GUIDED WAVES FOR MONITORING SETTING OF CONVENTIONAL AND NON- VIBRATED CONCRETE

A thesis report submitted in the partial fulfillment

of the requirement for the award of the degree

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IN
STRUCTURES

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DECLARATION

I hereby declare that the work which is presented in this thesis report entitled **"GUIDED WAVES FOR MONITORING SETTING OF CONVENTIONAL AND NON-VIBRATED CONCRETE"** in partial fulfillment of requirements for the award of the **MASTERS DEGREE IN STRUCTURES,** submitted in the **Civil Engineering Department, Thapar University, Patiala,** is an authentic record of the initial research carried out by him under the supervision of **Dr. Abhijit Mukherjee, Director, Thapar University, Patiala** and **Dr. Shruti Sharma, Assistant Prof., Civil Engineering Department, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

At early ages of concrete structures, strength monitoring is important to determine the structure's readiness for service. Concrete setting and hardening process are the most critical phases during construction works, influencing to properties of concrete structure, so the application of efficiency non-destructive test methods for early age concrete properties determination is crucial.

In this study, apart from standardized methods like Penetartion Vicat methods to study the setting of concrete, ultrasonic pulse velocity and suitability of ultrasonic guided waves methods for young concrete characterization is also explored. In ultrasonic method, guided wave is transmitted and received through a waveguide that is embedded in early age concrete. As the cementitious material sets and hardens, the strength of the received waves changes, indicating the transition from semi-fluid to solid state. This thesis proposes to use pulse transmission and pulse echo systems for monitoring setting and hardening phase change in conventional and self compacting concrete.This approach monitors the attenuation of the fundamental guided longitudinal wave mode, resulting from the leakage of energy from the cylindrical steel rod to the surrounding cementitious material. The evolution of the material's properties is related to the energy leakage or attenuation of the guided wave.

The use of guided waves for monitoring setting properties of conventionl concrete and non-vibrated (SCC) is presented in this work. The comparision in the setting process of two most commonly used concrete i.e. conventional and non-vibrated concrete is made in the research.

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CHAPTER 1

HEALTH MONITORING USING ULTRASONICS

1.1 INTRODUCTION

In-situ Structural Health Monitoring (SHM) is a key development that is driving a revolution in smart-structures technologies. Promising quantum gains in the performance and cost-effective maintenance of high-value assets such as aircraft, civil infrastructure, and Structural Health Monitoring technology will be an integral component of an increasing number of future engineering structures. The rapid advances that have been made in the past two decades in sensor technology, multifunctional materials and innovative structural concepts are now leading into the practical use of Structural Health Monitoring.

Structural Health Monitoring (SHM) is a highly interdisciplinary area of research focused on developing techniques to detect damage in structures such as buildings, bridges, aircraft, ships and spacecraft. Most Structural Health Monitoring research to date has focused either on global damage assessment techniques using low-resolution measurements of a structure's response to ambient excitation, or on limited independent damage detection mechanisms.

Structural health Monitoring is defined as the acquisition, validation and analysis of technical data to facilitate life cycle management decisions. (Kessler et al. 2002),

Structures are assemblies of load carrying members capable of safely transferring the superimposed loads to the foundations. They are constructed (e.g. buildings, bridges, dams, transmission towers, etc.) or manufactured (e.g. machines, trains, ships, aircraft, etc.) to serve specific functions during their design lives. Each structure forms an integral component of civil, mechanical or aerospace systems. In order to serve their designated functions, the structures must satisfy both strength and serviceability criteria throughout their stipulated design lives. However, with the passage of time, some amount of deterioration and damages are bound to occur, due to a variety of factors; such as environmental degradation, fatigue, excessive loads, and natural calamities or simply due to long endurance combined with intensive usage. Even the best designed structures, constructed from advanced high strength materials, are not 100% immune from damage.

To ensure structural integrity and hence maintain safety, in service health and usage monitoring techniques are employed in many engineering areas. Structural health is directly related to structural performance and in this respect it is one of the major parameter with regard to safety operation. This aspect of structural health is particularly relevant to civil structures. A number of different definitions can be proposed to describe **damage, health** and **monitoring** of structure. Intuitively, **health** is the ability to function /perform and maintain the structural integrity throughout the entire lifetime of the structure, **monitoring** is the process of diagnosis and prognosis, and **damage** is a material, structural or functional failure. In this context damage detection/monitoring and structural health monitoring have the same meaning.

Structural health Monitoring is a new and exciting field .SHM philosophies should be applied to two families of structural components. Structural health, or equivalent, the state of damage can be established either **directly or indirectly**.

Direct approach: The first approach checks for the damage type (e.g. cracks, corrosion or delamination) by applying an appropriate inspection technique. These techniques, based on physical phenomenon, in fact sometimes also amount to response measurements but in this case they have a very **local and direct** character. The established inspection techniques vary from visual inspection by the naked eye to passing the structure through a fully automated inspection gantry.

Indirect approach: In this approach structural performance or rather structural behaviour is measured and compared with the supposedly known **global** response characteristics of the undamaged structure. If the effect of certain damages on structural response characteristics is known, this approach provides an indirect measure of damage and of structural health.

Obviously in both the direct and indirect approaches the sensitivity and reliability of inspection are important quantitative performance measure. They are determined on the one hand by the laws of physics but on the other hand in practice also by the hardware and software quality of inspection equipment and, last but not least, by the equipment operator: the inspector. Health monitoring and preventive maintenance on large structures will significantly reduce operational costs and increase the lifetime of structures. By enabling early detection of damage, networked SHM systems can promote public safety.

1.2 MOTIVATION FOR SHM

As the field of SHM using NDT to detect damage constitutes important and challenging area of study, where wave propagation provides an efficient means of characterizing defects in structures, the main points which motivated me are as follows;

• Nearly all in-service structures require some form of maintenance for monitoring their integrity and health condition to prolong their lifespan or to prevent catastrophic failure.

• Current schedule-driven inspection and maintenance techniques can be time consuming, labor-intensive and expensive.

• Recent advances in smart structures technologies, sensors and actuators, new diagnostic technologies allows for the detection of damage to both existing and new structures in real time with minimal human involvement as well.

1.3 APPLICATIONS OF SHM

Though there are tremendous amount of fields where structural health monitoring can be utilized but **Fig1.1** shows the most exploited fields.

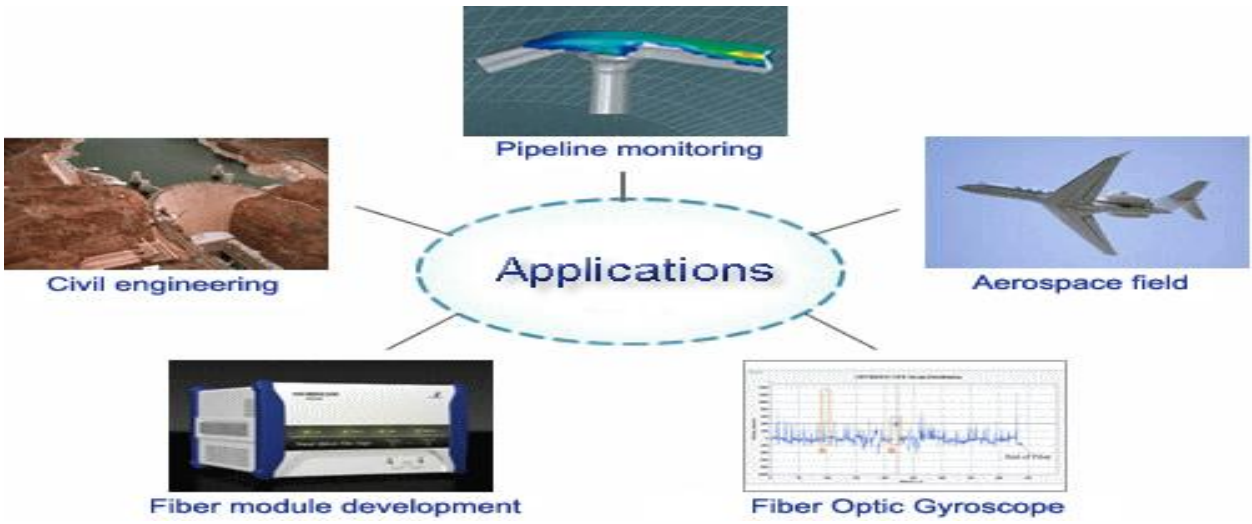


Fig 1.1 Different applications of SHM system (http://www.googleimages.com)

1.4 TECHNIQUES FOR SHM

Structural Health Monitoring (SHM) is estimating the state of structural health, or detecting the changes in structure that affect its performance. Two major factors are:-

- Time-Scale of change (how quickly the change occurs)
- Severity of change (the degree of change)

Two major categories of SHM are:-

- Disaster response (earthquake, explosion, etc.)
- Continuous health monitoring (ambient vibrations, wind, etc.)

This work is focused on continuous health monitoring. There are two different types of techniques are available to assess the health of structure are enlisted below:

Techniques for SHM are given below:

1. Local Techniques
2. Global Techniques

1.4.1 Local Techniques

1.4.1.1 *General*

Structural Health Monitoring is organized around the various sensing techniques used to achieve structural health monitoring. The main emphasis is on sensors, signal and data reduction methods and inverse techniques, allowing the identification of the physical parameters, affected by the presence of the damage, on which diagnostic is established. Structural Health Monitoring is not oriented by the type of applications or linked to special classes of problems, but presents the broader families of techniques: Another category of damage detection methods is formed by the so-called **local methods** based on either visual inspection or different non destructive testing (NDT) methods .Most of the NDT techniques were developed in the early to mid–1960s.

1.4.1.2 *Methods for Local Techniques*

A number of theoretical models and simulation/analytical techniques were developed in 1970s. Some of the methods in this category are shown in **Fig 1.2.**

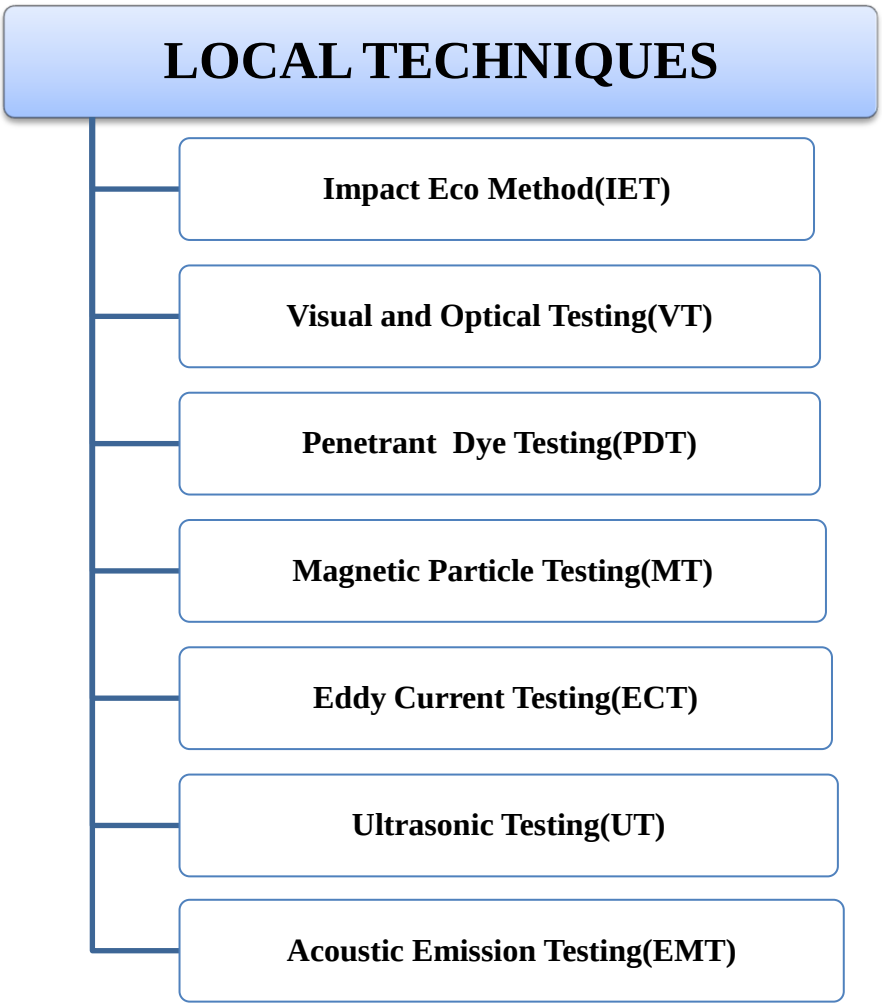


Fig 1.2 Local Techniques

• **Impact Echo Method:** The Impact-Echo method is a stress wave method for flaw detection in structural components which is based on monitoring the surface motion resulting from a short-duration mechanical impact (Carino, 2001). The basic principle of impact-echo technique is introducing a stress pulse into the structure using an impact source such as a hammer or a ball drop. The impact generated stress waves travel between the surface and the defects that may

exist in the structure and the reflected waves are monitored by transducers to detect the delaminations **(Fig 1.3)**.

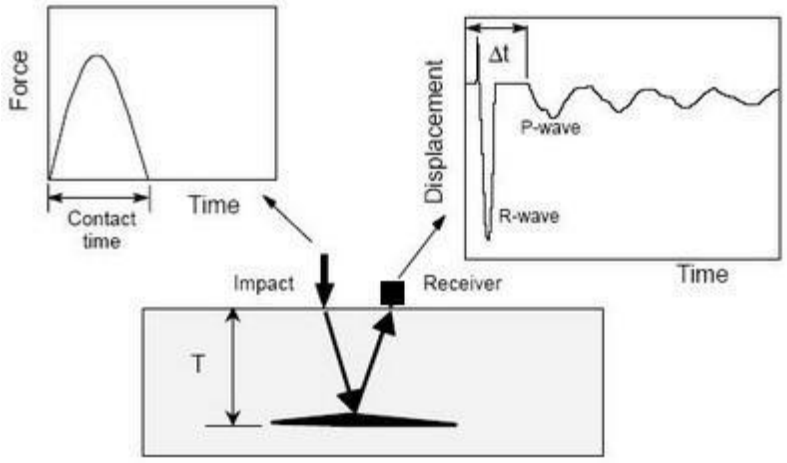


Fig 1.3 Impact echo method

• **Visual and Optical Testing:** Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses or mirrors gain access and more closely inspect the subject area.

• **Penetrant Testing:** The Liquid Penetrant Test (LPT) is one of the earliest forms of NDT methods. This technique is actually is an extension of visual inspection and is used for detecting surface breaking flaws such as cracks on non-absorbent materials by applying colored penetrants. After surface preparation (cleaning, paint removal, etc.), these colored penetrants are applied to the surface by brushing, dipping or spraying, and the excess penetrant is cleaned after enough time for the liquid to penetrate into cracks by capillary action. Then an absorbent developer, such as white dry powder, is applied to the cleaned surface. The developer draws the colored penetrant liquid out by reverse capillary action. The stain that remains on the developer due to the colored penetrant can then be seen by visual inspection as an indication of cracks. Florescent penetrants can be used for higher sensitivity; however, the surface requires to be viewed with ultraviolet (UV) light under darkened conditions.

• **Magnetic Particle Testing (MT):** This technique is based on using magnetic fields and fine magnetic particles, such as iron filings to detect flaws in components. The ferromagnetic material to be tested is first magnetized using an external magnetic field. When there is a crack close to or on the surface, magnetic poles are created at the edges of the crack. The air gap due to the crack cannot support as much magnetic field as the material, and therefore, the magnetic field spreads out (flux leakage). After magnetization, similar to the purpose of the penetrant in LPT, magnetic particles are sprinkled on the surface. These particles are usually in dry or wet suspended form and they can either be a visible type that can be seen in normal white light, or a fluorescent type which requires the use of a black light to be visible. After gently cleaning the excess particles, the ones that are attracted at the flux leakage fields are used as the indications of flaws. The above process and how cracks cause flux leakage is illustrated in **Fig 1.4.**

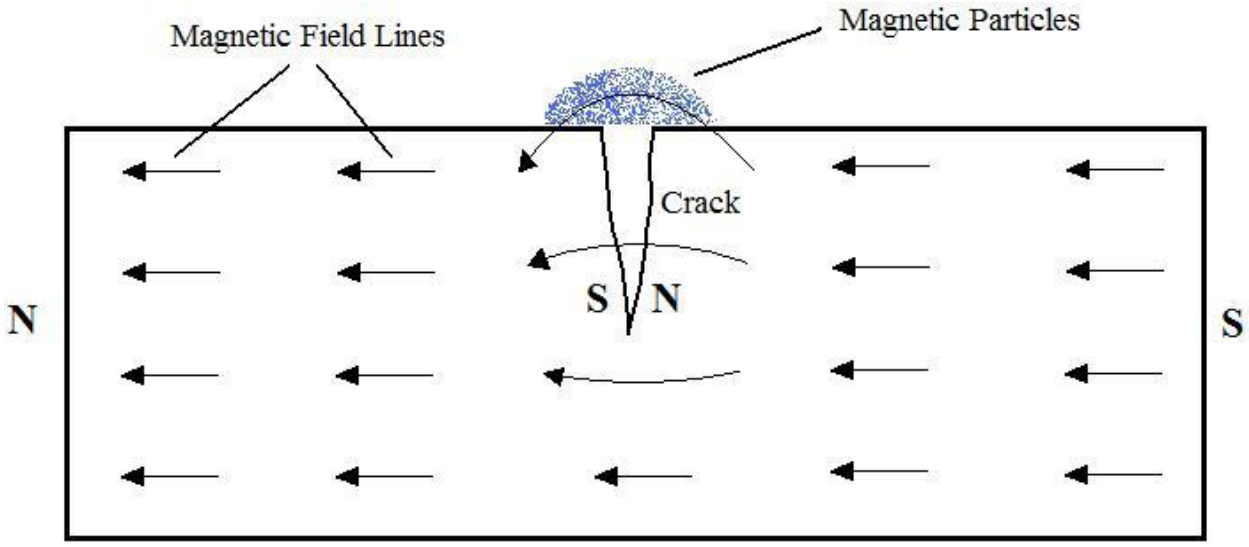


Fig 1.4 Effect of flux leakage in magnetic particle testing (http://www.googleimages.com)

• **Electromagnetic Testing (ET) or Eddy Current Testing:** Eddy currents are generated in a conductive material by an induced alternating magnetic field and they flow in circles at just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties, can be detected with the proper equipment.

• **Ultrasonic Testing (UT):** ultrasonic testing use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces.

• **Acoustic Emission Testing (AE):** when a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." as in ultrasonic testing; acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location.

1.4.2 Global Techniques

1.4.2.1 *General*

The global SHM techniques are using the dynamic characteristics of the structure to identify the damage, its approximate location and its severity, reducing the need for manual inspection. Global techniques are very attractive to civil engineers because they can be used without direct access to structural member and no previous knowledge of damage of structure is needed, reducing the time and cost to assess the damage in structure. These techniques can be further divided into two categories **dynamic** and **static**.

In **global dynamic** techniques, the test-structure is subjected to low-frequency excitations, either harmonic or impulse, and the resulting vibration responses (displacements, velocities or accelerations) are picked up at specified locations along the structure.

1.4.2.2 Techniques for Global Analysi*s*

Numerous techniques have been applied in the literature for health monitoring of structures. Several methodologies are described regarding damage detection based on change in basic modal properties. Investigators who have tried to examine changes in basic modal properties have encountered issues similar to those encountered in the offshore oil industry. In this context basic modal properties are defined as resonant frequencies, modal damping and mode shape vectors. The techniques commonly used for global analysis are as follows;

Techniques for Global analysis

1. Dynamically Measured Flexibility
2. Mode Shape Changes
3. Frequency Changes

4 Inverse Problem Strain Mode Shape Changes.

1.5 USE OF ULTRASONICS FOR NDT

1.5.1 Basic Principle

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below in **Fig 1.5** will be used.

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when echo was received. Signal travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

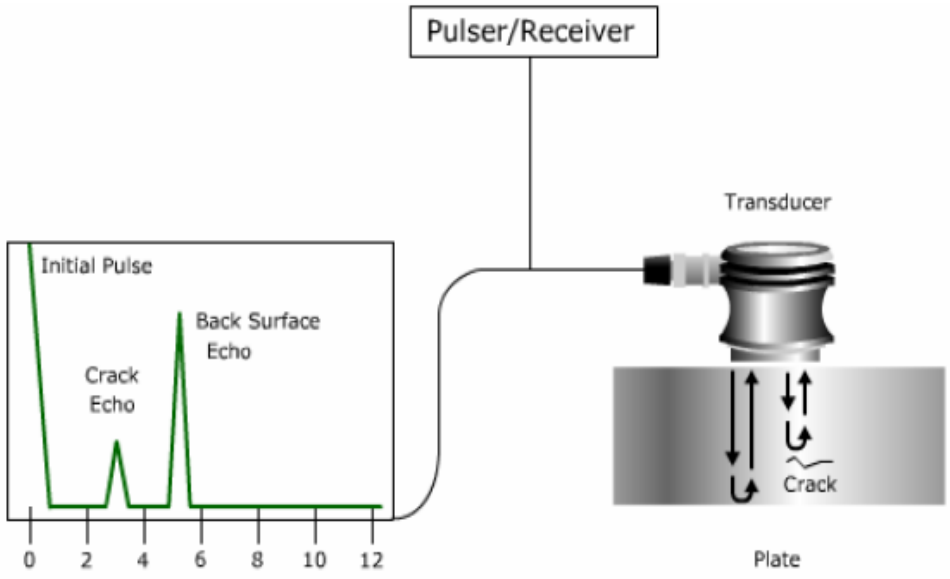


Fig 1.5 General (pulse echo method) ultrasonic Inspection Principle. (http://www.ndt-ed.org)

1.5.2 Piezoelectric Transducers for Ultrasonic Wave Generation

The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material with electrodes attached to two of its opposite faces. When an electric field is applied across the material, as shown in **Fig. 1.6**, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction.

A permanently-polarized material such as quartz (SiO_2) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect.

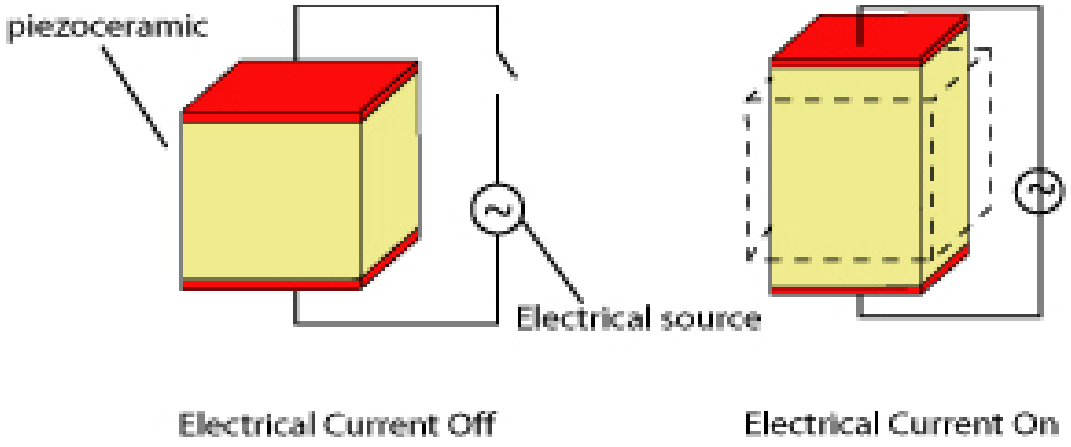


Fig. 1.6 Piezoelectric Crystal with Current Off and On (http://www.googleimages.com)

Main components of Transducer/Probe head as shown in **Fig 1.7** are;

1. Active element
2. Backing material
3. Matching layer

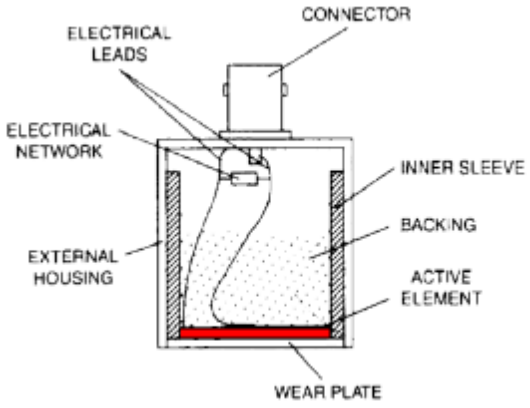


Fig. 1.7 Piezoelectric Transducer (http://www.googleimages.com)

The backing is most commonly a highly attenuative and very dense material and is used to control the vibration of the transducer crystal by absorbing the energy that radiates from the back face of the piezoelectric element. When the acoustic impedance of the backing material matches that of the piezoelectric crystal, the result is a highly damped transducer with excellent resolution. By varying the backing material in order to vary the difference in impedance between

the backing and the piezoelectric crystal, a transducer will suffer somewhat and resolution may be much higher in signal amplitude or sensitivity.

1.5.3 Methods of Ultrasonic Testing

1. Pulse echo method

2. Pulse transmission method

3. Two Transducer Method

1. Pulse echo method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy as shown in **Fig 1.8**. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer where the reflected energy is converted into an electrical signal. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

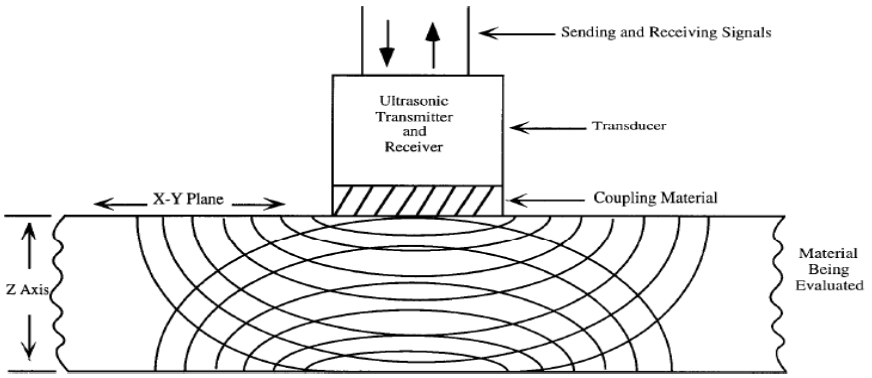


Fig 1.8 Principle of pulse echo method of inspection (Vermani, 2008)

2. Pulse-Transmission Method

In the pulse-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side. One unit acts as transmitter and the other unit as

receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed as shown in **Fig 1.9**. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

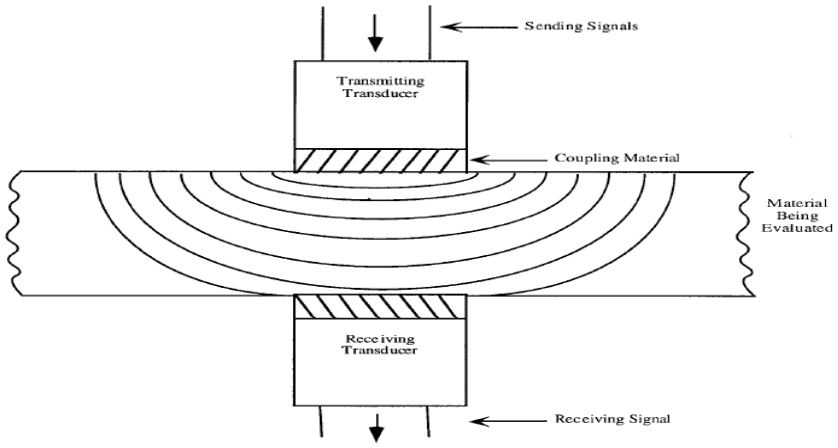


Fig 1.9 Principle of through transmission of ultrasonic testing (Vermani, 2008)

3. Two Transducer Method

The pulse echo method can be used with either single or double crystal unit in single transducer unit the probe acts as both transmitter and receiver .In two transducer arrangement, one transmits and other receives the ultrasonic waves .These are placed on same side of specimen and pulse wave is send in to the specimen by the transducer T (Transmitter) and the echoes reflected from the back surface or any defect are received by the transducer R (Receiver) and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used .These transducers are popularly known as 'twin' or T-R probes. For example, **Fig 1.10** in which two transducers are placed on the same side of the plate at certain angle to detect the damage.

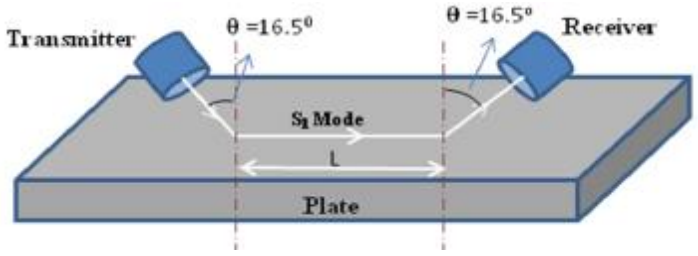


Fig 1.10 Transducers arranged at an angle to the Plate (http://www.googleimages.com)

1.6 ULTRASONIC PULSE VELOCITY (UPV)

The ultrasonic pulse velocity method has been used successfully to evaluate the quality of concrete for more than 60 years. This method can be used for detecting internal cracking and other defects as well as changes in concrete such as deterioration due to aggressive chemical environment and freezing and thawing. By using the pulse velocity method it is also possible to estimate the strength of concrete test specimens and in-place concrete. The pulse velocity method is a truly nondestructive method, as the technique uses mechanical waves resulting in no damage to the concrete element being tested. A test specimen can be tested again and again at the same location, which is useful for monitoring concrete undergoing internal structural changes over a long period of time.

1.6.1 Pulse Velocity Test Instrument

The test instrument consists of a means of producing and introducing a wave pulse into the concrete (pulse generator and transmitter) and a means of sensing the arrival of the pulse (receiver) and accurately measuring the time taken by the pulse to travel through the concrete. The equipment may also be connected to an oscilloscope, or other display device, to observe the nature of the received pulse. A schematic diagram is shown in **Fig 1.11**.

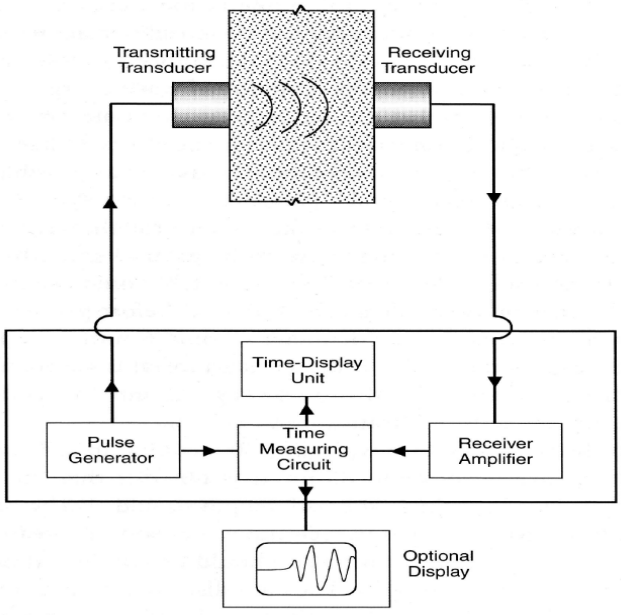


Fig 1.11 Schematic diagram of pulse velocity test circuit (http://www.googleimages.com)

Portable ultrasonic testing units are available worldwide. The equipment is portable, simple to operate, and may include a rechargeable battery and charging unit. Typically, pulse times of up to 6500 μs can be measured with 0.1-μs resolution. The measured travel time is prominently displayed. The instrument comes with a set of two transducers, one each for transmitting and receiving the ultrasonic pulse. Transducers with frequencies of 25 to 100 kHz are usually used for testing concrete. Transducer sets having different resonant frequencies are available for special applications: high-frequency transducers (above 100 kHz) are used for small-size specimens, relatively short path lengths, or high-strength concrete, Where as low-frequency transducers (below 25 kHz) are used for larger specimens and relatively longer path lengths, or concrete with larger size aggregates. These transducers primarily generate compressional waves at predominantly one frequency, with most of the wave energy directed along the axis normal to the transducer face. A commonly used instrument is shown in **Fig 1.12**

Fig1.12 Pulse velocity instrument. (Courtesy of James Instruments, Inc.)

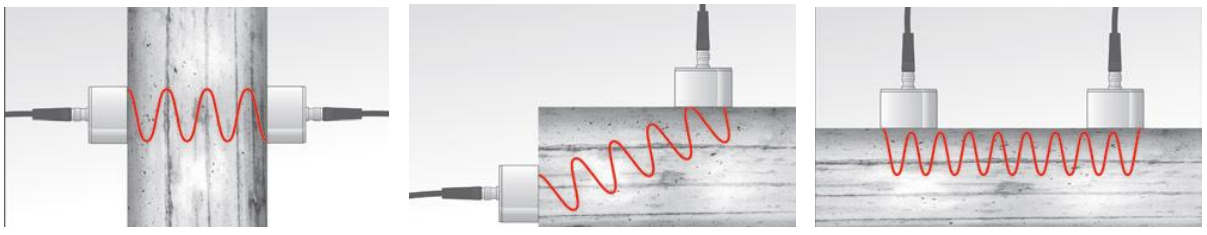
1.6.2 Pulse Velocity Method

The basic idea on which the pulse velocity method is established is that the velocity of a pulse of Compressional waves through a medium depend on the elastic properties and density of the medium.

The transmitting transducer of the pulse velocity instrument transmits a wave into the concrete and the receiving transducer, at a distance *L*, receives the pulse through the concrete at another point. The pulse velocity instrument display indicates the transit time, Δt, it takes for the compressional wave pulse to travel through the concrete. The compressional wave pulse velocity *V*, therefore, is

$$V = \frac{L}{\Delta t} \quad (1)$$

The compressional pulse transmitted through the concrete undergoes scattering at various aggregate– mortar boundaries. By the time the pulse reaches the receiving transducer it becomes transformed into a complex waveform, which contains multiply reflected compressional waves and shear waves. Of course, compression waves traveling the fastest arrive first at the receiver. To transmit or receive the pulse, the transducers must be in full contact with the test object; otherwise an air pocket between the test object and transducer may introduce an error in the indicated transit time. This error is introduced because only a negligible amount of wave energy can be transmitted through air. Many couplants available in the market can be used to eliminate air pockets and to assure good contact; petroleum jelly has proved to be one of the superior couplants. Other couplants are grease, liquid soap, and kaolin-glycerol paste. The couplant layer should be as thin as possible. While applying constant pressure on the transducers, repeated readings at a particular location should be taken until a minimum value of transit time is obtained. The pulse velocity for ordinary concrete is typically 3700 to 4200 m/s. Therefore, for a 300-mm path length, the travel time is approximately 70 to 85 μs. It is obvious that the instrument must be very accurate to measure such a short transit time. The path length should also be carefully measured. Because the pulse velocity method is a wave propagation technique. There are three possible configurations in which the transducers may be arranged, as shown in **Fig1.13 (a) to (c).** These are (1) direct transmission; (2) semidirect transmission; and (3) indirect or surface transmission. The direct transmission method, **Fig 1.13 (a),** is the most desirable and the most satisfactory.



(a) Direct Method **(b) Semidirect Method** **(C) Indirect Method**

Fig 1.13 Ultrasonic pulse velocity testing transmission methods (Randhawa, J. (2011))

Arrangement because maximum energy of the pulse is transmitted and received with this arrangement. The semi direct transmission method, **Fig 1.13(b),** can also be used quite satisfactorily. However, care should be exercised that the transducers are not too far apart;

otherwise the transmitted pulse might attenuate and a pulse signal might not be detected. This method is useful in avoiding concentrations of reinforcements.

The indirect or surface transmission method, **Fig1.13(c),** is least satisfactory because the amplitude of the received signal is significantly lower than that received by the direct transmission method. This method is also more prone to errors and a special procedure may be necessary for determining the pulse velocity.

Advantages and Limitations

The pulse velocity method is an excellent means for investigating the uniformity of concrete. The test procedure is simple and the available equipment in the market is easy to use in the laboratory as well as in the field. The testing procedures have been standardized by ASTM and other organizations, and test equipment is available from several commercial sources. With the availability of small portable digital instruments, which are relatively inexpensive and easy to operate, ultrasonic testing adds a new dimension to quality control of concrete in the field. Ultrasonic pulse velocity tests can be carried out on both laboratory-sized test specimens and concrete structures. This fact, combined with the knowledge that ultrasonic techniques provide an effective means of delineating both surface and internal cracks in concrete structures, enhances the usefulness of these tests. In as much as a large number of variables affect the relations between the strength parameters of concrete and its pulse velocity, the use of the latter to estimate the compressive and/or flexural strengths of concrete is not recommended unless previous correlation testing has been performed.

1.7 CLASSIFICATION OF ULTRASONIC WAVES FOR NDT APPLICATIONS

Ultrasonic waves can be classified in two types depending upon the NDT applications;

- Body waves or bulk waves
- Surface waves or guided waves.

Body waves propagate through a bulk material, hence attenuate, while the surface waves propagate along the surface of a body as shown in **Fig 1.14**. The inspection of large structures using conventional ultrasonic bulk wave (*longitudinal and shear waves)* techniques is slow because scanning is required if the whole structure is to be tested.

Surface waves are often called guided waves because the geometry of the body guides them. Ultrasonic guided waves (*Rayleigh and Lamb waves, bar, plate and cylindrical guided waves)* potentially provide an attractive solution to this problem because they can be excited at one location on the structure and will propagate many meters (Cawley, 2002).

Guided waves refer to mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bounded medium (such as pipe, plate, rod, etc.) parallel to the plane of its boundary.

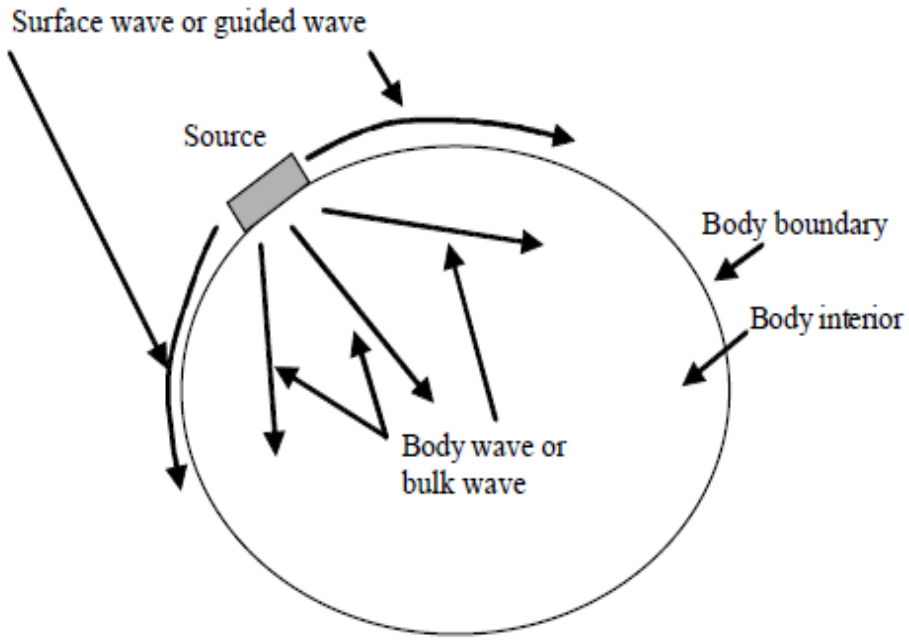


Fig 1.14 Body waves and surface waves generated by an ultrasonic source (Kundu, 2007)

Guided waves can further be classified into following types, as shown in **Fig 1.15**

• Bar waves

• Cylindrical wave

• Rayleigh waves

• Lamb waves

• Rayleigh-Lamb waves

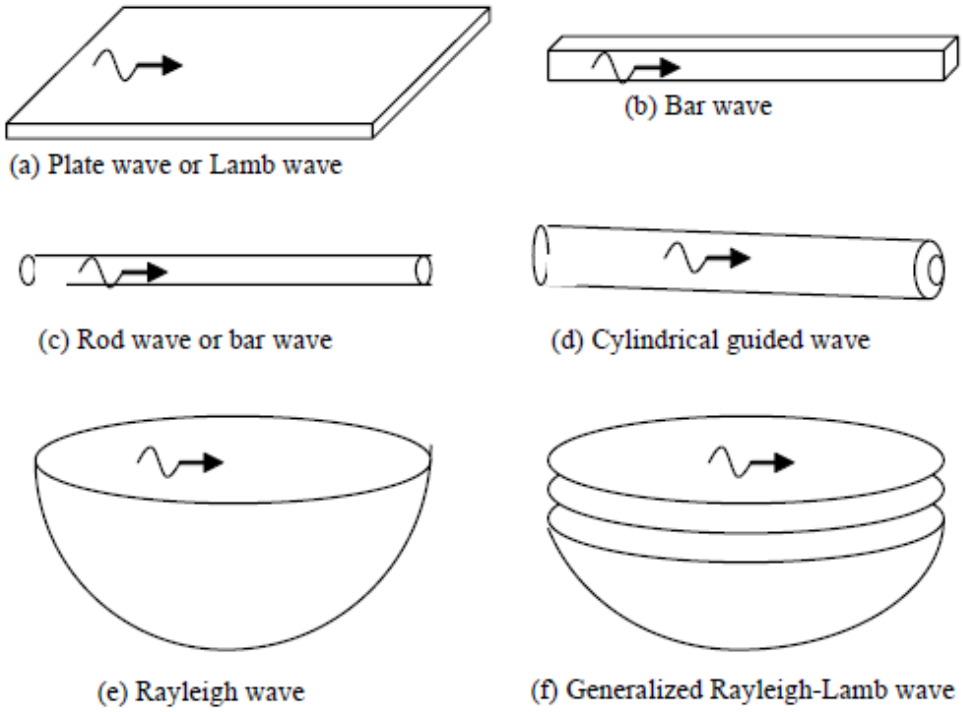


Fig 1.15 Different types of guided waves in various problem geometries (Kundu, 2007)

Cylindrical Guided Waves: Elastic waves propagating through a hollow cylinder or pipe are called cylindrical guided waves (**Fig 1.15(d))**. Since for a cylinder the two stress- free surfaces- inner and outer surfaces are parallel to each other as in a plate ,sometimes the cylindrical guided waves are also called Lamb waves.

Bar waves: When guided waves propagate through a rod or bar they are known as bar waves (**Fig 1.15(c))**.

Rayleigh wave: If the structure is a homogenous half-space then the guided wave propagating along the surface of the half-space is called Rayleigh wave (**Fig 1.15(e))**.

Lamb waves: Waves propagating through a plate type structure with two parallel stress-free boundaries are known as Lamb waves, again named after its inventor. Lamb waves are also known as plate waves because they propagate through plates (**Fig 1.15(a))**.

Rayleigh-Lamb waves: Waves propagating parallel to the free surface of a multilayered solid half-space are known as generalized Rayleigh-Lamb waves or simply Rayleigh waves (**Fig 1.15(f))**.

1.8 ULTRASONIC GUIDED WAVES

In an infinite isotropic solid medium only two types of independent wave propagation exist, i.e., compressional and shear waves. Both waves propagate with constant velocities and are non-dispersive. When geometry constraints are introduced and the dimensions are close to the wavelength, the wave becomes dispersive and is called a guided wave (Reis et al., 2005). In an infinite bulk of a perfectly elastic material, ultrasonic waves travel as bulk waves, decaying in amplitude because of the spread of the wave front. However, in a finite perfectly elastic medium, the sound wave is reflected from the structure boundaries, and the energy is contained within the elastic medium as a guided wave, which propagates with constant amplitude.

Ultrasonic Guided Wave inspection and structural health monitoring is being considered today in such natural wave guide structures as plates, multi-layer structures, rods, rails, piping and tubing, an interface, and curved or flat layers on a half space. An increased understanding of the basic physics and wave mechanics associated with guided wave inspection has led to an increase in practical nondestructive evaluation and inspection problems. Computing power today is also making dreams come true, where only a vision was possible decades ago. A principal advantage of guided waves is inspection over long distances with excellent sensitivity from a single probe position. There is also an ability to inspect hidden structures and structures under water, coatings, insulations, and concrete.

To think of the utilization of ultrasonic guided waves we can consider a variety of different natural wave guides as outlined in **Table 1.1**. Guided wave inspection is a natural for any of these structures so when you really think about it guided waves can be applied to many, many structures very quickly and efficiently.

Table 1.1: Natural Waveguides (Rose, 2004)

Plates (aircraft skin)
Rods (cylindrical, square, rail, etc.)
Hollow cylinder (pipes, tubing)
Multi-layer structures

Curved or flat surfaces on a half-space
Layer or multiple layers on a half-space
An interface

Table 1.2: Benefits of Guided Waves over Bulk waves (Rose, 2004)

Inspection over long distances from a single probe position
By mode and frequency tuning, to establish wave resonances and excellent overall defect detection and sizing potential.
Often greater sensitivity than that obtained in standard normal beam ultrasonic inspection or other NDT techniques. (Beam focusing is on the horizon for even improved sensitivity.)
Ability to inspect hidden structures and structures under water, coatings, insulations, and concrete with excellent sensitivity.
Cost effectiveness because of inspection simplicity and speed.

An understanding of the basic wave mechanics and wave propagation principles for various sensors and mode types is essential, though, if one is to carry out some reliable tests. The benefits of guided waves are illustrated in **Table 1.2**. The most interesting one of course is to be able to inspect over long distances from a single probe position.

The wave is termed "guided" because it travels along the medium guided by the geometric boundaries of the medium. Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave (Redwood et al., 1960 and Achenbach, 1975). In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of the guided waves varies significantly with the wave frequency and the geometry of the medium. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders (Sang-Young Kim et al., 2001). Guided waves travel either at boundaries (Surface Waves) or between the boundaries (Lamb Waves) as shown in **Fig 1.16**. Guided waves are the result of the intersection occurring at the interface between the two different materials. This interaction produces reflection, refraction and mode conversion between longitudinal and shear waves which can be predicted using appropriate boundary conditions. Guided waves are highly dependent on wavelength and

frequency, and propagating guided waves can only exist at specific combinations of frequency, wave number and attenuation.

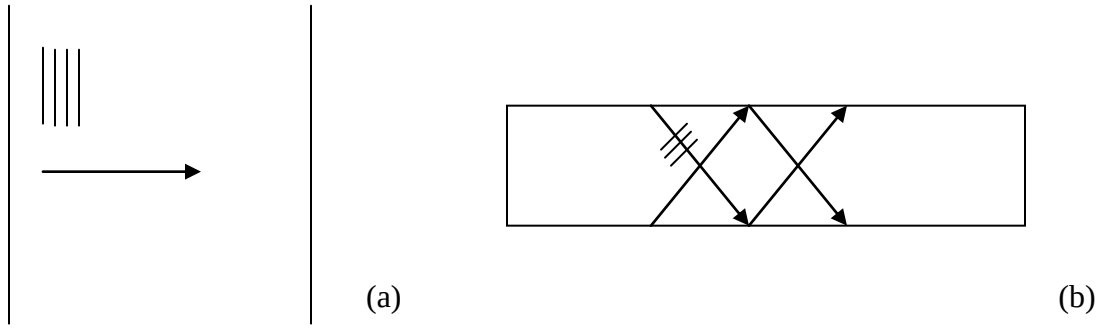


Fig 1.16 Schematic of (a) bulk wave and (b) Guided wave propagation (Demma, 2003)

The complex effect of the boundaries results in dispersion of the wave and generates different modes that have predictable frequency-dependent properties. The velocity-frequency relationships of guided waves can be displayed as dispersion curves (Pavalakovic et al., 2000). Every natural wave guided has associated with it a set of dispersion curves that presents to us the wave propagation possibilities in that structure. At each point of a dispersion curve there is a different wave structure. When studying the dispersion curve it is easy to understand that there is a corresponding frequency bandwidth associated with the abscissa value, but there is also a phase velocity bandwidth associated with the ordinate value on the phase velocity dispersion curve. This means that we are actually exciting a fairly large zone and multiple modes could propagate in a structure at the same time (Rose, 1999).

Adding further finite layers around the material, such as concrete around steel bar as in case of RC structures further complicates the waveguide, as energy can now be passed between the layers. In this case, a guided wave will still propagate in the structure as a whole, but with properties that depend on the elastic and damping properties of all the layers. Stress and displacement boundary conditions must be satisfied at the boundaries between layers. Attenuation through leakage can occur if the outermost layer may be considered infinite in extent. Hence, steel bar in concrete is modeled as a solid cylinder embedded in an infinite concrete medium, considering both the materials as isotropic, homogenous and elastic. A global matrix method is employed for solution of wave propagation equation using optimization techniques [Ervin et al., 2009] which was then developed

into a standard software Disperse (Pavalakovic et al., 2000).

For a layered system, the solution includes phase velocity, frequency and attenuation. Attenuation is due to material absorption and energy leakage into the surrounding concrete. The waves propagate in longitudinal, flexural and torsional modes due to complex effect of boundaries and they have frequency dependant properties. In such cases specific modes can be excited selectively by choosing a frequency bound. Longitudinal waveforms have axial and radial displacements, torsional waveforms have angular displacements and flexural waveforms have all three displacements. They are represented by L (m, n); T (m, n) and F(m, n) respectively where 'm' and 'n' represent the circumferential displacements and sequential order of mode respectively.

1.9 STATE OF ART IN ULTRASONICS IN CONCRETE

Pavlakovic et al. (2001). studied the dispersion relationships of a system comprising a circular bar imbedded in a solid medium having a lower acoustic impedance than the bar had been predicted. A generic study of such systems have been undertaken, motivated by a particular interest in the case of a circular steel bar imbedded in cement grout which had application to the inspection of tendons in post-tensioned concrete bridges; measurements to confirm the predictions had been carried out for this case. The attenuation dispersion curves show a series of attenuation minima at roughly equal frequency spacing. The attenuation minima occurred at the same frequencies as energy velocity maxima and they correspond to points at which the particle displacements and energy of the particular mode are concentrated towards the center of the bar so leakage of energy into the imbedding medium is minimized. The attenuation at the minima decreased with increasing frequency as the energy becomes more concentrated at the middle of the bar, until the material attenuation in the bar becomes a significant factor and the attenuation at the minima rises again. For the particular case of a steel bar in cement grout, the minimum attenuation is reached at a frequency-radius product of about 23 MHz-mm. The frequency-radius product at which the minimum attenuation is reached and the value of the minimum attenuation both increase as the acoustic impedance of the imbedding medium increases.

Kim et al. (2001) studied that long-range guided wave inspection is a new emerging technology for rapidly and globally inspecting a large area of a structure from a single test location. Also, a general overview of the guided wave properties and its application for long-range inspection of structures, the principle and instrument system for a guided wave inspection technology called "magnetostrictive sensor (MsS)" that generates and detects guided waves electromagnetically in the material under testing, and examples of long-range guided wave inspection of structures that can be accomplished using the MsS.

Kundu et al. (2001) invesitigated the feasibility of detecting and quantifying delamination at the interface between steel bar and concrete using ultrasonic guided waves. These waves can propagate a long distance along the reinforcing steel bar or concrete beam as guided waves are sensitive to interface bonding condition between the steel bar and concrete. The traditional ultrasonic methods are good for detecting large voids in concrete but are not efficient for detecting delamination at the interface between concrete and steel bar since they used reflection, transmission and scattering of longitudinal waves by internal discontinuities. He studied, special solid couplers between the steel bars (or concrete beam) and ultrasonic transducers had been used to launch flexural cylindrical guided waves (or lamb waves) in steel bar (or concrete). That investigation showed that the guided wave testing technique was an efficient and effective tool for health monitoring of reinforced concrete structures.

Iyer et al. (2002) studied with the investigation of an NDE method called C-scan imaging to detect corrosion and voids in post-tensioned specimens. Post-tensioned structures have experienced durability problems related to corrosion and voids in the grouted duct due to various reasons. The acoustics of ultrasound wave propagation were verified in the samples in this preliminary study to the desired level of satisfaction. It is critical to prove the authenticity of the technique through signal verification and image reconstruction. This study had achieved this. Corrosion at two different stages that could be detected and verified with the ideal plain grout sample and a definitive trend in the images was confirmed through this method. Although more tests on samples with different levels of corrosion are required to propose a robust detection and prediction model, the present tests have been successful in correlating the images at different depths using the ultrasound C-scan imaging technique. Voids within the casing were also detected from series of images and verified by autopsy done on the specimen. The location of void on the actual autopsied specimen and reconstructed image corresponded thus validating the

method of scanning. This scanning technique had been successfully implemented and proven in the fields of medical diagnosis and fatigue fracture detection in composite or sandwich materials. This study had shown that it can also be used on post-tensioned structures to detect structural integrity problems (like corrosion and voids) detrimental to the structure. A wide scope exists to improve the flaw gate location process which may yield better results in terms of information available from gates to reconstruct images.

Beard et al. (2003) proposed a method of inspection using guided ultrasonic waves , used a pulse-echo technique carried out from the free end of the structure. The maximum inspection range is determined by the amount of attenuation that the wave experiences as a result of leakage into the embedding material and material losses. He carried out with a focus on the inspection of the posttensioning tendons used to reinforce concrete. The experimental techniques were used to measure the attenuation in short lengths of grouted tendons, to evaluate the reflection coefficient of the modes from different geometry breaks, and to assess the impact of tendon curvature. The outcome of this shows that the inspection range for tendons is limited, but the outlook for the inspection of the larger diameter grouted bolts and rebars that are used in the construction industry is promising.

Kundu et al. (2003) investigated the feasibility of detecting interface degradation and separation of steel bars in concrete beams using Lamb waves. The Lamb wave can propagate a long distance along the reinforcing steel bars embedded in concrete as the guided wave and is sensitive to the interface bonding condition between the steel bar and the concrete. The traditional ultrasonic methods for inspecting defects in concrete use reflection, transmission, and scattering of longitudinal waves by internal defects. These methods are good for detecting large voids in concrete, but they are not very efficient for detecting delamination at the interface between concrete and steel bars. He studied a special coupler between the steel bar and ultrasonic transducers had been used to launch non-axisymmetric guided waves in the steel bar. This investigation showed that the Lamb wave inspection technique is an efficient and effective tool for health monitoring of reinforced concrete structures.

Reis et al. (2005) presented a waveform energy (indicative of attenuation) as an indicator of corrosion damage. He established that the loss of bond strength between the reinforcing steel and the surrounding concrete can be detected and evaluated using guided waves.

Reis et al. (2008) studied the guided longitudinal modes in both low (<200 kHz) and high (2–8 MHz) frequency ranges were invoked to monitor damage in reinforced mortar specimens undergoing accelerated uniform corrosion. The fundamental longitudinal mode, i.e. $L(0, 1)$, and the $L(0, 9)$ mode were invoked for low- and high-frequency testing, respectively. Because of the significant amount of axial displacement at the steel/mortar interface, the $L(0, 1)$ mode was so appreciably attenuated for the particular specimen size used that it was not detected until after corrosion had initiated and corrosion product accumulation caused mortar cracking. Once detected, the $L(0, 1)$ mode was sensitive to the combined effects of bond deterioration and mortar stiffness reduction. The $L(0, 9)$ mode had negligible radial and axial displacement at the steel/mortar interface. As a result, the $L(0, 9)$ mode was relatively insensitive to the surrounding interface conditions at high frequencies. This allows for changes in the steel cross-sectional area and bar topography to be isolated and monitored from the onset of corrosion up to severe pitting.

Ervin et al. (2009) studied the creation of an embeddable ultrasonic sensing network for assessment of reinforcement deterioration. Towards this effort, guided ultrasonic waves were used to monitor reinforced mortar specimens undergoing accelerated uniform and localized corrosion. Longitudinal waves were invoked at higher frequencies (2- 9MHz), where the attenuation is a local minimum. Using a through transmission configuration, waveforms were sensitive to both forms of corrosion damage. Scattering, mode conversions and reflections from irregularities at the bar surface from uniform corrosion and the severely tapered cross-section from localized corrosion were thought to cause the increase in attenuation. Because localized corrosion did not yield a discontinuity that was nearly perpendicular to the bar axis, incident waves were severely scattered, mode converted and rapidly attenuated. As evidence, this was the inability of pulse-echo testing to detect reflected waveforms for the localized corrosion.

Sharma et al. (2010) studied a nonintrusive corrosion monitoring technique for early detection of damages in steel embedded in concrete. In this study, longitudinal guided ultrasonic waves were utilized to monitor notch and debond defects in steel bars in concrete simulating pitting and delamination phenomena caused by corrosion. Two ultrasonic techniques of pulse transmission

and pulse echo were used to monitor the healthy and damaged specimens. The developed methodology was successfully applied for real time monitoring of RC beam specimens undergoing accelerated chloride corrosion. The ultrasonic signals effectively relate to the state of reinforcing bars.

Sharma et al. (2011) developed a corrosion technique for monitoring various types of corrosion occuring in widely varying environments using guided waves. The effect of rates of corrosion in the two environments on the ultrasonic signals is reported. Surface and core seeking guided wave modes were used to monitor beams undergoing accelerated impressed current corrosion in the presence chloride corrosion and absence of chlorides oxide corrosion. Effective combination of guided wave modes could relate to the differences in corrosion mechanisms and rates in the two environments. Ultrasonic test results correlated well with that of the destructive tests

Sharma et al. (2011) studied the use of ultrasonic waves for damage detection in bars in air, which was further extended to bar embedded in concrete. Minimum intrusion was effected by exciting one end of the bar with an ultrasonic pulse and recording its propagation at the other end using the bar as a waveguide. Ultrasonic guided waves with frequencies in the range of 1-4 MHz were generated in healthy and damage bars by varying the input frequencies of an ultrasonic transducer. Bar diameter of 12mm was used and damages were inflicted in the form of symmetrical area reduction in reinforcing bars. Two ultrasonic testing techniques, pulse echo and pulse transmission, were used to monitor healthy as well as damaged bars. Time of flight measurement in pulse echo indicated the damage location accurately. Amplitude of received signal in both pulse echo and pulse transmission was a measure of extent of damage. The two techniques when used in combination could predict the existence, location as well as the extent of damage in steel bars in air. The same methodology was then extended to steel bars embedded in concrete.

Sharma et al. (2012) reported the non-destructive evaluation of reinforcing bars that were corroding in the presence and absence of chlorides utilizing ultrasonic guided waves. The effect of rates of corrosion and its progression in the two environments on the ultrasonic signals was discussed. Surface and core seeking guided wave modes were used to monitor beams undergoing accelerated impressed current corrosion. Effective combination of guided wave modes could relate to the differences in corrosion mechanisms and rates in the two environments. Calibration

of the ultrasonic data with the physical condition of the bar in the two environments had been attempted.

1.10 CLOSING REMARKS

This chapter established the regime of ultrasonic guided waves for demage detection in RC/ concrete structures. It discusses the background of ultrasonics as a NDT technique successfully implemented as outlined in literature review.

CHAPTER 2

NON-VIBRATED OR SELF FILLING OR SELF COMPACTING CONCRETE

2.1 INTRODUCTION

Self-Compacting Concrete (SCC) is an innovative construction material that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. SCC is compacting itself alone due to its self-weight and is de-aerated almost completely while flowing in the formwork. In structural members with high percentage of reinforcement it fills completely all voids and gaps. SCC flows like ―honey and has nearly a horizontal concrete level after placing. The hardened concrete is dense, homogeneous and has the same engineering properties and durability as traditional vibrated concrete.

SCC offers a rapid rate of concrete placement, with faster construction times and ease of flow around congested reinforcement. The fluidity and segregation resistance of SCC ensures a high level of homogeneity, minimal concrete voids and uniform concrete strength, providing the potential for a superior level of finish and durability to the structure. SCC is often produced with low water-cement ratio providing the potential for high early strength, earlier de-moulding and faster use of elements and structures.

The elimination of vibrating equipment improves the environment on and near construction and precast sites where concrete is being placed, reducing the exposure of workers to noise and vibration. The improved construction practice and performance, combined with the health and safety benefits, make SCC a very attractive solution for both precast concrete and civil engineering construction.

2.2 HISTORICAL DEVELOPMENT

In Japan in the early 1980's, because of the increasing reinforcement volumes with smaller bar diameters and a reduction in skilled construction workers, full compaction was difficult to obtain or judge, leading to poor quality concrete (Okamura1999).For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan. The

creation of durable concrete structures requires adequate compaction by skilled workers. However, the gradual reduction in the number of skilled workers in Japan's construction industry has led to a similar reduction in the quality of construction work. One solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of Self-Compacting Concrete (SCC), which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction. The necessity of this type of concrete was proposed by Okamura in 1986. Studies to develop SCC, including a fundamental study on the workability of concrete, have been carried out by Ozawa and Maekawa at the University of Tokyo (Okamura et al. 1993).

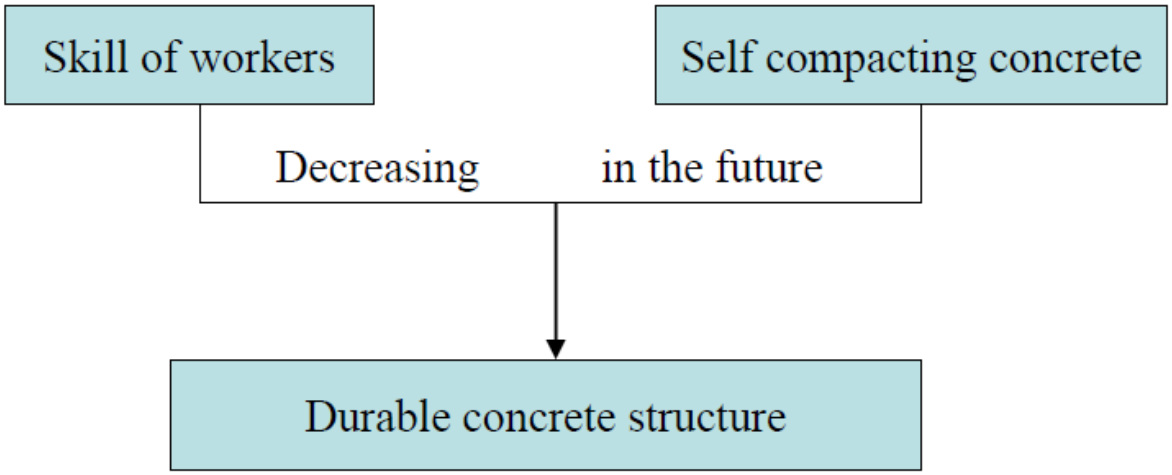


Fig. 2.1 Necessity for Self-Compacting Concrete (Okarama and Ouchi ,2003)

The prototype of SCC was first completed in 1988. The prototype performed satisfactorily with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening, and other properties.

Okamura (1995) proposed a concept for a design of concrete independent of the need for compaction. Ozawa and Maekawa produced the first prototype of SCC at the University of Tokyo in 1988. Since that time SCC has gone from a laboratory novelty to practical applications all over the world. The increasing numbers of papers published every year that deal with all

aspects of SCC, e.g. mix design, and physical properties and applications in practice, indicate research on this technology is thriving. Recommendations on the design and applications of SCC in construction have now been developed by many professional societies, including the American Concrete Institute (ACI), the American Society for Testing and Materials (ASTM), Center for Advanced Cement-Based Materials (ACBM), Precast Consulting Services (PCI) and Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (RILEM) etc. Symposiums and workshops on this topic have been organized by these societies and several test methods have been or are in the process of standardization.

2.3 ADVANTAGES OF SCC

Some of the advantages of SCC over normally vibrated concrete are:-

1) Can be placed at a faster rate with no mechanical vibration and lesser need of spreading, resulting in saving in placment costs.
2) Improved and more uniform architectural surface finish with little to no remedial surface work.
3) Ease of filling restricted sections and hard-to-reach areas. Opportunities to create structural and architectural shapes and surface finishes that are not achievable with conventional concrete.
4) Improved consolidation around reinforcement and bond with reinforcement.
5) Improved pump ability.
6) Improved uniformity of in-place concrete by eliminating variable operator-related.
7) Labor savings.
8) Shorter construction periods and resulting cost savings.
9) Reduction or elimination of vibrator noise potentially increasing construction hours in urban areas.
10) Minimizes movement of ready mixed trucks and pumps during placement.
11) Increased job-site safety by eliminating the need for consolidation.

2.4 APPLICATIONS OF SCC

One of the first big projects undertaken in Japan using SCC was the anchorage (83m long, 63m wide and approximately 45m high) of the Akashi-Kaikyo Bridge. This project is a very good example of where the use of SCC reduced the total construction time from 30 to 24 months.

Another project where the use of SCC reduced the construction time from 22 to 18 months was the 0.8m thick wall of the liquid natural gas tank for the Osaka Gas Company. More recent applications of SCC in Japan are lattice work (thin ribs), casting without a pump (discharging concrete from the truck and allowing it to flow freely to fill the formwork) and tunnel linings. SCC is used in lattice work because conventional concrete cannot be vibrated in this manufacturing process. To prevent cold joints in tunnel linings, SCC is used because it limits bleeding at joints.

Sweden started to develop SCC in 1993 with a project where walls were cast using different materials as fillers in the mixture designs. In 1998 a bridge was constructed using SCC. This was the first bridge outside Japan where SCC was used for the whole structure. Since then, SCC has been used in monolithic frame bridges, box tunnel monoliths, and rock lining monoliths, tunnel entrances, headwalls, foundations and frame supports. The current use of SCC in Sweden's pre-cast and ready mix concrete industry is about 10% of the total concrete use.

The development of SCC is particularly favored in the precast concrete industry. Some precast concrete producers in the Netherlands only use SCC in the manufacture of their products. Because of this extensive use of SCC, much experience has been gained and SCC is now used in pre-cast slabs, beams, walls, columns, arches and bridge elements. SCC has also been used in situ but only in special cases. The first major project was the façade of the National Theater in The Hague where only SCC could be used to fill the tiny ribs (8 mm deep). In some tunnel walls SCC was used because of congested reinforcement and the possibility of remote casting techniques. At the Rotterdam Zoo the heavily reinforced walls of a large fish pond was done with SCC to ensure a homogeneous watertight structure. The design and shape of the bridge piers for the ―South Tangent traffic connection between Haarlem and Amsterdam was of such a nature that only SCC could be used. In this project 1800 m3 of SCC was used. The most recent development in the Netherlands is self-compacting fibre reinforced concrete. Self-compacting fibre reinforced concrete is used to produce floor elements that are thinner and lighter.

Further examples of SCC applications are the steel form columns at the Toronto International Airport and the outrigger columns at Wall Centre in Vancouver (North America). A more interesting application was in the construction of houses in Houston where the exterior walls and slabs were cast monolithically out of SCC. The walls are textured and stained on the outside to resemble brick and have a polystyrene foam core for insulation. These houses are designed to withstand tornados and hurricane winds in excess of 218 km per hour.

2.5 PROPERTIES OF SCC

This section introduces the fresh and hardened properties of SCC. The experimentations and material constituents required to achieve these properties are then briefed in the following sections.

2.5.1 Fresh Properties

A concrete mix can only be classified as SCC if the requirements for all the following three workability properties are fulfilled (EFNARC, 2002):

1. Filling ability,
2. Passing ability, and
3. Segregation resistance.

Filling ability: It is the ability of SCC to flow into all spaces within the formwork under its own weight. Tests, such as slump flow, V-funnel etc, are used to determine the filling ability of fresh concrete.

Passing ability: It is the ability of SCC to flow through tight openings, such as spaces between steel reinforcing bars, under its own weight. Passing ability can be determined by using U-box, L-box, Fill-box, and J-ring test methods.

Segregation resistance: The SCC must meet the filling ability and passing ability with uniform composition throughout the process of transport and placing.

The above three key properties are to some extent related and inter-dependent. A change in one property will normally result in a change in one or both of the others. Both poor filling ability and segregation can cause insufficient passing ability, i.e. blocking. Risks of segregation increase as filling ability increases.

2.5.2 Hardened Properties

Self-Compacting Concrete is usually tested for compressive and split tensile strength to check its hardened properties. The hardened properties for the same are discussed below.

- **Strength**

Strength is one of the most important properties specified for concrete because it is a direct reflection of the capacity of the structure to resist forces and it is a reasonable indicator of other properties.

- **Compressive strength**

Compressive strength is the capacity of a material or structure to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. Where the W/P ratios are similar, the compressive strength and the strength development of SCC are not significantly different from normally vibrated concrete (NVC). To check and compare the compressive strength of SCC mixtures used in this investigation, cubes are made of each mixture. Standard 150 mm steel cube moulds are used to make these cubes. The SCC was placed into the moulds, without any compaction, after all the workability tests were done. After 24 hours the moulds are stripped and the cubes are put into the curing tank. After the desired time of curing, the cubes are taken out and the compression testing is done.

- **Split tensile strength**

The tensile strength of concrete is much lower than the compressive strength, because of the ease with which cracks can propagate under tensile loads, and is usually not considered in design. However, it is an important property, since cracking in concrete is most generally due to the tensile stresses that occur under load, due to enviromental changes.

For split tensile strength assessment, cylinders of diameter 100mm and length 200mm are prepared. Splitting tensile strength is measured by testing cylinders under diametric compression. The splitting tensile strength of SCC is higher than that of NVC. In general, the tensile to compressive strength ratio of SCC is 10~30% higher than that of NVC.

2.6 METHODS FOR FRESH PROPERTIES OF SCC

Many different test methods have been developed in attempts to characterize the properties of SCC. So far no single method or combination of methods has achieved universal approval and most of them have their adherents. Similarly no single method has been found which

characterizes all the relevant workability aspects so each mix design should be tested by more than one test method for the different workability parameters.

Table 2.1 List of Test Methods for Workability Properties of SCC (EFNARC , 2002)

S.No.	Method	Property
1	Slump Flow by Abram Cone	Filling Ability
2	T50cm Slump Flow	Filling Ability
3	V- Funnel	Filling Ability
4	V- Funnel at $T_{5mintues}$	Filling Ability
5	L-Box	Passing Ability
6	U-Box	Passing Ability

- **Slump Flow Test**

The simplest and most widely used test method for Self-Compacting Concrete is the slump flow test. The test, which was developed in Japan, was originally used to measure underwater concrete and has also been used to measure highly flowable concretes. The pictorial view of the slump flow is shown in the **Fig 2.2.**

To perform the test, a conventional slump cone is placed on a rigid, non-absorbent plate and filled with concrete without tamping. The plate must be placed on a firm, level surface. The slump cone is lifted and the horizontal spread of the concrete is measured. For an additional measure of flow ability, the time required for the concrete to spread to a diameter of 50 cm can be measured. This value of T50 generally ranges from 2-7 seconds. It is possible to assess the stability of concrete qualitatively after performing the slump flow test. A visual stability index (VSI) has been developed as a standard means of determining stability. A numerical score—on a scale of 0 to 3—is assigned based on a visual evaluation of the segregation and bleeding in the

concrete sample. Self-Compacting Concrete should exhibit a rating of 0 or 1 to be considered acceptable.

Fig. 2.2 Slump Flow Test (http://www.googleimages.com)

- **V- funnel test**

The V-funnel test is used to measure the filling ability of Self-Compacting Concrete and can also be used to judge segregation resistance. The test method is similar to the concept of the flow cone test used for cement paste. The test apparatus, shown in **Fig 2.3.**, consists of a V-shaped funnel with a height of 425 mm, a top width of 490 mm, a bottom width of 65 mm, and a thickness of 75 mm. At the bottom of the V-shape, a rectangular section extends downward 150 mm.

Alternatively, an O-shaped funnel with circular cross section can be used. The entire funnel is filled with concrete without tamping or vibration. The door at the bottom of the funnel is opened and concrete is allowed to flow out of the funnel and into a bucket. The flow time for all of the concrete to exit the funnel is recoded as a measure of filling ability. For self-compacting concrete, the flow time should be less

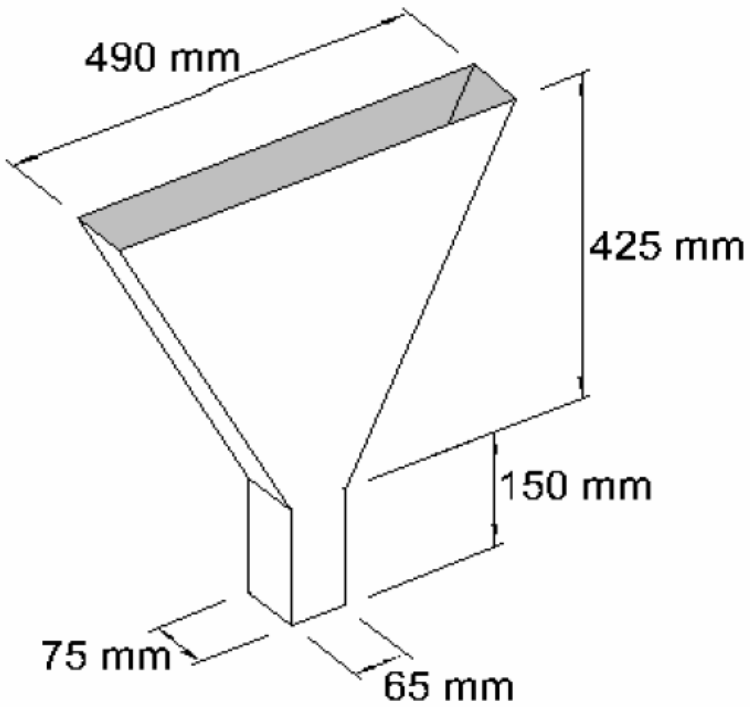


Fig. 2.3 V-funnel Test Apparatus (http://www.googleimages.com)

than 10 seconds. To measure segregation resistance, the V-funnel is refilled with concrete and allowed to sit for 5 minutes. The door is again opened and the flow time is recorded. The greater the increase in flow time after the concrete has remained at rest for five minutes, the greater will be the concrete's susceptibility to segregation. Further, non-uniform flow of concrete from the funnel suggests a lack of segregation resistance.

- **L-Box test**

The L-box test measures the filling and passing ability of Self-Compacting Concrete. Originally developed in Japan for underwater concrete, the test is also applicable for highly flowable concrete.

As the test name implies, the apparatus consists of an L-shaped box, shown in **Fig 2.4** concrete is initially placed in the vertical portion of the box, which measures 600 mm in height and 100 mm by 200 mm in section. A door between the vertical or horizontal portions of the box is opened

and the concrete is allowed to flow through a line of vertical reinforcing bars and into the 700 mm long, 200 mm wide, and 150 mm tall horizontal portion of the box. In the most common arrangement of reinforcing bars, three 12 mm bars are spaced with a clear spacing of 35 mm. Generally, the spacing of the reinforcing bars should be three times the maximum aggregate size. It should be noted that various dimensions for the L-box have been used and no one set of dimensions is considered official; however, the dimensions described above seem to be the most common.

The time for concrete to reach points 20 cm (T20) and 40 cm (T40) down the horizontal portion of the box is recorded. After the concrete comes to rest in the apparatus, the heights of the concrete at the end of the horizontal portion, H2, and in the vertical section, H1, are measured. The blocking ratio, H2/H1, for most tests should be 0.80 to 0.85. If the concrete being tested is truly self-leveling like water, the value of the blocking ratio will be unity. Segregation resistance can be evaluated visually. A concrete sample with coarse aggregate particles that reach the far end of the horizontal part of the box exhibits good resistance to segregation. The L-box can be disassembled after the concrete has hardened. By cutting out samples of the hardened concrete, additional information about the concrete's resistance to segregation can be determined.

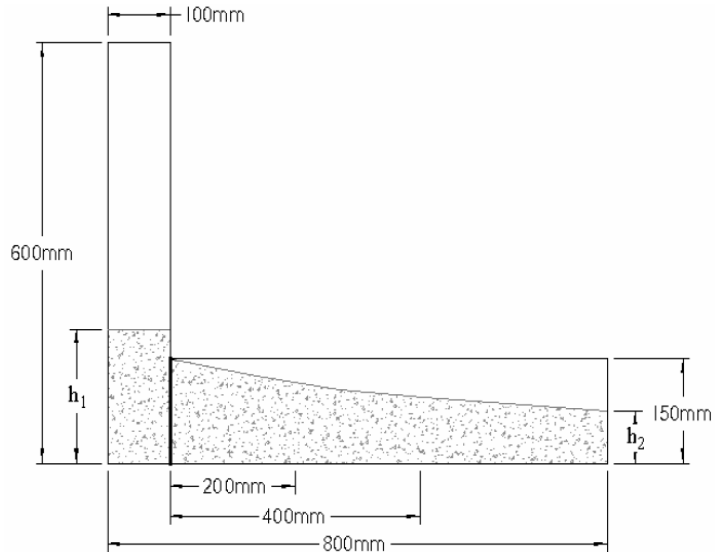


Fig. 2.4 L-Box Test Apparatus (http://www.googleimages.com)

While the test does give valuable information about filling and passing ability, and to a lesser extent, segregation resistance, the test is not as simple as the slump flow test. Since there are no standardized dimensions, results from different test apparatuses cannot be compared directly.

- **U-box Test**

The U-box test measures filling ability and is similar to the L-box test. The U-box test was developed in Japan and is sometimes referred to as the box-shaped test. Like other workability tests for SCC, the U-box test is also applicable to highly flowable concretes and underwater concretes. The apparatus consists of a U-shaped box, as shown in **Fig.2.5** concrete is placed in the left side of the box. An alternative version of the apparatus features a flat bottom instead of a curved bottom. Ideally, the box should be made of clear plastic to permit the observation of the concrete in the box. To start the test, the door dividing the two halves of the box is opened and concrete is allowed to flow from the left half of the box into the right half. Reinforcing bars are placed at the location of the door.

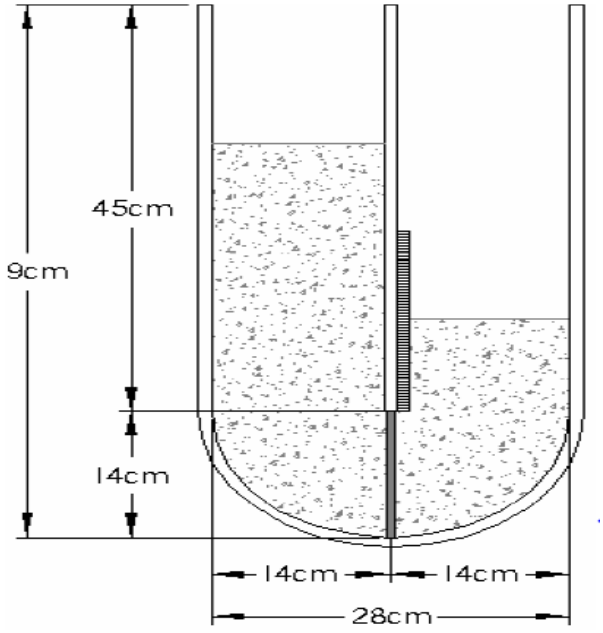


Fig. 2.5 U-Box Test Apparatus (http://www.googleimages.com)

Although the spacing of the bars is adjustable, the most common arrangement is 13 mm diameter bars with a clear spacing of 35 mm. The time from the opening of the door until the concrete ceases to flow is recorded. The height of the concrete in each side of the box is measured. A truly self-leveling fluid will rise to the same height on each side of the box. Concrete with good filling ability should reach a height of at least 30 cm on the right side of the box. In some versions of the test, a surcharge load is applied to the concrete on the left side of the box. This surcharge load is unnecessary for self-compacting concrete and is generally not use.

2.7 ACCEPTANCE CRITERIA

There are limits specified for the workability of the self compacting concrete. These workability test value limits are given below.

Table 2.2 Acceptance Criteria for Self-Compacting Concrete (Nagataki S et al., 1995), (EFNARC ,2002)

S.No.	Method	Unit	Typical Range Of Values	
			Minimum	Maximum
1	Slump Flow by Abram Cone	Mm	500	700
2	T_{50cm} Slump Flow	Sec	2	5
3	V-Funnel	Sec	6	12
4	V- Funnel 5min	Sec	0	3
5	L-Box	H_2/H_1	0.8	1
6	U-Box	(H_2-H_1)	0	30

The Review of literature for Non-vibrated concrete (Self Compacting Concrete) is given below:

Xie et.al (2000) reported the optimum mix parameters of high strength self –compacting concrete with ultra pulverized fly ash. All the materials used in this research were locally available. In this research cement was replaced by 30% of ultra pulverized fly ash of total cementitious material and sand was replaced by broken gravels. Super-plasticizer content is 1.0-1.6 % of total cementitious material for water content of 175l/m^3.When the super-plasticizer content is higher than 1.9% compressive strength decreases because of bleeding. The results of this research indicates that higher the sand ratio, better the workability of fresh SCC, and smaller the compressive strength difference between SCC and normal concrete and the sand ratio cannot be less than 40%. This SCC with UPFA has higher mechanical properties, excellent impermeability and freezing resistance, andlower drying shrinkage.

Su Nan et.al (2001) proposed a new mix design method for self-compacting concrete (SCC). First, the amount of aggregates required was determined, and the paste of binders were then filled into the voids of aggregates to ensure that the concrete thus obtained had flowability, self-compacting ability and other desired SCC properties. The amount of aggregates, binders and mixing water, as well as type and dosage of superplasticizer (SP) to be used are the major factors influencing the properties of SCC. Slump flow, V-funnel, L-flow, U-box and compressive strength tests were carried out to examined the performance of SCC, and the results indicate that the proposed method could produce successfully SCC of high quality.

Pereira-de-oliveira et al. (2005) evaluated slump flow, L box, V funnel test to get the SCC workability. The results of tests carried out to verify the self-compacting of concrete. The results of slump-flow test carried out in SCC concrete characterize the mixtures as being self compacting. However, the mixture SCCSF presents relationships H_1/H_0 below 0.80. This value has been recommended as minimum value for this test that simulates the capacity of concrete transit inside the formwork and it depends on the steel bars density contained.

Domone (2006) conducted slump flow test, which measures the flow capacity, has been universally used, and hence values of slump flow spread. Nearly 50% of the applications used

values in the range 650–700 mm, with nearly 90% in the range 600–750 mm. Flow rate values, expressed either as T500, V-funnel or Orimet times were reported in about half of the case studies. They varied considerably; T500 times ranged from 1.8 to more than 12 sec. and V-funnel or O-funnel times from 3 to 15 sec. there is thus a wide range in this property. There was no pattern of higher slump flows being associated with lower flow rate values, indicating the independence of these properties, and the ability to design mixtures with a combination thought suitable for a given application. L box blocking ratio values were all in excess of 0.8; U-box values were in excess of 300 mm, with the reinforcement spacing varied in some cases to suit the application.

Sukumar et al. (2007) studied the effects of high volume fly ash on the early age properties of SCC. Rate of gain in strength at different periods of curing such as 12 h, 18 h, 1 day, 3 days, 7 days, 21 days and 28 days are studied for various grades of different SCC mixes. Different relations have been established for the gain in strength at the early ages in comparison to the conventional concrete of same grades. Relations have also been formulated for compressive strength and split tensile strength for different grades of SCC mixes. It is found that strength at 12 h of all grades of SCC is more than 10% of the 28-day strength and 1-day strength is about 18–20% of the 28-day strength.

Khatib (2007) studied the influence of Fly Ash (FA) content in SCC when Portland cement was partially replaced with 0-80% FA. Seven mixes were prepared, in which three of them were plain mixes of SCC with different dosage of admixtures. And in the rest of 4 mixes Plain concrete was replaced with 0%, 20%, 40%, 60% and 80% of FA keeping the water to binder ratio constant at 0.36. Workability, compressive strength, ultrasonic pulse velocity, absorption and shrinkage were observed. All mixes exhibited high workability and it was found that using up to 60% of FA as PC replacement can produce SCC with high strength as 40N/mm^2.

Dinakar et al. (2008) studied on the durability properties of self compacting concretes (SCCs) with high volume replacements of fly ash. Eight fly ash self compacting concretes of various strength grades were designed at desired fly ash percentages of 0, 10, 30, 50, 70 and 85%, in

comparison with five different mixtures of normal vibrated concretes (NCs) at equivalent strength grades. The durability properties were studied through the measurement of permeable voids, water absorption, acid attack and chloride permeation. The results indicated that the SCCs showed higher permeable voids and water absorption than the vibrated normal concretes of the same strength grades. However, in acid attack and chloride diffusion studies the high volume fly ash SCCs had significantly lower weight losses and chloride ion diffusion.

Liu Maio (2010) studied the properties of SCC incorporating different levels of Fly ash of up to 80%. Tests on fresh properties of SCC were slump flow, V-funnel test, J-ring test and sieve stability test. Compressive strength and water absorption were also checked. It was found that SCC with 80% of fly Ash can be produced with satisfactory fresh properties but replacing cement with fly ash over 20% decreases the compressive strength significantly. Sorptivity of SCC with up to 40% fly ash are similar to that of plain SCC mix but increases significantly in mixes with 60-80% fly ash content.

Siddique (2010) studied the properties of self-compacting concrete (SCC) made with ClassF flyash. The mixes were prepared with five percentages of classF flyash ranging from 15% to 35%. Properties investigated were self-compactability parameters (slump flow, J-ring, V-funnel, L-box and U-box), strength properties (compressive and splitting tensile strength), and durability properties (deicing salt surface scaling, carbonation and rapid chloride penetration resistance). SCC mixes developed 28 day compressive strength between 30 and 35 MPa and splitting tensile strength between 1.5 and 2.4 MPa. The carbonation depth increased with the increase in age for all the SCC mixes. Maximum carbonation depth was observed to be 1.67 mm at 90 days and 1.85 mm at 365 days for SCC with 20% flyash content. Also, the pH value for all the mixes was observed to be greater than 11. Deicing salt surface scaling weight loss increased with the increase in flyash content except with mix containing 15%flyash. At 365 days age, the weight loss was almost consistent for all percentages of flyash varying between 0.525 and 0.750 kg/m^2. SCC mixes made with flyash exhibited very low chloride permeability resistance (less than 700 and 400 Coulomb) at the age of 90 and 365 days respectively.

Turk et al. (2010) studied that silica fume (SF) and fly ash (FA) were added separately as partial replacement of cement from 5% to 20% and from 25% to 40% at 5% intervals, respectively. In case, eight types of self-compacting concrete (SCC) were designed, in comparison with normal concrete (NC). Mechanical properties of NC and various SCC mixtures such as, compressive, splitting tensile strength, ultrasound pulse velocity (UPV) and the modulus of elasticity had been investigated. Tests were conducted for 3, 28 and 130 days whilst the elasticity modulus test was only performed for 28 days. Test results indicated that SCC specimens with SF/FA had higher the compressive and tensile strength than NC specimens for all ages whilst the compressive strength of SCC specimens decreased with an increase in both FA and SF content for 3 days. However, an increase in SF/FA content led to generally an increase in compressive and tensile strength for 130 days. Moreover, SCC specimens with FA had the highest UPV values followed by NC and SCC specimens with SF for 28 and 130 days, though, the UPV values of SCC specimens in general decreased for all ages when FA/SF content increased. The elasticity modulus of SCC with SF was highest in all specimens tested while SCC specimens with FA had lowest elasticity modulus. The elasticity modulus of SCC specimens with FA generally decreased with an increase in FA content but there was inversely for SCC specimens with SF except for SF20. In addition to these mentioned above, the values of the elasticity modulus had a good correlation with the values of the compressive, tensile strength and UPV with R2=0.99, 0.83 and 0.73, respectively, indicating that the use of different dosage of SF/FA had positive effect on the correlation between mechanical properties of SCC.

Kheelel et al. (2011) presented that the coarse aggregate properties such as maximum size, texture and type of coarse aggregate that had a direct effect on achieving SCC.. Coarse aggregate is one of these factors that have a significant influence on SCC. Three types of coarse aggregate are used, namely crush gravel, uncrushed gravel and crush limestone. To determine the workability, different test methods are adopted such as slump flow, V-funnel, L-box and U-box test. It was found that by increasing the maximum size of coarse aggregate, flowability and passing ability reduced. In addition it was observed that when uncrushed gravel was used in the concrete mixture, flow ability, passing ability and segregation resistance increased as compared to concrete with crushed gravel. Furthermore, the inclusion of 10% HRM as a partial replacement by weight of cement leads to reduce flow ability and increase viscosity. The

compressive and flexural strengths and modulus of elasticity was measured. It was noticed that concrete mixes prepared with crushed limestone showed higher strengths and modulus of elasticity than concrete mixes prepared with crushed and uncrushed gravel. In addition, lower maximum size of coarse aggregate leads to higher strengths compared to higher maximum size of coarse aggregate in SCC mixes.

2.8 CLOSING REMARKS

Self-Compacting Concrete (SCC), unlike the conventional concrete, doesn't require compaction using external force from mechanical equipments; instead SCC is designed in such as way that it gets compacted under its own weight. SCC offers a rapid rate of concrete placement, with faster construction times and ease of flow around congested reinforcement.

It is important to study setting of SCC during the intial 24 – 48 hours contiously.

CHAPTER 3

SETTING AND HARDENING OF CONCRETE PROPERTIES

3.1 GENERAL

Setting and hardening of fresh concrete are the most critical phases during the construction works, on which depend properties of concrete structure during its service life. During setting process, concrete mixture transforms from fluid state whose properties is important for placing into formworks into solid whose properties are important for the proper behavior of material in the service. Control of hardening phenomena can be used for determination of right moment for formwork removal, or load the structure. So, knowledge of fresh and young concrete is important from both, technical and economical aspects. It follows that accurate and useful testing methods for properties of young concrete properties determination are of great interest.

Conventional testing methods for fresh concrete and mortar properties determination are slump cone test, flow table test, penetration needle test, Vicat apparatus test, hydration temperature measurement, and for young concrete pull-out test. Main drawback of these methods is missing of continuous measurement data. Rhelological testing methods which use different types of viscosimeters mainly isn't successful because apparatus acts to fresh concrete with shear forces which destroy microstructure in the early ages of hydratation process.

Between the various NDT methods, ultrasound testing methods seems to be successful for more accurate determination of these properties.

3.2 SETTING AND HARDENING OF CONCRETE

Setting Time is defined as the transition from a fluid state to a plastic state. The stiffening of the concrete after it has been placed. A concrete can be 'set' in that it is no longer fluid, but it may still be very weak; for example, you may not be able to walk on it. Setting is due to early-stage calcium silicate hydrate formation. The terms 'initial set' and 'final set' are arbitrary definitions of early and later set; there are laboratory procedures for determining these using weighted needles penetrating into cement paste.

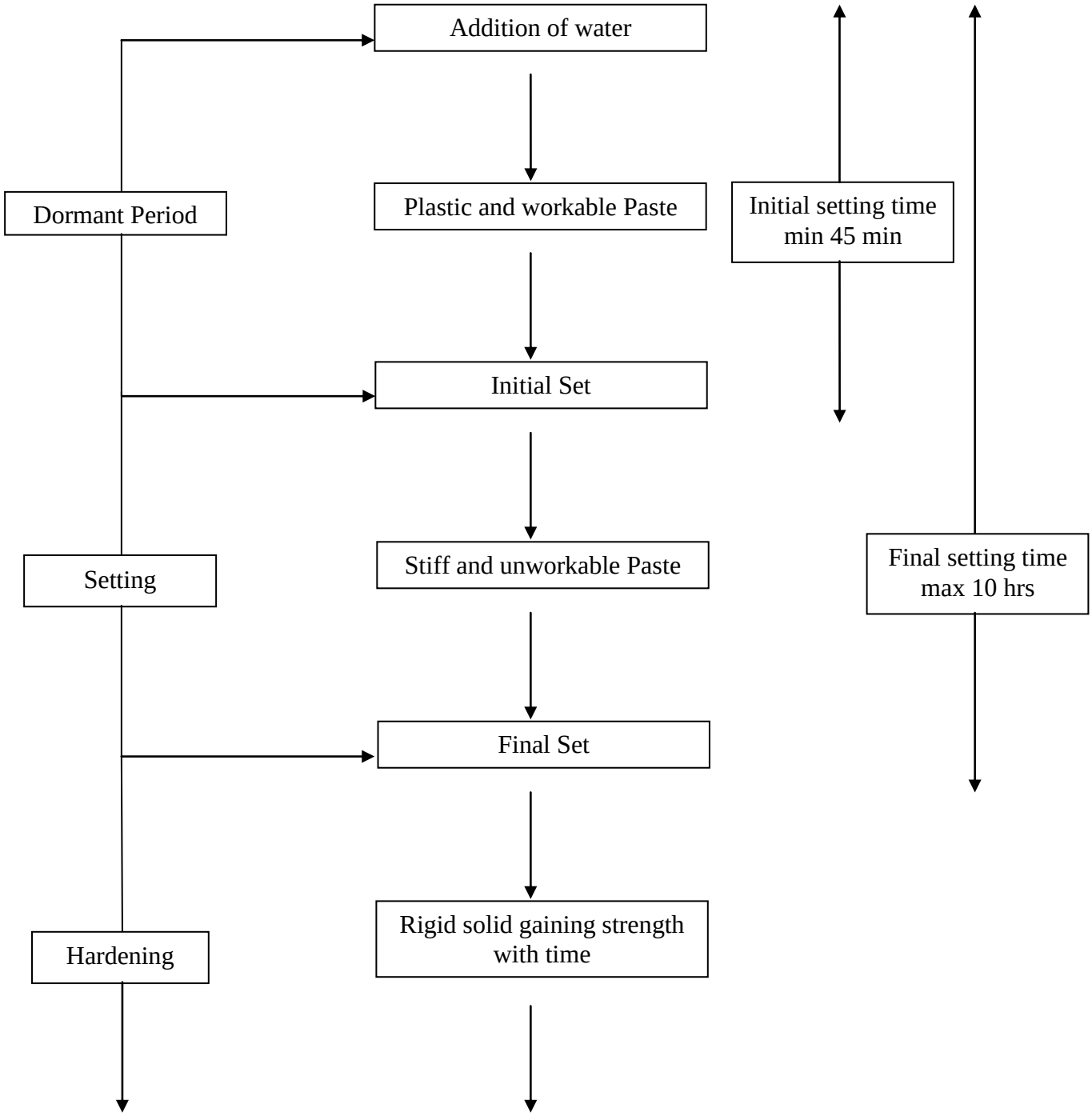


Fig 3.1 Schematic description of setting and hardening of a cement paste (Randhawa,2011)

This transition can occur in less than one hour or could take up to 24 hours. Initial set of cement paste is defined as the time when the paste has gained enough rigidity to no longer be in a fluid state. The final setting time is when rigidity has increased to a point that the paste becomes a solid of very low strength. In general, cement exhibit initial set in 2 to 4 hours and final set in 5 to 8 hours. Final set is then followed by substantial increases in strength, referred to as the hardening stage.

Hardening is the process of strength growth and may continue for weeks or months after the concrete has been mixed and placed. Hardening is due largely to the formation of calcium silicate hydrate as the cement hydrates. Hardening time is when concrete has a sufficient bearing capacity to support construction loads. This hardening of concrete may occur in a few hours, or could take up to 2-3 weeks.

Factors that affect the setting and hardening time include, but are not limited to

- Type and amount of cementitious material (cement and fly ash).
- Water content.
- Presence of admixtures (accelerators, air entrainers, and water reducers)
- Volume of fill.
- Properties of surrounding soil (permeability and degree of saturation).
- Ambient temperature and
- Curing conditions.

The complete process of how concrete early setting and hardening takes place has been shown in **Fig 3.1.**

3.3 Motivation and Physical Background

Modern concrete technology faces several challenges:

- There is a great demand by the design engineer for high-strength concrete, high-performance concrete, fibre concrete.
- Contractors are demanding for highly workable concrete, self-levelling concrete; slip formed concrete, retarded mixes.
- There is less workmanship on the construction site available.

- There is increasing quality required for durable concrete structures in an agressive environment.

The materials producers have a basket full of admixtures and additions which are deemed to affect the fresh or the hardened state of concrete. The user is sometimes inclined to combine various products in order to achieve the maximum success. However, not all mixtures lead to the expected result.

An advanced process technology needs proper control by reliable and - as much as possible - objective measurements. A possible solution is the ultrasonic technique, where amplitude-, velocity- and frequency-variations depending on the age of the mortar can be observed during the hardening process. The properties of cementitious materials are changing from a suspension to a solid during the stiffening process caused by the hydration of the cement-matrix. Biot's theory (Biot, M. A., 1956) describes the physical properties of this class of materials in an adequate way. Based on this approach, using wave propagation theory, it became obvious that ultrasound experiments measuring elastic waves in Pulse-transmission are able to characterize the material during the stiffening process.

Although the whole waveform is representing the material properties, for quantitative analysis techniques some parameters have to be extracted out of the signals recorded by a measuring device. Parameters that are easy to determine are the velocity (extracted by measuring the onset time of the signals knowing the travel path of the wave), the energy (calculating the integral sum of the wave amplitudes) and the frequency content (using Fast-Fourier-Transform techniques). One has to keep in mind that there are, of cause, also several other parameters that can be used. Even though one single wave parameter could be sufficient to characterize the material, the reliability of the method in increased by evaluating more than one.

Till now various NDT techniques like UPV, Penetration Test, Rebound hammer, embedding piezoelectric transducers etc have been used but very less work is done in monitoring early age strength and hardening of concrete with the help of Ultrasonic Pulse-transmission method. So this is the main objective to use this method in this experimental approach.

Review of literature for Setting and Hardening properties of concrete are as follows:

Guang et al. (2001) conducted an ultrasonic experimental set-up to monitor the development of the microstructure of fresh concrete at different temperatures (isothermal curing at 10, 20, 30 and 50^{o} C) and water/cement ratios (0.40, 0.45 and 0.55). The Ultrasonic Pulse velocity (UPV) was used as an indication for microstructure development of concrete at early age.

The results indicated that the ultrasonic pulse velocity largely depends on the water/cement ratio and state of hydration during first 24 hours. The numerical cement hydration simulation model HYMOSTRUC was also used for investigating the relation between the change of microstructure and evolution of ultrasonic pulse velocity. The result indicated the relation between ultrasonic pulse velocity and compressive strength is almost linear at early stage. Thus it was concluded that ultrasonic pulse velocity method is proved to be applicable in the recording and monitoring the microstructure development and strength at early stage.

Yaman Ozgur Ismail et. al (2001) investigated the relationship between velocities of ultrasonic stress waves transmitted along direct and indirect paths . Tests were conducted on plain concrete slabs of dimensions 1000 x 1500 mm, with a thickness of 250 mm. Direct ultrasonic wave transmission tests were conducted between top and bottom surfaces of the slabs and indirect tests were conducted along the slab surface. A test procedure, described in BS 1881 to determine indirect wave velocities, was refined by defining the number and spacing of transducers. Comparisons were made between direct and indirect wave velocity measurements using staristical analysis. The statistical analysis revealed that direct and indirect wave velocities could be used interchangeably in evaluating the properties of the concrete. The minimum number of test points required for a reliable estimate of indirect wave velocity was studied and recommendations are provided. The most significant conclusion is that the indirect UPV is statistically similar to direct UPV measured on the concrete slab specimens provided that there are uniform properties, including moisture gradient along the surface and along the depth.

Reinhardt H.W & Grosse C.U. (2003) studied the two main properties of cementitious mortar and concrete, i.e. rheology and setting and hardening. A testing device was developed which utilizes the velocity of ultrasound (US)-waves in order to continuously monitor the setting and hardening of cementitious materials. Two development steps were emphasised, i.e. the design of

the container and the exact determination of the transmitted Ultrasonic-pulse. It was shown that the method leads to very reproducible results. The results showed that the beginning of setting can be determined from the velocity vs. age of mortar curve by a mathematical procedure, the final setting is still due to empirical experience. It was concluded the method is adjustable to concrete and can also be used for other materials like gypsum, lime, starch and other stiffening materials. The paper also suggested, it can be used for quality control in production of admixtures and new binders and for control of constancy of concrete production.

Lee .H.K. et al. (2004) observed that the present standard test available for the setting times of concrete is the penetration resistance test specified by ASTM C403. This test, while good for standard concrete mixtures, may not be appropriate for high-performance concrete (HPC) because of the high viscosity of the mortar. To address this issue, the ultrasonic pulse velocities (UPV) were measured using an ultrasonic monitoring system during the first 24 hrs of age for mortar and concrete specimens having various water-to-cementitious materials (w/cm) ratios and with and without fly ash (FA). Various characteristics observed from the measured UPV agreed with the previous theory of cement hydration, which describes the mixture as viscous suspension transforming into saturated porous solid phase. It was also found that the development of UPV in concretes, particularly without FA, was faster than that of mortars with the same w/cm. The values of concrete UPV corresponding to the initial and final setting (ASTM C403) didn't showed a trend consistent with those of mortar UPV. Two alternative criteria were applied to determine the setting characteristics from the UPV evolution curves. They were found to better represent the microstructural changes than the penetration method, as suggested by the consistent trend with decreasing w/cm among various mortars and concretes. Thus, the potential use of these alternative methods was suggested by specifying, at each w/cm, general target UPVs that are valid for both mortar and concrete with or without FA. It was finally concluded that the methods and monitoring device used in this research were useful for the in-situ monitoring of the setting of concrete, particularly in HPC.

Kamada Toshiro et al. (2005) described the relationship between the setting/hardening properties of cement paste and ultrasonic propagation characteristics from both a macroscopic and a microscopic point of view. The first experimental series was aimed at evaluating changes

in the physical properties of high-early-strength cement paste. In the experiment, a single cylinder rotational viscometer was used for viscosity measurement. The second series of experiments was aimed at evaluating changes in the chemical properties of ultra-rapid-hardening cement paste. In the experiment, scanning electron microscopy
(SEM) and powder X-ray diffraction analysis were done to investigate the generation of hydration products. As a result, it was confirmed that the maximum amplitude of the obtained waveform adequately reflects the changes in shear resistance of cement paste. On the other hand, change in ultrasonic wave velocity is well correlated with the formation of ettringite crystals as observed by SEM and powder X-ray diffraction analysis.

Mikulić .D et al. (2005) studied the importance of non-destructive test methods like ultrasound methods for monitoring young concrete setting and hardening process which are the most critical phases during construction works .He showed how Ultrasonic waves can propagate through media as transversal, longitudinal and Rayleigh waves. With ultrasonic methods, it is possible to determine the kinetics and degree of hydratation, setting time, compressive strength and dynamic modulus of elasticity (Sekulić D. et al., 2004). In this paper measurements of longitudinal compressive wave velocity through concrete and mortar during hardening process were performed. For mixtures preparation different additives were used. Obtained results indicate possibility for hardening process monitoring and time of cementitous materials setting determination.

Robeyst .N et al. (2007) studied the setting of fresh mortar and concrete samples, made with Portland cement and four types of blast-furnace slag cement. The early age properties of mortar and concrete samples were continuously monitored with the ultrasonic wave transmission method. A revised measurement setup with new sensors and a preamplifier improved the quality of the acquired signal at very early age. The evolution of the velocity and frequency spectrum of the ultrasonic wave was investigated and compared with the results of traditional methods, such as penetrometer tests.

The results lead to the conclusion that characteristic points in the graphs of penetration resistance and the ultrasonic velocity curves are correlated.

Darquennes et al. (2009) conducted three different techniques to study the evolution of the setting and the hardening of concrete which were later compared: (1) ultrasonic monitoring using the FreshCon system, (2) a resistivity method and (3) the mechanical Kelly-Bryant method. The experimental tests were carried out on two slag cement concretes in order to compare these methods and to evaluate their ability to monitor continuously the setting and hardening process of concretes with different slag content in the cement. Globally, the initial setting age values given by the three methods was in good agreement, but only the two non-destructive methods (ultrasonic and electric) allow determining the final setting. However, it was concluded that the three methods were complementary and the nondestructive methods give additional information (like chemical reactions, stiffness evolution) about the hydration process of cementitious materials. They were also able to tackle the differences in the setting behaviour due to the slag content in the cement.

Muhammad et al. (2009) studied the setting and hardening properties for understanding the green concretes behaviour at early age. The setting and hardening behaviour since casting time of six green concrete mixtures containing high percentage of mineral additions were monitored by applying non-destructive ultrasonic waves. During the test, the ultrasonic velocity, the energy and the frequency spectrum (FFT algorithm) evolution as function of concrete age were computed. The point corresponding to the first inflexion point on the velocity vs. age plot was related to the initial setting time. Tests were carried out at two temperatures (20°C and 10°C) for six mixtures proportions : a reference concrete with Portland cement and the others containing various proportions of blast furnace slag (30%, 50% and 75% of the binder mass content) and fly ash (30% and 50%). In order to check the results obtained with the ultrasonic method, the initial setting time was compared with the Kelly Bryant method. It was concluded that the initial setting measured by the ultrasonic velocity coincides rather well with the time of increase of the pulling force by Kelly Bryant method & increase in mineral addition content delays the setting phenomenon, in case of slag due to its latent hydraulic property and due to slow pozzolanic reaction in fly ash. Result also showed that initial temperature has an inverse effect on the setting of concrete, lower temperature delays the setting notably.

Robeyst .Nicolas & De Belie. Nele (2009) noted that research on ultrasonic methods to monitor the setting of concrete has mainly focused on the wave velocity as a useful quantity. So in order to investigated the application of wave energy as a parameter, the ultrasonic wave transmission technique was performed on several concrete and mortar samples in which increasing amounts of the Portland cement was replaced by blast-furnace slag or fly ash. The transmitted ultrasonic wave energy was calculated as the sum of the squared amplitudes of the received signal, divided by the reference energy (E/Eref). The increase of the energy during setting was retarded if ordinary Portland cement was replaced by blast-furnace slag or fly ash. The final setting determined by the standard penetration resistance test occurred shortly after the peak in the derivative curve of the ultrasonic energy. In addition, the values E/Eref = 0.02 and 0.15 were proposed to easily calculate respectively initial and final setting based on the ultrasonic energy measurements. Due to the sensitivity of the energy measurement to the quality of the sensor contact, it was suggested that care should be taken to limit drying shrinkage of the cementitious samples.

Dumoulin C´edric et al. (2012) noted with the use of embedded piezoelectric transducers to monitor the ultrasonic P-wave velocity evolution during the setting and hardening phases of concrete subsequent to casting time. The main advantage of the technique is the possibility of overcoming the limitations of traditional methods which prevent the application of specific mechanical boundary conditions during the measurement. The embedded transducers are based on the 'smart aggregates' concept previously developed at the University of Houston, Texas. Two piezoelectric transducers are embedded in a prismatic mold and the evolution of the P-wave velocity is recorded for the first 24 h in concrete after the casting time. The results are very promising and show a good agreement with classical ultrasonic tests using external transducers.

Sanish et al. (2012) studied with application of ultrasonic methods on early age concrete to track the strength development in concrete**.** Ultrasonic non-destructive testing is applied in numerous ways to assess the condition of concrete in structures. The applications range from determination of setting characteristics to studying damaged concrete.In the investigation, ultrasonic through-transmission signals were analyzed for their amplitude, and pulse velocity. When concrete changes from the fresh, fluid state to hardened, solid state, changes in the amplitude of the

ultrasonic signal passed through the concrete specimen can be observed. Amplitude values are an indication of total energy passing through the test specimen, from which one can derive energy curves. As the concrete hardens, the amount of energy transmitted through concrete increases and this change is related to strength development in concrete. The methodology was applied in this investigation to a number of different concretes, with mineral and chemical admixtures. Conventional ultrasonic methods for concrete primarily deal with the analysis of the pulse velocity. However, results from this study clearly indicated that velocity need not be the best indicator of strength development. The analysis of the entire ultrasonic signal, rather than just the time of flight, can give useful details that can help in characterizing the early age strength development of concrete, the amplitude of the ultrasonic transmitted pulse, as well as the transmitted energy, were able to present a clearer picture of the rate of change of strength in concrete, as compared to the pulse velocity value.

3.4 CLOSING REMARKS

This chapter gives a general aspect and introduction about the early age strength and hardening of concrete. It discusses the setting and hardening properties of concrete successfully implemented as outlined in literature review.

CHAPTER 4

EXPERIMENTAL INVESTIGATIONS – SETTING PROPERTIES OF CONVENTIONAL AND NON – VIBRATED CONCRETE

4.1 GENERAL

Setting and hardening of fresh concrete are the most critical phases during the construction works, on which properties of concrete structure depends during its service life. During setting process, concrete mixture transforms from fluid state to solid state whose properties are important for the proper behavior of material in the service. This chapter discusses about the guided wave approach that characterizes the early age setting/strength of concrete for conventional concrete which is vibrated and SCC which is non – vibrated. Using a **Pulse-transmission system** and **Pulse echo system**, the method measures the energy leakage of the longitudinal wave mode from a cylindrical mild steel rod to the surrounding concrete. The evolution of the concrete properties is related to the energy leakage or attenuation of the guided wave. The development of concrete (both conventional and self compacting) setting is also studied with well established methods of UPV and Vicat Penetration tests.

In this chapter two properties of concrete are discussed i.e. vibrated and non – vibrated concrete. The various testing techniques, equipment, specimens, concrete mixes used are also highlighted**.**

4.2 EXPERIMENTAL INVESTIGATIONS: ULTRASONIC GUIDED WAVES STUDIES

4.2.1 Setup & Specimen details

The experimental setup consists of DPR 300 pulser/receiver which generates the pulse for every given time interval. The pulse generated has been sent to the transducer which transfers the pulse to an ultrasonic wave. Transmitter transducer has been in contact with the solid mild steel bar of 25mm diameter and 500mm length which is embedded in a concrete slab of size 300 mm x 300 mm x 100 mm and mild steel bar of 25mm diameter and 150mm length which is embedded in a concrete cube of size 150mm x 150mm x 150mm **(Fig 4.1& Fig 4.2)** with the help of a couplant

(ultrasonic gel) and the other end the receiver transducer has been also arranged in the same way. These transducer are connected back to the pulser/receiver, sends the signals to the digitizer card which has been connected to computer hardware as shown in **Fig 4.3& Fig4.4.**

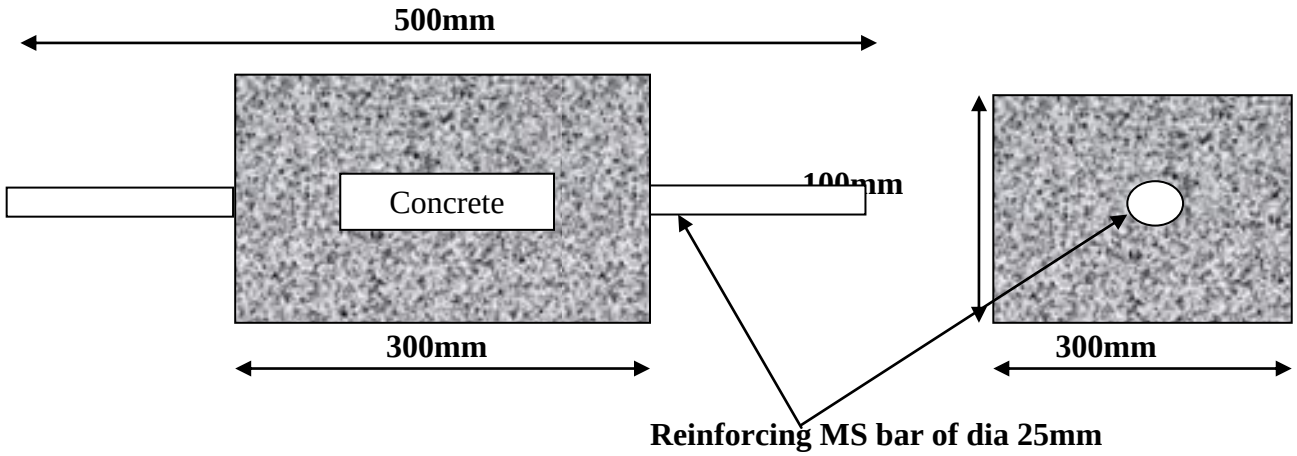


Fig 4.1 Concrete Slab Specimen for guided wave investigations (Pulse transmission)

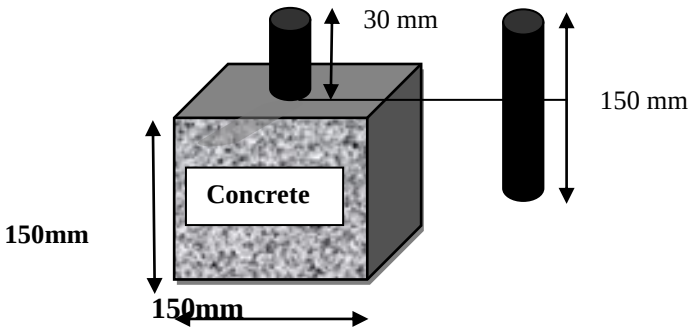


Fig 4.2 Concrete Cube Specimen for guided wave investigation (Pulse echo)

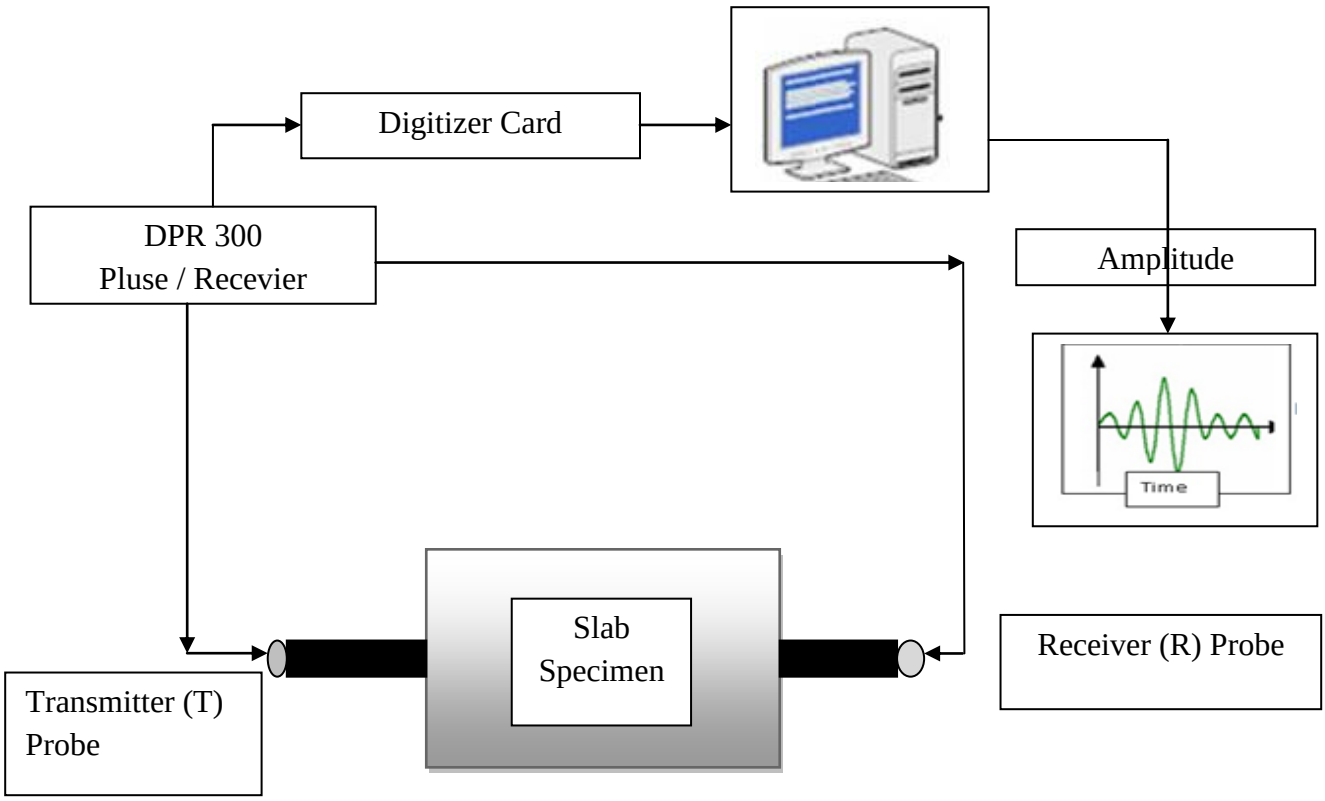


Fig 4.3 Schematic details of Set-Up

Fig 4.4 Actual Set- Up in Use

Driven by the pulser/receiver, the compressional transducer generates ultrasonic pulse that propagates through the steel bar in the form of guided waves. When concrete start setting the surrounding concrete begins making bond with the embedded steel rod which result in attenuation i.e. loss of wave energy occurs. This attenuation is due to material absorption and energy leakage into the surrounding concrete. This attenuation energy is picked up by the receiver transducer and then converted into an electrical signal which has been processed in a computer and digitized for display.

Features of the equipment used are as follows:

(a) Transducer:

It is a single element longitudinal wave transducer. It can be used in straight beam flaw detection and thickness gauging, detection and sizing of delamination, material characterization and sound velocity measurements, inspection of plates, billets, bars, forgings castings, extrusions, and a wide variety of other metallic and non-metallic components. S 24 HB 0.1S (KARL DEUTSCH) & S 24 HB 0.1 E (KARL DEUTSCH) Standard transducers of 0.1 MHz frequency and 24 mm diameter has been used, as shown in **Fig. 4.5.**

Fig. 4.5 Standard KARL DEUTSCH Transducer

(b) JSR Ultrasonics DPR 300 Pulser/ Receiver System:

JSR Ultrasonics DPR300 pulser shown in **Fig 4.6** produces a high voltage electrical excitation pulse (up to 475 Volt) and applies this pulse to the instrument's T/R connector. An ultrasonic transducer connected to the T/R connector via a length of 50 Ω coaxial cable has been then

employed to convert the electrical energy of the excitation pulse into an ultrasonic pulse that has been propagated into a test material or medium.

(a)

(b)

Fig 4.6 JSR Ultrasonics DPR300 Pulser/Receiver (a) Front View & (b) Back View

DPR 300 can be configured to both pulse-echo and through transmission mode operations as discussed below;

- With the DPR300 configured for pulse-echo mode operation, acoustic echoes reflected from interfaces or defects within the test material are converted by the transducer into electrical signals that are presented to the T/R connector of the DPR300. The low-noise DPR300 receiver amplifies these electrical signals, and the signals then pass through adjustable high pass and low pass filters. The DPR300 receiver gain has been adjustable between -13 dB and 66 dB, and there are six high pass and six low pass filter settings for band-limiting the receiver frequency response. The amplified and filtered signals are available on the instrument's Receiver Output connector.

- The DPR300 may also be used in transmission mode operation wherein a separate receiving transducer has been used to detect acoustic pulses that have propagated through a test material or medium.

Fig. 4.7 gives the details of the inside layout of the JSR pulse generator. The sub-units of the JSR pulse-receiver are as given below:

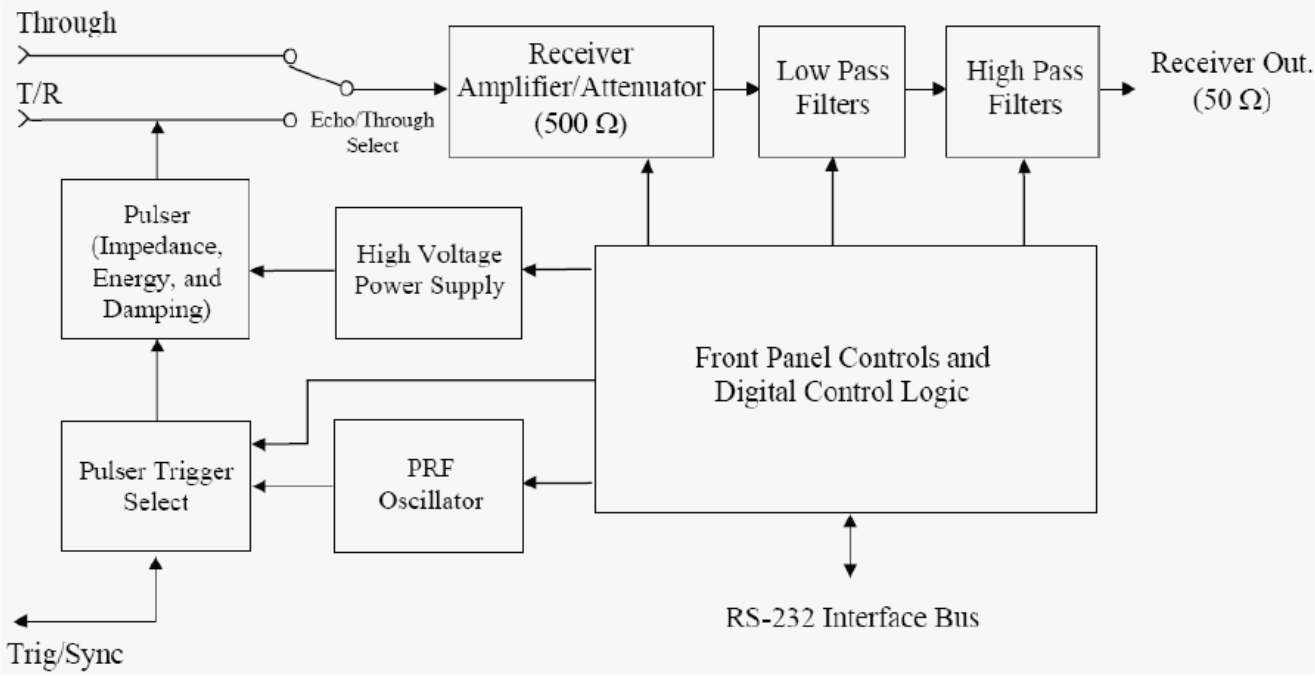


Fig 4.7 Detail circuit diagram of Pulser/Reciever system

PRF Oscillator & Pulser Trigger control:

The internal PRF oscillator generates repetitive trigger pulses for the pulser subsystem under the control of the PRF control. Pulser Trigger control selects between the internal PRF oscillator and an external source applied to the Trig/Sync connector as trigger sources for the DPR 300 Pulser.

Pulser (Impedance/Energy/Damping):

The pulser generates an excitation pulse upon receiving a trigger event from a selected source. There are four energy and two impedance values, and the single Energy and impedance control adjusts the pulse energy and the pulser impedance.

Receiver amplifier:

It controls the amplification or attenuation of signals processed by the DPR300 receiver. The receiver gain can be varied from -13dB to 66 dB.

Low Pass and High Pass filters:

Low filters are available for reducing the bandwidth of the DPR300 receiver. High Pass filters are available for eliminating undesirable low frequency energy from the DPR300 receiver signal. High pass filtering can be used as a means of providing faster receiver recovery from strong signals such as the excitation pulse or strong interface echoes.

Table 4.1 gives the specifications of JSR pulse-receiver.

Table 4.1 Specifications of JSR pulse-receiver

Pulser	
Pulse Type	Negative Spike Pulse
High Voltage Supply	100V to 475V
Initial Transition (Fall Time)	<5 ns (10-90%) typical for 475V pulsers
Pulse Amplitude	-475V peak. Amplitude depends on Energy, Impedance, Damping control settings, and pulser type

Pulse Energy	1.55 μJoules minimum, 304 μJoules maximum for 475V pulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically 10-70 ns FWHM for 50 Ω load. Function of the Energy, Impedance, and Damping controls
Damping	16 Damping values: 331, 198, 142, 110, 92, 77, 67, 59, 52,47, 43, 39, 37, 34, 32, and 30 Ω
Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically 80 dB at 10 MHz
Pulser Repetition rate	Internal: 100 Hz -5 kHz for 475V pulsers. External: 0-5 kHz for 475V pulsers.
Sync Output	Maximum +5 V, tr <30 ns, tw=50 ns.min. TTL and CMOS compatible. Minimum value of load impedance is 50 Ω
Pulser Trigger Source	Selectable by computer between internal oscillator and external source
External Trigger Input	2- 5 V positive going pulse. Triggering will occur synchronously with leading edge of trigger signal. TTL and CMOS compatible
Receiver	
Gain	-13 to 66 dB in 1 dB steps controlled by the host computer
Phase	0° (non inverting)
Input Impedance	500 Ω (through transmission)

Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHZ
High Pass Filter	DC,1,2.5,5,7.5 and 12.5 MHz
Low Pass Filter	3,7.5,10,15,22.5 (35 MHz BW) or 5,10,15,22.5,35 (50MHz BW)
Receiver Noise	Typically 49 μV pk-pk input referred (measured at 60dB,35 MHz bandwidth)
Output Impedance	50 Ω
Output Voltage	± 0.5 V into 50 Ω

(c) Dual-Channel High-Resolution Waveform Digitizer:

Model DC438 Dual-channel, 12-bit, 100 MHz, 200 MS/s, 4-M point acquisition memory card had been used to capture the waveform. Waveforms are transferred directly into the digitizer large acquisition memories so that complex signals can be stored over very long time periods. Large memories are essential for maintaining fast sampling rates and therefore timing resolution. **Table 4.2** gives the specifications of the Digitizer Card.

Table 4.2: Specifications of Digitizer Card

Model DC438	
Bandwidth(-3 dB)	DC to 100 MHz
Full Scale Range (FSR)	250 mV, 500 mV, 1 V, 2 V, 5 V and 10 V
Impedance	50 Ω ± 1% @ DC
Connector	BNC, gold-plated
Channels	Two
Coupling	DC

Maximum Input Voltage	±10 V DC (2 W) or 10 V RMS at 50 Ω
Bandwidth Limit Filter	35 MHz 2-pole Bessel filter (DC438)
Minimum Amplitude	1 V pk-pk
Impedance	50

4.2.2 Methodology

4.2.2.1 Method Of Testing

Pulse-transmission method is used for characterizing the young concrete strength and hardening process. To produce guided waves in the bar of concrete slab two transducers (Karl Deutsch contact type) are attached at the two ends of the bar in projected slab. One transducer acting as a transmitter and the other acting as a receiver are attached parallel to the axis, Similarly Pulse echo method is used for characterizing the young concrete strength and hardening process. To produce guided waves in the bar of concrete slab and cube one transducer (Karl Deutsch contact type) is attached to the bar which is acting perpendicular to the axis of slab and cube. Transducers having longer wave form duration and a relatively narrow frequency bandwidth with centre frequency of 0.1 MHz (surface seeking mode) has been used because the main aim of the experiment was to monitor the bonding between the 25mm mild steel rod & the surrounding concrete in the slab and cube.

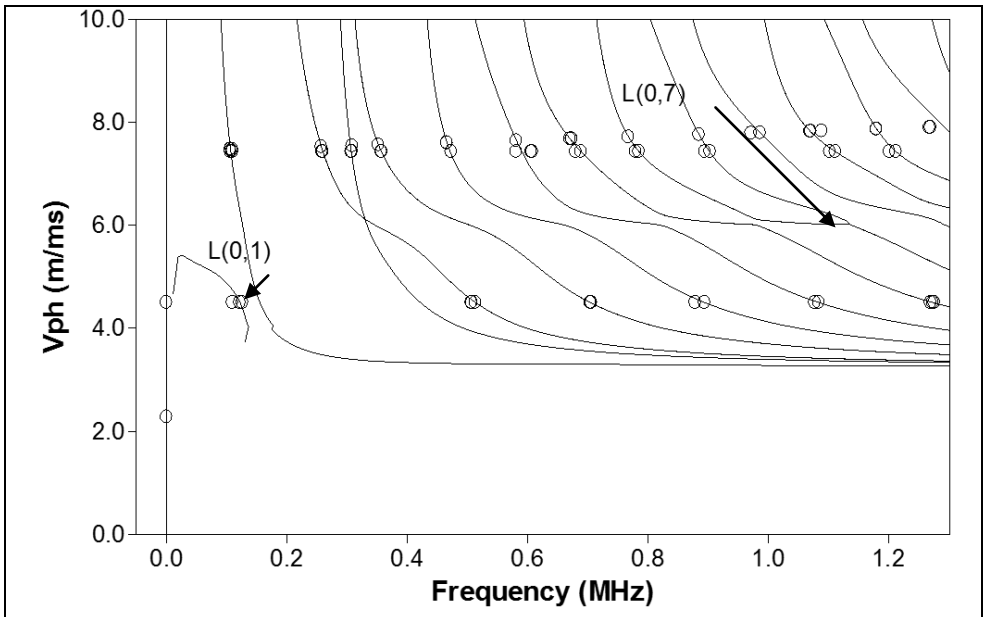
4.2.2.2 Selection of Excitation Mode and Frequency

The selection of frequencies for testing is done using the software Disperse (Pavalakovic and Cawley, 2000). The selection of a suitable test mode and frequency can be made by close examination of the dispersion curves. The modes that are easily distinguishable and have lowest signal attenuation are selected (Sharma and Mukherjee, 2010).It is desirable to use a mode at a point of low attenuation, to maximize the inspection range, and to use a mode at a point of maximum energy velocity, to limit the effects of dispersion, and to reduce the risk of other modes complicating the received signal (Beard et al. 2003). Dispersion curves for a 25mm bar embedded in concrete are plotted as shown in **Fig 4.8**. Only longitudinal modes have been considered in the

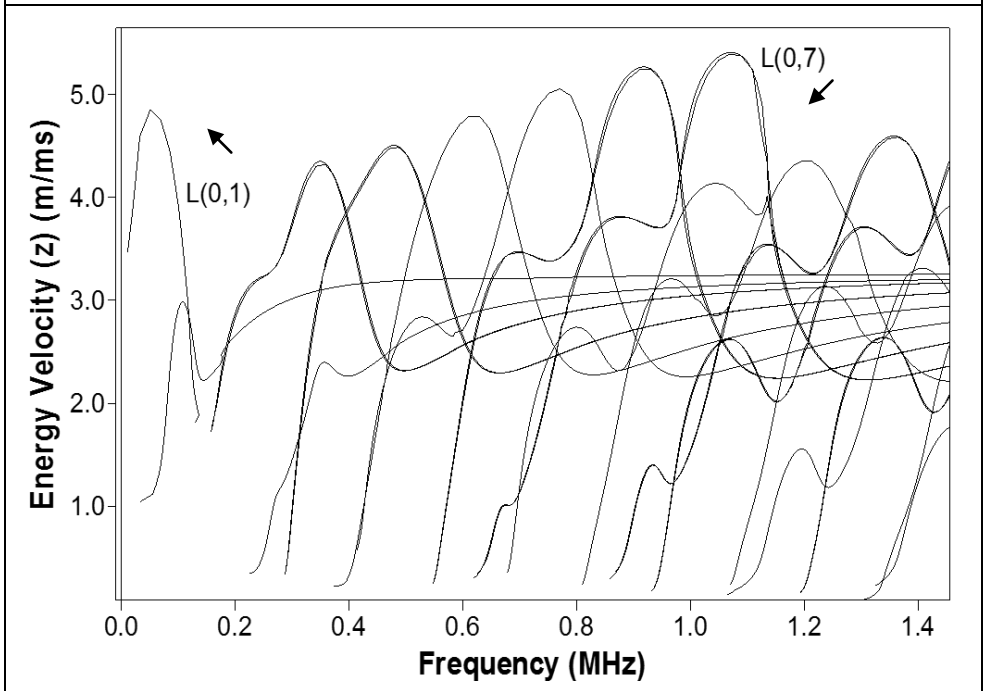
study as the flexural and torsional modes experience high theoretical attenuation. Guided longitudinal waves are produced in the embedded bars by keeping compressional transducers parallel to the guiding configuration at the two ends of the bars embedded in concrete. The different longitudinal modes are excited by varying the excitation frequencies. The selection of frequencies for testing is done based on the phase velocity dispersion curves **Fig 4.8(a)**. They are validated by experimentally confirming the signal fidelity.

In this work where bars are embedded in concrete, which is a layered waveguide system, leakage plays an important role. High frequency low attenuating modes with displacement profiles centered in the middle of bar to minimize leakage (Bazant, 1979) are found to be the best for layered systems. Phase velocity dispersion curves show the fundamental L (0, 1) mode starting at zero frequency with each higher order mode starting from a higher cut off frequency. Each of the higher modes shows a plateau region around the steel longitudinal bulk velocity line.

Another contributing factor to the selection of mode is the relative sensitivity of ultrasonic waves to setting of concrete. **Fig 4.9(b)** shows the displacement mode shape and radial strain energy density distribution for L (0, 7) mode not selected in the present investigation. The energy is concentrated in the central core portion of the bar and has relatively less surface component. Hence, it should be more sensitive to local bar topography or loss of material changes and not the surface profile changes. ***It is a core seeking mode***. Thus, this mode may not be sensitive to bonding between mild steel rod and surrounding concrete that is more of a surface phenomenon. A mode that has significant surface component would be sensitive to bonding effect of concrete on the bar. Such mode is L (0, 1) mode at a low frequency of 100 kHz (0.1 Mhz) having negligible amount of signal loss due to material absorption. This mode shows significant axial displacement at the interface and is ***a surface seeking mode*** as shown in **Fig 4.9(a)** and hence, is chosen to monitor the bond development at 100 kHz.

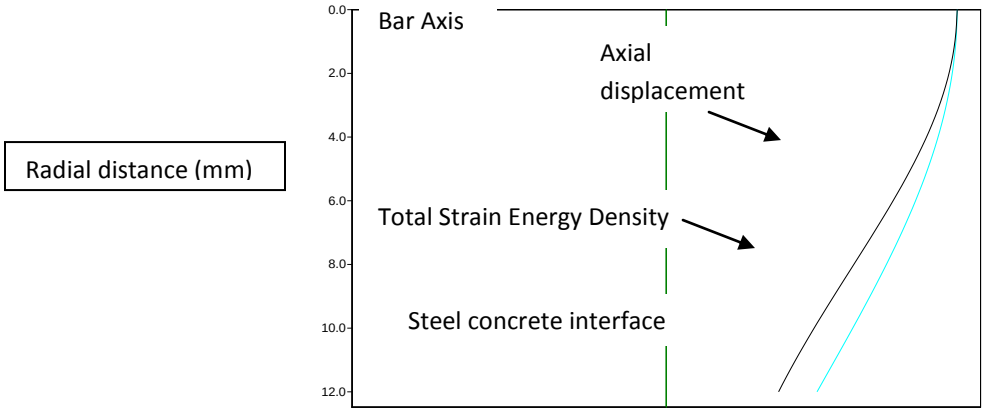


(a) Phase velocity Vs Frequency

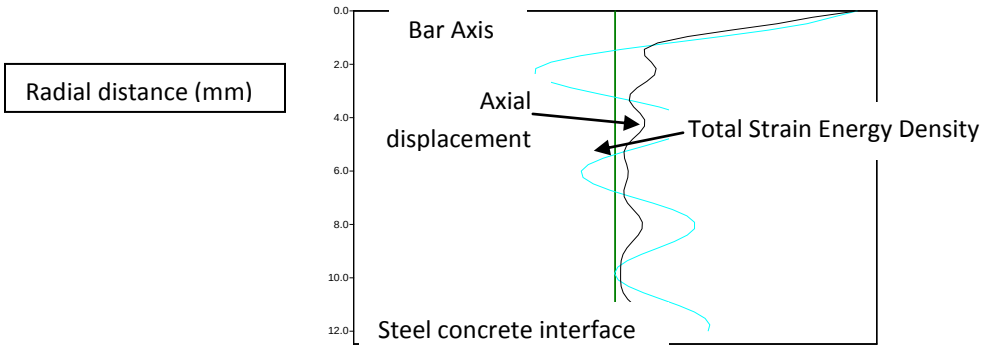


(b) Energy Velocity Vs Frequency

Fig 4.8 Dispersion curves for 25mm diameter bar (Sharma and Mukherjee, 2010)



(a) Surface Seeking Mode L(0,1) at 0.1 Mhz



(b) Surface Seeking Mode L(0,7) at 1 Mhz

Fig.4.9 Mode Shapes (Sharma and Mukherjee, 2010)

4.3 EXPERIMENTAL INVESTIGATIONS OF ULTRASONIC PULSE VELOCITY (UPV)

4.3.1 Set-Up & Specimen Detail

TICO Ultrasonic Instrument: ZI 10006 as shown in **Fig 4.10** was used to measure the velocity(m/sec) of the ultrasonic wave as it passes from concrete specimen as it gain its strengthduring first phase (setting) .

Fig 4.10 TICO Ultrasonic Instrument : ZI 10006

The concrete specimens used in UPV testing are shown in **Fig 4.11**. During the first phase the UPV test is performed on cube during the whole setting process (hrs).

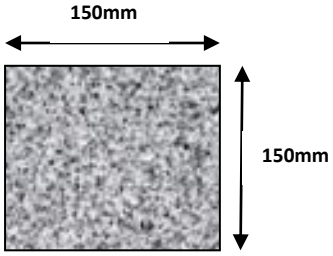


Fig 4.11 Concrete cube specimen for UPV investigation

Components of TICO Ultrasonic Instrument

The various components of TICO UPV Instrument have been shown in **Fig 4.12**.

Fig 4.12 Components of TICO Ultrasonic Instrument

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer, which is held in contact with one surface of the concrete specimen under test. When the pulse generated is transmitted into the concrete from the transducer using a liquid coupling material such as grease or cellulose paste, it undergoes multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves develops, which include both longitudinal and shear waves, and propagates through the concrete. The first waves to reach the receiving transducer are the longitudinal waves, which are converted into an electrical signal by a second transducer and displayed in the digital display unit as shown in **Fig 4.13**. Electronic timing circuits enable the transit time T of the pulse to be measured.

Longitudinal pulse velocity (in km/s or m/s) is given by:

$$v = \frac{L}{T} \qquad \ldots\ldots. (4.1)$$

Where;

V is the longitudinal pulse velocity, L is the path length, T is the time taken by the pulse to traverse that length.

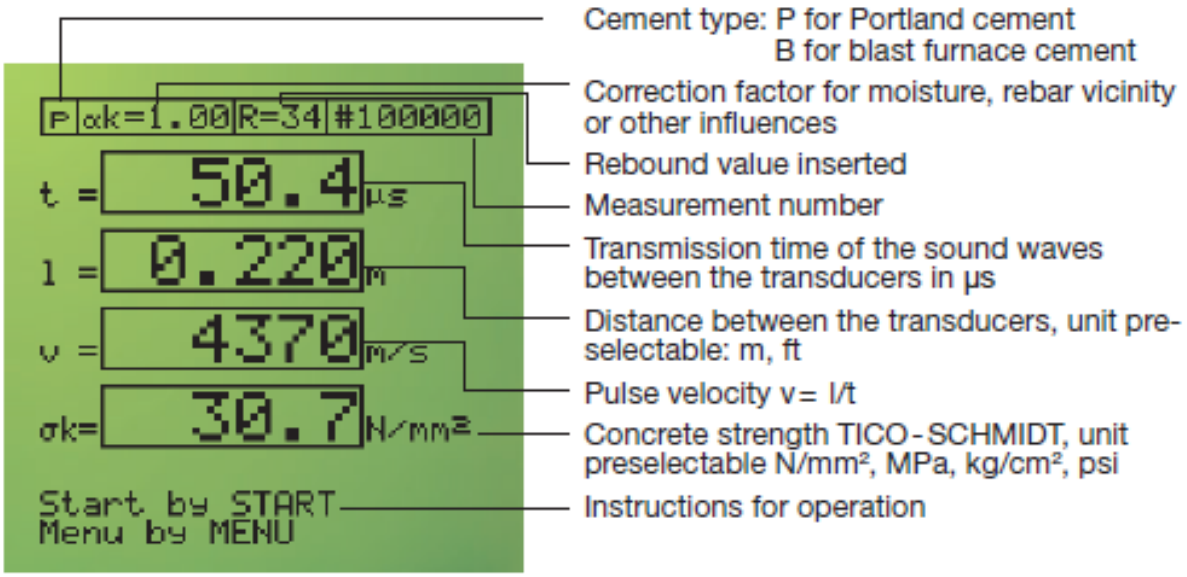


Fig 4.13 Display Unit of TICO Ultrasonic Instrument

The technical specifications of the display unit are given in **Table 4.3** as follows;

Table 4.3 Specifications of TICO Ultrasonic Instrument Display Unit

Display	128 x 128 graphic LCD
Interface	RS 232 or with adapter* to USB
Integrated software	for transmission of the measured values to PC
Measuring range	~15 to 6550 µs
Resolution	0.1 µs
Voltage pulse	1 KV
Pulse rate	3/s
Impedance at input	1MΩ

Temperature range	-10° to + 60°C for instrument
Recommended range for measurements	0°C to 50°C only
Battery	6 LR 6, 1.5 V (30 hours operation)

4.3.2 Methodology

In this research work, UPV measurements are taken by **direct transmission** arrangement of transducers in both early age setting (first phase) at different hrs for both vibrated and non-vibrated concrete specimen as shown in **Fig 4.14.** Direct transmission arrangement of transducers was used, since the transfer of energy between transducers is at its maximum and the accuracy of velocity determination is therefore governed principally by the accuracy of the path length measurement.

Fig 4.14 First phase i.e. early age setting or strength monitoring

4.4 EXPERIMENTAL INVESTIGATIONS OF VICAT PENETRATION TEST

Penetration testing was conducted using a Vicat Penetration apparatus as shown in **Fig 4.15** during the first phase only when the concrete is wet. The main objective of this test was to study the penetration depth in mm of the needle in concrete cylinder as shown in **Fig 4.16**.

(a) Vicat Needle Apparatus (b) Measuring Scale attached to instrument

Fig 4.15 Vicat Penetration Testing Apparatus

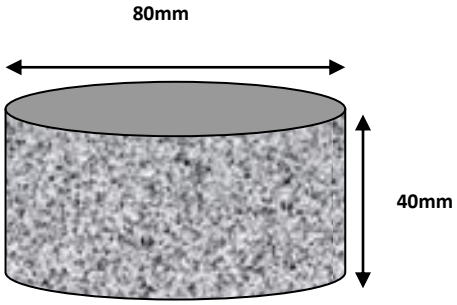


Fig 4.16 Concrete Cylinder for Vicat Penetration Test investigations

4.5 EXPERIMENTAL INVESTIGATIONS OF DESTRUCTIVE TESTING

Automatic Universal Testing Machine (UTM) of capacity 1000kN was used to conduct various destructive tests on different concrete specimens in the hardening phase. The various tests performed on UTM are as follows:

4.5.1 Compressive Strength Testing

Compression test was carried out in order to determine the strength developed by the concrete specimen (both vibrated and non-vibrated) i.e. cubes at different curing times (3, 7& 28 days) as shown in **Fig 4.17**.

(a) Complete setup **(b) Before Testing** **(c) After Testing**

Fig 4.17 Compression Testing of Cube using UTM

4.5.2 Split Tensile Testing

Split Tensile Testing was conducted on cube and cylinder specimen of specifications belonging to final phase for both vibrated and Non-vibrated concrete i.e.(3.7&28 days) **(Fig 4.18).**

(a) Showing Placing of Test specimen **(b) Before Test** **(c) After Test**

(a) Before testing **(b) After Testing**

Fig 4.18 Split-Tensile Testing of Cylinder and Cube using UTM

4.6 SETTING PROPERTIES OF CONVENTIONAL CONCRETE

In this work ultrasonic guided waves approach is used for monitoring setting properties of vibrated concrete by means of ultrasonic investigations . To characterize the phenomenon of hardening of concrete ,destructive tests like compressive test and Split-tensile test were also conducted at different stages of hardening of concrete . Idea was to corelate the ultrasonic test results with other established strength development methods and also with in-situ strength of concrete.

4.6.1 Experimental Investigations

The experimental program in this work has been divided into two phases whose details are given in **Fig 4.19** .

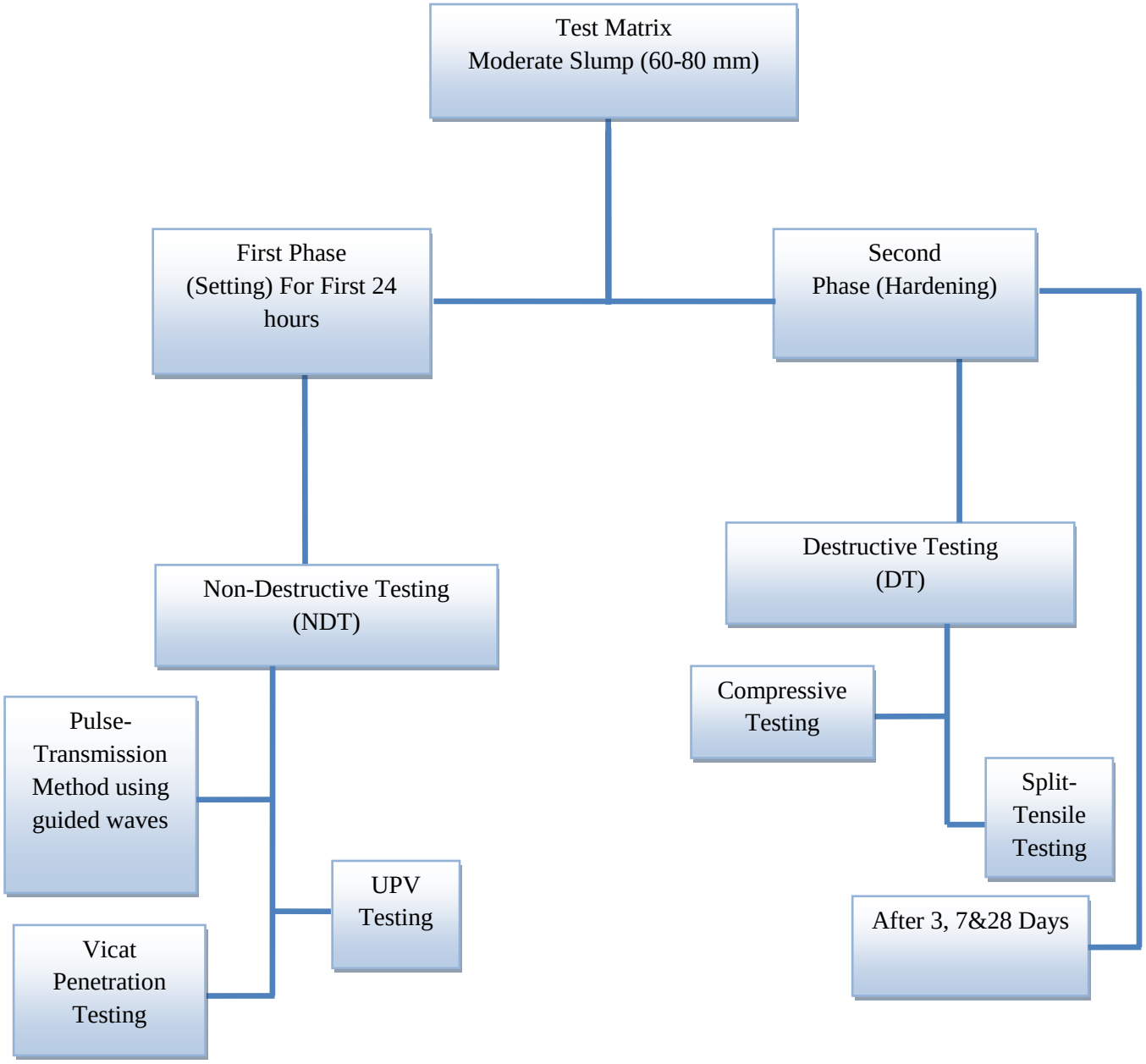


Fig 4.19 Experimental Program For Conventional Concrete

Experimantal Study

The experiments were divided into two phases.In the initial phase, setting phenomenon is studied using non-destructive techniques . For this purpose guided waves investigation in pulse echo and pulse transmission modes was undertaken. Results were compared with established setting property parameters of UPV and Vicat Penetration depth to establish relation between ultrasonic voltages and in-situ strength of concrete. Mix proportions of the constituents for vibrated concrete are given in **Table 4.4**.

Table 4.4 Concrete Mix Used

Concrete Mix	Mix Proportions				w/c Ratio	Slump (mm)
	Cement	Fine Aggregate	Coarse Aggregate	Superplastizer (%)		
M_1	1	1.5	3	------	0.42	Moderate 60 – 80

In the Second phase , the hardening phenomenon was studied by conducting destructive tests of compessive strength and split- tensile strength after 3,7 and 28 days of curing.

Specimen Specifications for intial and hardening phase are detailed in **Fig 4.5**.

Table 4.5 Specimens Used For Conventional Concrete

Phase	Specimen	Specifications	Test Conducted	
			Non – Destructive	Destructive
	Concrete Slab with embedded mild steel bar	Slab = 300x300x100 Steel Bar = 25 dia & 500 length	Ultrasonic Pluse transmission (UPT)	

First Phase (Setting)	Thin Cylinder	Diameter = 80 Height = 40	Vicat Penetration Test	
	Concrete cube	Cube= 150x150x150 Steel Bar =25 dia & 150 length	Ultrasonic Pulse Velocity(UPV) Ultrasonic Pluse transmission	
Second Phase (Hardening)	Concrete cube	Cube =150x150x150		Compressive Test & Split Tensile Test
	Cylinder	Diameter = 150 Height = 300		Split Tensile Test

4.6.2 Physical Properties Of Materials Used

4.6.2.1 Cement

Portland Pozzlana Cement (PPC) of 53 grade from a single lot was used throughout the course of investigation . The properties match with requirements of specification given by IS:8112-1989 . The physical properties of PPC are shown in **Table 4.6**.

Table4.6 Physical Properties Of PPC

Characteristics/ Properties	Observed Value
Fineness	1%

Initial Setting Time	2 hour		
Final Setting Time	4 hour		
Specific Gravity	3.03		
Standard Consistency	34%		
Compressive Strength (MPa)	3 days	7 days	28 days
	15.71	21.61	35.97

4.6.2.2 Fine Aggregate

Sand made of crushed aggregates was used as fine aggregates.. The properties match with requirement of specifications given by IS: 383-1970. The sieve analysis and physical characteristics of fine aggregate is discussed in **Table 4.7** and **Table 4.8** respectively.

Table 4.7 Sieve Analysis of Fine Aggregate

S.No.	**Sieve Size**	**Mass Retained**	**Percentage Retained**	**Cumulative Percentage**	**Percent Passing**
1	4.75mm	90.5	9.05	9.05	90.94
2	2.36mm	37	3.7	12.75	87.25
3	1.18mm	65	6.5	19.25	80.75

4	600µ	257	25.7	44.95	55.05
5	300µ	413	41.3	86.25	13.75
6	150µ	135.5	13.5	99.8	.2
7	Pan	2	0.2	∑=272.00	0

Total Weight taken = 1000gm

Fineness Modulus Of Fine Aggregate = 2.72

Table 4.8 Physical Characteristics of Fine Aggregate

S.No.	Characteristics	Values
1	Specific Gravity	2.6
2	Fineness Modulus	2.72
3	Water Absorption	0.8%
4	Grading Zone	Zone III
5	Bulk Modulus	1.4

4.6.2.3. Coarse Aggregate

Locally available crushed stone aggregates of 12.5 mm nominal maximum size were used as coarse aggregate. The aggregate was first sieved through 50 micron sieve in order to remove the dirt and other impurities. The sieve analysis of coarse aggregate is discussed below in **Table 4.9 .**

Table 4.9 Sieve Analysis of Coarse Aggregate

Designation	Weight retained (Grams)	Percentage weight retained (%)	Cumulative percentage weight retained (%)
40 mm	0	0	0
20 mm	0	0	0
10 mm	1131	56.55	56.55
4.75 mm	827	41.35	97.9
Pan	42	2.10	100

Fineness modulus = 7.54

Specific gravity = 2.64

Bulk Density = 1690 Kg/m^3

4.6.2.4 Water

Portable tap water is used in the entire study.

4.7 Non-Vibrated Concrete (Self Compacting Concrete)

It is proposed in this work to use ultrasonic guided wave approach for studying setting properties of self compacting concrete. It is the first attempt in area of SCC using non – destructive technique.The progression of setting process is monitored by means of ultrasonic investigations. The development of concrete setting is also studied with well established methods of UPV and Vicat Penetration tests. To characterize the phenomenon of hardening of concrete, destructive tests like compressive test, & split-tensile test were also conducted at different stages of hardening phases. Two mixes of SCC with variable slump wereb fabricated to study the effect of superplastizier dosage on the setting characteristics.

4.7.1 Experimental Investigation

The experimental program in this work is divided into two phases whose details are given in **Fig 4.20**.In the initial phase ,setting properties of SCC are studied using guided waves ,ultrasonic pulse velocity measurements and Vicat Penetration test .

In the final phase, hardening properties of SCC are studied using compression test and split-tensile test.

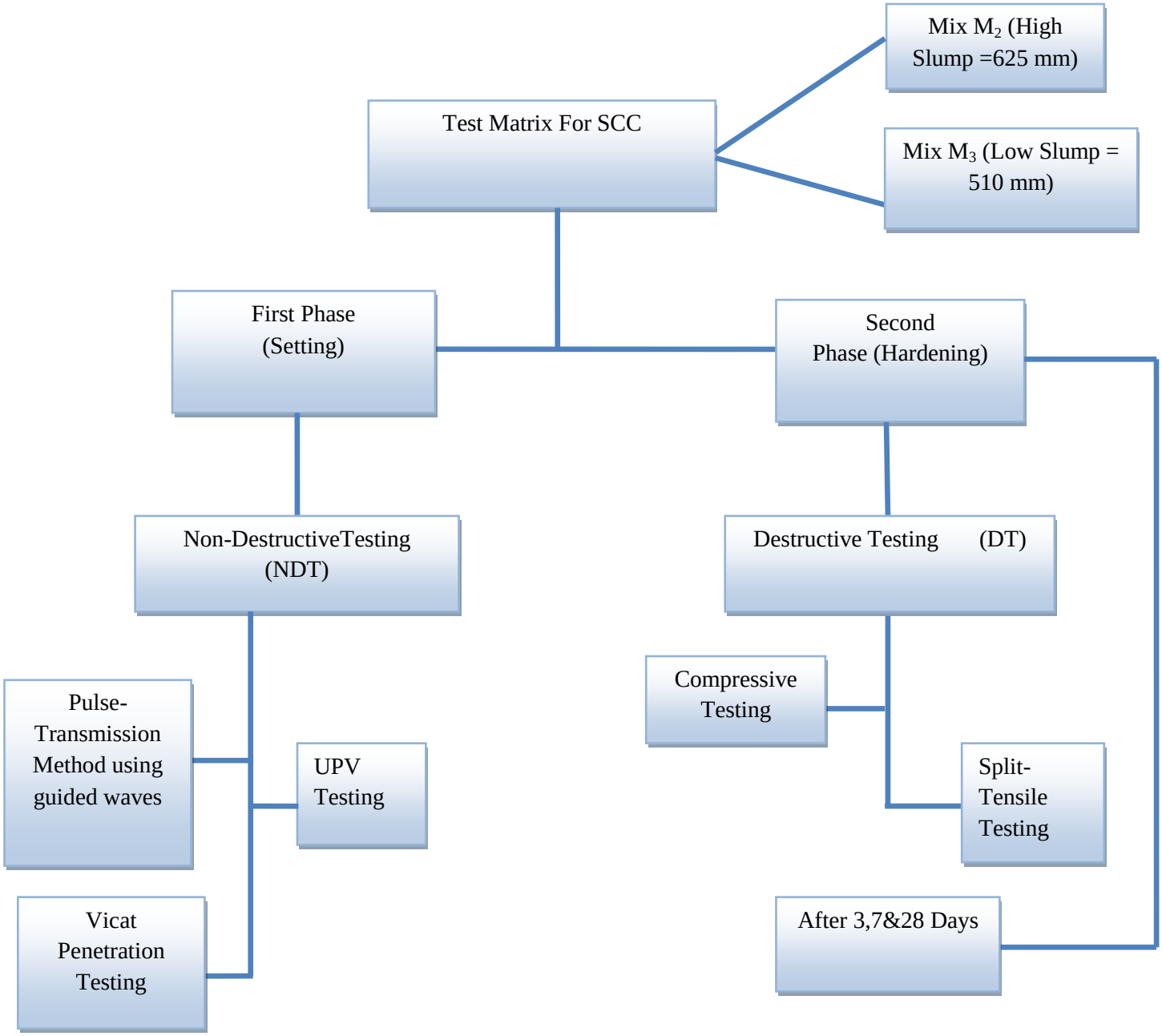


Fig 4.20 Experimental Program For Non-Vibrated Concrete

4.7.2 Physical Properties Of Material Used

4.7.2.1 Cement

Portland Pozzlana Cement (PPC) as used in conventional concrete was used for SCC mix also.

4.7.2.2 Fine Aggregate

Sand made of crushed aggregate as used in conventional concrete was used for SCC mix also.

4.7.2.3 Coarse Aggregate

Locally available crushed stone aggregates of 10 mm nominal maximum size were used as coarse aggregate. The physical properties of coarse aggregate are discussed below in **Table 4.10.**

Table 4.10 Physical Properties of Coarse Aggregate

S.No.	Characteristics	Value
1	Type	Crushed
2	Specific gravity	2.62
3	Total water absorption	0.8%
4	Fineness modulus	7.94

4.7.2.4 Superplastisizer

Conplast SP430 complies with IS: 9103 :1973 and BS:5075 part3 and ASTM-C-494 Type 'F' as a high range water reducing admixture.Conplast is based on sulphonated napthalene formaldehyde condensate ploymers . It is supplied as brown liquid instantly dispersible in water and specially formulated to give high water reduction up to 25% without loss of workability with specific gravity ranging from 1.22 to 1.225 at 30^0C . Physical properties of SP430 are discussed in the **Table 4.11.**

Table 4.11 Physical properties of SP430

Physical properties of SP430		
1	Physical State	Liquid
2	Colour: Brown. Odour: Slight/faint. pH(concentrate): 7 - 8 Boiling Point/Range (°C): >100 °C Flash Point (closed	Brown
3	Odour	slight/faint
4	pH	7 – 8
5	boiling point	>100
6	flash point (closed)	None
7	vapour pressure	2.3 (water)
8	Relative density	1.20
9	water solubility	Soluble

4.7.3 Mix Design

There is no specific method to prepare SCC but few researchers have given their mix design methods and some guidelines. **Su Nan (2001)** method for mix design of SCC was followed to prepare mix design. But the mix design prepared did not satisfy the limits for the various tests specified by **EFNARC (2002)**. The initial mix design (Kg/m^3) based on **Su Nan (2001)** method is as follows:-

Cement	Fly ash	Sand	Coarse Aggregate	Water
200	159	1117	816	161

But this mix design was not successful to prepare SCC. So, the adjustments were done and the different trial mixes were prepared by varying the binder, coarse aggregate and fine aggregate contents. Then, the following mix designs were got after some adjustments in the different contents as given in the **Table 4.12.**

Table 4.12 Mix Proportions For SCC (in kg/m^3)

Concrete Mix No.	**Cement**	**Fine Aggregate(10mm)**	**Coarse Aggregate**	**Water**	**Superplastizer (%)**	**w/p Ratio**
M_2	600	890	530	260	2%	0.433
M_3	600	890	530	255	1.7%	0.425

The test mixes were subjected to various tests to ensure the composition and characteristics of SCC.

4.7.4 Fresh Properties Of SCC

Self- Compacting Concrete is characterized by filling ability, passing ability and resistance to segregation. Many different methods have been developed to characterize the properties of SCC. No single method has been found till date, which characterizes all the relevant workability aspects, and hence, each mix has been tested by more than one test method for the different workability parameters. **Table 4.13** gives the recommended values for different tests given for mix to be characterized as SCC mix.

Table 4.13 Recommended Limits for Different Properties (Nagataki S et al., 1995), (EFNARC ,2002)

S.No.	Property	Range
1	Slump Flow Diameter	500-700mm
2	T_{50cm}	2-5 sec
3	V-Funnel	6-12 sec
4	L-Box	0.8 to 1.0
5	U- Box	0-30mm

Slump Flow Diameter

Slump flow test measures the filling ability of SCC. The freshly prepared concrete mix was poured in the slump cone and when the cone is filled, the cone is pulled off. The diameters of the concrete are measured twice diagonally and mean diameter is considered. The optimum value of slump flow is 500 – 700 mm according to Nagataki S et al.,(1995). Also the time for crossing the 500 mm diameter on the steel plate was recorded for every mix. According to EFNARC, (2002), the T_{500} value should lie between 2 to 5 sec.

Fig4.21 Slump-Flow

V-Funnel test

The freshly prepared SCC mix was filled in the V-funnel and the gate of the funnel was opened. The time taken by SCC to pass through the V-funnel was noted. The time limits should lies between 6-12 seconds according to EFNARC, (2002) This procedure measures the filling ability of the SCC. Segregation resistance of the fresh SCC was also tested using V- funnel apparatus. To measure segregation resistance, the V-funnel was refilled with concrete and allowed to sit for 5 minutes. The door was again opened and the flow time was again recorded.

Fig4.22 V-funnel

L-box test

The L-box test measures the filling and passing ability of self-compacting concrete. SCC so obtained is passed from L-box. The L-box was filled with SCC and then gate of the L-box was opened. After the concrete came to rest in the apparatus, the heights of the concrete at the end of the horizontal portion, H2, and in the vertical section, H1, were measured. The value of blocking ratio, H2/H1 measures the passing ability of every SCC. The value of blocking ratio should lie between 0.8 to 1.0 according to EFNARC ,(2002).

Fig4.23 L- Box

U- box test

The U-box test measures filling ability and is similar to the L-box test. The U-box was filled with SCC and the door dividing the two halves of the box is opened and concrete is allowed to flow from the left half of the box into the right half. Reinforcing bars are placed at the location of the door. The time from the opening of the door until the concrete ceases to flow is recorded. The height of the concrete in each side of the box is measured. The value of height (h_2-h_1) mm should varied between 0 to 30 mm according to , EFNARC ,(2002).

Fig 4.24 U-Box

In the experimental work as per the apparatus available V – Funnel, Slump Flow Diameter ,L Box and U- Box test, should conducted and results are mentioned in **Table 4.14** below.

Table 4.14 Workability test for Non-Vibrating Concrete

Mix	V- funnel Time (sec)		Slump Flow Dia.(mm)		Slump Flow Time t_{500}(sec)		L-box (H_2/H_1)		U-box	
	Values obtained	Acceptance* Criteria	Values obtained	Acceptance* Criteria	Values obtained	Acceptance* Criteria	Values obtained	Acceptance* Criteria	Values obtained	Acceptance* Criteria
M_2	7.1	6-12	625	500-700	3.5	2-5	0.98	0.8-1	26	0-30
M_3	11	6-12	510	500-700	4.5	2-5	0.83	0.8-1	28	0-30

*Acceptance Criteria as per (Nagataki S et al., 1995), (EFNARC, 2002)

As can be seen, the two mixes satisfied the workability requirements for SCC and were further used for studying the bond development and setting properties of SCC according to test matrix given in **Fig4.20.**

In the second phase SCC mixes M2 and M3 were used for casting specimens as given in **Table 4.15** , for curing of 3 days , 7 days and 28 days . After completion of these tests such as compressive test, and Split-Tensile Test were performed

Table 4.15 Specimens Used in the Experimental Program

Phase	Specimen	Specifications	Test Conducted	
			Non - Destructive	Destructive
First Phase (Setting)	Concrete Slab with embedded mild steel bar	Slab = 300x300x100 Steel Bar = 25 dia & 500 length	Ultrasonic Pluse transmission (UPT)	
	Thin Cylinder	Diameter = 80 Height = 40	Vicat Penetration Test	
	Concrete cube	Cube= 150x150x150 Steel Bar =25 dia & 150 length	Ultrasonic Pulse Velocity(UPV) Ultrasonic Pluse transmission	
	Concrete cube	Cube =150x150x150		Compressive Test & Split Tensile Test

Second Phase (Hardening)	Cylinder	Diameter = 150 Height = 300		Split Tensile Test

4.8 CONCULDING REMARKS

This chapter gives the physical characteristics of materials used for making conventinal concrete and self compacting concrete.The outline of the experimental program with details of the specimens and tests to be conducted for determining the setting properties of the conventional and self compacting concrete to draw the comparision between the two is done.

CHAPTER 5

RESULTS AND DISSCUSSIONS

This Chapter discusses the results obtained by conducting different experiments on conventional concrete and self compacting concrete to determine the setting characteristics and phenomenon. The schedule and test method of experiment is given in Chapter 4.

5.1 GUIDED WAVE INVESTIGATION RESULTS

Ultrasonic pulse transmission (UPT) using frequency of 0.1 MHz was conducted on a slab specimen of size 300mm x 300mm x 100mm with an embedded mild steel rod of 25 mm diameter and 500mm length. Ultrasonic pulse echo (UPE) using frequency of 0.1 MHz recorded on cube specimen of size 150mm x 150mm x 150mm with an embedded mild steel rod of 25 mm diameter and 150mm length **(Fig 4.3)**. The tests were done on both vibrated and non – vibrated concrete. The ultrasonic signatures were taken at regular time intervals. One such image of waveform captured by digitizer card is shown in **Fig 5.1** below. The results are plotted as V-t (Voltage vs Time) graphs and pk-pk voltage is measured.

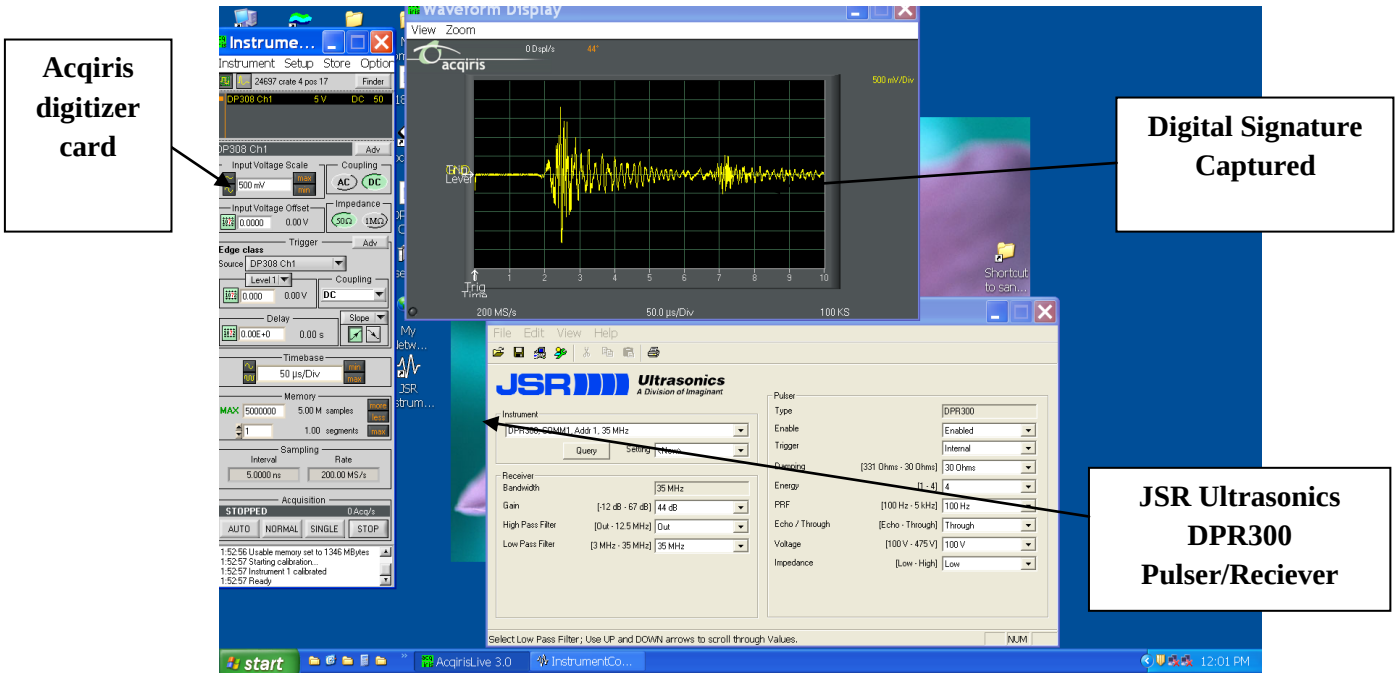


Fig 5.1 Image of waveform captured slab in pulse transmission for Vibrated Concrete

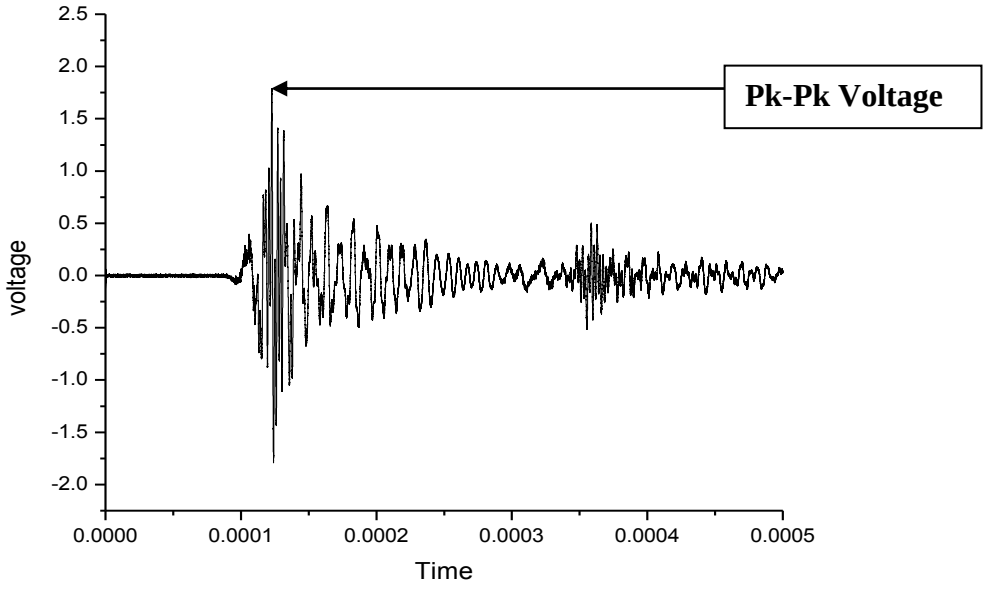


Fig 5.2 pk-pk V-t Signature of ultrasonic pulse transmission (UPT) slab specimen for vibrated concrete

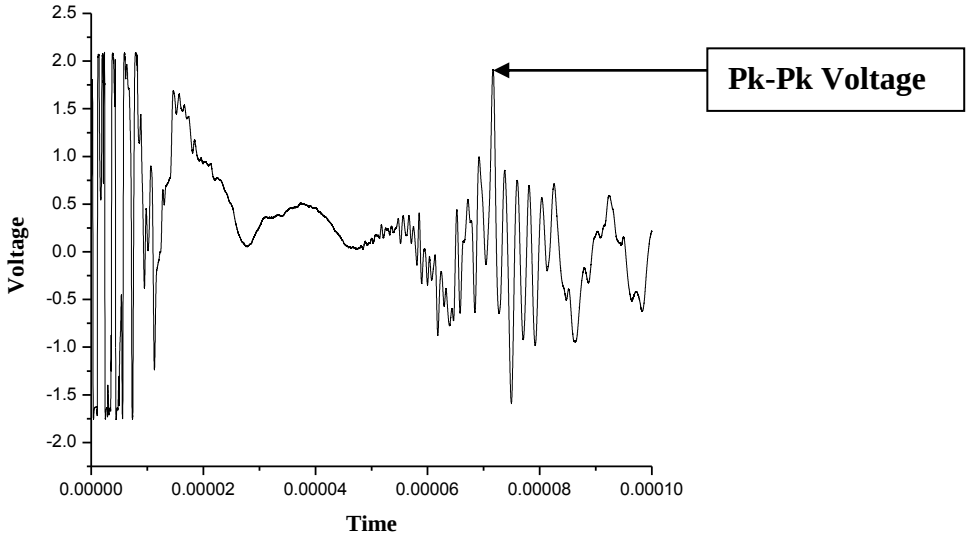


Fig 5.3 pk-pk V- t Signature of UPE cube specimen for vibrated concrete

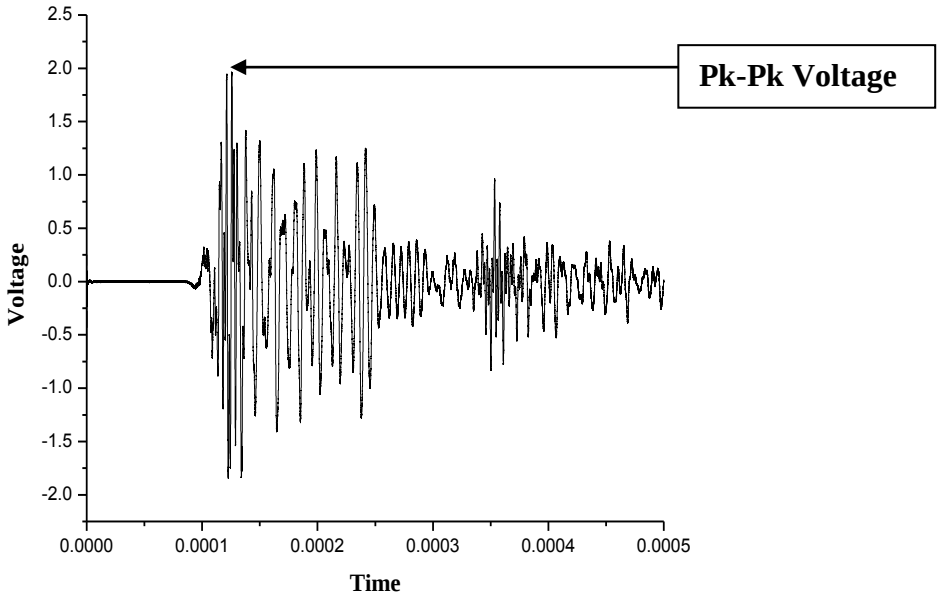


Fig 5.4 pk-pk V-t Signature of UPT slab specimen for non-vibrated concrete

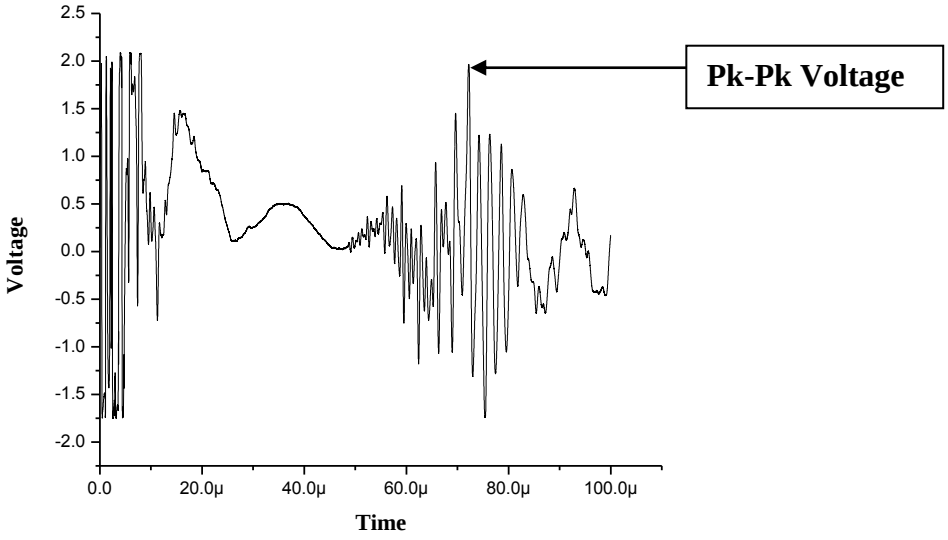


Fig 5.5 pk-pk V- t Signature of UPE cube specimen for non-vibrated concrete

As concrete sets and hardens drop in pk-pk voltage and the signature also observed. This is because of the surface seeking nature of the mode selected. This mode picks up the bond development between the reinforcing mild steel bar and the surrounding concrete. As the concrete sets, bond develops between steel and surrounding concrete. The bond development indicates more energy leakage into the surrounding concrete hence causing drop in signal strength. Thus the fall in signal strength is a measure of development of bond between bonding rebar and concrete and hence relates to the setting of concrete.

As outlined in chapter 4, the Ultrasonic Pulse-Transmission (UPT) readings and Ultrasonic Pulse- Echo (UPE) are taken for vibrated and non – vibrated concrete specimens throughout process of setting of concrete at regular time intervals respectively. To ensure repeatability minimum two samples were tested for each test.

5.1.1 Setting of Conventional Concrete

The signature plotted for UPT in slab and UPE in cube are used to compute pk-pk voltage trends throughout the setting process of conventional concrete. This is done for 24 hours at regular 1 hr interval. The trends are plotted for slab in UPT as shown in **Fig 5.6** and for UPE in cube as shown in **Fig 5.7**.

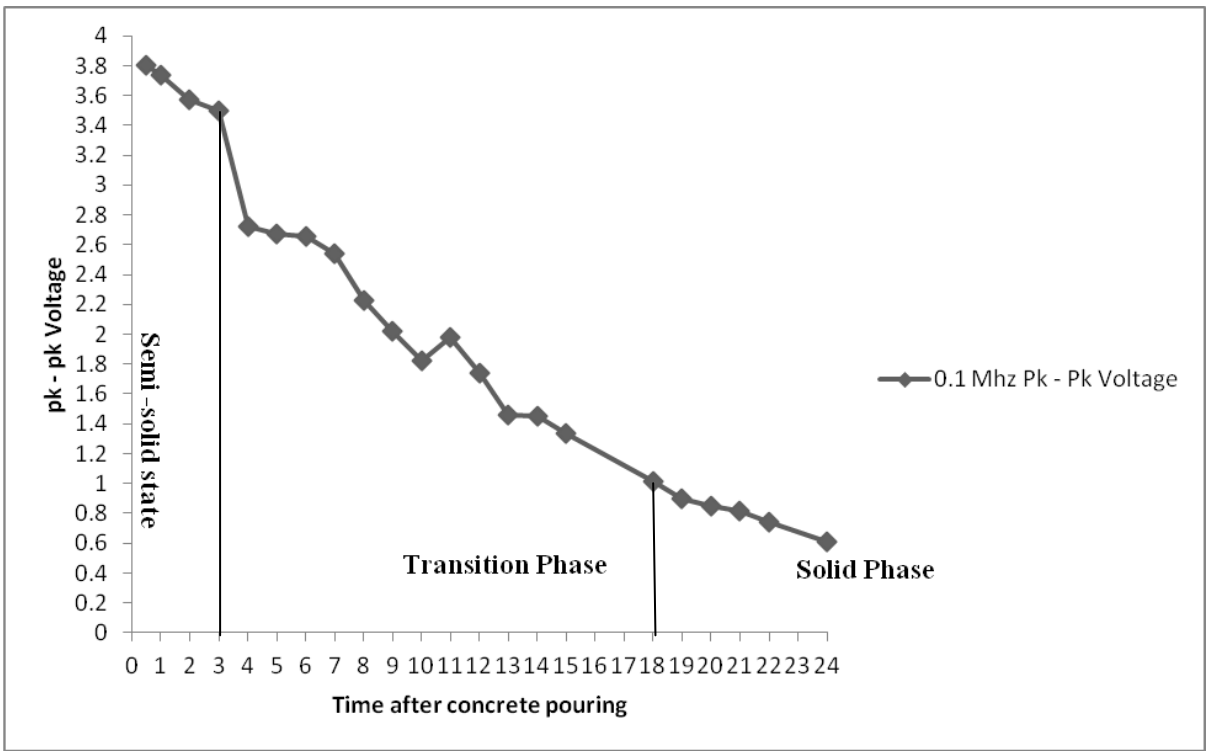


Fig 5.6 UPT for Slab using 0.1 MHz for M_1 mix

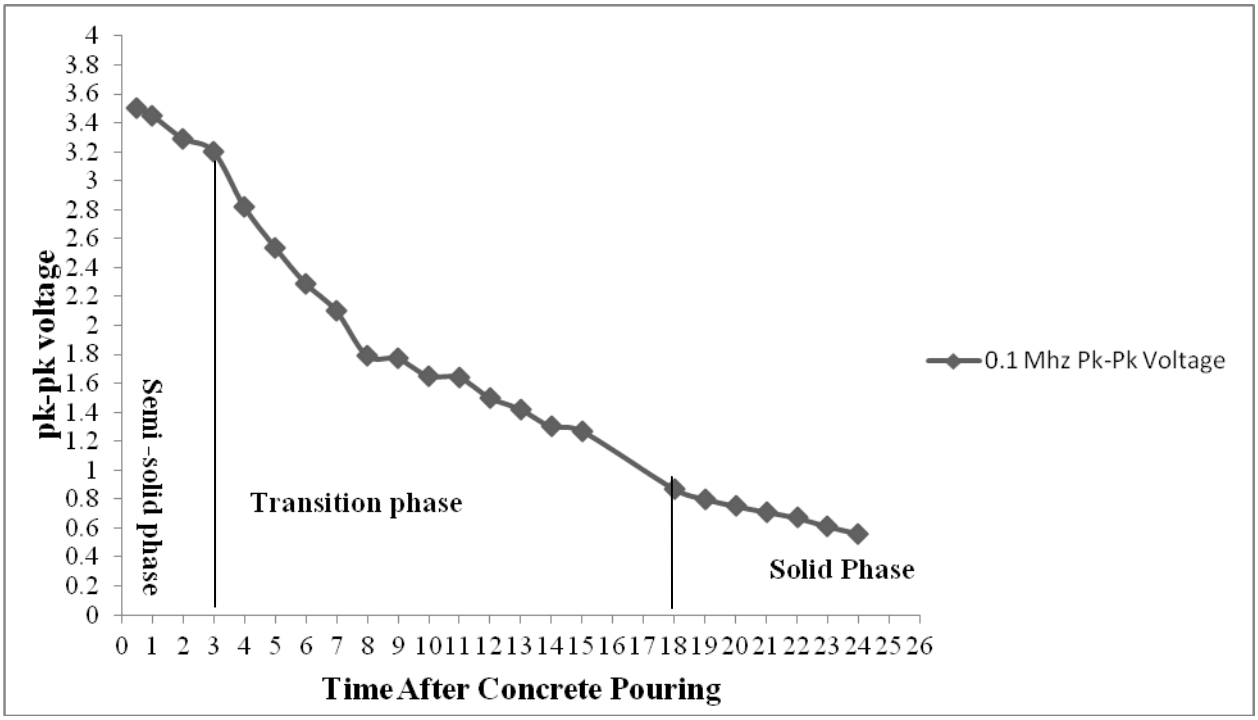


Fig 5.7 UPE for Cube using 0.1 MHz for M_1 mix

From the ultrasonic testing in pulse echo and transmission mode the following observations were made for conventional concrete:

- Drop in pk-pk voltage is observed throughout the duration indicating development of bond and hence setting of concrete. As setting increases more energy leaks into concrete causing fall in signal voltage.
- The phenomenon of attenuation of surface seeking mode signal is a measure of setting of concrete.
- From UPT and UPE graph that concrete setting process can be divided into 3 phases i.e. semi –solid, transition and solid phase.
- In semi – solid phase i.e. first 3 hours, concrete is almost fluid. No heavy fall in pk – pk voltage is indicating there is no significant setting or bonding between the mild steel bar and the surrounding concrete during the phases of pouring concrete in mould.

- From 3 – 18 hours the concrete is undergoing change from semi solid state to solid state. It is termed as transition phase. Maximum fall in pk -pk voltage is observed in this phase. This indicates that concrete is starting to set or making bond with embedded mild steel bar.

- From 18 – 24 hours, the fall in pk – pk voltage is slow indicating the concrete has become almost solid. This is termed as solid phase. There is hardly any setting or bonding occurring in this phase which shows that the maximum setting or bonding occur upto 18 hours after casting.

- Hence it can be concluded that UPT technique is also successful in picking the early changes in concrete as the environmental conditions changes as it is poured in mould.

- The NDT technique can go a long way in determining the time of formwork removal and putting the structure to use.

- In P/E the rate of fall of signal is fast since length of travel of signal is double.

- Both P/T as well as P/E mode can be used for monitoring setting process in conventional concrete

- During testing P/E is preferable since only one side access is required of the bar.

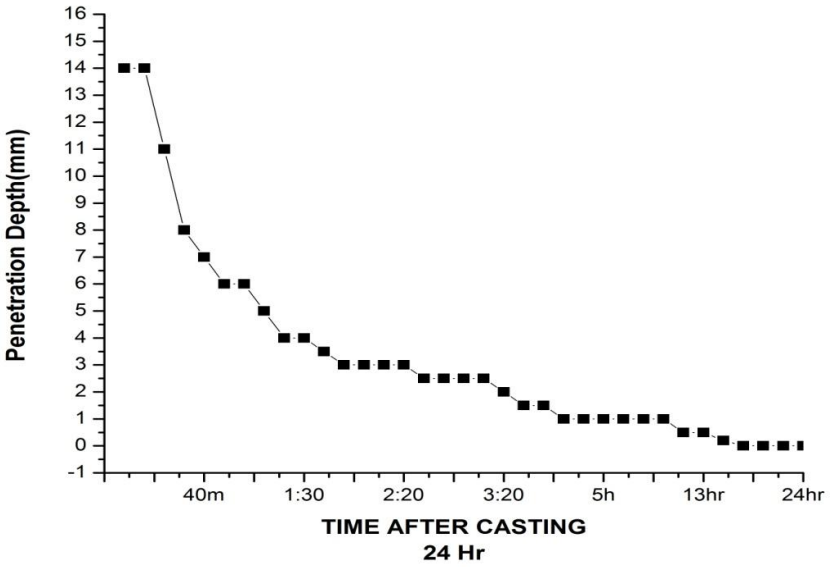


Fig 5.8 Penetration Test results for M_1 mix

During the initial 24hrs of monitoring setting of concrete,established techniques of penetration test was also done.

From the penetration test the following observations were made:

It is clear from penetration test graph that concrete setting phase can be divided into 3 phases i.e. semi- solid, transition and solid phase.

- In Semi-solid phase, the penetration test result show that the maximum penetration depth is achieved till 3.5 hrs indicating that concrete is in liquid phase and has not gained sufficient strength/ hardening.
- In Transition phase, there is hardly any increase in the penetration depth values indicating that concrete has sufficiently hardened / set to make any noticeable change in penetration value. On the other hand, using UPT and UPE , drop in signal is huge in this phase indicating bond development.
- In Solid Phase, there is no change in penetration depth indicating that concrete has sufficiently hardened. Not to make any change in penetration values.
- Penetration test is only feasible during 3to 4 hours when concrete is wet and hence cannot be used as a measure of setting phenomenon cementitious materials.

5.1.2 Setting Properties of Self Compacting Concrete with high slump M_2

The signature plotted for UPT in slab and UPE in cube are used to compute pk-pk voltage trends throughout the setting process of self compacting concrete. This is done for 48 hours at regular 1 hr interval. The trends are plotted for slab in UPT as shown in **Fig 5.9** and for UPE in cube as shown in **Fig 5.10.**

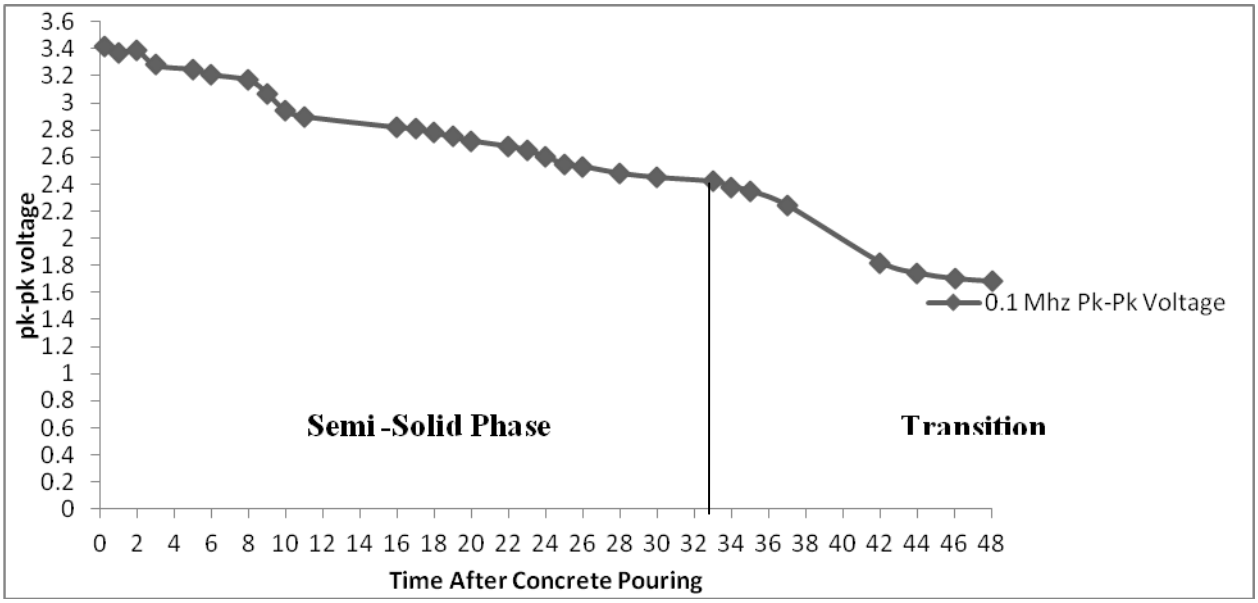


Fig 5.9 UPT for Slab using 0.1 MHz for M_2 high slump

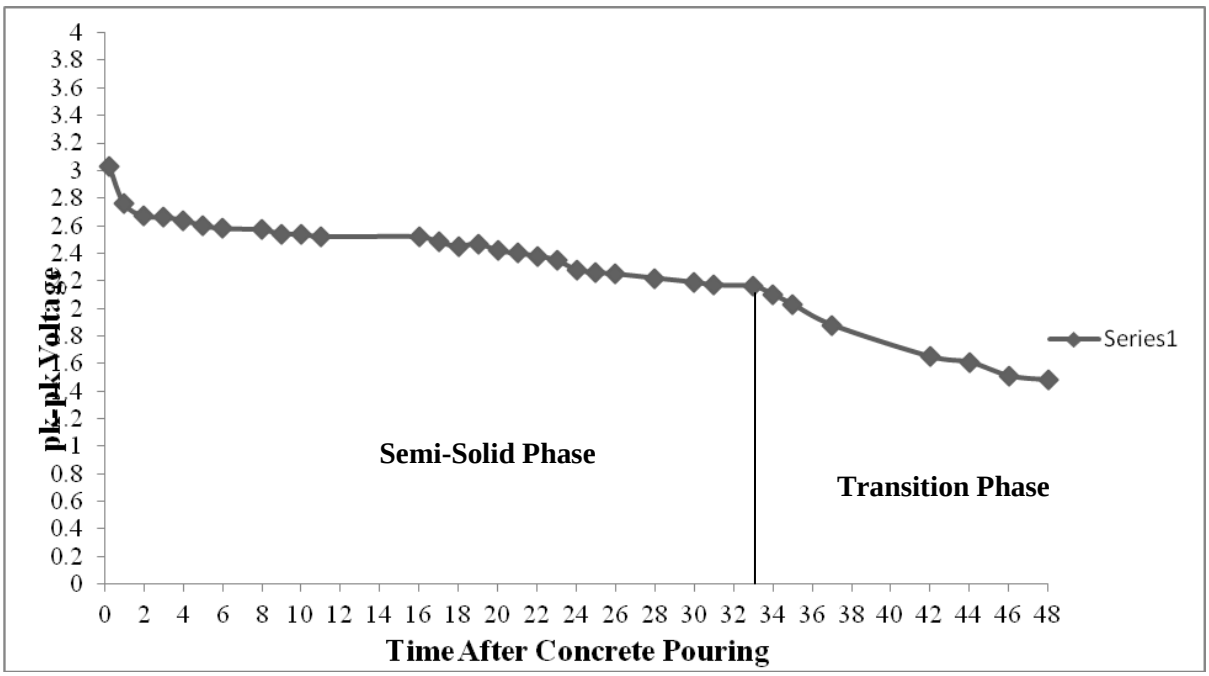


Fig 5.10 UPT for Cube using 0.1 MHz for M_2 high slump

From the ultrasonic testing in pulse echo and transmission mode the following observations were made:

- Drop in pk-pk voltage is observed throughout the duration indicating development of bond and hence setting of concrete. As setting increases more energy leaks into concrete causing fall in signal voltage.

- The phenomenon of attenuation of surface seeking mode signal is a measure of setting of concrete.

- From UPT and UPE graph that concrete setting process can be divided into 2 phases i.e. semi –solid and transition phase.

- In semi – solid phase i.e. first 33 hours, concrete is almost fluid and there is slow fall in pk –pk voltage observed. It indicates slow setting or bond development between the mild steel bar and the surrounding concrete. In self compacting concrete on comparing with conventional concrete, setting process is slow in SCC.

- From 33– 48 hours the concrete is undergoing change from semi solid state to solid state. It is termed as transition phase. The fall in pk-pk voltage large as observed in this phase. This indicates that concrete is starting to set or making bond with embedded mild steel bar.

- Bond development continues after 48 hours. It can be concluded that UPT technique is also successful in picking the early changes in self compacting concrete as the environmental conditions changes.

- Solid phase is not obtained in 48 hours. Hence it is recommended to continue the till it is percentage fall achieved.

- Percentage fall in conventional concrete for slab in semi-solid state is 7.89 % and that of SCC is 29.23%.For cube, the percentage fall in conventional concrete is 8.5 % and that of SCC is 28.71.

- Percentage fall in conventional concrete for slab in transition state is 71.14 % and that of SCC is 30.57 %.For cube, the percentage fall in conventional concrete is 72.8 % and that of SCC is 31.48%.

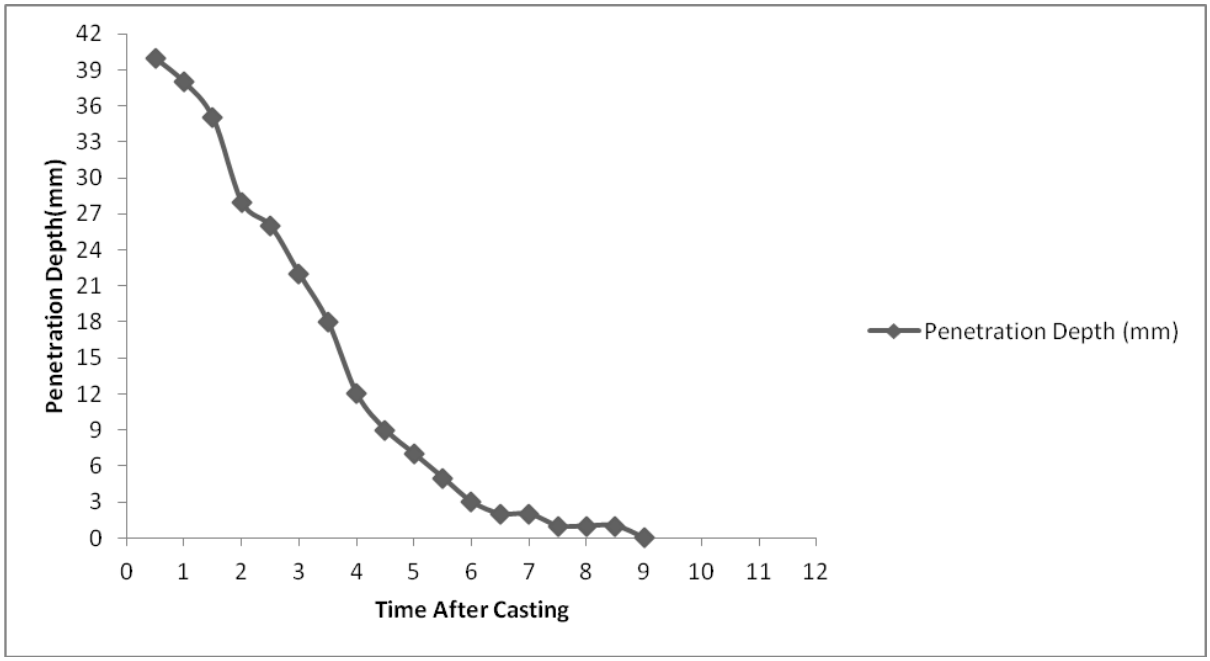


Fig 5.11 Penetration Test after for M_2 High slump.

During the initial 48hrs of monitoring setting of concrete,established techniques of penetration test was also done.

From the penetration test the following observations were made:

It is clear from penetration graph that concrete setting phase can be divided into 3 phases i.e. semi- solid, transition and solid phase.

- In Semi-solid phase, the penetration test result show that the maximum penetration depth is achieved till 5 hrs indicating that concrete is in liquid phase and has not gained sufficient strength/ hardening.
- In Transition phase, there is hardly any increase in the penetration depth values indicating that concrete has sufficiently hardened / set to make any noticeable change in penetration value. On the other hand, using UPT and UPE, drop in signal is huge in this phase indicating bond development.
- In Solid phase there is no change in penetration depth indicating that concrete has sufficiently hardened not to be taking any change in penetration values.
- Penetration test is only feasible during 9hours when concrete is wet and hence cannot be used as a measure of setting phenomenon in cementious materials.

- From penetration test it is concluded that setting is slow in M_2 high slump in comparison to conventional concrete.

5.1.3 Setting Properties of Self Compacting Concrete with low slump M_3

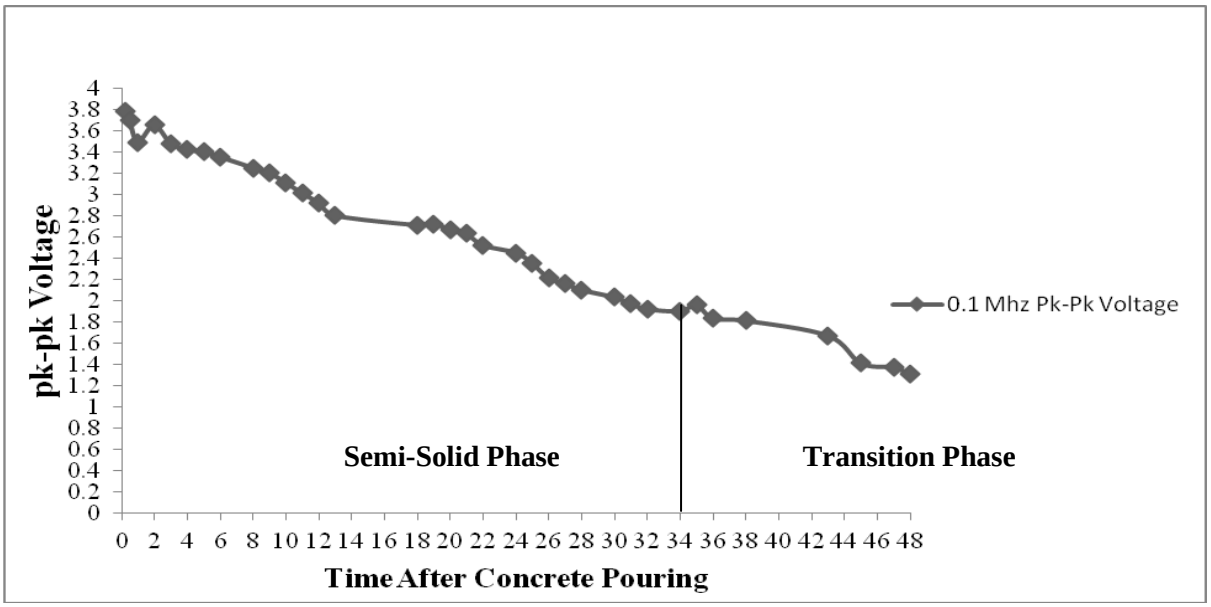


Fig5.12 UPT for Slab using 0.1 MHz for M_3 low Slump

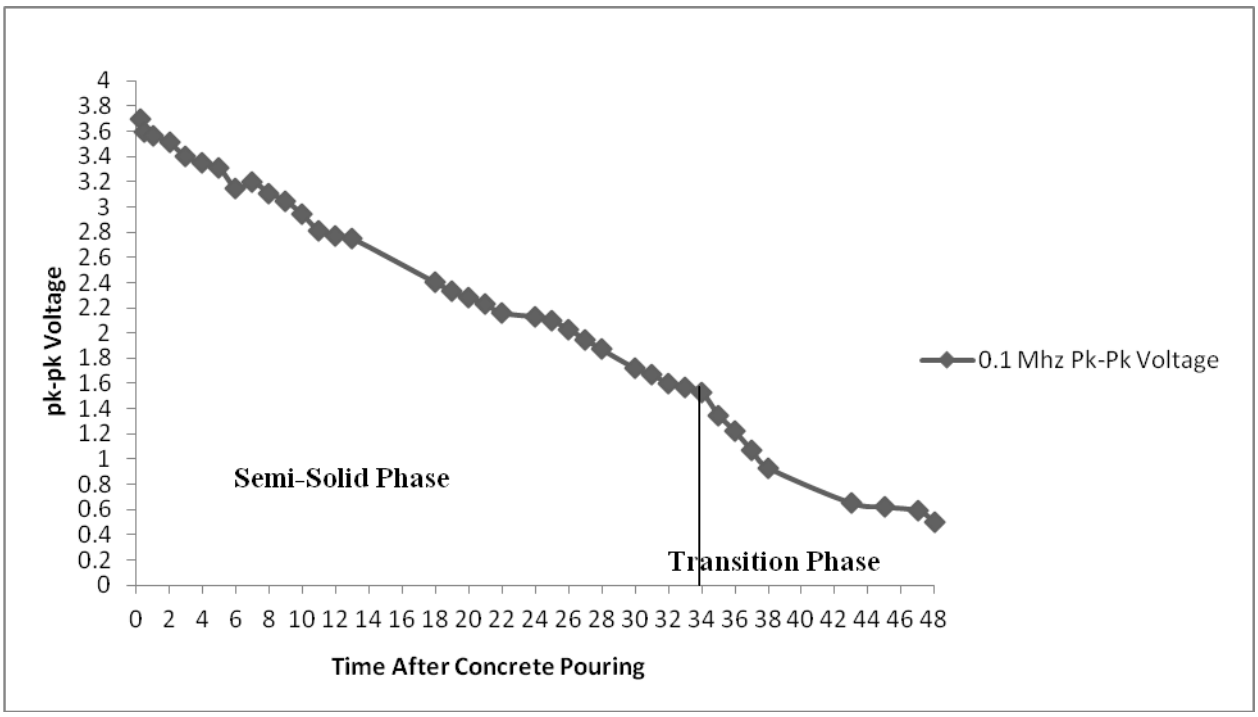


Fig5.13 UPE for Cube using 0.1 MHz for M_3 low Slump

From the ultrasonic testing in pulse echo and transmission mode the following observations were made:

- Drop in pk-pk voltage is observed throughout the duration indicating development of bond and hence setting of concrete. As setting increases more energy leaks into concrete causing fall in signal voltage.

- The phenomenon of attenuation of surface seeking mode signal is a measure of setting of concrete.

- From UPT and UPE graph that concrete setting process can be divided into 2 phases i.e. semi –solid and transition phase.

- In semi – solid phase i.e. first 34 hours, concrete is almost fluid and there is slow fall in pk – pk voltage observed. It indicates slow setting or bond development between the mild steel bar and the surrounding concrete. In self compacting concrete on comparing with conventional concrete, setting process is slow in SCC.

- From 34– 48 hours the concrete is undergoing change from semi solid state to solid state. It is termed as transition phase. The fall in pk-pk voltage large as observed in this phase. This indicates that concrete is starting to set or making bond with embedded mild steel bar.

- Bond development continues after 48 hours. It can be concluded that UPT technique is also successful in picking the early changes in self compacting concrete as the environmental conditions changes.

- Solid phase is not obtained in 48 hours. Hence it is recommended to continue the till it is percentage fall achieved.

- Percentage fall in conventional concrete for slab in semi-solid state is 7.89 % and that of SCC M_2 is 29.23% and that of SCC M_3 is 49.73% .For cube, the percentage fall in conventional concrete is 8.5 % and that of SCC M_2 is 28.71 and that of SCC M_3 is58.64.

- Percentage fall in conventional concrete for slab in transition state is 71.14 % and that of SCCM_2 is 30.57 % and that of SCC M_3 is 31.01%.For cube, the percentage fall in

conventional concrete is 72.8 % and that of SCC M_2 is 31.48% and that of SCC M_3 is 67.32%.

From the penetration test the following observations were made:

It is clear from penetration graph that concrete setting phase can be divided into 3 phases i.e. semi- solid, transition and solid phase.

- In Semi-solid phase, the penetration test result show that the maximum penetration depth is achieved till 5 hrs when the concrete is in liquid phase and has not gained sufficient strength/ hardening.
- In Transition phase, there is hardly any increase in the penetration depth values indicating that concrete has sufficiently hardened / set.
- In Solid phase there is no change in penetration depth indicating that concrete has hardened / set.
- Penetration test result are only feasible during 9hours when concrete is wet.

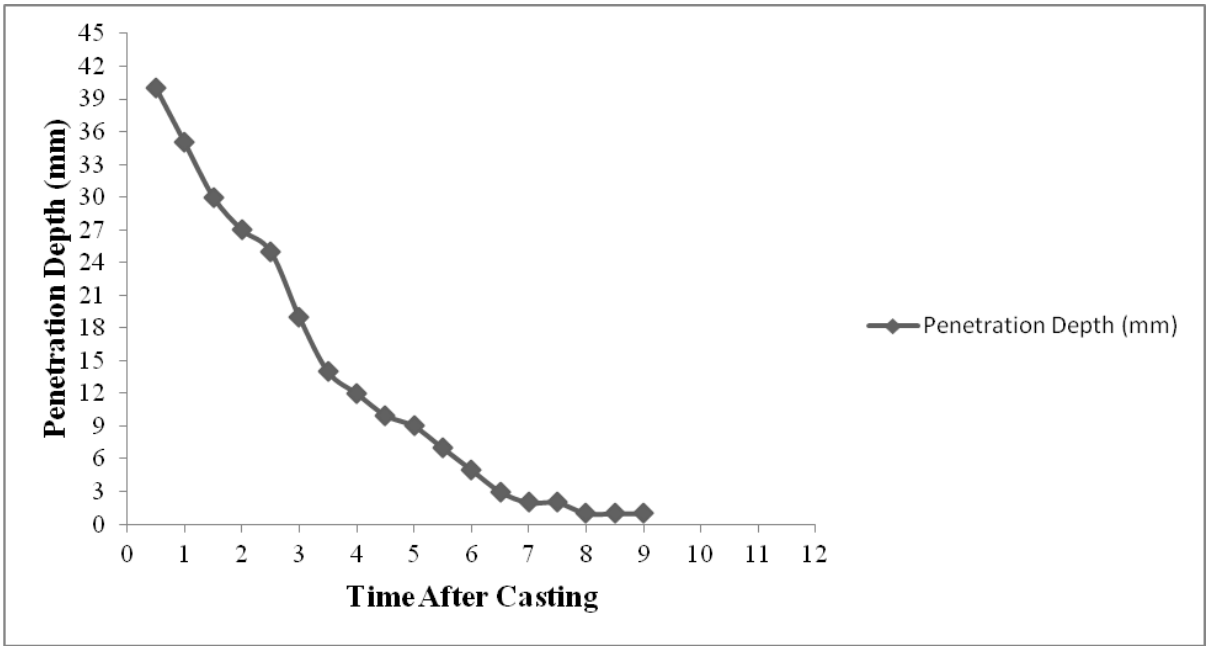


Fig5.14 Penetration Test for M_3 low Slump

5.2 UPV RESULTS

UPV test were also conducted on cubes of size 150 mm x 150 mm x 150 mm alongside UPT test for mix M_1, M_2 & M_3 in order to check the microstructure development of concrete using its early or setting phase . The results obtained are plotted as velocity vs time graphs for 24 hrs for M_1 and 48 hrs for M_2 & M_3. **(Fig 5.15, 5.16 and 5.17)**.

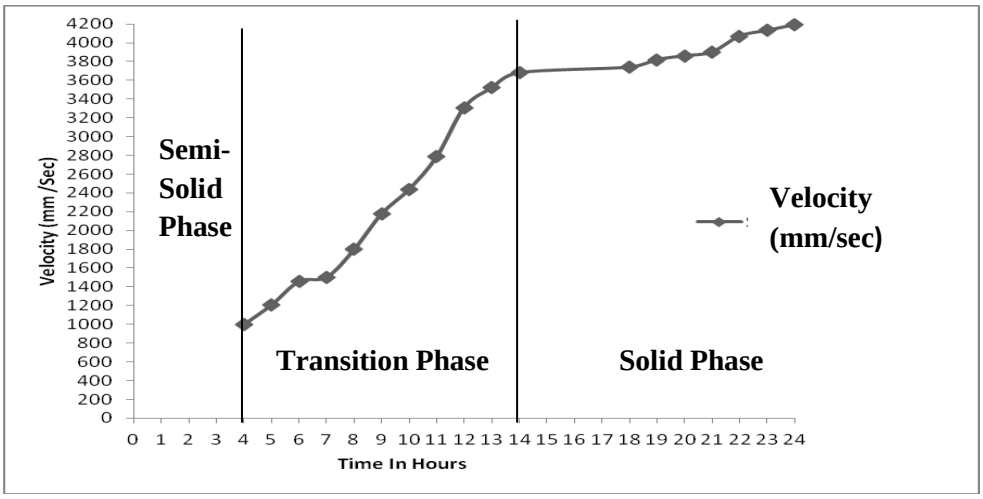


Fig 5.15 UPV For Conventional Concrete

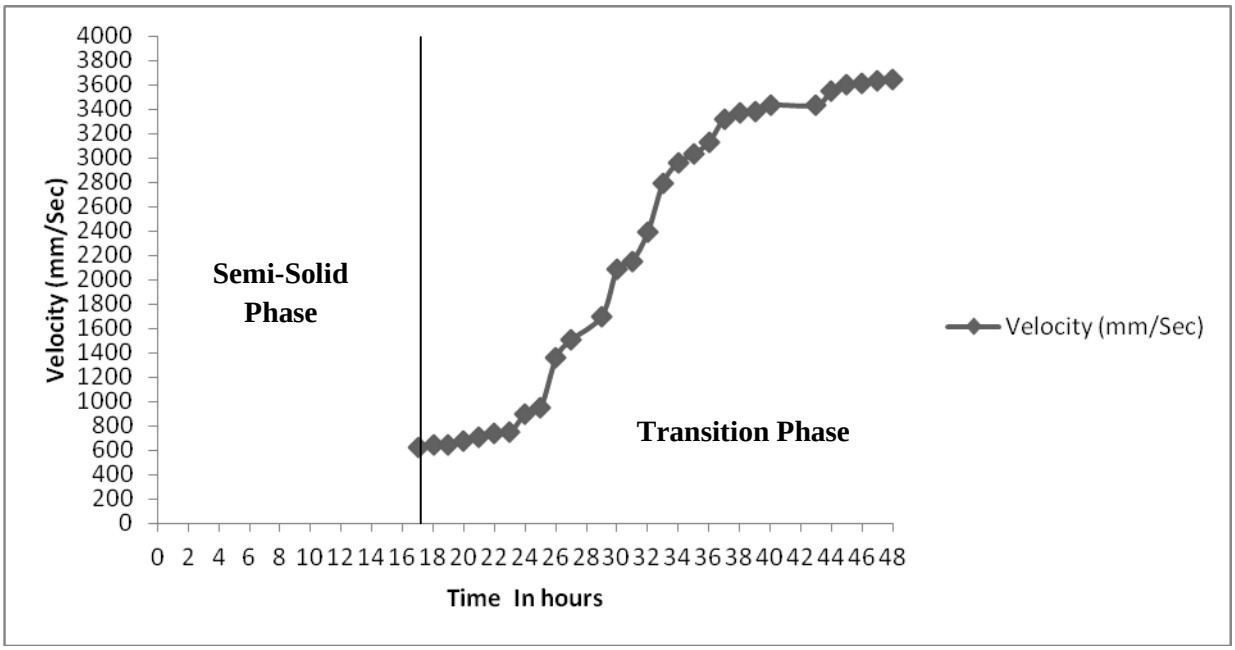


Fig 5.16 UPV for M_2 high slump

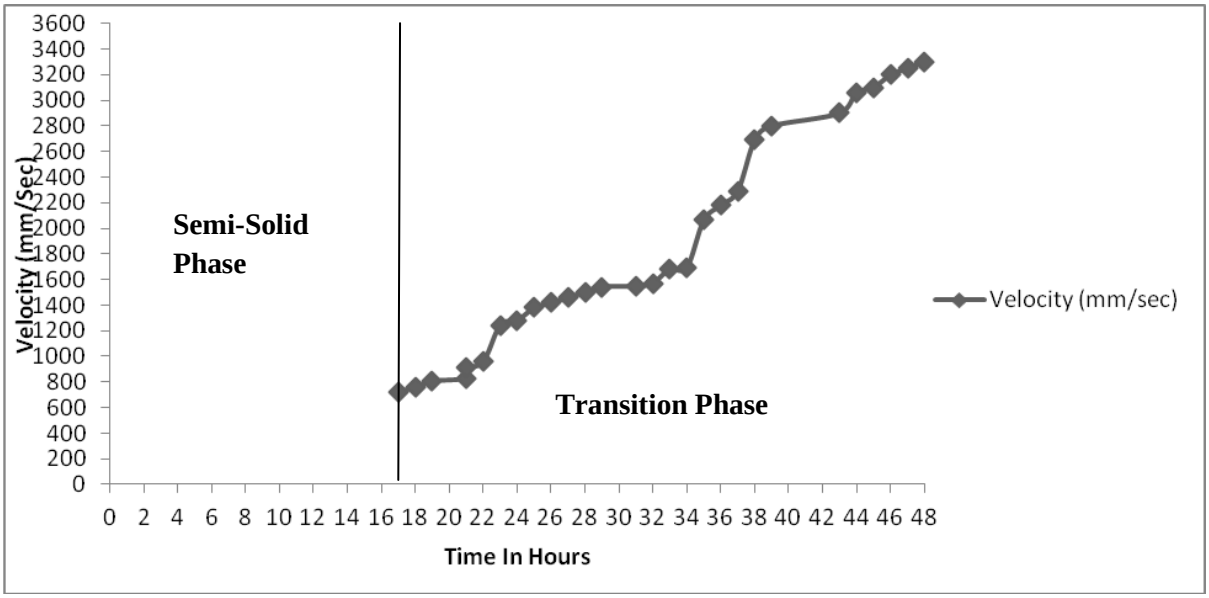


Fig5.17 UPV for M_3 low slump

From the UPV testing the following observations were made:

- As figures shows that the velocity increases with time. This is because as the concrete starts to set the amount of ultrasonic waves attenuation i.e. loss of energy decreases and thus wave velocity increases.

- But as we compare UPV with UPT and UPE technique we can clearly see that UPV method is unable to record the velocity during the semi-solid Phase i.e. first 4 hrs for M_1 and first 17 hrs for M_2 and M_3 as concrete is wet and starts sticking to the transducers. To overcome this problem special frame arrangement has to be made, thus making it unpractical during the in-situ monitoring of concrete.

- In **Transition Phase**, the graph shows steep rise in velocity for conventional concrete and slow rise in velocity for SCC M_2 and M_3 because of slow bond development in SCC mixes.

5.3 HARDENING PHASE

In the hardening phase destructive tests like Compressive Strength Test and Split tensile test were conducted on the specimens of concrete mixes M_1, M_2 and M_3. The purpose behind these tests is to ensure that adequate strength development has been achieved in concrete

during curing. The results of these tests are shown below in **Table (5.1)** and **Fig (5.18, 5.19 and 5.20)**

Table 5.1 Results of Destructive Tests in Hardening Phase

Concrete Mix	**Testing Duration (Days)**	**Compressive Strength (kN/mm^2)**	**Split –Tensile Strength (kN/mm^2) (Cube)**	**Split –Tensile Strength (kN/mm^2) (Cylinder)**
M_1	3	19.13	1.4	1.23
	7	24.49	2.32	1.59
	28	44.41	3.45	2.64
M_2	3	11.88	1.34	1.15
	7	20.08	1.85	1.67
	28	35.17	3.25	
M_3	3	13.93	0.98	0.87
	7	18.5	1.46	1.07
	28	31.60	2.64	1.55

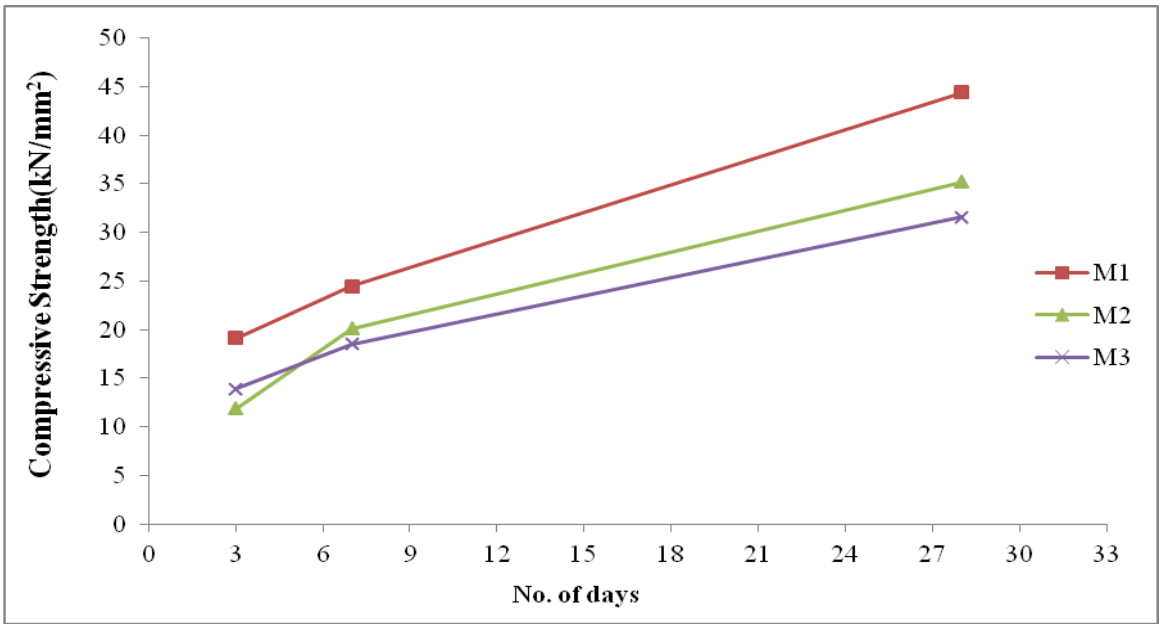


Fig 5.18 Comressive strength of cubes for M_1, M_2 and M_3 mixes

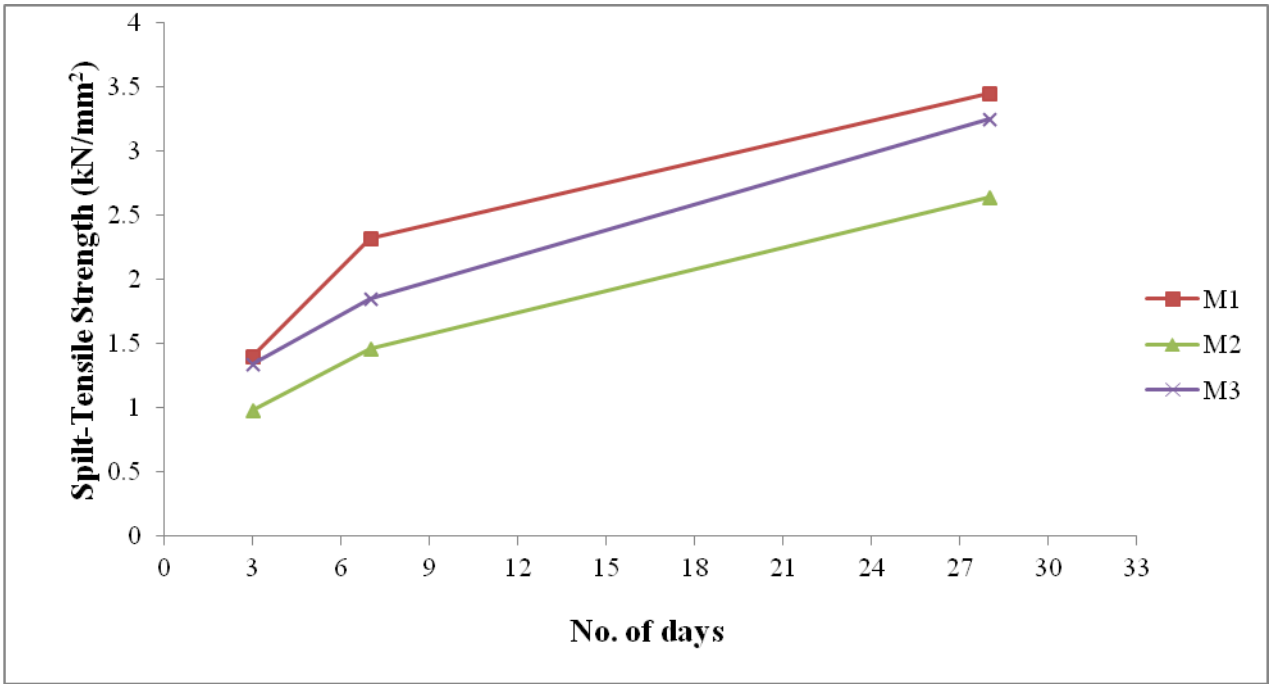


Fig 5.19 Split-Tensile strength of cubes for M_1, M_2 and M_3 mixes

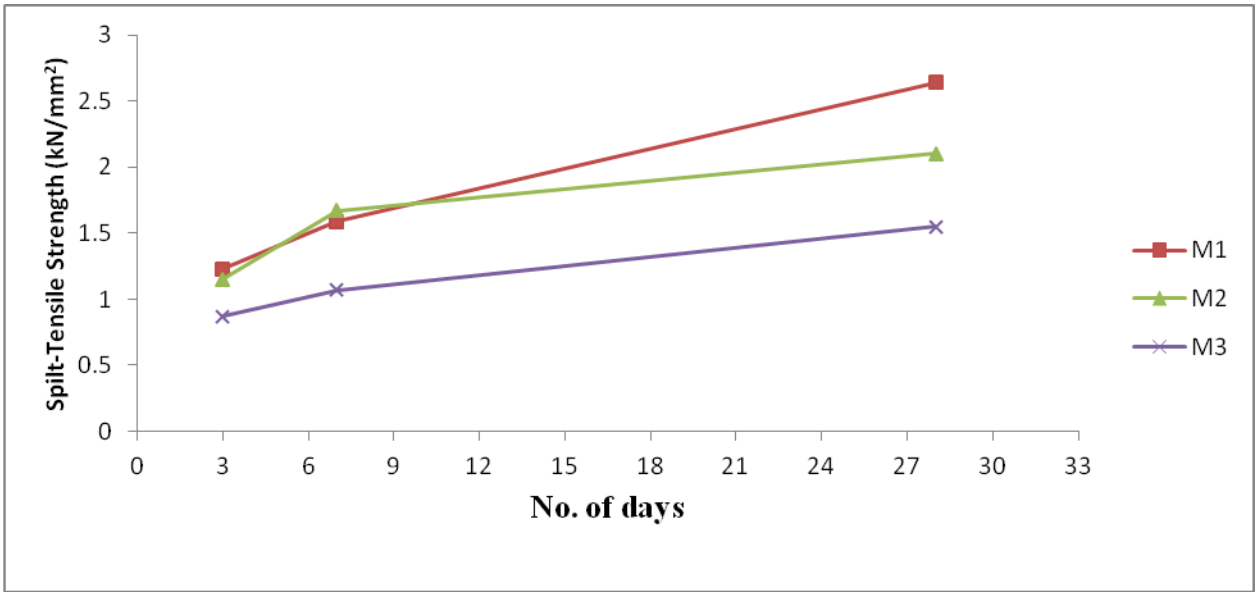


Fig 5.20 Split – Tensile strength of cylinder for M_1, M_2 and M_3 mixes

Following the observations obtained from these graphs:

- The highest compressive strength is that of conventional concrete when compares to SCC M_2 and M_3.The compressive strength in M_1 and M_3 increases uniformly as the curing of days increases but in the case of M_2 compressive strength increases at higher rate for 7 days as compared to days to follow (7 -28 days).

- The target strength of M20 conventional concrete considering 5% standard deviation for 28 days calculated is 28.25 kN/mm2. The achieved strength is more than the target strength.

- The highest split – tensile strength of cube is that of conventional concrete when compares to SCC M_2 and M_3.The compressive strength of M_3 increases uniformly as the curing of days increases but in the case of M1and M_2 compressive strength increases at higher rate for 7 days as compared to days to follow (7 -28 days).

- The highest Split – tensile strength of cylinder is that of conventional concrete when compares to SCC M_2 and M_3.The compressive strength in M_1 and M_3 increases uniformly as the curing of days increases but in the case of M_2 compressive strength increases at higher rate for 7 days as compared to days to follow (7 -28 days).

5.4 CLOSING REMARKS

This chapter shows the results obtained by ultrasonic pulse transmission , ultrasonic pulse echo ,ultrasonic pulse velocity and penetration depth in setting phases and destructive test like compressive test and split tensile test in hardening phases. Finally different techniques are compared with each other.

CHAPTER 6

CONCLUSIONS AND SCOPE OF FUTURE WORK

6.1 GENERAL

The experimental study carried out on various concrete specimens during the two phases indicate that ultrasonic's is capable of detecting the early age strength (within first 24 hrs for convemtional concrete and first 48 hrs of non-vibrated concrete) and hardening process (upto 28 days) of concrete.

Following conclusions can be drawn from the observations of **Convetional Conerete**

- Maximum bond development or early setting is achieved during Transition Phase i.e. from 3 hrs to 18hrs for mix M_1, when concrete is changing from semi-solid to solid.
- The other well established NDT and destructive tests methods are not capable of monitoring continuously early age strength of concrete during the first 24 hrs as compared to UPT and UPE method using ultrasonic guided waves.
- Variation in properties like slump value of concrete affects the test results.
- The penetration depth will achieved 3.5 hours, when concrete is in semi -solid phase.

Conclusions which can be drawn from the observations of **Non-Vibrated Concrete**

- Maximum bond development or early setting is achieved during Transition Phase i.e. from 33 hrs to 48 hrs for mix M_2,for both slab and cube and 33to 48 hrs for mix M_3 for slab and 30 to 48 hrs for cube for mix M_3 when concrete is changing from semi-solid to solid.
- The other well established NDT and destructive tests methods are not capable of monitoring continuously early age strength of concrete during the first 48 hrs as compared to UPT and UPE method using ultrasonic guided waves.
- Variation in properties like slump value of concrete affects the test results.

- The penetration depth will achieved in 4 to 5 hours, when concrete is in semi-solid phase.

6.2 SCOPE OF FUTURE WORK

- Ultrasonic monitoring of SCC/non-vibrated concrete was done for 48 hrs only. The study can be extended for another 1or 2 days to understand complete process.
- Correalations of ultrasonic voltages with destructive tests can be established.
- Setting properties of various concrete like High Performance concrete, High strength concrete etc. with different minearal admixtures.

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