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ASSESS MATERIAL PROPERTIES OF CONCRETE USING COMBINED NDT METHODS

Abhishek Chitti
Southern Illinois University Carbondale, abhishekchitti16@gmail.com

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by

Abhishek Chitti

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A Thesis
Submitted in Partial Fulfillment of the Requirements for the
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THESIS APPROVAL

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Approved by:

Dr. Tsuchin Philip Chu, Chair

Dr. Rasit Koc

Dr. Farhan Chowdhury

Graduate School
Southern Illinois University Carbondale
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TITLE: ASSESS MATERIAL PROPERTIES OF CONCRETE USING COMBINED NDT METHODS

MAJOR PROFESSOR: Dr. Tsuchin Philip Chu

The aim of this research is to assess the material properties of concrete like modulus of elasticity, compressive strength, and Poisson's ratio using various nondestructive Testing (NDT) methods like Ultrasonic Pulse Velocity (UPV) and Rebound Hammer (RH). Assessment of material properties of concrete are important for structural design process. Various NDT methods are applied to ensure the quality and determine material properties of concrete specimens. The UPV method is used to test the internal condition of the concrete specimen. RH is a surface hardness testing method and can be used to test the homogeneity of the specimen. For this study, several batches of concrete samples with three different design strengths of 6000 psi, 8000 psi, and 12000 psi were casted. Modulus of elasticity and Poisson's ratio were calculated from UPV P-wave and S-wave velocities. A Nomogram was developed by combining the longitudinal UPV values, rebound numbers, and compressive strengths. This combined NDT correlation curve can be used to estimate compressive strength of concrete using UPV and rebound values. The accuracy of these NDT methods were determined by comparing estimated strength to the actual strength. Furthermore, the effect of moisture content on UPV and rebound values was reviewed and also studied dynamic modulus of elasticity and its relation with static modulus of elasticity of the concrete was investigated for better understanding.

DEDICATION

I would like to dedicate this thesis to my beloved parents and sister for their hard work, sacrifices, unconditional love and endless support to pursue my dream. I would like to thank my love, Sushmitha Priya, for being a great source of motivation and support during my thesis.

I would also like to thank my friends who believed and supported me while pursuing this master's degree.

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CHAPTER 1

INTRODUCTION

Concrete is most common material used in construction industry. The need for in-situ testing of concrete is important for quality controlling and compliance purposes. Usually to find the strength of concrete core samples are drilled out of the existing structures which will damage the structure. The location at which core has been removed should be repaired which increases the cost and labor. NDT methods can be employed to overcome all these issues.

Many NDT methods are capable for both assessing and determining the properties and strength of the concrete specimen. Based on the requirement, whether to find defects or to determine the material property or to assess the strength of concrete structure, NDT method can be selected. Combined NDT methods can be used to increase the accuracy. The current research is focused on estimating the modulus of elasticity, Poisson's ratio and compressive strength of the concrete specimen using NDT methods. Considering the advantages of combining UPV and RH methods, these are selected as NDT methods of our interest. Factors that mostly affect the ultrasonic and rebound measurements are aggregate size, moisture content, and water to cement ratio of the concrete. UPV method is a dynamic NDT method that can be used to assess the concrete structure in-place. Material property of concrete like modulus of elasticity can be obtained from UPV tests and this is considered as dynamic modulus of elasticity. Theoretically, there is a relation between Young's modulus and compressive strength of the material. Compressive strength calculated using dynamic modulus of elasticity obtained from UPV tests show huge difference when compared to actual strength of the material. This issue is addressed by investigating the relation between dynamic modulus of elasticity and strength of concrete.

Multiple regression analyses was performed on results obtained from ultrasonic pulse velocity, rebound hammer and compressive strength tests. The estimated compressive strength obtained from regression analyses was compared to actual strength and the difference was calculated to determine the accuracy of this developed correlation. Digital image correlation is one of the technique used to determine the Poisson's ratio by calculating and analyzing full-field deformation of concrete specimens under splitting tension test. This research aims to determine to assess the material properties using combined NDT methods. Furthermore, the influence of moisture content on UPV and rebound values was studied.

1.1 Objective

The existing methods to find the concrete material properties are costly, time consuming and are destructive. This research deals with assessing the material properties of concrete like modulus of elasticity, Poisson's ratio and compressive strength using combined nondestructive testing methods which would reduce time consumption and cost. A combined NDT correlation will be able to estimate the compressive strength of the concrete specimen if UPV and rebound values are known. This knowledge will advance the development of reliable NDT methods to evaluate quality of concrete accurately. Furthermore, this research is extended in two directions, one by studying the effect of moisture content on UPV and rebound values and other by investigating the relation between dynamic modulus of elasticity and compressive strength of concrete.

1.2 Scope

The scope of this research includes casting of concrete samples for the testing. The UPV, RH and compression strength tests were performed on concrete samples. The results from these three tests were fused to perform multiple regression analyses. Combined NDT correlation curve was developed for estimating compressive strength of concrete specimen. The accuracy of this correlation was determined by comparing the predicted strength values from multiple regression analysis to actual strength values. To study the effect of moisture content on UPV and rebound numbers, another new batch of concrete was fabricated. Besides this, another study has been conducted to investigate the relation between dynamic modulus of elasticity and compressive strength of concrete. The shear wave velocities through concrete samples were measured using UPV method and Poisson's ratio was determined using the relation between longitudinal, shear wave velocities with Poisson's ratio of the material. The relation between dynamic modulus of elasticity and compressive strength of concrete was investigated and necessary recommendations were provided.

1.3 Sequence of Presentation

Chapter 1 provides readers with the introduction followed by objective and scope of this research. This includes the motivation and gives brief description regarding different tests performed during experimental process. The following chapters the principles behind UPV, RH, and compression strength tests are discussed.

Chapter 2 begins with basic principles of ultrasound and its propagation in general. Also, brief description about ultrasonic pulse velocity (UPV) testing, basic principle, different types of transducer configurations are discussed. Then basic principles of rebound hammer (RH) tests, and compressive strength test are explained.

Chapter 3 reviews the previous and related work, which have been conducted in this current field of research. Chapter 4 describes the engineering approach applied in this research. This chapter reviews sample fabrication, test setup and procedures.

Chapter 5 presents the results from all the experiments. This is followed by discussions on the experimental results and investigations from other research studies. Chapter 6 finally ends the research discussion with concluding remarks about the data and overall information from the research project. This presentation then ends with a list of future research recommendations.

CHAPTER 2

THEORETICAL BACKGROUND

This chapter deals with the theoretical background related to the research experiments. It explains basic principles behind different testing methods employed in this research. This chapter begins with basic ultrasonic testing and will move to ultrasonic pulse velocity testing in specific then followed by rebound hammer, compression strength tests.

2.1 Ultrasonic Testing

Sound generated above the human hearing range (typically 20 kHz) is called ultrasound. Unlike electromagnetic waves such as light, microwave, and X-rays, ultrasonic waves require an elastic medium (solid, liquid, air) to propagate. Ultrasound is used in various fields like sonography (ultrasound imaging) in medicine, it is also used for mixing, cleaning and accelerating chemical process in industry. Ultrasonic waves have shorter wavelengths i.e., they will be reflected off very small surfaces like defects inside materials. This property is used for testing materials in nondestructive testing [1]. The range of frequency used for ultrasonic inspection in NDE of materials is usually from 40 kHz – 50 MHz, depending upon the application and material being inspected.

Ultrasound can propagate in four principle modes, in solid materials, based on the particle oscillation. These four different modes are namely longitudinal waves, shear waves, surface waves and plate waves. These waves are further explained in following section.

2.1.1 *Longitudinal Waves*

In longitudinal waves, the particles oscillate in longitudinal direction or direction of wave propagation. They are also referred as compressional waves or pressure waves because the compression and dilation forces are active in these waves. The particle movement and propagation of longitudinal waves is illustrated in Figure 1. [2] They are also called as density waves since the particle density varies as they move.

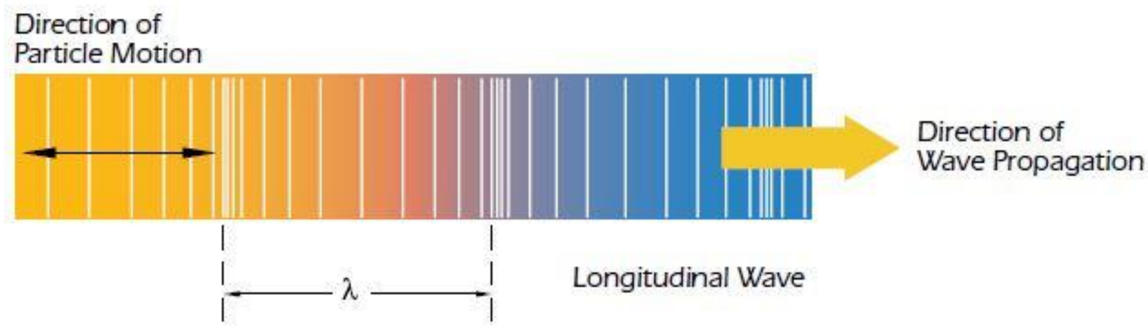

Figure 1. Longitudinal wave propagation

2.1.2 *Shear Waves*

In shear waves, the particles oscillate in perpendicular or transverse to the direction of wave propagation and hence are also called as transverse waves. The particle motion is illustrated in the Figure 2. [2] Shear waves require an acoustically solid material for effective propagation and therefore cannot effectively propagated in materials like liquid or gases. Shear waves are weaker when compared to longitudinal waves. They are in fact generated using some energy form longitudinal waves [1].

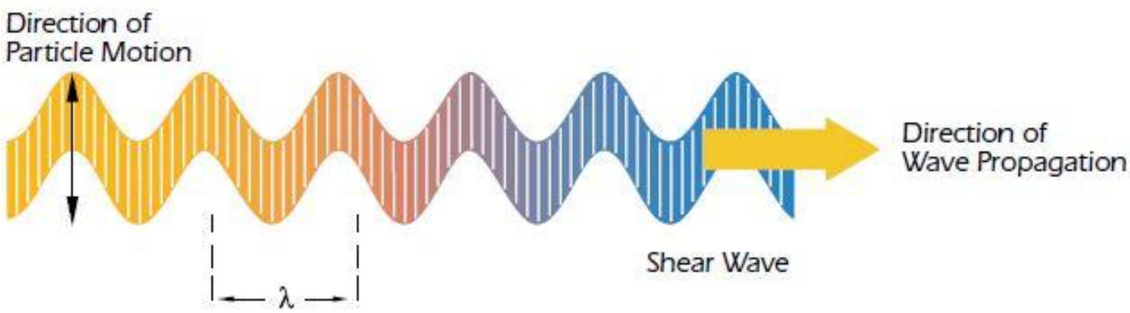

Figure 2. Shear wave propagation

2.1.3 Surface Waves

Surface waves propagate in a relatively thick solid materials penetrating to a depth of one wavelength (λ). Surface waves combine both longitudinal and shear waves to create an elliptical orbit motion as illustrated in Figure 3. [1] The major axis of elliptical orbit is perpendicular to the surface of the solid. They are also called as Rayleigh waves and travel at a velocity of 90% of shear wave velocity. Rayleigh waves are used to inspect surface around curves or any areas that other waves have difficulty in reaching.

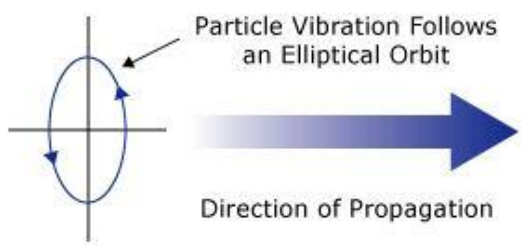

Figure 3. Surface wave propagation

2.1.4 Plate Waves

Plate waves are similar to surface waves except they can only be generated in a material that is usually few wavelengths thick. These waves are most commonly referred as Lamb waves in NDT field. The propagation of lamb waves is greatly influenced by the density and elastic property of the material. There are two common modes of propagation of lamb wave namely symmetrical and asymmetrical modes as illustrated in Figure 4. [1] The symmetrical mode is sometimes called as "extensional mode" as the wave is stretching and compressing. Whereas the asymmetrical mode is called as "flexural mode" because of the large portion of wave moving in the normal direction to the plate. Lamb waves travel several meters are used to scan plates, wires, and tubes [1].

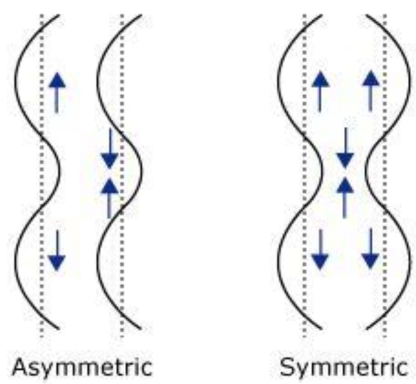

Figure 4. Lamb wave propagation modes

2.2 Ultrasonic Pulse Velocity (UPV) Testing

The ultrasonic pulse velocity (UPV) method is used to establish the homogeneity of the concrete and detect the presence of cracks, voids, and any other imperfections. UPV testing can also be used to assess the quality and changes in the structure that occur over period of time. Apart from inspection, UPV method can also be used to determine the dynamic modulus of elasticity. The ultrasonic pulse is generated by an electro-acoustical transducer and this pulse is induced in to the concrete specimen under testing.

The basic principle of UPV testing is sending an ultrasonic pulse generated by an electro-acoustical transducer and inducing this pulse in to concrete specimen under testing. This induced ultrasonic pulse is detected by a receiving transducer which is placed at a known distance. The receiving transducer detects the onset of the longitudinal waves, which is the fastest. The pulse velocity is calculated by measuring the time it takes to reach the receiving transducer placed at a known distance. The testing apparatus consists of a pulse generator, a pair of transducers (transmitter and receiver), an amplifier, a time measuring circuit and time display in to one unit as illustrate in Figure 5. [4] An ultrasonic couplant gel with is applied between the transducer and test surface. This couplant gel plays an important role in UPV testing as it fills any air gaps and enables to achieve maximum contact between the transducer and test surface.

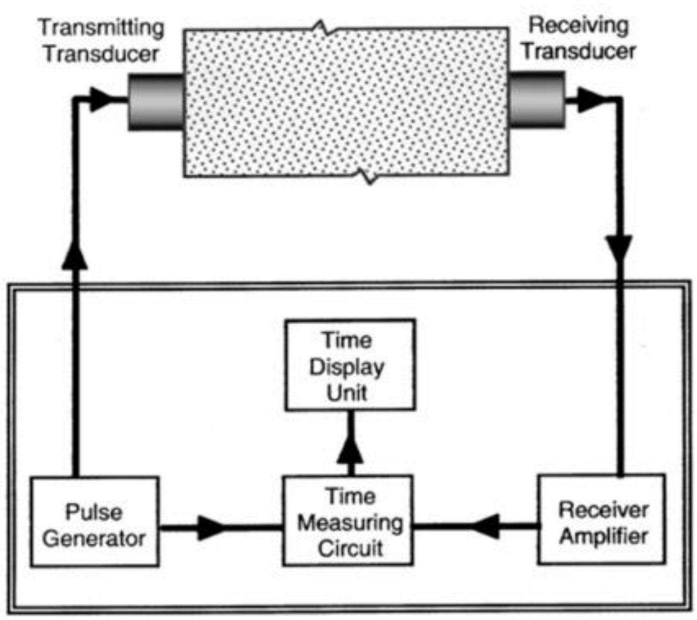

Figure 5. Schematic of UPV test apparatus

The travel time of ultrasonic waves reflects the internal condition of test area with in concrete specimen. Comparatively higher velocities are obtained when the quality of concrete in terms of density, homogeneity is good. Lower velocities are obtained for poorer quality of concrete if there is any crack or void inside the specimen, as the pulse strength is attenuated and passes around discontinuity which makes the path longer. According to the Indian standard IS 13311, the pulse velocity bands for concrete quality are classified as shown in Table 1 below.

Table 1. Classification of concrete quality based on pulse velocities

Ultrasonic Pulse Velocity (m/s)	Quality of Concrete
4500 and higher	Excellent
3500 - 4500	Good
3000 - 3500	Medium
Lower than 3000	Doubtful

There are three different configurations of transducer that can be used to perform a UPV test and they are direct transmission, semi-direct transmission, and indirect transmission modes. Depending on the specimen, shape, size and surface accessibility suitable transmission mode is selected.

2.2.1 Direct Transmission Mode

In direct transmission mode, both the transmitting and receiving transducers are placed opposite to each other on both the surfaces. This type of configuration is optimum with maximum signal amplitude. This is the most accurate method of pulse velocity determination.

The path length is measured from center to center of the transducers as illustrated in Figure 6. [3] This type of transmission mode requires access to both sides of the specimen.

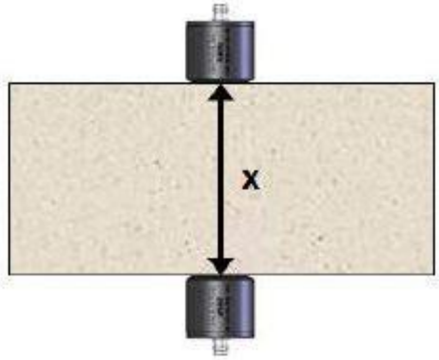

Figure 6. Direct transmission mode

2.2.2 Indirect Transmission Mode

In this type of configuration, both the transmitting and receiving transducers are placed on the same side of the specimen under testing as illustrated in Figure 7. [3] This type of transmission mode is also called as “surface transmission”. Signal amplitude is very weak in this type of transmission when compared to direct transmission. This kind of transducer arrangement can be employed when there is only access to single side of the specimen.

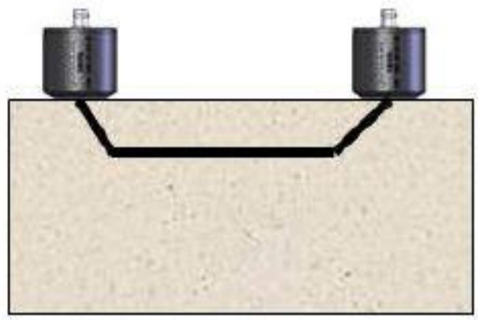

Figure 7. Indirect transmission mode

2.2.3 Semi-direct Transmission Mode

In semi-direct transmission mode, transmitting and receiving transducers are placed perpendicular to each other as illustrated in Figure 8. [3] The sensitivity of this type of transmission is somewhere between direct and indirect transmission modes. The path length is measured from center to center of the transducers. This type of transducer arrangement is useful to inspect a corners of column specimen.

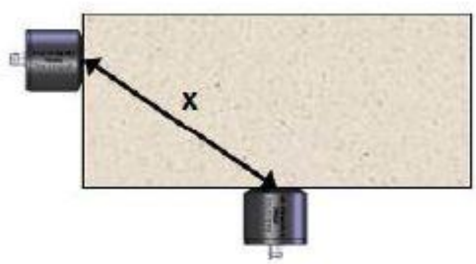

Figure 8. Semi-direct transmission mode

During direct transmission, with one transducer used as a transmitter and another used as a receiver, the acoustic speed c (c_L for longitudinal or p-waves, c_S for shear or s-waves) is calculated as

$$c = d/\Delta t \ , \qquad (2\text{-}1)$$

where d is the distance from the transmitter to the receiver and Δt is the measured time needed for the pulse to travel between the transducers. In the case of pulse-echo measurement, the ultrasonic pulse passes through the material twice from the transmitter to the far wall, and back to the receiver so Eq. (2-1) is modified to show $d = 2z$, where z is the thickness of the measured item.

Furthermore, UPV can be measured using either p- or s-waves. In general, the speeds of these two types of wave are not equal: $c_L \neq c_S$.

The difference between these two speeds provides additional material information. The relationships between the ultrasonic pulse speeds and material parameters [4] is

$$c_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(2-\nu)}} \tag{2-2}$$

and

$$c_S = \sqrt{\frac{G}{\rho}} \tag{2-3}$$

where E is the dynamic Young's modulus, G is the shear modulus, ν is the dynamic Poisson's ratio, and ρ is the mass density. Since the Poisson's ratio describes the difference between the two moduli, it is possible to calculate the Poisson's ratio and use it to demonstrate the relationships among the four critical structural parameters:

$$\nu = \frac{1-2\left(c_S/c_L\right)^2}{2\left[1-\left(c_S/c_L\right)^2\right]}\ , \tag{2-4}$$

$$\rho = \frac{E\left[1-\left(c_S/c_L\right)^2\right]}{c_S^2\left[3-4\left(c_S/c_L\right)^2\right]} = \frac{G}{c_S^2}\ , \tag{2-5}$$

and

$$E = \frac{\rho c_S^2\left[3-4\left(c_S/c_L\right)^2\right]}{1-\left(c_S/c_L\right)^2} = 2\rho c_S^2(1+\nu) = 2G(1+\nu)\ . \tag{2-6}$$

According to the American Concrete Institute (ACI), concrete's compressive strength, f_c, can be calculated using the equation [5]

$$E_c = w_c^{1.5} 0.043\sqrt{f_c'} \tag{2-7}$$

where w_c (1440 kg/m^3 $\leq w_c \leq$ 2560 kg/m^3) is density of concrete in kg/m^3, f_c' is the specified compressive strength of concrete in MPa, and E_c is the modulus of elasticity for concrete in MPa.

2.3 Rebound Hammer (RH) Testing

Rebound Hammer is a NDT method which provides an indication of the compressive strength. Rebound hammer is also called as “Schmidt hammer” as it was first developed by a Swiss engineer named Ernst Schmidt to measure the hardness of concrete. Rebound hammer test works based on rebound principle, which states that the rebound of an elastic body depends on the hardness of the surface against which the body strikes. This distance of rebound is measured on a graduated scale and this reading is referred to as rebound index or rebound number. Empirical correlations have been established between compressive strength and the rebound number.

Rebound hammer test method is conducted to assess the in-place uniformity and strength of the concrete specimen. This testing method can be used to differentiate the poor quality regions of the structure by comparing the rebound numbers obtained from test region with readings obtained from acceptable regions of structure.

Rebound hammer consists of a spring loaded mass that slides on a steel plunger, indicator, latch mechanism and all these parts are housed in a cylindrical metal casing. The working principle of rebound hammer is illustrated in the Figure 9. [6] The plunger of the rebound hammer is pressed against the surface of concrete with increasing force. At a preset amount of force applied a spring-controlled hammer is released; the energy of the hammer strike is usually calibrated to 2.207 J. The hammer rebounds from the surface and the amount of rebound, still pushing against the spring, is measured. This rebound value is read from a graduated scale. The extent of rebound depends on the hardness of the surface tested. Since compressive strength correlates with surface stiffness, the rebound value from a surface with high compressive strength is larger than that from a low-strength surface. Six readings of the rebound number are taken at each point and the average of the readings is considered as rebound index at that point. The point of impact should be at least 20 mm away from the edge of the material or any other discontinuity.

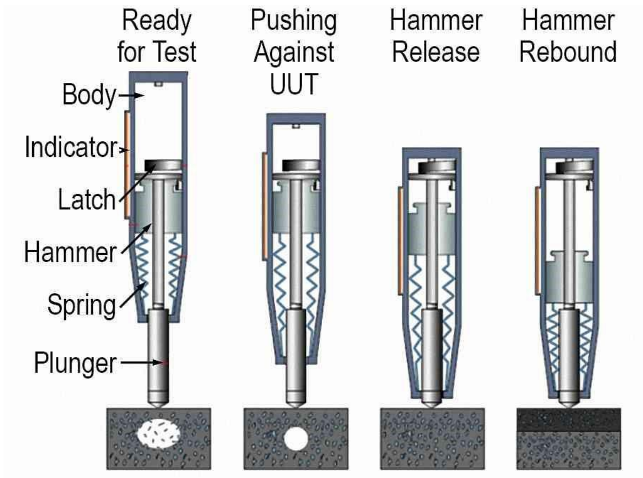

Figure 9. Operation of rebound hammer

Several improvements have been made to the original Schmidt hammer, resulting in the digital and silver Schmidt series. The digital series replaces the mechanical gauge with an electrical transducer, making it easier to take measurements and increasing measurement accuracy. The silver Schmidt hammer has two distinct advantages over the original hammer. First, the test result that is obtained is not affected by gravity. This makes this unit suitable for operation in a full range of 360° degrees with no correction necessary. Second, this unit uses the digital scale from the digital hammer and includes the capability of calculating the material properties internally.

The calibration curve which expresses compressive strength as a function of the rebound number is shown in Figure 10. The test hammer symbols in the figure indicate the direction of impact and the respective conversion curve. Concrete cylinders of 150 mm diameter and 300 mm length are normally used as test specimens.

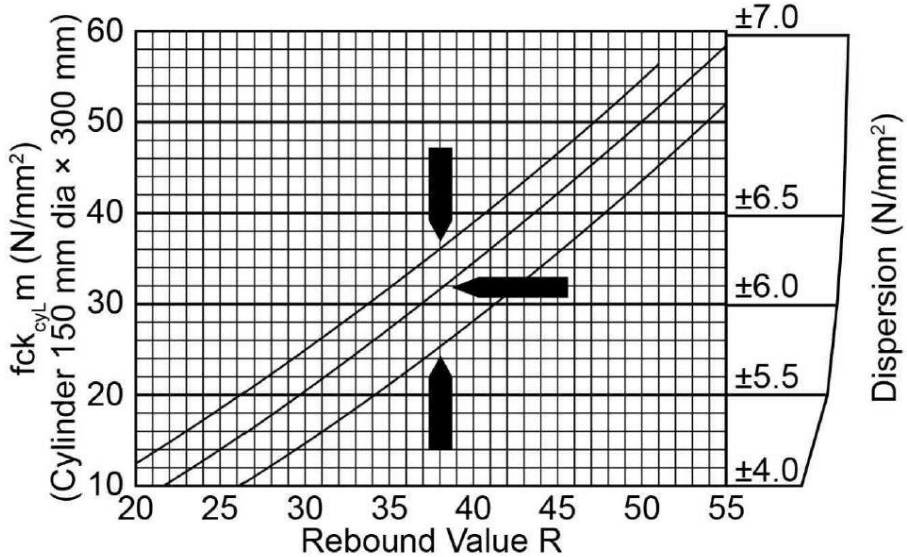

Figure 10. Conversion curve for rebound hammer

Relationship between rebound number and compressive strength provided by instrument manufacturer can only be used to find the relative strength of concrete at various locations in a structure [7]. For a specific concrete mixture, rebound number is affected by many factors such as moisture condition, effect of carbonation and surface condition of the test location. All of these factors need to be considered while measuring compressive strength of the specimen. Correlations must be established by correlating rebound numbers measured on structures to the compressive strengths of the cores taken from that locations. This correlation will enable us to estimate the compressive strength of that structure with higher accuracy.

2.4 Compressive Strength Testing of Concrete

Combined strength results from cast cylinders are used to ensure that the concrete mixture meets the design strength. These results may be used for quality control, acceptance of concrete, for estimating the strength in structure, or evaluating the adequacy of curing of the structure [8]. Field-cured specimens are tested for estimating the in-place strength. Compressive strength tests are performed on both cylinders and cubes according to different testing standards followed by different nations. In Unites States, compressive strength tests are performed on cylindrical specimens. Cylindrical specimens are tested in accordance with the testing standard of ASTM C39 [9]. Standard sizes of cylindrical specimens are 4×8 in. (100×200 mm) or 6×12 in. (150×300 mm) concrete cylinders. Smaller cylinders are usually easy to handle in both field and laboratory.

Figure 11. Compressive strength testing of concrete cylinder

Mostly, concrete specimens are tested for their compressive strength after the curing period of 28 days. At least two samples taken from same concrete mix and age are tested for their strength and average value is considered as the compressive strength. Concrete samples are mounted on the hydraulic press and are capped with neoprene pads to make sure that the uniform load is applied as illustrated in Figure 11. Load is gradually increased till complete failure using a hydraulic press. This load at which the specimen has failed is noted and divided by cross-sectional area to find the compressive strength of that specific sample.

CHAPTER 3

LITERATURE REVIEW

This chapter deals about the work done relating to this research are reviewed. Previous and current research conducted on nondestructive testing of concrete using ultrasonic pulse velocity, rebound hammer, and combining two or more various NDT methods to inspect or assess material properties of concrete. Furthermore, factors affecting UPV, RH tests and concluded with discussion on application of DIC on concrete.

3.1 Ultrasonic Pulse Velocity Testing

The UPV has been successfully used to evaluate quality of concrete by detecting internal cracks and other defects like voids. Development of Pulse velocity method has begun in Canada and England at about same time. Since the 1960's, pulse velocity methods have moved out of laboratories and to construction sites [10]. Malhotra [11] has complied an extensive list of papers published on ultrasonic testing of concrete. Bungey [12] has conducted research on validation of UPV testing of in-place concrete for strength and concluded that detailed knowledge on relative moisture conditions under test is vital in establishing correlation. Yaman et al. [13] have made comparisons between direct and indirect wave velocities and found that indirect wave UPV is statistically similar to direct UPV if there are uniform properties along the specimen. Helal et al. [14] have identified and described the most common successful methods of NDT as applied to concrete structures. It was found that the majority of NDT methods rely on comparing tested parameters with established correlations. Al-Nu'man et al. [15] have conducted an experimental research on 880 concrete samples received from various construction projects and found that no unique relation can be established to cover all concrete specimens. Azreen et al. [16] have conducted tests on concrete slabs with different grades of concrete including ultrahigh performance concrete (UHPC). It was observed from test results that UPV for UHPC was higher than normal grade concrete specimens. Mahure [17] has conducted research on developing UPV and strength relationship curves for different mixes of concrete used in concrete structures of hydroelectric project. The estimated correlation curves are verified to be suitable for prediction of strength in health monitoring during its service. Popovics and John [18] has studied the effect of stresses on ultrasonic pulse velocity measurements and found that the ultrasonic pulse velocity in concrete is independent of the stress level. Ongpeng et al. [19] have conducted a study on characterizing of damage using ultrasonic testing on different types of concrete. In this study 36 samples of nine different mixtures varying water-cement ratios, aggregate sizes, and mixing steel fibers have been prepared and tested using UPV before and after the damage of samples. UPV was found to be less sensitive to characterize micro-damage inside the concrete. Lencis et al. [20] conducted research to evaluate the impact of reinforcing bars on UPV in concrete. This research has applied longitudinal, transverse and surface wave propagation by using direct and indirect transmission to measure in both locations at plain concrete and rebar zones. The experimental results shown reduction of UPV values, which is an opposite effect to the previous studies and standards. The reason behind this has been stated to be difference in concrete properties in transition zone and coarse aggregate concentration around rebar. Lee and Oh [21] have analyzed the statistical distribution of P-, S-, and R- wave measurements on pre-stressed concrete slabs and all the P-S-, and R-wave velocities increased by 3% due to pre-stressed condition.

3.2 Rebound Hammer Testing

In 1948, Ernst Schmidt, a Swiss Engineer has developed a test hammer for measuring the hardness of concrete by rebound principle [10]. Rebound hammer has been used to find the hardness of concrete which is further correlated to compressive strength of concrete. Mitchell and Hoagland [22] have attempted to correlate rebound number with modulus of elasticity of the concrete specimens and concluded that no general valid correlation could be made between rebound number and statistic modulus of elasticity. Aydın and Saribiyik [23] have conducted a study on correlating concrete strength and rebound numbers. In order to calibrate the Schmidt hammer, cube specimens of 28-90 days and a number of core samples from different existing reinforced concrete structures have been tested. The best fit correction factors for the compressive strength to rebound hammer relationship were obtained which can be applied to in situ concrete strength. Sanchez and Tarranza [24] have investigated the reliability on rebound hammer as a means of estimating the compressive strength of three group of concrete cube specimens. The high dispersion of data for rebound number plotted against actual compressive strength has reinforced the prior findings that the rebound hammer test is not substitute for obtaining compressive strength if used alone. Kim et al. [25] have conducted experimental research to clarify the influence of carbonation on rebound number and concrete strength evolution. A new equation was developed from this research for strength reduction coefficient, which compensates the influence of surface carbonation in the rebound hammer method. Ismail et al. [26] has conducted a study on concrete chevron samples with hematite aggregates. This study correlated rebound number to density of concrete. Comparisons were made between concrete with Hematite aggregates and concrete with normal and granite aggregate. Concrete with fine aggregate yielded lower rebound numbers and density. In general as density increases rebound number increases, but the use of finer aggregate and Sike admixture has increased the density but reduced the rebound number. Concrete with granite aggregate has yielded higher rebound numbers than hematite aggregate though density is lower when compared. Hinnachi and

Guetteche [27] have revisited the rebound hammer method by emphasizing on methodology, standards, and factors that influence rebound numbers while assessing compressive strength of concrete. This study concluded that calibration for specific area of concrete under evaluation, at least 9 test locations for rebound test have to be selected and cores must be drilled and tested for their strength. Liu et al. [28] attempted to increase the accuracy of calculating concrete strength using rebound value, material design parameters, and regression analysis. Results from this study showed that accuracy of calculating strength using this method is based on material design parameters of concrete mix. Statistical regression analyses of estimating concrete strength using rebound numbers and various design parameters, including age and moisture content, had an average accuracy of 5.5%.

3.3 Combined NDT Methods for Testing Concrete

Many investigations have applied more than one NDT method at same time to predict strength of concrete more accurately. During 1950's, Kesler and Higuchi [29] has pioneered in this field. During this study, dynamic modulus of elasticity and damping constant were determined from resonance tests and they correlated with compressive strength of concrete and found that this method was unsuitable for in-situ measurements. The results from UPV and RH methods have been combined to predict the compressive strength of the concrete. Many factors like moisture content, aggregate size content are likely to affect the reliability, sensitivity, and reproducibility of results. There are some exceptions in those cases when a variation in properties of concrete produce opposite effects on result of each component [10]. An increase in the moisture content increases UPV value but decreases the rebound number. RILEM Technical Committees 7 NDT and 43 CND [30] has put large efforts on developing the SONREB method. This method has been developed combining both ultrasonic pulse velocity and rebound hammer measurements to create a correlation curve. These curves can be used to estimate the compressive strength but the difference between estimated and actual strength is up to 20%. Tsioulou et al. [31] have examined samples from two different mixes of ultra-high performance concrete (UHPC), one without reinforcement and other with 3% steel fiber reinforcement. UPV and RH tests performed at various curing ages are combined with compressive strength tests to develop models for correlation of NDT and mechanical testing. This study highly recommended the SonReb method as it offered higher accuracy. Bzeni and Ihsan [32] have correlated the results from UPV and RH tests with compressive strength results. These tests were carried out on concrete cube specimens from six different mixes of self-consolidated concrete (SCC) varying in cementious material content. Various statistical analysis like sum of square residuals, type of fit, and correlation coefficient were determined for developed correlation equations. The accuracy of prediction has shown significant improvement on combining UPV values with rebound numbers and rebound number readings were found to be less sensitive to assess strength of SCC, but introducing age of concrete has improved strength prediction. Many research studies concluded that correlations developed by combining UPV and rebound hammer test results with concrete compressive strength results have been proved to have better accuracy to predict the compressive strength [27] [33] [34].

CHAPTER 4

EXPERIMENTS AND EXPERIMENTAL SETUP

This chapter explains the engineering approach followed to conduct this research and this approach is illustrated using a flowchart. The approach starts with concrete sample fabrication with various strength properties. This section is followed by describing the experimental procedures of UPV, RH and compressive strength tests. Experimental setup which includes the specifications of test equipment used were also provided in this section. This chapter is concluded by discussing the statistical regression analyses performed by correlating the test results from both NDT and destructive tests.

4.1 Engineering Approach

The goal of this research is to estimate the material properties of the concrete samples using combined NDT methods. This research started with the concrete sample fabrication under the guidance of concrete experts. Samples with different targeted compressive strengths ranging from 6000 psi, 8000 psi, and 12000 psi were fabricated. For each targeted strength, 2 batches of samples will be fabricated and each batch consists of a 9 concrete cylinders. The fabricated concrete cylinders were 4 inch in diameter and 8 inch in length. These samples have undergone ultrasonic pulse velocity (UPV) testing, rebound hammer (RH) testing and finally compressive strength testing. The results from all these tests were used to perform multiple regression analyses using Microsoft Excel. Furthermore, a combined correlation curve has been developed by combining the results from above mentioned nondestructive and destructive tests. The accuracy of this correlation curve has been determined by comparing the estimated compressive strength to measured compressive strength.

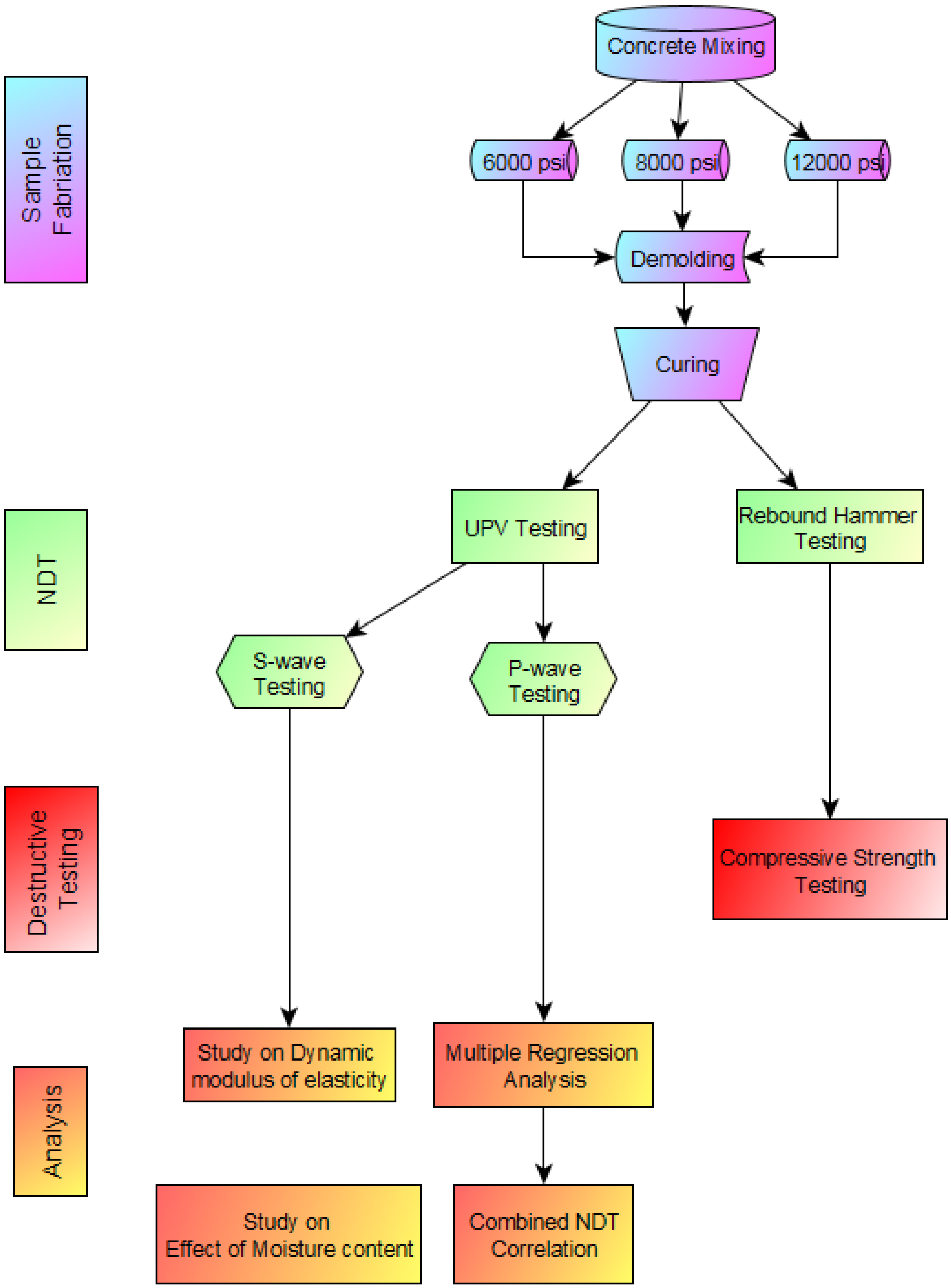

Figure 12. Flowchart depicting engineering approach

The relationship between dynamic Young's modulus and the compressive strength of concrete was investigated by studying various research papers. The schematic of the overall approach is shown as flowchart in Figure 12.

4.2 Sample Fabrication

This section explains the material used for fabrication and steps followed for sample fabrication. All the samples were prepared under laboratory conditions and under proper supervision.

4.2.1 Material Description

Concrete is prepared by mixture of coarse aggregate, fine aggregate, cement, and water in predefined proportions. In order to improve the properties of concrete, other materials like admixtures and super plasticizers were added. The purpose of these admixtures is usually to increase compressive strength.

High strength concrete (HSC) is fabricated with a reduced water/cement ratio, taking care to reduce porosity, inhomogeneity, and cracks during hydration. These defects usually occur in the cement paste and the transition zones between the paste and the aggregate. Densification of the transition zone, due to the improved method, enables efficient load transfer among cement, mortar, and aggregate.

4.2.2. Sample Specification

Different mixes of concrete cylinders with dimensions of 4 inches × 8 inches were fabricated based on three different concrete mixtures. These mix designs were targeted to attain compressive strengths of 41 MPa (6000 psi), 55 MPa (8000 psi), and 83 MPa (12000 psi), as presented in Table 2. Mix 2 and Mix 3 are considered as high strength concrete. All the mix designs used for concrete were according to the Illinois Department of Transportation's (IDOT,

2012) method of concrete mixing and ACI 211 (2002) committee report, which provides guideline for the selection of different proportions for standard concrete with Portland cement. The consistency of the fresh concrete mixture was assessed using the slump test. Then the fresh concrete was poured into cylindrical molds, compacted in three layers, and kept on vibratory platform to eliminate air voids, shown in Figure 13. The molded cylinders were then left in the open air for 24 hours to set. After that period the cylinders were demolded, labeled, and cured in a control tank held at a temperature of 74 ˚F (24 ˚C), shown in Figure 14. These samples were tested for compressive strength after curing for 28 days.

Table 2. Descriptions of Sample Mixes of Concrete

Mix	Targeted Compressive Strength, MPa (psi)
Mix 1	41 (6000)
Mix 2	55 (8000)
Mix 3	83 (12000)

Figure 13. Molded cylinders placed on vibratory table

Figure 14. Curing the samples in water

Group of concrete cylinders are referred as batches throughout this report. For the whole research project several batches of concrete samples with different mixes, as mentioned in Table 2, were prepared. Each batch consisted of 9 concrete cylindrical samples. Several concrete batches of different mixes were casted at different periods during this project. These samples were tested for study different aspects of the research and are tabulated in Table 3. The purpose of casting concrete samples of different mixes was to the achieve wide spread results for developing correlations between UPV, rebound numbers and compressive strength, so that that these correlations can be used for estimate both normal and high strength concrete specimens. As a whole, 108 concrete cylinders with varying compressive strengths were casted for this research. All of these samples are identical in shape and dimensions. However, weight of the samples varied based on their densities for each different mix.

Table 3. Overview of sample fabrication based on different studies conducted

Study	Concrete Mix	Number of Batches	Number of Samples
Preliminary	Mix - P	2	18
Periodic Tests- UPV,RH, and Compressive strength	Mix - 1	1	9
	Mix - 2	1	9
	Mix - 3	1	9
Effect of moisture	Mix - 2	1	9
UPV, RH and combined NDT correlation	Mix - 1	2	18
	Mix - 2	2	18
	Mix - 3	2	18
Total number of samples			108

Preliminary study was conducted to make sure that the concrete samples were able to attain the design strength. A special mix (Mix – P) was designed to attain a targeted compressive strength of 10000 psi (69 MPa). These samples were tested for their compressive strength after curing periods of 3-, 7-, 14-, and 28-days.

Initially three batches of concrete cylinders (Mix - 1, 2, and 3) were casted to study to attain the compressive strengths of 6000 psi, 8000 psi, 12000 psi respectively. The purpose of selecting this range of strength is to clearly understand the usage of UPV and RH equipment on concrete members with different strength. UPV and RH tests were performed after a curing periods of 7-, 14-, and 28- days and then crushed to measure the compressive strength.

Another batch of concrete cylinders of Mix -2 was casted especially to study the effect of moisture content on results of UPV and RH tests. Detailed explanation of this study is given in further sections of the report.

Finally there are 6 batches of concrete cylinders comprising of two batches from each mix design (1, 2, and 3) were casted specifically to develop the correlations between UPV and compressive strength, rebound numbers and compressive strength. This study primarily focuses on developing a combined NDT correlation to estimate compressive strength.

4.3 Experimental Procedure

There are two different NDT methods and one destructive testing method used in this research. The NDT methods include ultrasonic pulse velocity (UPV) testing and rebound hammer (RH) testing. The compressive strength testing method is destructive method employed in this research. All these three methods are explained this this section.

4.3.1 Ultrasonic Pulse Velocity (UPV) Testing

After the samples have been cured for a specific period, these samples were subjected to UPV, RH and compressive strength tests in the respective order. All the samples were labeled and measured for their length and weight. UPV test was performed using Proceq PUNDIT PL-200 equipment (Figure 15) and following the ASTM C 597 [4] standard. The equipment consists of following components

- Display unit
- Pair of 54 kHz Longitudinal Transducers
- Pair of 40 kHz Dry Point Contact (DPC) Shear Wave Transducers
- Calibration / Zeroing block
- Zeroing Plate
- Ultrasonic couplant gel
- Connecting wires
- Charging cables

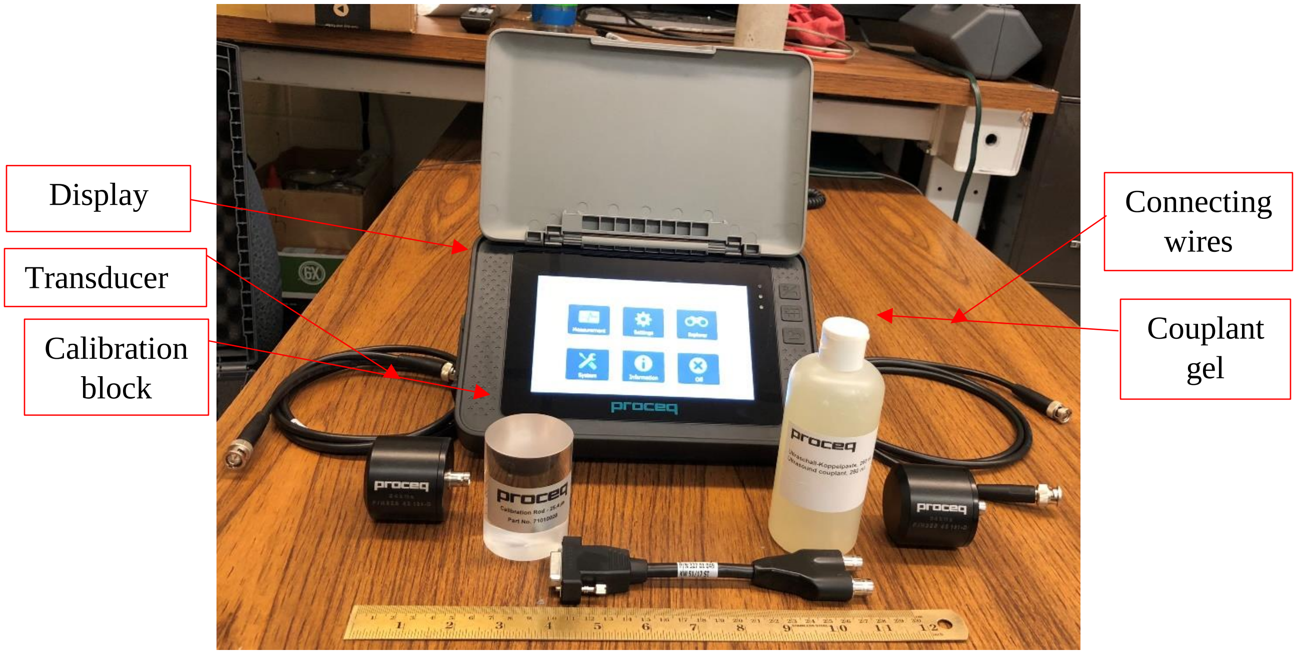

Figure 15. Equipment for UPV testing

During the initial UPV tests performed on the concrete cylinders, there was lot of noise observed in the displayed signal. After consulting a technician from Proceq, it was figured that improper contact of transducer and test surface would show noises and may affect the measured readings. It was observed that either sides of concrete cylinder are rough and causing poor contact between transducer. To overcome this issue, both sides of the cylinder were cut by ¼ inch. Another challenge faced while performing the UPV test was to constrain the sample movement. As the sample is cylindrical in shape it tends to roll when placed on table, to overcome this a wooden sample holder was fabricated to constrain the rolling of cylinder, this fixture has made the test to perform lot easier and smoother.

The samples were held in a sample holder and the couplant gel was applied on both the transducers and pressed against the surfaces of the cylinder as illustrate in Figure 16. The length of the samples was provided as input and the UPV values were measured and recorded for each of the sample.

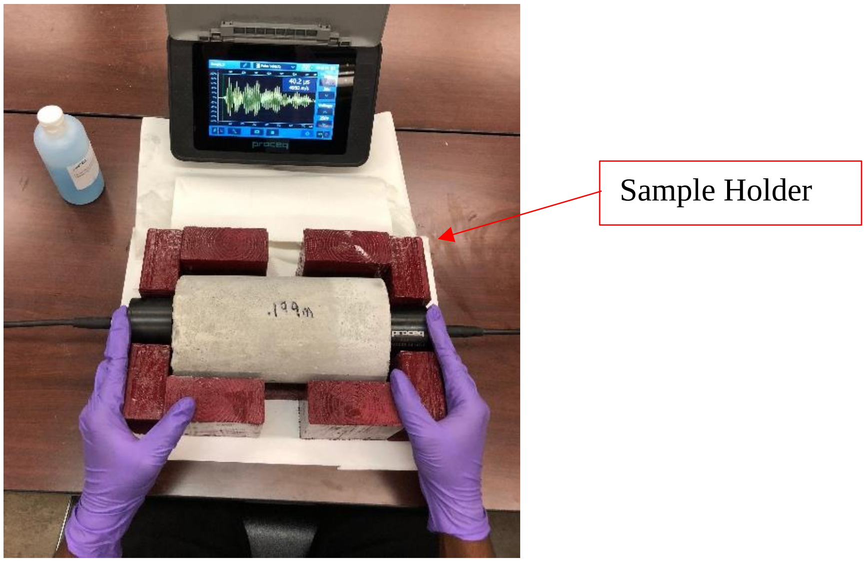

Figure 16. Equipment setup for UPV testing

It is important to calibrate the transducers every time after turning on the equipment, whenever the transducers are changed or whenever the equipment is continuously used over an hour. Ultrasonic couplant gel also effects the measurements. Insufficient coupling do not give good results and also signal strength is found to be very low. Couplant can be applied to either transducer or test surface or both.

In order to calculate the dynamic modulus of elasticity modulus of elasticity and dynamic Poisson's ratio, shear wave velocities were measured. To perform shear wave velocity measurements, a pair of 40 kHz shear wave transducers shown in Figure 17 were used. These transducers can be used without any couplant and hence are called as dry point contact (DPC) transducers. These transducers are calibrated using a thin Aluminum zeroing plate before taking measurements.

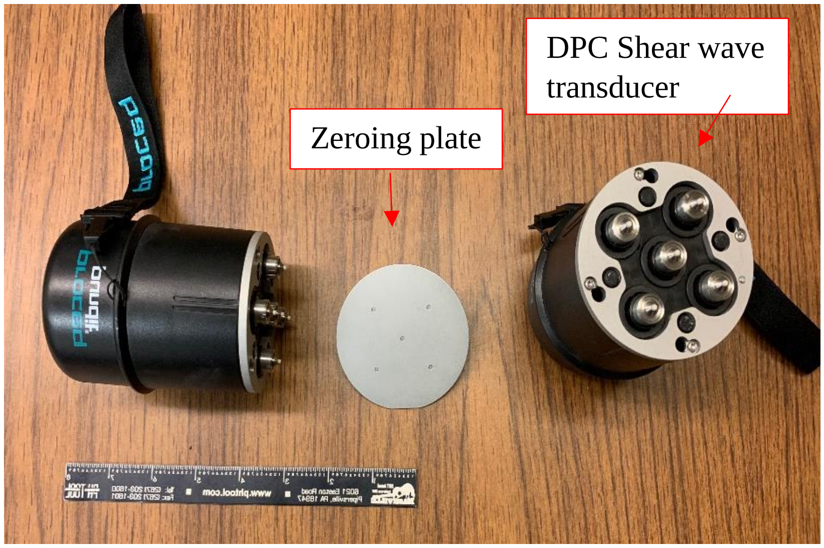

Figure 17. Ultrasonic dry point contact shear wave transducers

Various factors like surface roughness, aggregate size, cement type, admixtures, moisture content and temperature effect UPV measurements. Some of these factors like surface roughness is mitigated by grinding the surface using hand held concrete grinder as shown in Figure 18 The effect of moisture content on UPV values has been studied and discussed in further sections of this document.

Figure 18. Grinding concrete surface using a hand held concrete grinder

4.3.2 Rebound Hammer (RH) Testing

After conducting the UPV test, each sample was mounted on compression strength testing machine to constrain its motion during impact. Rebound hammer test was performed using Proceq Original Schmidt hammer, which consists of a plunger with a spring loaded mass and graduated scale to measure the rebound number is attached to equipment as shown in Figure 19. This test was performed according to ASTM C 805 [7] standard. This equipment was provided with the grinding stone and the manufacturer's conversion curve. It is recommended to create our own correlation curve by correlating rebound number measurements to compressive strength values of concrete cores, if at filed or samples, if at lab.

Figure 19. Rebound hammer testing equipment

Surface condition has a great effect on the rebound value measurements. It is very important to choose a surface free from defects (pits or cracks) and rebar. It has been made sure that the there are no coarse aggregate particles on surface, as the tip crushes the aggregate and producing a lower rebound number. Test surface was grinded using a grinding stone to obtain smoother surface.

Rebound hammer was held perpendicular to the surface and plunger was unlocked by giving gentle push as illustrated in Figure 20. Then the plunger is forced against the surface of concrete specimen until the spring loaded mass hits the plunger and creates impact on the concrete surface. Then the extent of rebound was measured using a scale graduated on the equipment. The reading can be locked by pressing lock button on side of the equipment. Ten readings were taken at different locations on the concrete cylinder and the average of these 10 values was considered to be the rebound number of that sample. No two readings were taken at identical locations. The test locations on the sample that were selected were free from visible pores and discontinuities. The rebound number for each samples was measured and recorded.

Figure 20. Rebound hammer test on concrete cylinder

4.3.3 Compressive Strength Test

After performing the RH tests, the sample was held in same position on compression strength testing machine as shown in Figure 20. The load on the sample was subsequently increased until the sample was crushed as shown in Figure 21. Then compressive strength results were recorded for each of the concrete sample. The results obatined from this test are considered as actual compressive strength of the concrete samples. These strength values are correlated with UPV and RH test results to develop correlation curves by performing statistical analyses.

This test was performed acording to the ASTM C39 [9] standard. There is a clear description about this test standard provided in the section 2.4.

Figure 21. Concrete cylinder crushed for compressive strength

4.4 Experimental study of effect of moisture content on UPV and RH measurements

A new batch of concrete with a targeted compressive strength of 8000 psi (Mix-2) was prepared and nine samples were casted. The present study mainly focused to understand the influence of moisture content on UPV measurements. These 9 samples were tested after a curing period of 7-, 15-, and 28- days, with three samples at each period. The observations made from preliminary tests on concrete samples show that the surface roughness effects the UPV measurements. For this study, ends of all samples were cut by approximately ¼ inch to obtain straight and smooth surface. Out of three samples, one of the samples were tested for UPV, rebound number, and crushed for measuring compressive strength on the same day after taking out from the immersion tank. Whereas the remaining two samples were placed in oven for quick drying. Both the samples were taken out after 24 hours and allowed to cool down. Then UPV and RH tests was performed on both the samples and one of these samples was crushed to find compressive strength and another sample was placed back in oven for another 24 hours. The same procedure was repeated on third sample after 24 hours of drying in oven.

4.5 Statistical Regression Analyses

In statistical modeling, regression is commonly used for predictive analysis. This analysis is used to develop a relation between dependent and independent variables. For this particular study, the main aim is to estimate/predict the compressive strength of concrete by fusing UPV value and rebound number measurements. This regression analyses were also performed to predict the compression strength values by correlating with UPV and rebound values individually.

There are total of 54 samples casted based on three different concrete mixtures (Mix-1, Mix-2, and Mix-3). Two batches of concrete for each type of mix were casted and each batch consisted of 9 samples. These samples were tested for UPV, rebound numbers and compressive strength values after the curing period of 28 days. After gathering all the results, multiple regression analyses was performed to develop a combined NDT correlation. UPV and rebound number values are considered to be independent variable and estimated compressive strength as dependent variable to develop combined NDT correlation.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter discusses the results obtained from the experimental tests mention in the chapter 4. This chapter starts with results acquired from preliminary study and then moves to periodic study of UPV, RH, and compressive strength tests. Later in this chapter, results from study conducted on effect of moisture content on UPV and RH measurements are discussed and this section is followed by discussions on combined correlation curve to estimate the compressive strength of the concrete. Finally, this chapter is concluded by discussion on the determination of dynamic properties of concrete and investigating the relation between static and dynamic modulus of elasticity.

5.1 Preliminary Study

During the preliminary study, two batches of concrete mixes were prepared to achieve high strength concrete. The targeted strength was 10000 psi (69 MPa). Compressive strength tests were performed on these samples after different curing periods of 3, 7, 14, and 28 days. The results from one of the batch are shown in Table 4. The results show that the design mix was successful to attain targeted strength after a curing period of 28-days. Sample 4 and Sample 9 from that batch were not tested, so the average value of other two samples tested on same day was assigned in the table below.

Table 4. Compressive strength results from preliminary tests

Targeted Strength 10000 psi	Compressive Strength (psi)			
	3-Day	7-Day	14-Day	28-Day
Sample 1	7559.9			
Sample 2		9072.09		
Sample 3		8753.78		
Sample 4	Average	8912.935		
Sample 5			8519	
Sample 6			9156	
Sample 7				10748
Sample 8				10509
Sample 9			Average	10628.5

5.2 Periodic study of UPV, RH, and compressive strength tests

Three different mixes of concrete samples were casted. These three mix designs were made to achieve the compressive strengths of 6000 psi, 8000 psi and 12000 psi, respectively. The purpose of selecting these range of compressive strengths is to clearly understand the usage of equipment UPV and RH on concrete members with different strengths.

During this study, initially UPV values measured were very insignificant and signals displayed were noisy and had many glitches. It was figured that the surface hardness has impacted most of these uncertainties. So, the results achieved from initial results were insignificant. Later in order to attain smoother and straight surface ends of the sample were cut by ¼ inch.

Tests were performed in the order of UPV, RH and finally compressive strength tests. The results obtained from three different mixes are shown in Table 5. Firstly, all the mixes were successful in attaining the targeted strength. UPV values measured seemed to be increasing as the strength of the sample is increased. UPV is greatly affected by density and high strength concrete has higher density compared to lower strength concrete samples. Rebound hammer results have also followed similar trend but the difference in rebound numbers measured for lower strength and higher strength concrete was very high.

The best-fit line, given the three points measured for only the 28-day curing period (Figure 22), has the equation

$$f_c = 7.701\, c_L - 115{,}500 \tag{5-1}$$

with f_c representing the compressive strength in psi and c_L the UPV in ft/s. The fit is quite good, as indicated by the high coefficient of determination, R^2 = 97.08%.

Table 5. Results from UPV and compressive strength measurements

Sample		Curing Period	UPV		Compressive Strength	
Mix	Strength (psi)		(ft/s)	(m/s)	(psi)	(MPa)
Mix 1	6000	7 days	15335	4674	6501	44.82
		14 days	16193	4936		
		28 days	15807	4818		
Mix 2	8000	7 days	15229	4642	8099	55.84
		14 days	16468	5019		
		28 days	16114	4912		
Mix 3	12000	7 days	14855	4528	11479	79.14
		14 days	16363	4987		
		28 days	16457	5016		

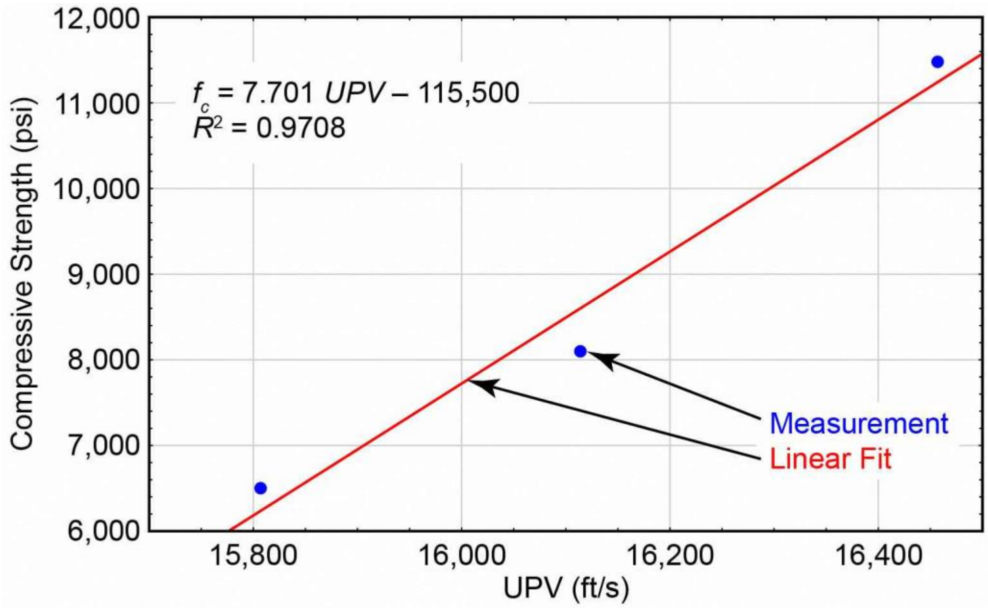

Figure 22. Compressive strength correlated with UPV

The difference between the UPV values measured on low strength and high strength samples was less than anticipated. This could be due to several factors that are influencing UPV measurements. Further study is focused on reducing the variables affecting the measurements.

As expected, the higher rebound numbers correlated to the higher compressive strength measurements, indicating that higher compressive strength correlates to larger surface hardness. The mixes listed here are the same as those shown in Table. 6.

Table 6. RH and Compressive Strength values for 28-day Cured Samples

Sample	Rebound Number	Compressive Strength	
		(psi)	(MPa)
Mix 1 – 28 days	17	6501	44.82
Mix 2 – 28 days	21	8099	55.84
Mix 3 – 28 days	25	11479	79.14

The equation of the best-fit line is given in Eq. 5-2, relating rebound number to strength as

$$f_c = 622.3\,n - 4374 \tag{5-2}$$

where f_c is the compressive strength in psi, and n is the rebound number (unit less). The coefficient of determination, R^2, is 95.90%, indicating that the line is a good description of the relationship between rebound number and compressive strength. A linear fit to this data is shown in Figure 23.

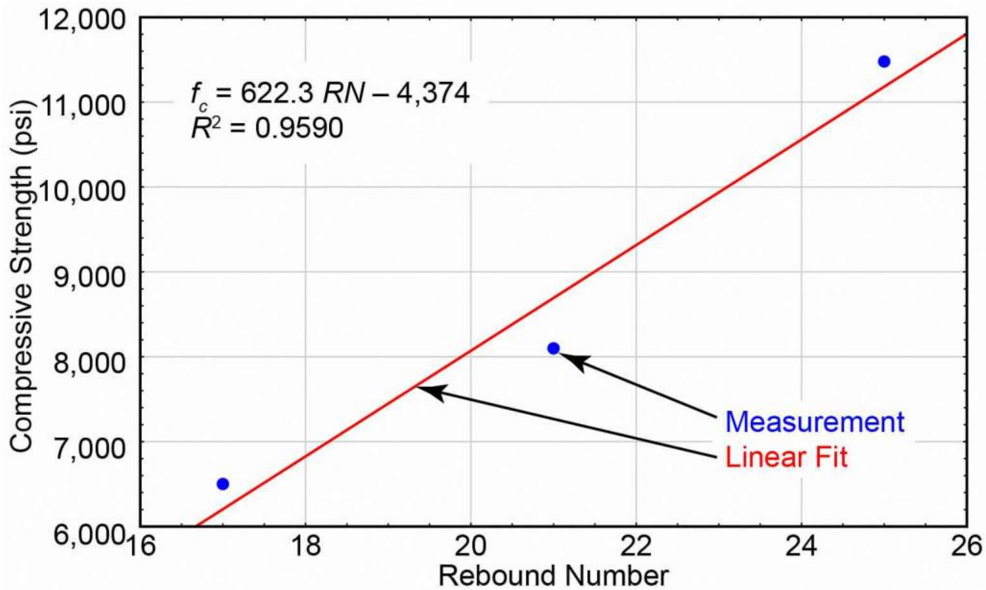

Figure 23. Compressive strength correlated with rebound number

As this study concluded with only 3 data points, further research study was aimed to get more data points with different range of strengths. This idea has given motivation to cast new batch of samples and test all of them after curing periods of 28- days.

5.3 Effect of moisture content on UPV and RH test results

A new batch of concrete samples were casted based on Mix-2 to achieve the compressive strength of 8000 psi. UPV, RH and compressive strength tests were performed on 3 samples after each curing period of 7-, 15-, and 28- days. This concrete batch was targeted to attain compressive strength of 8000 psi. The detailed explanation of procedure followed in this experimental study is given in the section 4.4 of this document. The results obtained from UPV, RH, and compressive strength tests at every stage of study are presented in Table 7.

Table 7. Results from every stage of study on effect of moisture content

	Sample	Drying Condition	UPV (m/s)	Rebound Number	Compressive Strength (psi)
7- Day	Sample- 3	Surface dried	4907	18	6691
	Sample- 2	Oven (24- hours)	4920	23	7135
	Sample- 6	Oven (48- hours)	4933	24	7331
15- Day	Sample- 1	Surface dried	5029	20	7325
	Sample- 5	Oven (24- hours)	5000	25	7246
	Sample- 9	Oven (48- hours)	4947	25	7568
28- Day	Sample- 4	Surface dried	5069	21	8161
	Sample- 7	Oven (24- hours)	4919	25	7762
	Sample- 8	Oven (48- hours)	4912	28	7808

The results from 7, 15, and 28 day tests show that there is a significant effect of selected drying procedure on the Rebound hammer measurements. It is observed from the results that the moisture content in the sample leads to decrease in the rebound number. There was a slight increase in the UPV measurements taken during 7- day tests. But the UPV measurements from 15 and 28 day tests have shown a decreasing trend when compared among the surface dried and other two oven dried samples. Therefore, slight decrease in the UPV values have been observed if the moisture content is reduced. The compressive strength results from 28-day tests show that we have been successful in achieving the targeted strength of 8000 psi. The primary purpose of this study was to determine the effect of moisture in the concrete samples on the UPV measurements. The results do not show a conclusive relationship between the presence of moisture and UPV. The change (increase) in the RH values and any change in the compression strength may have been impacted by the drying temperature. Therefore, changes in the RH values and compressive strengths are more reliable when the concrete samples are cured and tested under the conventional conditions.

5.4 Combined NDT correlation curve

The experimental study has been conducted on 54 concrete cylinders with three different range of compressive strengths. After a standard curing period of 28 days, UPV, RH, and compressive strength tests were performed on all of the samples from different batches. The compressive strength is presented by averaging the strength values obtained by 18 samples for each type of mix (Table 8 summarizes compressive strength results). Our experimental results indicated that Mix-1(6000 psi) had an average compressive strength of 43.5 MPa (6308 psi), Mix-2 (8000 psi) had an average compressive strength of 61.2 MPa (8871 psi), and Mix-3 (12000 psi) had an average compressive strength of 75.4 MPa (10942 psi). The test results of Mix-1 and Mix-2 have exceeded their targeted strength at 28 days. Mix-3, however, did not reach the targeted strength of 83 MPa but stopped at 75.4 MPa.

Table 8. Summary of an average compressive strength of concrete cylinders

Mix	Targeted Compressive Strength		Average Compressive Strength Obtained	
	MPa	psi	psi	MPa
Mix-1	41	6000	6308	43.5
Mix-2	55	8000	8871	61.2
Mix-3	83	12000	10942	75.4

UPV and RH tests were the nondestructive tests performed on concrete cylinders from three different mixes. All these measurements were performed in accordance with relevant standards - ASTM C597 [4] for UPV test and ASTM C805 [7] for RH test. The results obtained from UPV, RH, and compressive strength tests performed on Mix-2 and d Mix-3 are summarized in Table 9.

Longitudinal (p-wave) velocities of the concrete cylinders, across different mixes, were measured during this study. The average values of UPV and rebound numbers measured for samples of Mix-1 are 4919 m/s and 20 respectively. The UPV values obtained from all samples of Mix-1 were higher than expected. The reason for this was found to be higher density of the samples. As samples from Mix-1 have been targeted to achieve conventional strength. The UPV values for conventional strength concrete are usually lesser than high strength concrete. Statistical analysis performed to obtain the relation between UPV and compressive strength did not show good fit when UPV values from Mix-1 are included. To obtain a better fit and relation between UPV and compressive strength the Mix-1 values are not considered for analysis.

The average values of UPV measured from all samples of Mix-2 and Mix-3 were 4950 m/s and 4849 m/s respectively. The UPV values ranged from 4800 – 5000 m/s, for samples with compressive strength ranging from 8000 – 12000 psi. The relatively high UPV values are due to the higher densities in high strength concrete. The relationship between measured UPV values and compressive strength, shown in Eq. (5-3), was obtained and illustrated in Figure 24. The R^2 fit value, adjusted for degrees of freedom, was 68.3%, with errors up to ~10%.

$$Y_1 = 87020 - 15.739\ (X_1) \tag{5-3}$$

where Y_1 is predicted compressive strength (psi) and X_1 is longitudinal UPV (m/s).

Table 9. Experimental results from UPV, RH, and compressive strength tests

Mix (Design Strength)	Batch	UPV (m/s)	Rebound Number	Measured Compressive Strength	
				psi	MPa
Mix-2 (8000 psi)	Batch-1	4926	21	8667	59.8
		4975	22	8538	58.9
		4975	21	9150	63.1
		4927	21	8740	60.3
		4926	22	8768	60.5
		4976	21	8283	57.1
		4939	22	8585	59.2
		4939	23	8958	61.8
		4951	22	8811	60.7
		4950	22	9256	63.8
	Batch-2	4927	22	9043	62.3
		4951	22	9055	62.4
		4903	21	8883	61.2
		4988	22	9306	64.2
		4951	21	8404	57.9
		4988	23	9151	63.1
		4975	23	9354	64.5
		4939	23	8725	60.2
Mix – 3 (12000 psi)	Batch -1	4819	28	10667	73.5
		4902	26	10697	73.8
		4831	28	11529	79.5
		4819	27	11063	76.3
		4879	28	11373	78.4
		4832	28	11339	78.2
		4821	26	11136	76.8
		4832	26	10192	70.3
		4843	27	10741	74.1
	Batch - 2	4879	27	10882	75.0
		4831	27	10869	74.9
		4832	26	10487	72.3
		4819	29	11063	76.3
		4878	28	11207	77.3
		4832	27	10892	75.1
		4854	27	10769	74.2
		4867	28	10957	75.5
		4903	28	11097	76.5

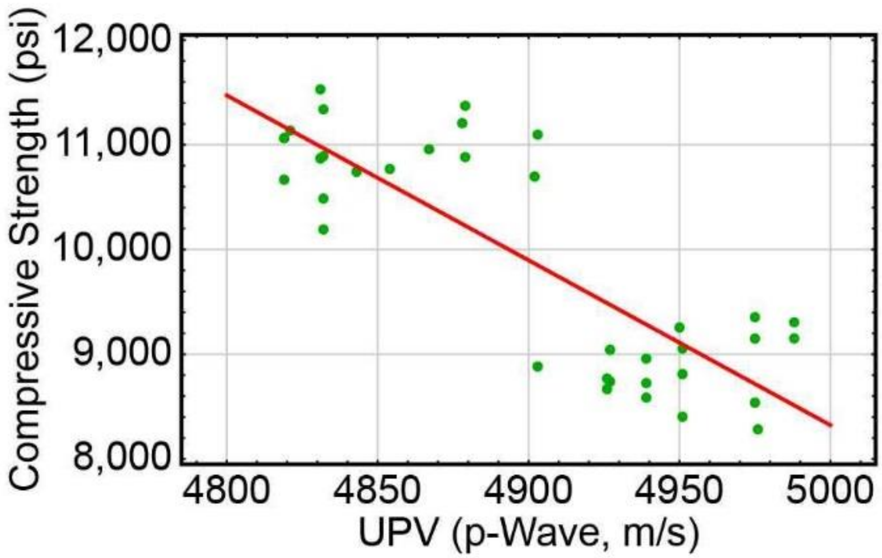

Figure 24. Relation between measured compressive strength and UPV values

The average values of rebound number measured from all samples of Mix-2 and Mix-3 were 22 and 27 respectively. The rebound number values ranged from 20 – 30, for samples with compressive strength ranging from 8000 – 12000 psi. The relatively high rebound number values are due to the higher surface hardness for high strength concrete samples. The relationship between rebound numbers and measured compressive strength was obtained and illustrated in Figure 25. The equation to predict the compressive strength from rebound number, shown in Eq. (5-4), was found. The R^2 fit value, adjusted for degrees of freedom, was 92.3%.

$$Y_2 = 369.91\ (X_2) + 812.81 \qquad (5\text{-}4)$$

where Y_2 is predicted compressive strength (psi) and X_2 is measured rebound number.

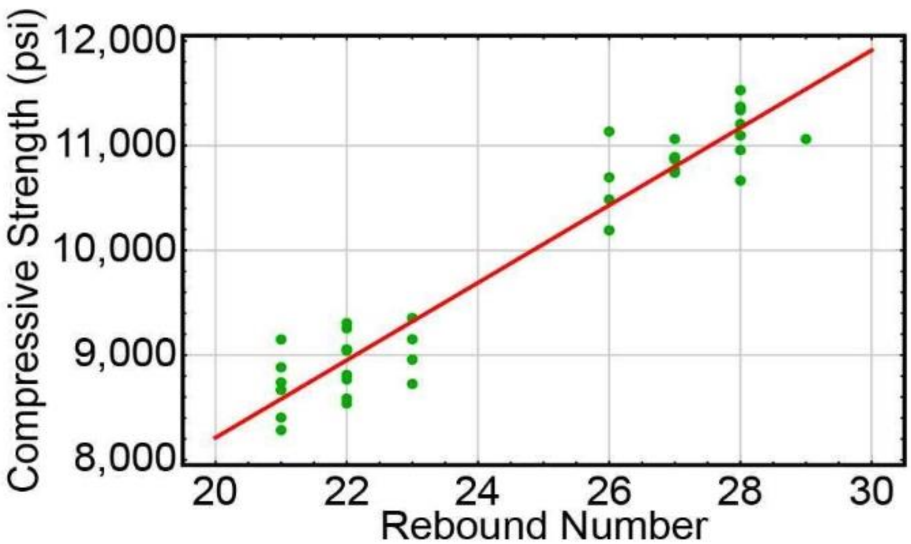

Figure 25. Relation between measured compressive strength and rebound number

A correlation was developed by performing multiple regression analyses using spreadsheet. A bi-linear equation was developed considering UPV and rebound numbers as independent variables and estimated compressive strength as the dependent variable. A nomogram (Figure 26) was developed by plotting the curves between rebound numbers and estimated compressive strengths at different UPV values ranging from 4800 – 5000 m/s. The R^2 value of the bivariate fit is 92.4%, better than the fit either UPV or RH alone and the fit errors are ~3%. A significant improvement was achieved by combining the UPV and RH values to estimate the compressive strength, shown in Eq. (5-5).

$$Y = 3.97\ (V) + 599.11\ (R) - 24565.65 \qquad (5\text{-}5)$$

where *Y* is the estimated compressive strength (psi), *V* is the longitudinal ultrasonic pulse velocity measured (m/s), and is the rebound number (R) measured.

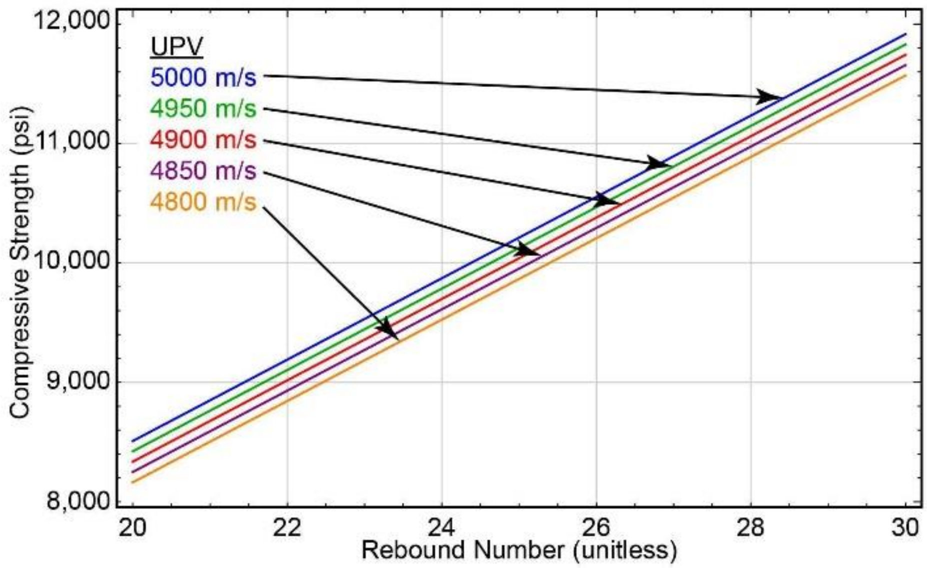

Figure 26. Combined NDT Correlation curve to estimate compressive strength of concrete

Plotting this in 3D (Figure 27), it can be seen that while the strength is modeled as linear in both UPV and RH, the variation with RH is much greater than that with UPV over the range of measurements considered.

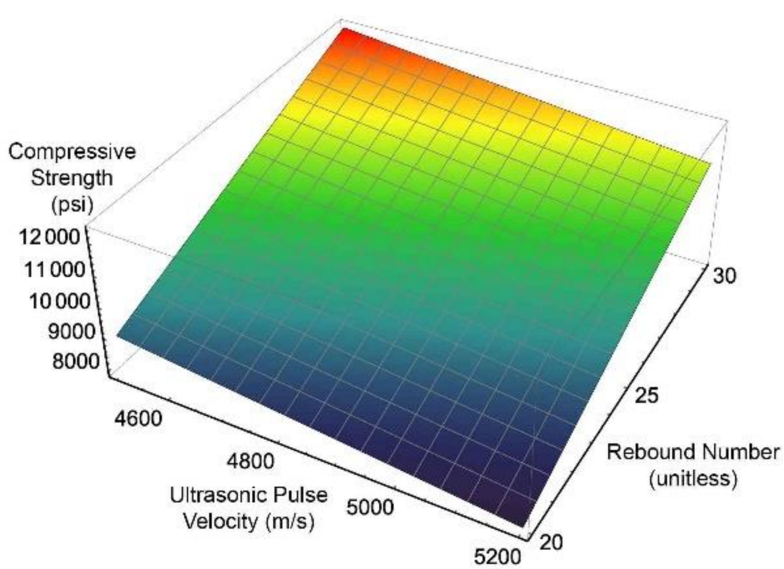

Figure 27. 3-D fit to predict compressive strength of concrete with UPV and rebound number

5.5 Determination of dynamic material properties

Shear wave velocities of the samples from all the batches from three mixes mentioned in section 5.4 were measured using ultrasonic shear wave transducers. These shear wave velocities and longitudinal velocities (section 5.4) were combined to calculate the dynamic modulus of elasticity and dynamic Poisson's ratio using the relations mentions in Eq. (2-4) and Eq. (2-6). Density of the samples was calculating using the measure length and weight before testing. The dynamic modulus of elasticity and dynamic Poisson's ratio calculated for all the samples from Mix-1 are shown in Table 5.7.

Table 10. Dynamic material properties of concrete samples from Mix-1

Mix	Batch	P-wave (m/s)	S-wave (m/s)	Density (kg/m3)	Dynamic - E (GPa)	Dynamic-*v*
Mix-1 (6000 psi)	Batch-1	4963	2466	2377	38.6	0.34
		4890	2451	2400	38.4	0.33
		4975	2463	2407	39.1	0.34
		4963	2454	2401	38.7	0.34
		4866	2415	2354	36.7	0.34
		4963	2440	2369	37.8	0.34
		4843	2428	2354	37.0	0.33
		4890	2451	2398	38.4	0.33
		4963	2463	2416	39.2	0.34
	Batch-2	4987	2448	2403	38.6	0.34
		4938	2451	2384	38.3	0.34
		4988	2445	2395	38.4	0.34
		4963	2503	2399	40.0	0.33
		4866	2424	2395	37.6	0.33
		4832	2457	2369	37.9	0.33
		4902	2436	2363	37.5	0.34
		4809	2445	2357	37.4	0.33
		4938	2469	2402	39.1	0.33

5.6 Investigation of relation between dynamic and static modulus of elasticity

Concrete is a composite material with many different constituents in it. Concrete behaves as an elastic material when stress is applied for short period of time, but the behavior of concrete is complex when subjected to higher loads.

Modulus of elasticity is a used to calculate the deflection and strain of concrete for many structural design applications. Modulus of elasticity is considered as the slope of stress strain curve. It can also be referred as Young's modulus but it is limited only to linear region of stress-strain curve. A good amount of knowledge on stress-strain curve of concrete is required to determine different modulus of elasticity of concrete. The stress-strain relations very from different materials and is explained below.

The material is said to be pure elastic if the strain appears and disappears up on application and removal of stress. Different materials exhibit different elastic behavior. Pure elastic can be divided in to a) linear and elastic b) non-linear and elastic. Similarly non-elastic materials also exhibit two different behaviors namely c) linear and non-elastic d) non-linear and non-elastic [35]. These stress strain curves for above mentioned behaviors are illustrated in Figure 28. The main difference in behavior between pure elastic and non-elastic materials is, the loading and unloading curves coincide for pure elastic and non-elastic materials have different loading and unloading curves. Concrete exhibits the non-linear and non-elastic behavior as illustrated in Figure 28. (d).

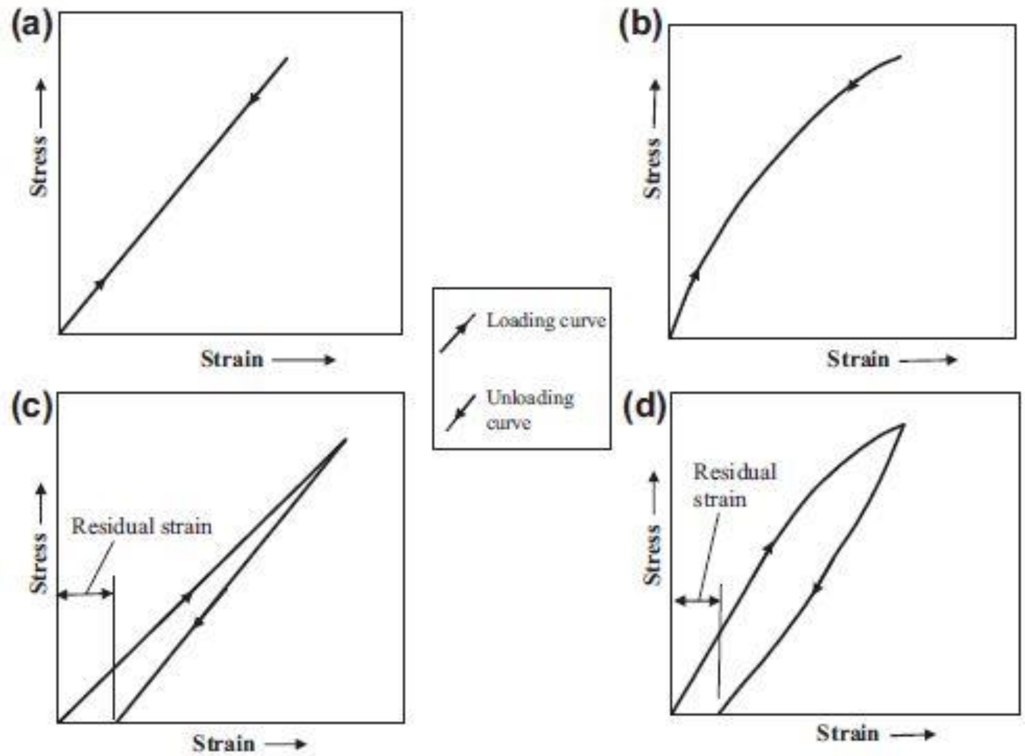

Figure 28. Stress –strain relations a) Liner and elastic b) Linear and non-elastic
c) Non-linear and elastic d) Non-Linear and non-elastic

There are several methods to determine modulus of elasticity of concrete and are explained using the Figure 29. The tangent to the loading stress-strain curve at zero near the origin is called 'initial tangent modulus of elasticity'. This initial tangent modulus (E_{to}) is approximately equal to 'dynamic modulus of elasticity (E_d)'. Where dynamic modulus of elasticity is determined by vibrating the concrete specimen at high frequency (like UPV method). Dynamic modulus of elasticity represents the pure elastic effects since there is only small amount of stress applied and there is no micro-cracking [35].

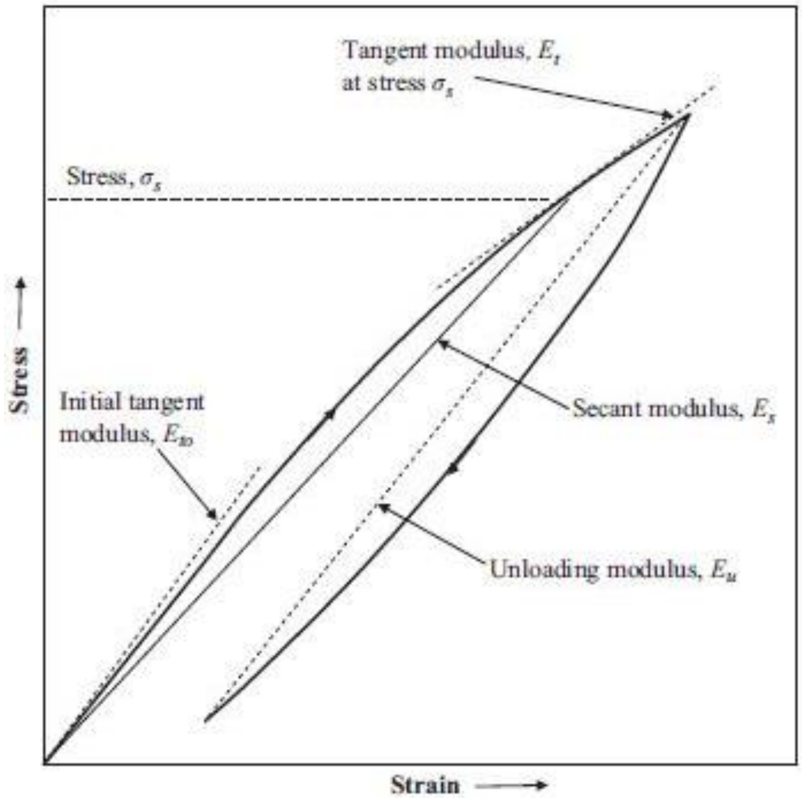

Figure 29. Generalized stress-strain curve for concrete

The strain response after applying specific stress (σ_s) is given by the 'secant modulus of elasticity' (E_s) and this is also called as 'static modulus of elasticity'. The stress and strain during decreasing load or unloading is given by 'unloading modulus' (E_u).

Static modulus of elasticity is determined by the loading and unloading the cylindrical specimen of 150 × 300 mm cylinder/prism at a constant rate according to the respective standards (like ASTM C 469 or BS 1881-121). Where dynamic modulus of elasticity is determined by ASTM C215 [36] standard. According to this standard, the resonant frequency is determined by subjecting the concrete specimen to high frequency longitudinal vibrations. These vibrations are propagated through specimen by using an electromagnet exciter on one end and pick up transducer at the other end. The sample is clamped at its midpoint as illustrated in Figure 30.

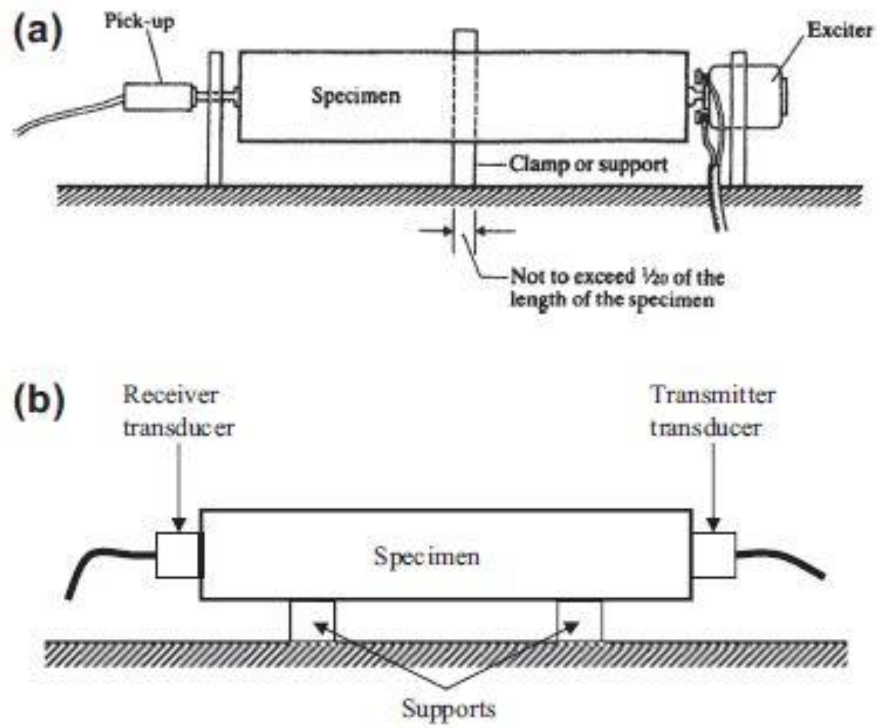

Figure 30. Measurement of dynamic modulus of elasticity a) Dynamic modulus test setup b) Ultrasonic pulse velocity test setup

Resonance frequency of concrete specimen under testing is determined when the amplitude reaches maximum. The frequency at this amplitude is considered as n (Hz), and length of the specimen as L (m), density as ρ (kg/m^3), and acceleration due to gravity as g (m/s^2). Then the dynamic modulus of elasticity(E_u) is calculated by Eq. (5-6).

$$E_d = 4n^2L^2\frac{\rho}{g} \tag{5-6}$$

This test apparatus is limited to laboratory purpose only, the dynamic modulus of elasticity of concrete can also be determined by ultrasonic pulse velocity (UPV) method (refer section 4.3.1) according to ASTM C 597 standard [4].

As the dynamic modulus is approximately equal to tangent modulus of elasticity (E_d), it is always greater than the secant or static modulus of elasticity (E_c) due to the shape of stress-strain curve [36] which is formed due to non-linear behavior of concrete. But the relation between E_c and E_d is not always linear because many factors like age of concrete would increase the strength which results in higher ratio of $E_c$and E_d. According the British standard, BS 8112-2, the relation between $E_c$and E_d is given as:

$$E_c = 1.25\ E_d - 19 \tag{5-7}$$

This relation shown in Eq. (5-7) is not applicable to concrete containing a cement content of more than 500 kg/m^3, in this case the relation was given as:

$$E_c = 1.04\ E_d - 4.1 \tag{5-8}$$

Several attempted to empirically correlate $E_c$and E_d for concrete. Lydon and Balendran [37] have proposed the relation as:

$$E_c = 0.83\ E_d \tag{5-9}$$

Popovics et al. [38] has conducted a study on range concrete cylinder and beam samples along with the data matrix from over 200 high strength concrete samples. The samples were tested with resonance frequency (vibration method) method and ultrasonic pulse velocity (propagation method) method. This study aimed to obtain better understanding of dynamic methods to determine E_d and its relation with E_c. This research group has performed same tests on cylinder and beam samples made of aluminum. The material properties of aluminum were evaluated using the above mentioned ultrasonic and resonance frequency method. The longitudinal vibration method has underestimated the actual value whereas transverse vibrations has overestimated the value. Dynamic test methods performed on concrete specimens confirmed that UPV method gives best prediction among other methods employed. Also, $E_d$is always higher than E_c because of the composite behavior, rather than the non-linear behavior of concrete at various strain levels.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings from this research conducted on concrete samples using two different nondestructive tests and a destructive test. The conclusions drawn from this research and the recommendations for future works in this research field were provided.

The research was conducted to assess the material properties of concrete using combination of two NDT methods. The fabrication of concrete specimens (4 × 8 inches) with normal strength to high strength (6000 psi, 8000 psi, and 12000 psi) made the developed correlations applicable to wide range concrete specimens. The preliminary fabrication of samples has confirmed that the concrete design mix is successful to reach the targeted strength.

Initial testing on concrete samples at different curing periods was performed to understand the testing methods clearly. It was found that the surface roughness and moisture content of the concrete samples affect the measurements made from UPV and rebound hammer tests. Effect of surface roughness was eliminated by cutting the samples by ¼ inch on both sides. Later, instead of cutting the sample, the surfaces were grinded using the concrete grinder to achieve smoother surface for maximum contact with transducer.

During this initial testing, regression analysis was performed on the results obtained from UPV tests and RH tests on 3 samples after 28 days curing period. The individual correlations between UPV, rebound numbers with compressive strength have shown better fits and these results motivated to fabricate new batch of samples for further research.

Six new batches of concrete samples with three different mixes were casted and tested after a curing period of 28 days. This study was conducted mainly to get more data points to develop a correlation with better fit. Regression analysis was performed using the data from Mix

-2 and Mix -3 samples to predict the compressive strength from UPV and from rebound numbers alone. The R^2 fit values, adjusted for degrees of freedom, were 68.3% from UPV and 92.3% from RH, with errors up to ~10%. Both the UPV and RH results were combined to perform multiple regression analyses and a combined NDT correlation has been developed. This combined NDT correlation showed the R^2 value of the bivariate fit as 92.4% better than the fit either UPV or RH. A nomogram was developed using this correlation which is more accurate with only 3% errors.

Study conducted on a batch of samples with Mix-2 design. These samples were tested to study the effect of moisture condition. The results have shown that there is significant change in rebound numbers and the value increased as the moisture content is reduced. Whereas UPV values did not show conclusive relation with presence of moisture condition.

The study was conducted to refer to other research papers to find the relationship between dynamic modulus of concrete and static modulus of concrete. It is observed that dynamic modulus of elasticity is always greater than static modus of elasticity due to the non-linear behavior of concrete during stress-strain curves. A research conducted by a group of 3 people concluded that it is composite nature of concrete rather than the non-linear behavior of concrete at various strain deformations.

Recommendations for future work could be implementing UPV, RH and any other NDT method to completely characterize the material properties of concrete. It is recommended to make sure that the sample surface is smooth in order to eliminate errors in UPV measurements. It is recommended to know the effect of other factors like age of concrete, aggregate size, and admixture on any NDT measurements.

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APPENDICES

APPENDIX A

UPV tests on samples of different shapes and sizes

A study was conducted to verify if the different shapes and sizes of the specimen affect the ultrasonic pulse velocity measurements. In order to study this a new batch of concrete samples with Mix-1 (6000 psi) was prepared. This batch of samples consisted of 4 different samples with different shapes and sizes. Out of 4 samples, 2 concrete cylinders with dimensions of 6 × 12 inches, one concrete cylinder with dimensions of 4 × 8 inches, and one beam samples with L×W×D dimensions of 16×4.25×3 inches were casted. These samples are shown in Figure 31.

Figure 31. Concrete samples with different shapes and sizes

As all of these samples are casted from same mix of concrete, it is expected to show the same UPV values if the shape and size has no effect on the measurements. All of the samples were taken out of immersion tank after a 7-day curing period and then UPV test was performed.

The UPV measurements were made using a pair of longitudinal transducers with frequency of 54 kHz. The equipment was calibrated using the zeroing block, before performing the measurements. The UPV test was then performed using the direct transmission method and the test results are shown in Table 11.

Table 11. Results from UPV (P-wave) tests on samples with different shape and size

Shape	Dimensions (inches)	Sample	UPV- P wave (m/s)
Cylinder	4 × 8	Sample 1	4695
	4 × 8	Sample 2	4654
Cylinder	6 × 12	Sample 3	4680
Beam	16×4.25×3	Sample 4	4629

The results shown in Table A-1 show that all the UPV (P-wave) velocities are almost same and thus it is verified that the shape or dimensions of the specimen do not vary the UPV measurements. This implies that UPV testing can be used for in-situ measurements to evaluate specimens of different shapes or size, provided if they are from same concrete mix.

APPENDIX B

UPV P-wave and S-wave measurements using Proceq PUNDIT PL-200

P- wave and S-wave velocity measurements were made on samples from a batch of 6000 psi mix. Proceq PUNDIT – PL 200 equipment is capable of storing the results while performing tests. These test results can be retrieved by connecting the equipment to computer. The following Figures 31 and 32 shown are set of P-wave and S-wave measurements taken on samples (1 &2) from batch-1 of 6000 psi.

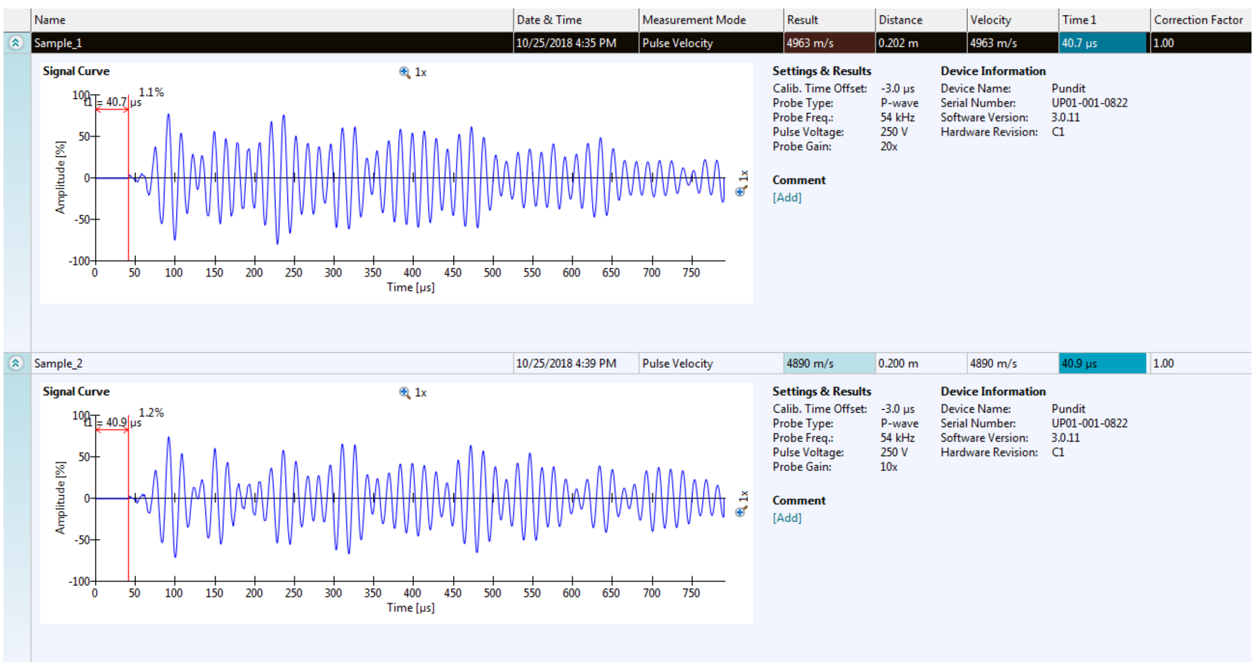

Figure 32. P-wave velocity measurements on Sample (1 & 2) from batch-1 of 6000 psi

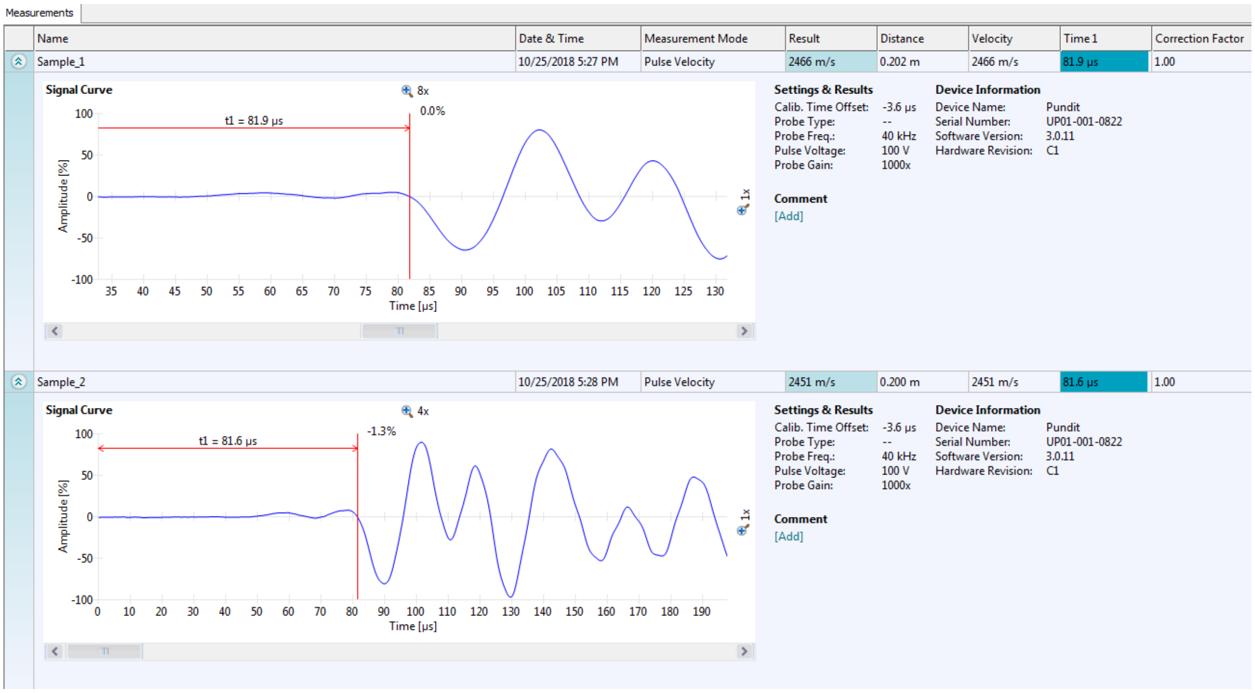

Figure 33. S-wave velocity measurements on Sample (1 & 2) from batch-1 of 6000 psi

APPENDIX C

Concrete Mix design specifications

There are three different mix designs used for preparing the concrete samples. These mix designs were prepared to meet the strength of 6000 psi and 8000 psi. The below shown Tables provide information on all the constituents used and their weight specifications according for each different type of mix.

Table 12. Mix design specifications for 6000 psi samples

Mixture Designation: NCAMK0%SK0% **Mix-1**: 6000psi **w/c ratio**: 0.5

	For 1 yd^3		For Reqd. Batch Size	
	Weight (lb)	**Volume ft^3**	**Weight (lb)**	**Weight (gram)**
Portland Cement	564.00	2.869	12.53	
Fly Ash	0.00	0.000	0.00	
Coarse Aggregate	1502.89	8.978	33.40	
Natural Fine Aggregate	1618.52	10.363	35.97	
Bottom Ash	0.00	0.000	0.00	
FBC Ash	0.00	0.000	0.00	
Water	296.09	4.519	6.58	
Air Content	0.00	0.270	0.00	
Metakaolin	0.00	0.000	0.00	
Silica fume	0.00	0.000	0.00	
High Range Water Reducer	0.00	0.00	0.00	0.00
High Range Water Reducer	0.00	0.00	0.00	0.00
Air Entrainment Admixture	0.00	0.00	0.00	0.00
Batch Total	**3981.50**	**27.00**	**88.48**	

Table 13. Mix design specifications for 8000 psi samples

Mixture Designation: NCAMK0%SK5% **Mix-2**: 8000psi **w/c ratio**: 0.4

	For 1 yd^3		For Reqd. Batch Size	
	Weight (lb)	**Volume ft^3**	**Weight (lb)**	**Weight (gram)**
Portland Cement	724.38	3.685	16.10	
Fly Ash	0.27	0.000	0.01	
Coarse Aggregate	1502.89	8.978	33.40	
Natural Fine Aggregate	1388.68	8.891	30.86	
Bottom Ash	0.00	0.000	0.00	
FBC Ash	0.00	0.000	0.00	
Water	317.02	4.859	7.04	
Air Content	0.00	0.270	0.00	
Metakaolin	0.00	0.000	0.00	
Silica fume	38.13	0.268	0.85	
High Range Water Reducer	3.57	0.05	0.08	36.06
High Range Water Reducer	0.00	0.00	0.00	0.00
Air Entrainment Admixture	0.00	0.00	0.00	0.00
Batch Total	**3933.24**	**27.00**	**87.41**	

VITA

Graduate School
Southern Illinois University

Abhishek Chitti

Abhishekchitti16@gmail.com

Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya University, Tamilnadu, India
Bachelor of Engineering, Mechanical Engineering, May 2016

Thesis Paper Title:
Assess Material Properties of Concrete Using Combined NDT Methods

Major Professor: Dr. Tsuchin Philip Chu