pulse of longitudinal vibration. This longitudinal vibration travels a known path length in the concrete and then converted into an electrical signal by the second transducer. The electronic timing device measures the transit time of the pulse. Longitudinal pulse velocity is given by the equation 2.1 below.

$$V = \frac{L}{T} \qquad 2.1$$

Where;

v is the longitudinal pulse velocity,

L is the path length,

T is the time taken by the pulse to traverse that length.

Longitudinal vibration or longitudinal wave is one of four types of ultrasonic waves. Other three types are shear waves, surface waves, and plate waves. This classification is based on the way particles of a medium vibrate with respect to the direction of propagation of the waves. In longitudinal waves, the vibration of particles occurs in the longitudinal direction or the direction of wave propagation. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves [3].

Because of its easy generation and detection, this type of ultrasonic wave is most widely used in ultrasonic testing. This type of wave can propagate in solids, liquids and gases [2]. Since concrete or cement mortar consists of both solid and liquid phases, use of longitudinal wave is most suitable.

In concrete testing the natural frequency of the transducers are normally within the range 20 kHz to 150 kHz. As pass through the concrete high frequency pulses become attenuated more rapidly than pulses of low frequency. It is therefore preferable to use high frequency transducers (60 kHz to 200 kHz) for short path lengths (down to 50 mm) and low frequency transducers (10 kHz to 40 kHz) for long path lengths (up to a maximum of 15 m). Transducers with a frequency of 40 kHz to 60 kHz are found to be useful for most applications [3]. In this study, transducers of 54 kHz were used to measure 40 mm path length, which complies with the above requirements.

Frequency of a wave is the same as that of the vibration or oscillation of the atoms of the medium in which the wave is travelling [2]. It is expressed as the number of cycles per second. Hertz is the international term for a cycle per second which is named after the physicist H. Hertz and is abbreviated as Hz.

Concrete is inherently inhomogeneous material which consists of all three phases as solid, liquid and gas. This inhomogeneity disturbs the propagation of ultrasound wave greatly. Therefore the intensity of an ultrasonic beam that is sensed by a receiving transducer is considerably less than the intensity of the initial transmission. Attenuation is the term used to describe this condition of energy loss. Scattering, absorption, surface roughness and diffraction are four causes of attenuation for longitudinal wave [2].

Scattering is the reflection of ultrasonic waves other than its original direction of propagation. Scattering occurs in inhomogeneous materials. The inhomogeneities can be anything that will present a boundary between two materials of different acoustic impedance.

Acoustic Impedance is the resistance offered to the propagation of an ultrasonic wave by a material. It is denoted by the letter Z and is determined by multiplying the density of the material by the velocity of the ultrasonic wave in the material as given by equation 2.2 [2].

$$Z = \rho \, v \qquad 2.2$$

On the other hand velocity of the longitudinal wave in the material is the speed with which energy is transported between two points in a medium by the motion of waves is known as the velocity of the waves.

Concrete is made out of cement, sand, gravel and water which differ greatly in density and elasticity. The velocity of propagation of longitudinal wave depends on the elastic modulus (E) and the density (ρ) of the material and relationship is given by equation 2.3 below [2].

$$V = \sqrt{\frac{E}{\rho}} \qquad 2.3$$

Considering equation 2.2 and 2.3 it can be seen that the acoustic impedance also depends on the elastic modulus (E) and the density (ρ) of the material. Therefore materials in concrete have different acoustic impedances which make the scattering of ultrasound wave.

Absorption is the second cause of attenuation in ultrasound wave. When a sound wave is travelling through a material, part of the sound energy converts into heat. This results a decrease of intensity of sound wave sensed by the receiving transducer.

Third cause of attenuation is transmission loss due to coupling medium and surface roughness of the material.

Diffraction is another cause of attenuation in ultrasound wave. Diffraction can occur when the wave impinges upon aggregates or voids in concrete. A portion of the sound energy bends around aggregates or voids and because of that ultrasonic wave diverts from where it would normally be received [2].

In UPV testing transducer arrangement can be done in three different ways namely direct transmission, semi-direct transmission and indirect or surface transmission [4]. (See figure 2.1)

In this study direct transmission method was selected due to following reasons.

i) High sensitivity because maximum energy is propagated at right angles to the face of transmitting transducer
ii) Access to opposite surfaces is available.

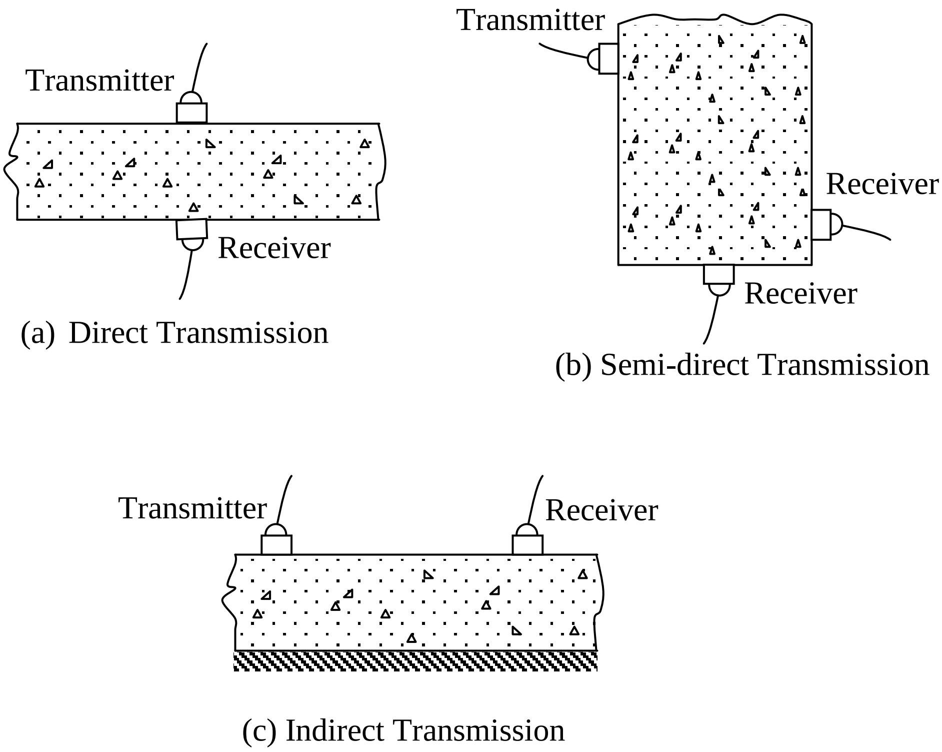

Figure 2.1: Transducer positioning

Source: "Testing concrete – Part 4: Determination of ultrasonic pulse velocity", Standard BS EN 12504-4, 2004, p. 6.

It has been found that following factors have influence on the pulse velocity in concrete structures [4].

i) Moisture content
ii) Temperature of the concrete
iii) Path length
iv) Shape and size of specimen
v) Reinforcing bars
vi) Cracks and voids

Moisture content has both chemical and physical effect on concrete. This is accounted by the difference in water/cement ratio of concrete mixer and curing conditions of the concrete. If both of these factors are kept constant, influence by moisture content can be minimized. If the temperature of the concrete is below 10 ^{0}C and above 30 ^{0}C, a correction should be made to pulse velocity. However temperature between 10 ^{0}C and 30 ^{0}C has been found to cause no significant influence. UPV is not generally influenced by changes in path length, but there can be a slight reduction of velocity with increasing path length due to attenuation. If the least lateral dimension is less than the minimum value specified in table 2.1, the pulse velocity may be reduced appreciably. This factor has to consider in cases where concrete elements of significantly different sizes are being compared. It is recommended to take measurements avoiding steel reinforcing bars, in close proximity and parallel to the direction of pulse propagation. Air filled cracks and voids cause concrete-air interfaces where sound energy attenuated. If projected length of crack or void in a concrete is larger than the width of the transducers and the wavelength of sound used, the transit time will be higher than that of similar concrete with no defects. On the other hand relatively small cracks or voids have little or no effect on transmission time [4].

Table 2.1: Effect of specimen dimensions on pulse transmission

Transducer frequency kHz	Pulse velocity in concrete km/s V_c = 3.50 Minimum recommended lateral specimen dimension mm	 V_c = 4.00	 V_c = 4.50
24	146	167	188
54	65	74	83
82	43	49	55
150	23	27	30

Source: "Testing concrete – Part 4: Determination of ultrasonic pulse velocity", Standard BS EN 12504-4, 2004, p. 11.

However in this research water/cement ratio, curing condition, path length and shape and size of specimen were kept constant. Sample preparation and all the inspection were carried out at 27 ^{0}C at which there is no significant effect. Reinforcing bars are not present in the samples used. Since all specimens were prepared using same standard method distribution of voids can be assumed to be similar. Therefore influence of above factors on cement mortar specimens can be considered minimum.

2.2 Hydration of Portland cement

Portland cement is hydraulic cement that hardens in water to form a water-resistant compound. Portland cement consist of four major cement minerals which are C_3S (Tricalcium silicate), C_2S (Dicalcium Silicate), C_3A (Tricalcium Aluminate), and C_4AF (Tetracalcium Aluminoferrite). Other minor constituents are calcium sulfate, alkali sulfates, unreacted (free) CaO and MgO. The four major minerals are obtained by partial fusion of lime (CaO), silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) [5].

When cement contacts with water, series of chemical reactions takes place. This results the setting and hardening of concrete which is also referred as hydration. To understand the strength development of cement, knowledge of the chemistry of hydration is necessary.

The hydration of cement can be described as two step process as dissolution and precipitation. In the first step, the cement dissolves in water releasing ions into the mixed water. This aqueous solution contains variety of ion species. Since Gypsum (calcium sulphate) and cement minerals C_3S and C_3A dissolve quickly, the concentration of ionic species in the solution increase rapidly. Eventually the concentrations increase and the solution become supersaturated. At this point, it is energetically favorable for some of the ions to combine into new solid phases than remain dissolved. Therefore new solid phases precipitate and they are called hydration products. These hydration products are different from the starting cement minerals. Precipitation relieves the supersaturation of the solution which helps to continue the dissolution of cement minerals. Therefore cement hydration is a continuous process in which cement minerals are replaced by new hydration products.

Both C_3S and C_2S react with water to produce calcium silicate hydrate known as C–S–H gel which is the main ‘glue’ which binds the sand and aggregate particles together in concrete or cement mortar. However the C_3S hydrates much more quickly than the C_2S. These two cement minerals are responsible for strength development of cement. The hydration of C_3S gives early strength to the cement paste while C_2S gives later strength. The C_3A and C_4AF minerals also hydrate but they contribute little to the properties of cement paste. The crystal structures of these cement minerals are quite complex but these structures do not play an important role in the properties of cement paste.

With the continuation of hydration reactions, the aqueous suspension transforms to solid phase. An illustration of the development of solid phase in cement paste is given in figure 2.2. With the time hydration product have become interconnected, causing final set and giving paste some minimal strength. By 28 days the paste is dominated by C-S-H gel and the porosity has noticeably decreased. The final amount of porosity will depends strongly on the initial water/cement ratio of the paste. Finally the hardened cement paste consists of C-S-H hydrates, unreacted centers of coarse particles, precipitates as calcium hydroxide, water and pores [5].

Amount of C-S-H solid phase in cement paste depends on the amount of cement minerals present in the cement clinker. To control the clinker composition the ratio, namely Lime saturation factor (LSF) is used. Since the optimization of plant performance is also assisted by LSF, cement obtained from different plants contains different ratios. LSF is calculated using equation 2.4.

$$\text{Lime Saturation Factor} = \frac{(CaO) - 0.7\,(SO_3)}{2.8\,(SiO_2) + 1.2\,(Al_2O_3) + 0.65\,(Fe_2O_3)} \tag{2.4}$$

cement paste is affected by total amount of solid phase present in the cement paste. The proportion of C_3S and C_2S is not affecting the UPV. Therefore if UPV method is used to monitor strength development of cement mortar, the knowledge of the composition of cement minerals is not necessary.

2.4 UPV and compressive strength of cement-based materials

UPV testing of concrete has been studied over decades but studies on UPV testing of cement mortar are quite limited. In 1990 K. Tharmarathnam and B.S. Tan performed experiments to examine the relationship of the quality of cement mortar to pulse attenuation (UPA) and to pulse velocity, and also they evaluated the combined UPA and UPV method for strength estimation. They concluded that the pulse attenuation correlate well to compressive strength of cement mortar [6].

Correlation between the ultrasonic wave parameters (speed, amplitude and energy) passing through the fresh cement paste and setting time determined using the Vicat test method is analyzed by I. Gabrijel, D. Mikulic and B. Milovanovic in 2011. They have presented the correlation between setting time, ultrasonic pulse velocity and acoustic emission parameters and correlation between setting time, temperature and acoustic emission parameters graphically [7].

P. N. Gözde evaluated the properties of cement mortar by ultrasound. He used UPV method to determine the effect of transducer frequency and specimen size and shape on UPV in cement mortar. He has used three different ultrasonic frequencies (54 kHz, 82 kHz, and 150 kHz) and six different sizes of specimens. Also he has studied the effect of water/cement ratio on UPV and effect of capillary porosity on UPV. It was concluded that increase of water/cement ratio results a decrease of UPV and increase of capillary porosity in cement mortar also decrease UPV [8].

Correlation between porosity, permeability and ultrasonic parameters of mortar with variable water / cement ratio and water content was studied by Z. Lafhar in 2006. Z. Lafhar proposed a simple model to relate ultrasonic pulse velocity with porosity and permeability which could be used to predict the evolution of structural parameters of the material from non-destructive measurements [9].

A mathematical model for the prediction of cement compressive strength at the ages of 7 and 28 days within 24 hours has been developed by G. F. Kheder, A. M. Al Gabban and S. M. Abid. In this work an attempt has been made to combine following three approaches for the first time.

i) A mathematical model with variables affecting the hydration and strength development of cement.
ii) Accelerated strength testing results.
iii) Velocity of ultrasonic pulse and density of mortar.

The variables used in this mathematical model are;

i) Phase composition
ii) Fineness of cement
iii) Chemical analysis parameters and soundness
iv) 1-day accelerated strength of cement
v) Density of accelerated strength mortar cubes
vi) UPV of accelerated strength mortar cubes

Finally it was found that using each of the accelerated compressive strength, UPV and density of the mortar cubes yielded high correlation with the compressive strength than any of the other variables [10].

A study on Nondestructive Monitoring of Setting and Hardening of Portland Cement Mortar with Sonic Methods was carried out by T. Voigt and S. P. Shah. They examined the fundamental relationship between the reflection loss, measured with shear waves, and the hydration kinetics of Portland cement mortar, represented by setting time, dynamic elastic moduli, compressive strength and degree of hydration. Dynamic elastic moduli were measured by fundamental resonant frequency and ultrasonic pulse velocity using compression and shear waves. Degree of hydration was determined by thermogravimetric analysis and adiabatic heat release. The water/cement ratio was varied for the tested mixture composition. At the end following conclusions have been made [11].

1. The relationship between reflection loss and compressive strength has a bilinear character for the tested mortar mixtures at early ages (70 to 90 hours).
2. Dynamic shear moduli calculated from torsional resonant frequency and reflection loss are linear related at early ages. This shows that the wave reflection method is governed by the evolution of an important mechanical parameter.
3. Degree of hydration and reflection loss are linear related at early ages. This demonstrates the high sensitivity of the presented wave reflection method to changes in the microstructure of cementitious materials due to hydration.

Further they have done a comparison of ultrasonic wave reflection method and maturity method in evaluating early-age compressive strength of mortar. In this work they used cement mortars with different water–cement ratios (0.35, 0.5, 0.6) cured under different isothermal and non-isothermal conditions (15 ^{0}C, 25 ^{0}C, 35 ^{0}C, 15–35 ^{0}C). As per the results obtained, they found that the relationship between compressive strength and reflection loss of a mortar mixture cured at three different temperatures to be unique. This relationship can be used for estimating the strength development of a non-isothermally cured mortar of the same water–cement ratio without further modification [12].

In 1993 C.M. Sayers and R.L. Grenfell studied ultrasonic propagation through hydrating cements. They reported measurements of the velocity of ultrasonic longitudinal and shear waves in ordinary Portland cement undergoing hydration. It has been observed that the velocity of both types of waves increase with the time. The ultrasonic shear modulus and the ultrasonic longitudinal modulus were calculated using shear wave velocities and longitudinal wave velocities respectively. Then the relationship between the ultrasonic shear modulus and the Poisson's ratio has been studied. Finally they concluded that, after the time at which the cement becomes interconnected, the effective bulk modulus of the cement is linearly related to the effective shear modulus and the effective Poisson's ratio is observed to decrease from the value of 0.5 which is characteristic of a fluid, to values characteristic of a porous solid [13].

An experimental study on ultrasonic pulse velocity evaluation of the microstructure of cementitious material at early age was carried out by G. Ye, K.van Breugel and A.L.A. Fraaij in 2001. They monitored the development of microstructure of fresh concrete at different temperatures (isothermal curing at 10, 20, 30 and 50 ^{0}C) and water/cement ratios (0.40, 0.45 and 0.55). They have used a numerical cement hydration simulation model called HYMOSTRUC to investigate the change of microstructure. Their results indicated that the UPV increases with time, UPV decrease with increase of water/cement ratio, UPV increases with increase of compressive strength and UPV increase with increase of solid phase volume. They also stated that the relation between UPV and compressive strength is almost linear at early stage [14].

In the study of "Ultrasonic wave dispersion and attenuation in fresh mortar" by D.G. Aggelis and T.P. Philippidis, it was found that sand content and size has significant influence on wave parameters. Attenuation increases approximately proportionally to the sand content. It was also concluded that for materials with the same sand content, low water/cement ratio specimens exhibit higher pulse velocities for most frequencies. In the hardened mortar the attenuation behavior seems to be a function of porosity and aggregate size, being also proportional to frequency. Further it was concluded that scattering dominates the attenuation behavior in cement mortar mainly due to sand and air bubbles [15].

Another study by I. Gabrijel, D. Mikulić and N. Bijelić reveals that the hydration process can be monitored by changes in the velocity and changes in the attenuation of the ultrasonic signal. It was observed that with the increase of cement paste age, velocity and relative signal strength of ultrasound increase. They obtained a correlation between compressive strength and UPV of cement paste for different water/cement ratio and observed that the increase of the water/cement ratio reduces compressive strength, UPV and signal strength of ultrasound of the cement paste [16].

In 2009, J. Zhang, L. Qin and Z. Li monitored hydration of cement-based materials with resistivity and ultrasonic methods. They studied the setting and hardening behavior of cement paste during the first 7 days of hydration using the above techniques. They found that the resistivity method was able to study both the chemical reaction and physical change during hydration, while ultrasonic method was sensitive to physical change of cement only [17].

A study of using the ultrasonic wave reflection technique to monitor the hydration process of early-age cement-based materials throughout their setting and hardening was carried out by T. Öztürk, O. Kroggel, P. Grübl and J.S. Popovics. The focus of the investigation was to monitor the stiffening behavior of cement pastes under constant curing conditions. They concluded that obtained ultrasonic data are correlated to mechanical and chemical properties of the specimens and applied experimental wave reflection technique is suitable to monitor the stiffening of cement pastes accurately [18].

Propagation of ultrasound through hydrating cement pastes at early times was studied by C.M. Sayers and A. Dahlin, in 1993. They observed that the compressional wave velocity decreases slightly during the first few hours after mixing, followed by a rapid rise as the solid phase becomes interconnected. They identified that this point is of practical significance since the connectivity of the solid phase is responsible for the load-bearing capacity of set cement [19].

A. Boumiz, C. Vernet and F. C. Tenoudji applied Ultrasonic, calorimetric, and conductometric techniques simultaneously to the same batches of cement pastes and mortars, to better understand the relations between the hydration reactions and the evolution of the mechanical properties. In their study they found that the development of mechanical properties is governs by two main mechanisms, i.e. connection of cement particles and filling of capillary pores by the hydrates [20].

In 1990, S. Popovics, J. L. Rose and J. S. Popovics studied the behaviour of ultrasonic pulses in concrete. In their study they have concluded following factors [21].

1. The pulse velocity in the longitudinal direction of a concrete cylinder differs from the velocity in the lateral direction
2. At low velocities the longitudinal velocities are greater, whereas at high velocities the lateral ones
3. This difference is more pronounced with lower frequencies
4. The pulse velocity in concrete increases with higher frequencies, that is, concrete is a dispersive material
5. The dispersive nature of concrete decreases with age
6. The pulse velocity is independent of the stresses in concrete to a large extent

An experimental study to investigate the influence of curing temperature and mix design on the rate of strength gain and the ultrasonic transverse wave reflection loss was carried out by Y. Akkaya, T. Voigt, K. V. Subramaniam and S. P. Shah. At the end they have made following conclusions [22].

1. The reflection loss of T-wave reflections at a steel concrete interface is sensitive to the hydration of concrete. The compressive strength development and the reflection loss gain measured at the surface of the concrete specimen are linearly related at early ages. Changing curing temperatures and different concrete mix designs and materials do not affect the linearity of the correlation in this time range.
2. Once the reflection loss change of the concrete is calibrated to the strength gain of the concrete, it can be used to predict the concrete strength at early ages.
3. The described method of ultrasonic reflection loss measurement can be used to predict the time of initiation of the concrete strength gain nondestructively.

4. Discontinuous reflection loss measurements can be performed and a mathematical model can be applied to predict the complete behavior of the reflection loss change in time.

In 2011, J. Zhu, S. Kee, D. Han and Y. Tsai investigated the effects of air voids on ultrasonic wave propagation in fresh cement pastes, and relate ultrasonic wave parameters to cement setting times. Their experimental results indicated that existence of air bubbles in cement paste significantly decreases the P wave velocity, but has little effect on the shear wave propagation [23].

S. A. Abo-Qudais was conducted an experimental study to evaluate the effect of concrete aggregate gradation, water–cement ratio, and curing time on measured ultrasonic wave velocity. The ultrasonic equipment used in this study was the portable ultrasonic non-destructive digital indicating tester (PUNDIT) with a generator having amplitude of 500 V producing 54 kHz waves. Following conclusions were made after his study [24].

1. The UPV was found to decrease with the increase of water cement ratio.
2. The larger the aggregate size used in preparing Portland cement concrete, the higher the measured velocity of ultrasonic waves
3. UPV was found to be increased as concrete curing time increased
4. Lower water–cement ratio produced higher concrete strength
5. The concrete compressive strength increased as maximum aggregate size decreased

J. Carette and S. Staquet used Compression and shear waves' velocity to monitor the setting process of mortar. In their study it was seen that S-waves seem to be better indicators of the setting of cement-based materials, since they are more sensitive to the solid matrix connectivity. They proposed a new methodology, based on the combined monitoring of P- and S-waves, to determine the setting time of mortars containing two types of fly ashes [25].

A study on Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method, was carried out by J. Alexandre Bogas , M. G. Gomes and A. Gomes in 2013. In their study, compressive strength of a wide range of structural lightweight aggregate concrete mixes was evaluated by the non-destructive ultrasonic pulse velocity method. They have proposed a simplified expression based on the dependence of the ultrasonic pulse velocity on the density and elasticity of concrete, to estimate the compressive strength, regardless the type of concrete and its composition [26].

T. Voigt, T. Malonn and S. P. Shah investigated the transition of the mortar from plastic and deformable to hardened state. In addition, wave transmission and reflection measurements with P- and S-waves were conducted to obtain further information about the microstructural changes during the setting and hardening process. The propagation of P-waves was found to be indicative of the internal structure of the tested mortars as influenced, for example, by the addition of fine clay particles. S-waves used in transmission and reflection mode proved to be sensitive to the inter-particle bonding caused by the cement hydration and expressed by an increase in compressive strength [27].

Apart from above mentioned past researches with respect to ultrasonic testing and cement mortar, there are numerous studies on ultrasonic testing and concrete. However with respect to cement mortar, correlation between UPV, compressive strength and Lime saturation factor have not been studied. Therefore prediction of 28 day compressive strength of ordinary Portland cement mortar by 2 day compressive strength using UPV will be a novel thing.

3 METHODOLOGY

3.1 Materials Used

3.1.1 Cement

Ordinary Portland cement of grade 42.5 N which were imported to Sri Lanka was used in this research. Ten samples of cement from different manufacturers were obtained. All these cement are conformed to the requirements given in SLS 107: 2008 standard [1].

3.1.2 Sand

ISO standard sand was used for the experiment. Packets of sand of 1350±5 g which has particle size distribution as in Table 3.1 were used.

Table 3.1: Particle size distribution of standard sand

Square mesh size mm	Cumulative percentage (%) retained
0.08	99 ± 1
0.16	87 ± 5
0.50	67 ± 5
1.00	33 ± 5
1.60	7 ± 5
2.00	0

3.1.3 Water

Distilled water was used for all specimen preparations.

3.2 Apparatus

3.2.1 Mixer

The mixer consist of a stainless steel bowl, with a capacity of about 5 l, a stainless steel blade of a typical shape and an electric motor. The mixer used for this experiment is shown in figure 3.1 [28].

samples were different. These mortars were then tested for UPV and compressive strength at 2 day, 7 day, 15 day and 28 day. These time periods are standards time periods with respect to compressive strength in cement and concrete industry. At the end of the first part of the experiment two relationships, i.e. UPV and compressive strength and UPV and curing time, were obtained.

In the second part of the experiment, five (05) samples of cement obtained from different manufacturers were used to prepare five (05) samples of mortar same as the above. UPV of these five samples were measured at 2 day. Using the relationships obtained by the previous work UPV and compressive strength at 28 day were predicted. After 28 days samples were destructively tested to verify the relationships.

4. RESULTS AND DISCUSSION

4.1 UPV and Compressive strength of cement mortar

UPV and compressive strength of ten samples (named as A, B, C, D, E, F, G, H, I & J) at 2 days, 7 days, 15 days and 28 days were plotted separately and shown in figure 4.1 to figure 4.10 below. X axis represents UPV of the sample and y axis represents compressive strength. Each point in the graph represents UPV and compressive strength at a particular age and the line provides the best fit through the points. Each result of UPV represents arithmetic mean of nine (09) readings. Each result of compressive strength represents arithmetic mean of six (06) readings. Standard deviation of each data point was shown in the graph itself by error bars.

The equation for the line and R^2 value is given in the graph itself. R^2 shows the goodness of fit for the line through the given points. An R^2 value of 1 would indicate a perfect fit, meaning that all points lie exactly on the line.

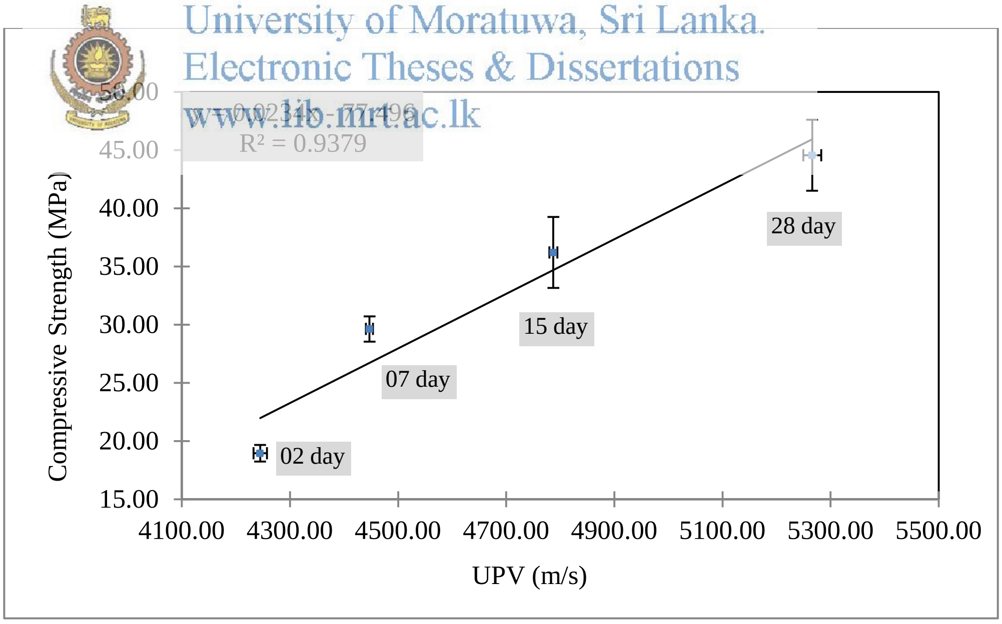

Figure 4.1: Relationship between UPV and Compressive Strength of Sample A

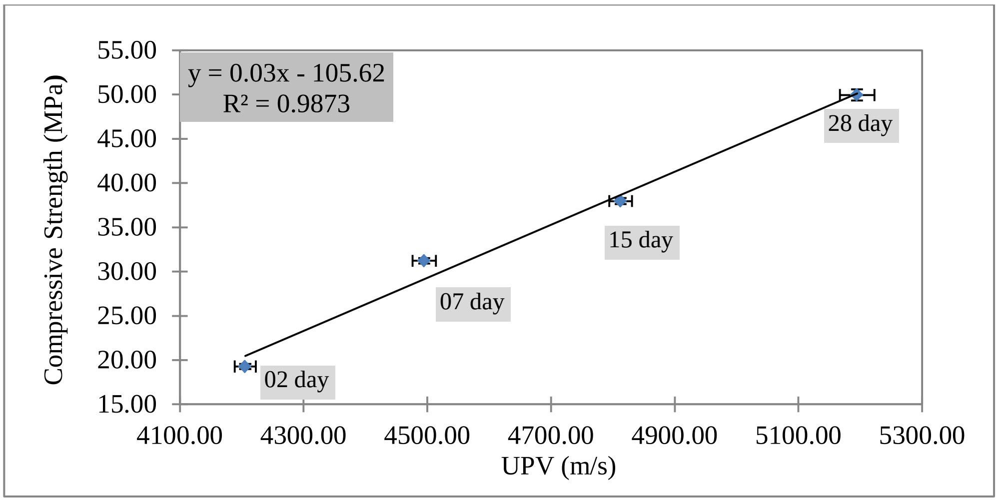

Figure 4.2: Relationship between UPV and Compressive Strength of Sample B

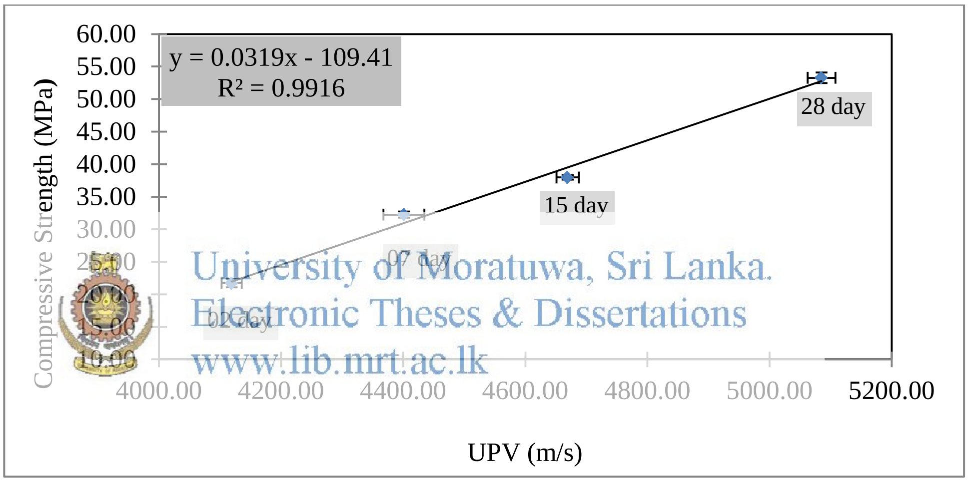

Figure 4.3: Relationship between UPV and Compressive Strength of Sample C

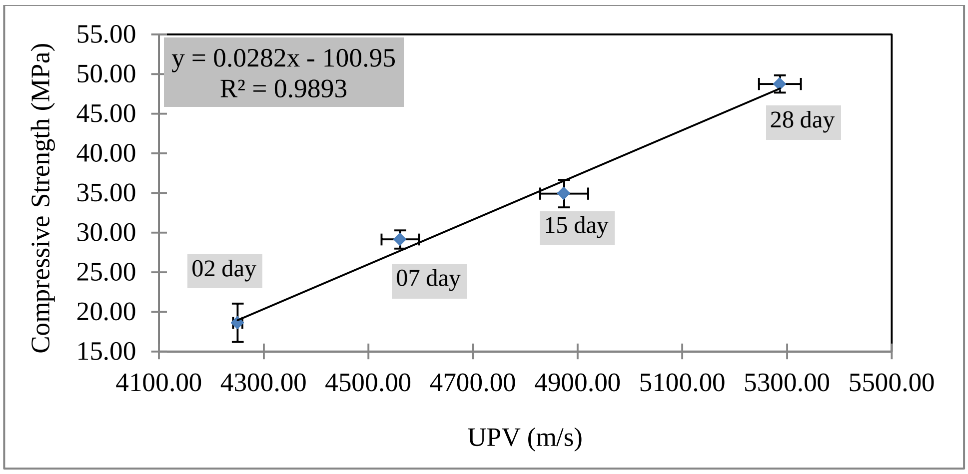

Figure 4.4: Relationship between UPV and Compressive Strength of Sample D

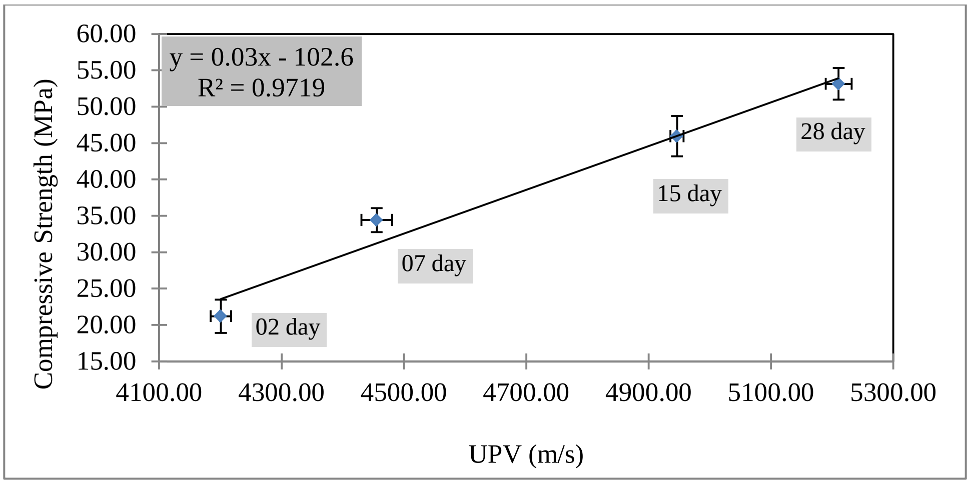

Figure 4.5: Relationship between UPV and Compressive Strength of Sample E

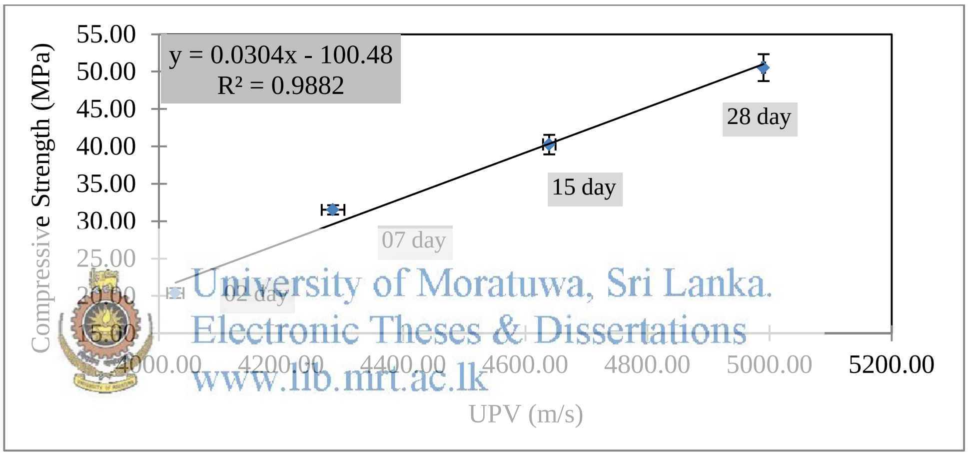

Figure 4.6: Relationship between UPV and Compressive Strength of Sample F

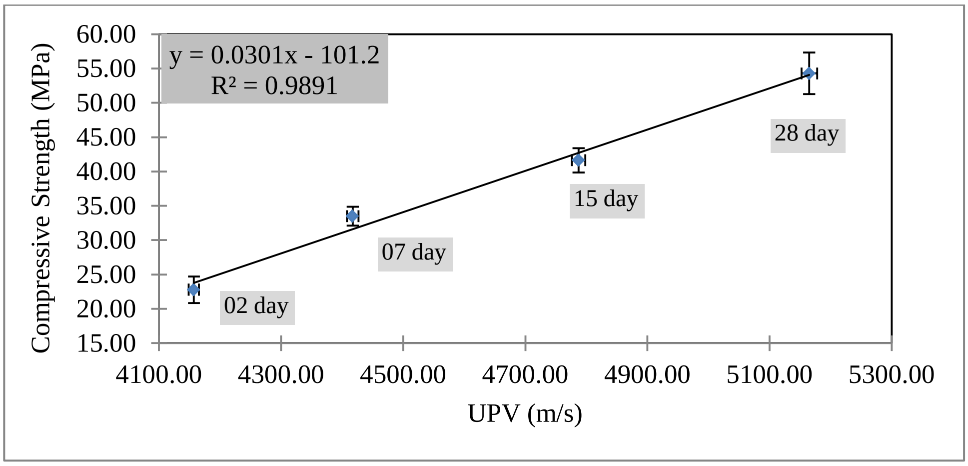

Figure 4.7: Relationship between UPV and Compressive Strength of Sample G

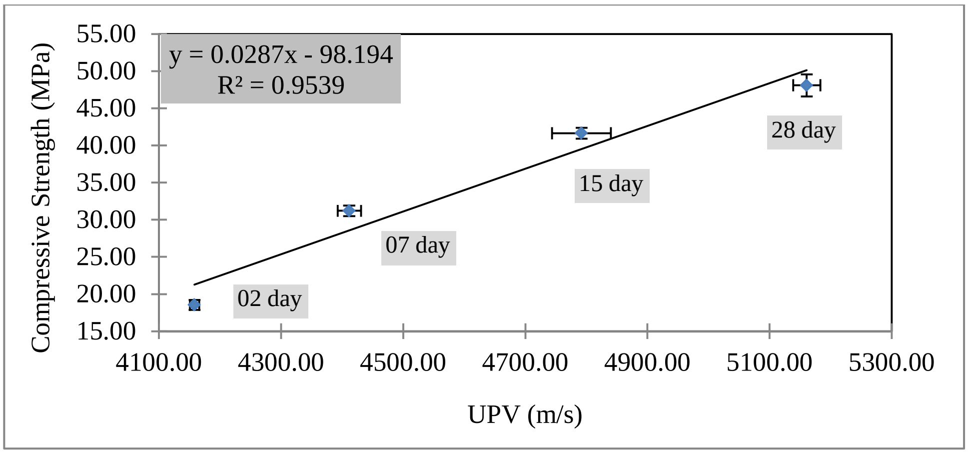

Figure 4.8: Relationship between UPV and Compressive Strength of Sample H

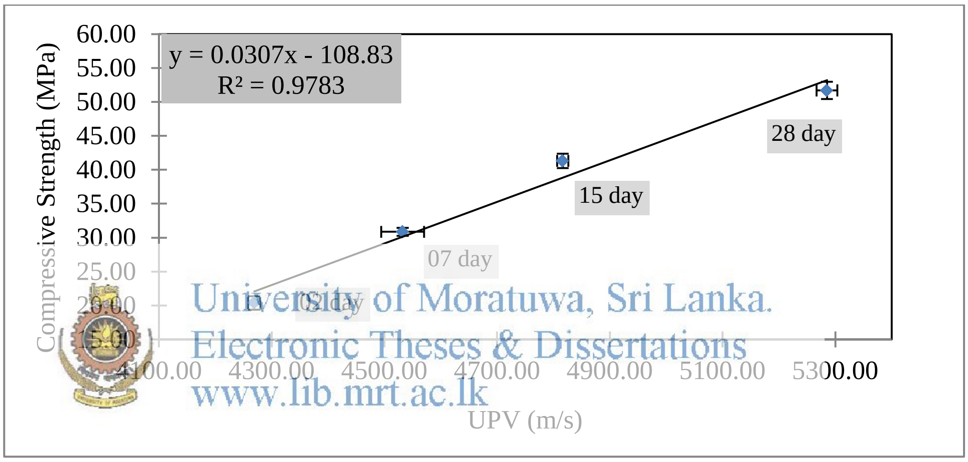

Figure 4.9: Relationship between UPV and Compressive Strength of Sample I

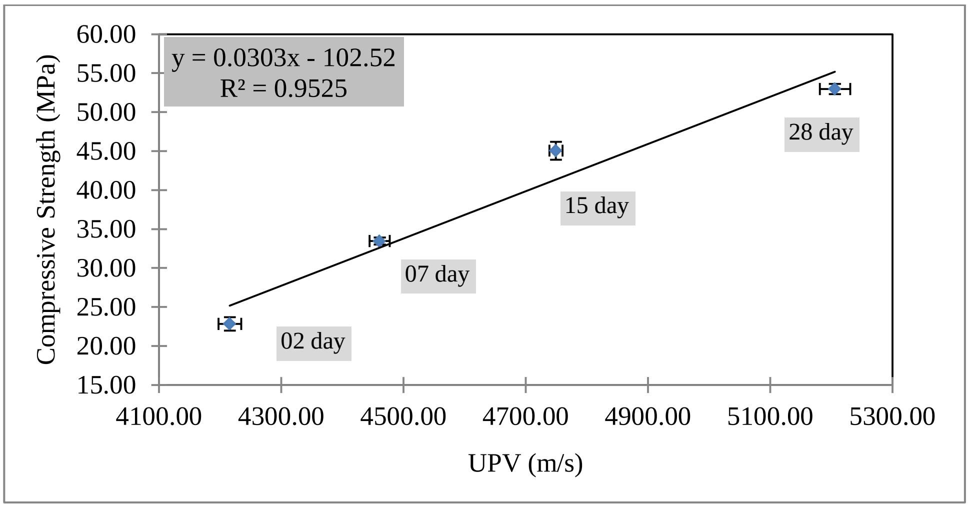

Figure 4.10: Relationship between UPV and Compressive Strength of Sample J

All the above graphs combined in to one graph to see the relationship between samples. Figure 4.11 shows all ten samples in one graph. It can be observed that with increase of curing time UPV and compressive strength also increase and the gradient of all the graphs are almost same except sample A. The equations and the R^2 values for the curves of these ten samples are given in table 4.1. Here x and y represent UPV and compressive strength respectively.

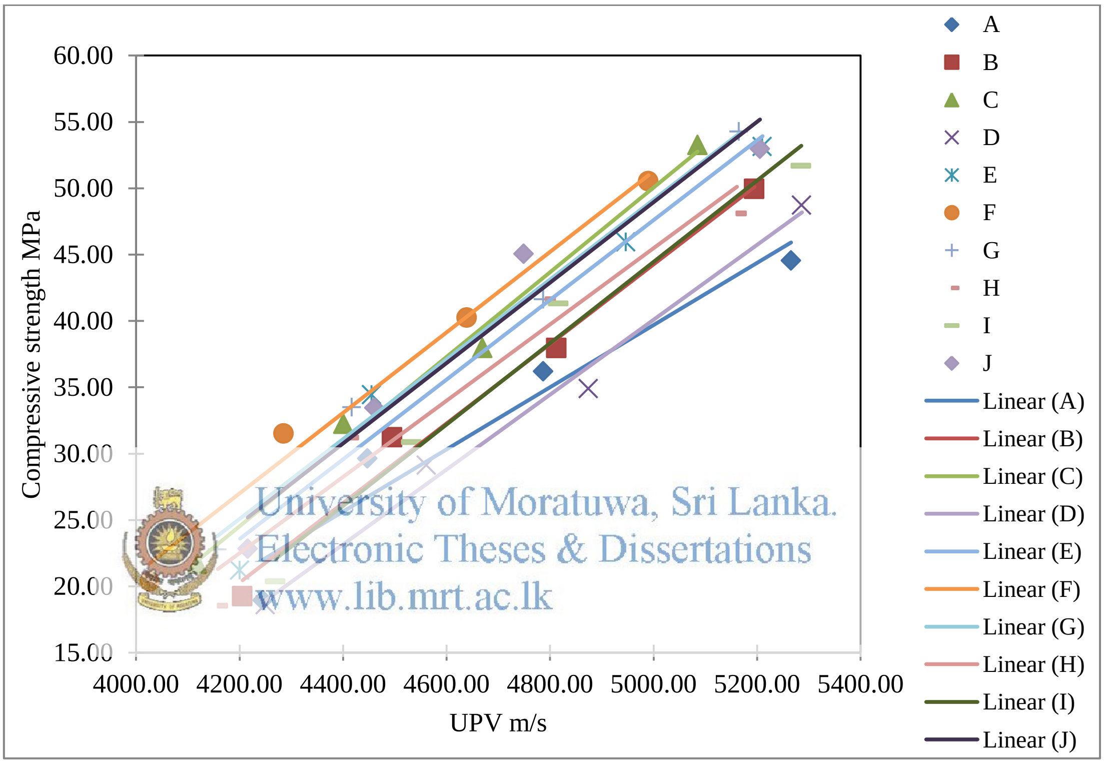

Figure 4.11: Relationship between UPV and Compressive Strength of Sample A to J

Table 4.1: Equations for the graphs and coefficient of determination

Sample Identification	Equation	R^2
A	y = 0.0235 x – 77.65	0.9384
B	y = 0.0300 x – 105.63	0.9871
C	y = 0.0319 x – 109.42	0.9916
D	y = 0.0282 x – 100.92	0.9892
E	y = 0.0300 x – 102.60	0.9719
F	y = 0.0304 x – 100.48	0.9882
G	y = 0.0301 x – 101.20	0.9891
H	y = 0.0287 x – 98.204	0.9539
I	y = 0.0307 x – 108.83	0.9783
J	y = 0.0303 x – 102.51	0.9524

Considering the relationship between UPV and compressive strength of ten samples, it can be seen that a linear relationship exist with very high coefficient of determination (R^2).

This can be explained considering cement hydration. When cement is in contact with water, cement minerals (i.e. C_2S, C_3S, C_3A, C_4AF) are dissolved in water and it becomes a viscous suspension of cement particles. With the time as cement minerals react with water, Calcium-Silicate-Hydrate (C-S-H) gel which is a solid hydrate phase, forms around the C_2S and C_3S grains. This solid hydrate is formed in what was originally water-filled space and also space occupied by the smaller cement grains. This C-S-H gel is responsible for most of the engineering properties of cement phase. This is because it forms a continuous layer that binds together the original cement particles into a cohesive whole. Therefore as a result of hydration, cement begins to transforms from a viscous suspension into a porous elastic solid.

As discussed in Literature review, velocity of Ultrasound in solid is higher than that of in air/liquid. As cement hydrates, amount of solid phase present in mortar increases. Because of that velocity of ultrasound increases with the time. Further with the formation of C-S-H gel compressive strength also increase with time. These phenomenons can be seen in all ten samples shown above.

When considering the equations of the ten samples it can be seen that gradient of the equations are almost same (except in sample A), and only Y intercepts differ. Considering sample A as an outlier, one equation can be derived as follows;

$$y = 0.03\,x - C \qquad 4.1$$

where;

y – Compressive strength

x – UPV

C – Constant

Since the source of cement is the only variable for these ten samples, relationship between the y intercept of graphs and chemical composition of cement was analyzed. When considering properties of cement Lime Saturation Factor (LSF) is the most critical parameter which is determined by the ratio of lime (CaO), to silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3), and governs by the relative proportions of C_3S and C_2S. Furthermore C_3S and C_2S contribute strength development of cement by generating the main hydration product, C-S-H gel. Therefore LSF is the main property which has influence on both compressive strength and UPV.

LSF of nine (09) samples and the y intercept of relevant equations were plotted to analyze the relationship and the graph is given in figure 4.12.

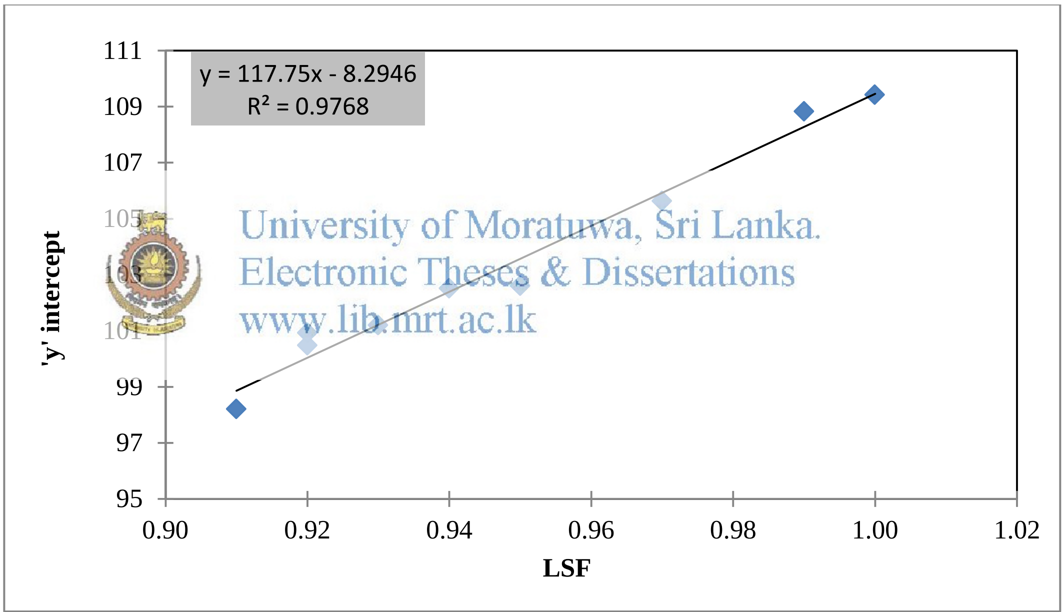

Figure 4.12: Relationship between LSF and 'y' intercept of graphs

This gives a linear relationship with a good R^2 value and it is given below.

$$y = 117.75\,x - 8.2946 \qquad 4.2$$

Where

y = C, the constant of equation 4.1

x = LSF of cement sample

Therefore equation 4.1 and 4.2 can be used to determine compressive strength of cement mortar in non-destructive manner. Also it is obvious that with the increase of curing time, both UPV and compressive strength of cement mortar increase.

To observe the development of UPV from 02 days to 28 days, a graph was plotted for all ten samples and it is shown in figure 4.13. The percentage increase of UPV from 02days to 28 days for each sample was calculated and given in the graph itself.

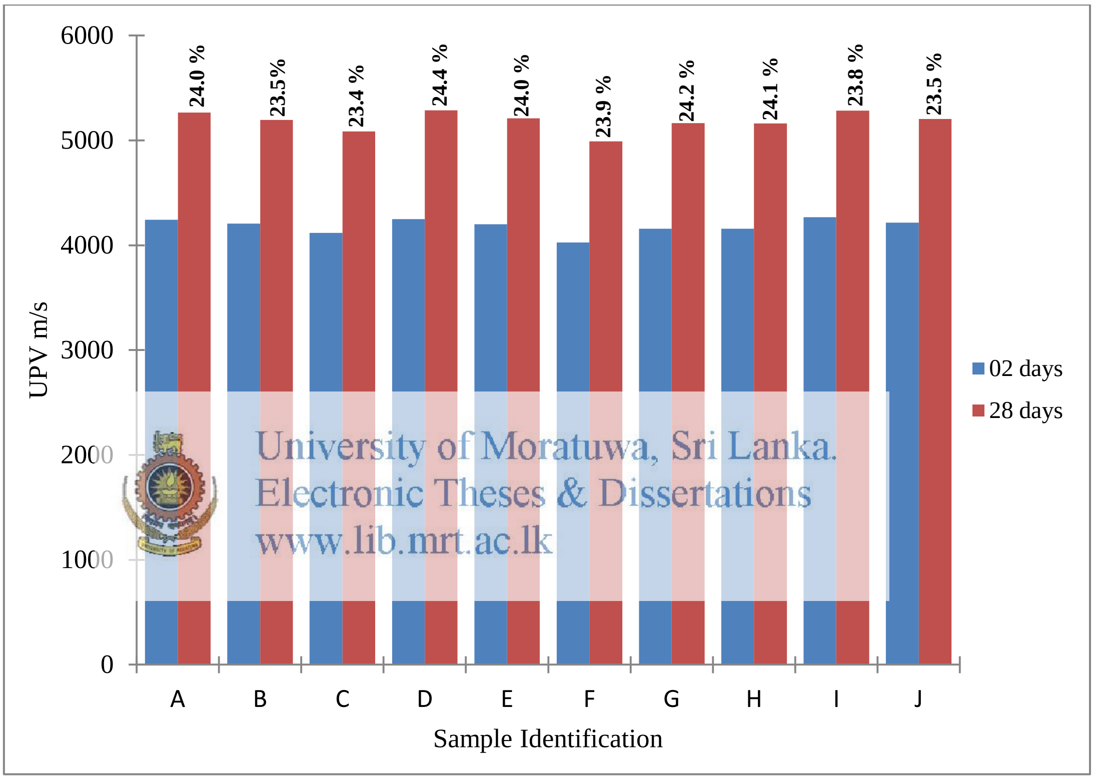

Figure 4.13: UPV at 02 days and 28 days for ten samples

The values of percentage increase of ten samples have a standard deviation of 0.33, which indicates that all values are very close to the mean value. That implies taking the mean value of ten readings is logical and therefore it can be considered that in all ten samples UPV at 02 day has increased by 23.9% at 28 day. The reason for above phenomenon can be explained as follows.

Since a standard procedure was followed to prepare cement mortar, following factors were constant for all ten samples.

i) Water/cement ratio
ii) Particle size of sand
iii) Curing temperature
iv) Mixing method
v) Compaction method

Chemical composition is the only variable for these samples. As discussed above LSF has more influence on UPV than other parameters of cement composition. LSF of the ten samples used for this study lies between 0.90 and 1.00, which is a very narrow range of 0.1

Strength development of cement mortar is a result of cement hydration process. Hydration of C_3S and C_2S contributes in different way for strength development of cement. C_3S occupy 40-70 wt% of the cement and its hydration gives cement paste most of its early strength. C_2S occupy 10-30 wt % of the cement and its hydration gives cement paste its later strength [5]. Since these two cement minerals contribute in different ways to strength development, without the knowledge of composition of cement minerals, it is difficult to predict 28 day strength by 02 day strength.

On the other hand UPV is influenced by the amount of solid phase present in the cement paste. Both C_3S and C_2S contribute to form this solid phase (i.e. C-S-H gel). Formation of solid phase continues with time regardless the proportions of C_3S and C_2S. Therefore percentage increase of the solid phase is not much influence by the proportions of C_3S and C_2S. Therefore cement samples of different chemical compositions show almost same amount of percentage increase of UPV.

Therefore UPV at 28 days can be predicted by obtaining UPV at 02 days of cement mortar.

4.2 Verification of proposed UPV-Compressive strength curve

To verify the results obtained in 4.1, five (05) samples of cement mortar (named as a, b, c, d & e) were used. UPV at 02 day of five (05) samples of cement mortar were determined and results are given in Table 4.2. LSF of the same samples also determined. Considering the fact that UPV of cement mortar at 02 day increases by 23.9%, UPV of cement mortar at 28 days were predicted and results are given in table 4.2.

Table 4.2: Results of measured UPV at 02 day and predicted UPV at 28 days

Sample Identification	Measured UPV at 02 day m/s	Predicted UPV at 28 day m/s
a	4196.05	5198.91
b	4070.09	5042.84
c	4162.06	5156.79
d	4297.53	5324.64
e	4183.79	5183.68

With the knowledge of LSF of samples and using the equation 4.1 and equation 4.2, compressive strength of cement mortar at 28 days was predicted. After that, five (05) samples of cement mortar were crushed at 28th day to determine the actual compressive strength. The comparison results are shown in table 4.3. All the calculated results are within ± 5% deviation from the actual value. This verifies the suitability of the proposed relationship curves for prediction of cement strength with a measured UPV value.

Table 4.3: Comparison of predicted and actual compressive strength of five samples.

Sample Identification	Calculated compressive strength MPa	Actual compressive strength MPa
a	46.51	47.98
b	48.89	50.14
c	51.14	53.95
d	51.46	49.09
e	47.23	49.47

5. CONCLUSION AND RECOMMENDATION

Based on the results obtained with respect to above mentioned objectives, following conclusions can be made.

- UPV and compressive strength of cement mortar has a linear relationship and LSF also has an indirect influence on this relationship.
- UPV at 02 day increases about 24% at the end of 28 days if following factors kept constant;
  - i. Water/cement ratio
  - ii. Amount and size of aggregates
  - iii. Curing media (i.e. water)
  - iv. Curing temperature (i.e. 27 ± 1 ^{0}C)
- Correlations given in (3) and (4) can be used to predict compressive strength of cement at 28 days within 02 days with only ± 5% deviation.

Results of this study can be used to expedite the testing of OPC at laboratory scale and hence will be beneficial for import inspection scheme operated by SLSI.

However, since LSF of the cement samples used for this study lie between 0.90-1.00 and throughout the entire experiment the temperature was maintained at 27 ± 1 ^{0}C, the correlations can be recommended for the samples which have LSF of the same range and a stable temperature condition. For samples having LSF out of the above range and for varying temperature conditions further studies have to be carried out.

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APPENDIX – A: INDIVIDUAL RESULTS, MEAN VALUE AND STANDARD DEVIATION OF UPV AND COMPRESSIVE STRENGTH OF 10 SAMPLES (30 SPECIMENS) OF CEMENT MORTAR.

Sample ID	Age	UPV m/s					Compressive strength MPa				
		Specimen no.			Mean	Stdev	Specimen no.			Mean	Stdev
		i	ii	iii			i	ii	iii		
A	02	4259.22	4236.97	4238.43	4244.87	12.44	18.72	19.82	18.93	18.96	0.72
							18.84	19.64	17.81		
	07	4453.3	4440.45	4447.89	4447.21	6.45	28.41	28.74	30.81	29.64	1.08
							29.2	29.64	31.05		
	15	4786.38	4780.00	4795.18	4787.19	7.62	31.43	40.42	36.18	36.2	3.04
							34.46	37.26	37.45		
	28	5248.9	5266.57	5282.13	5265.87	16.62	46.36	42.22	46.15	44.55	3.05
							41.9	41.68	49.01		
B	02	4195.8	4195.8	4225.35	4205.65	17.06	18.75	19.1	19.44	19.27	0.29
							19.5	19.41	19.41		
	07	4483.15	4516.98	4484.96	4495.03	19.03	31.51	30.73	30.95	31.22	0.31
							31.41	31.39	31.33		
	15	4819.28	4826.61	4792.00	4812.63	18.24	37.68	37.76	38.06	37.96	0.34
							37.56	38.33	38.38		
	28	5226.09	5172.41	5186.15	5194.88	27.88	50.58	49.69	48.83	49.95	0.63
							50.14	50.08	50.39		
C	02	4109.56	4137.93	4109.59	4119.04	16.36	22.03	21.60	20.91	21.71	0.62
							21.94	21.18	22.63		
	07	4411.76	4363.64	4428.04	4401.15	33.49	31.63	31.85	32.58	32.24	0.46
							32.79	32.08	32.5		
	15	4651.16	4669.26	4687.5	4669.31	18.17	37.68	37.76	38.06	37.96	0.34
							37.56	38.33	38.38		
	28	5111.11	5067.8	5016.27	5085.06	22.96	54.19	53.20	54.30	53.27	0.8
							52.89	52.58	52.49		
D	02	4255.32	4255.32	4240.28	4250.31	8.68	16.62	22.18	17.64	18.60	2.42
							18.91	20.47	15.78		
	07	4545.45	4535.85	4601.53	4560.95	35.48	27.46	28.54	28.74	29.12	1.15
							29.53	30.84	29.61		
	15	4822.58	4889.80	4909.84	4874.07	45.70	33.06	33.29	36.73	34.91	1.74
							34.69	34.44	37.24		
	28	5324.44	5244.54	5290.75	5286.58	40.11	50.35	49.09	48.39	48.73	1.08
							47.63	47.54	49.34		
E	02	4181.18	4210.53	4210.53	4200.75	16.94	19.12	24.68	20.14	21.21	2.28
							21.41	22.97	18.91		
	07	4460.97	4477.61	4428.04	4455.54	25.23	33.71	34.79	34.99	34.43	1.65
							35.78	31.46	35.86		
	15	4938.27	4942.39	4958.68	4946.45	10.79	45.56	45.79	49.23	45.95	2.78
							40.94	46.94	47.24		
	28	5186.15	5222.71	5222.71	5210.52	21.11	53.48	54.71	54.02	53.14	2.16
							50.26	50.76	55.59		

Cont.

Sample ID	Age	UPV m/s					Compressive strength MPa				
		Specimen no.			Mean	Stdev	Specimen no.			Mean	Stdev
		i	ii	iii			i	ii	iii		
F	02	4026.85	4040.40	4013.38	4026.88	13.51	21.41	20.56	19.53	20.37	0.68
							20.70	19.78	20.26		
	07	4293.91	4263.35	4297.49	4284.91	18.77	31.01	31.03	32.26	31.51	0.64
							32.17	30.83	31.79		
	15	4651.16	4633.20	4633.20	4639.19	10.37	40.81	40.89	41.81	40.25	1.31
							40.69	38.33	39.00		
	28	4991.67	4987.50	4991.67	4990.28	2.41	51.31	49.39	51.34	50.53	1.80
							49.01	53.39	48.77		
G	02	4152.25	4166.67	4152.25	4157.05	8.32	23.45	22.86	22.48	22.79	0.44
							22.58	23.13	22.28		
	07	4411.76	4411.76	4428.04	4417.19	9.4	32.88	33.10	33.83	33.49	0.46
							34.04	33.33	33.75		
	15	4780.88	4800.00	4780.88	4787.25	11.4	41.83	41.67	42.20	41.64	0.74
							40.81	40.76	42.59		
	28	5172.41	5150.21	5172.41	5165.01	12.82	53.61	53.68	51.66	54.28	1.64
							54.98	56.16	55.61		
H	02	4155.71	4152.25	4166.67	4158.21	7.53	17.57	19.50	18.04	18.54	0.69
							18.66	18.47	19.01		
	07	4404.41	4433.33	4397.06	4411.60	19.18	31.63	31.85	31.96	31.20	0.7
							30.29	30.83	30.63		
	15	4842.11	4746.03	4788.00	4792.05	48.16	40.81	41.67	42.20	41.64	0.74
							41.83	40.76	42.59		
	28	5163.79	5137.34	5181.82	5160.98	22.37	46.93	49.08	49.29	48.09	1.49
							49.60	45.86	47.79		
I	02	4271.43	4257.14	4278.57	4269.05	10.91	21.88	19.69	20.96	20.37	0.99
							20.75	19.31	19.63		
	07	4513.21	4576.34	4507.52	4532.35	38.2	31.38	29.94	31.02	30.86	0.6
							31.05	31.46	30.33		
	15	4815.26	4826.61	4807.23	4816.37	9.74	40.66	41.39	39.67	41.31	1.05
							41.44	42.71	41.96		
	28	5305.31	5268.72	5281.94	5285.32	18.53	51.76	52.00	50.54	51.69	1.29
							53.46	49.91	52.47		
J	02	4218.31	4233.22	4195.80	4215.78	18.83	22.31	21.60	23.65	22.84	0.85
							23.26	22.47	23.76		
	07	4444.44	4477.61	4460.97	4461.01	16.58	33.88	33.42	33.16	33.46	0.44
							33.38	34.06	32.88		
	15	4743.08	4743.08	4761.90	4749.36	10.87	45.75	43.89	46.29	45.06	1.15
							43.94	46.24	44.26		
	28	5181.82	5204.35	5231.44	5205.87	24.85	53.16	52.13	53.34	52.97	0.65
							52.19	53.70	53.30		