MONITORING EARLY AGE STRENGTH AND HARDENING OF CONCRETE USING ULTRASONIC GUIDED WAVES

A thesis report submitted in the partial fulfillment

of the requirement for the award of the degree

MASTERS OF ENGINEERING
IN
STRUCTURES

Submitted by

Jashanjeet Randhawa

Roll No.800922004

Under guidance of

Dr. Abhijit Mukherjee	**Dr. Shruti Sharma**
Director	**Assistant Prof.,CED**
Thapar University , Patiala	**Thapar University , Patiala**

DEPARTMENT OF CIVIL ENGINEERING
THAPAR UNIVERSITY, PATIALA-147004, INDIA

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DECLARATION

I hereby declare that the work which is presented in this thesis report entitled **"MONITORING EARLY AGE STRENGTH AND HARDENING OF CONCRETE USING ULTRASONIC GUIDED WAVES "** 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.

Dated: 15th July 2011 **(Jashanjeet Randhawa)**

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

(Dr. ABHIJIT MUKHERJEE)
Director & Supervisor
Thapar University, Patiala.

(Dr. SHRUTI SHARMA)
Assistant Prof.& Supervisor
Thapar University, Patiala.

Countersigned by:

(Dr. MANEEK KUMAR)
Professor & Head, CED
Thapar University, Patiala.

(Dr. S. K. MOHAPATRA)
Dean, Academics Affairs
Thapar University, Patiala.

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Jashanjeet Randhawa

(Roll No. 800922004)

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 Pull out and Vicat needle 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 through transmission system; a wave transmitted on one end of an embedded waveguide using a sensor arrangement and then it is received on the opposite end of the propagating bar with another sensor. 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.

Experiments were performed on concrete mixtures with varying slumps like 35mm (Low), 80mm (Moderate) & 350mm (High). For ultrasonic guided waves, beam specimens of size 150 mm x150 mm x 300 mm with embedded mild steel rod of 25mm diameter and 600 mm length were used to monitor early strength (i.e. first 24 hrs of hydration) & hardening process (i.e. during curing). Ultrasonic pulse velocity was also carried out side by side on a standard cube (150 mm x 150 mm x 150 mm) of same concrete mixture to study the microstructure development of concrete.

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CHAPTER 1

INTRODUCTION

1.1 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.

1.2 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.

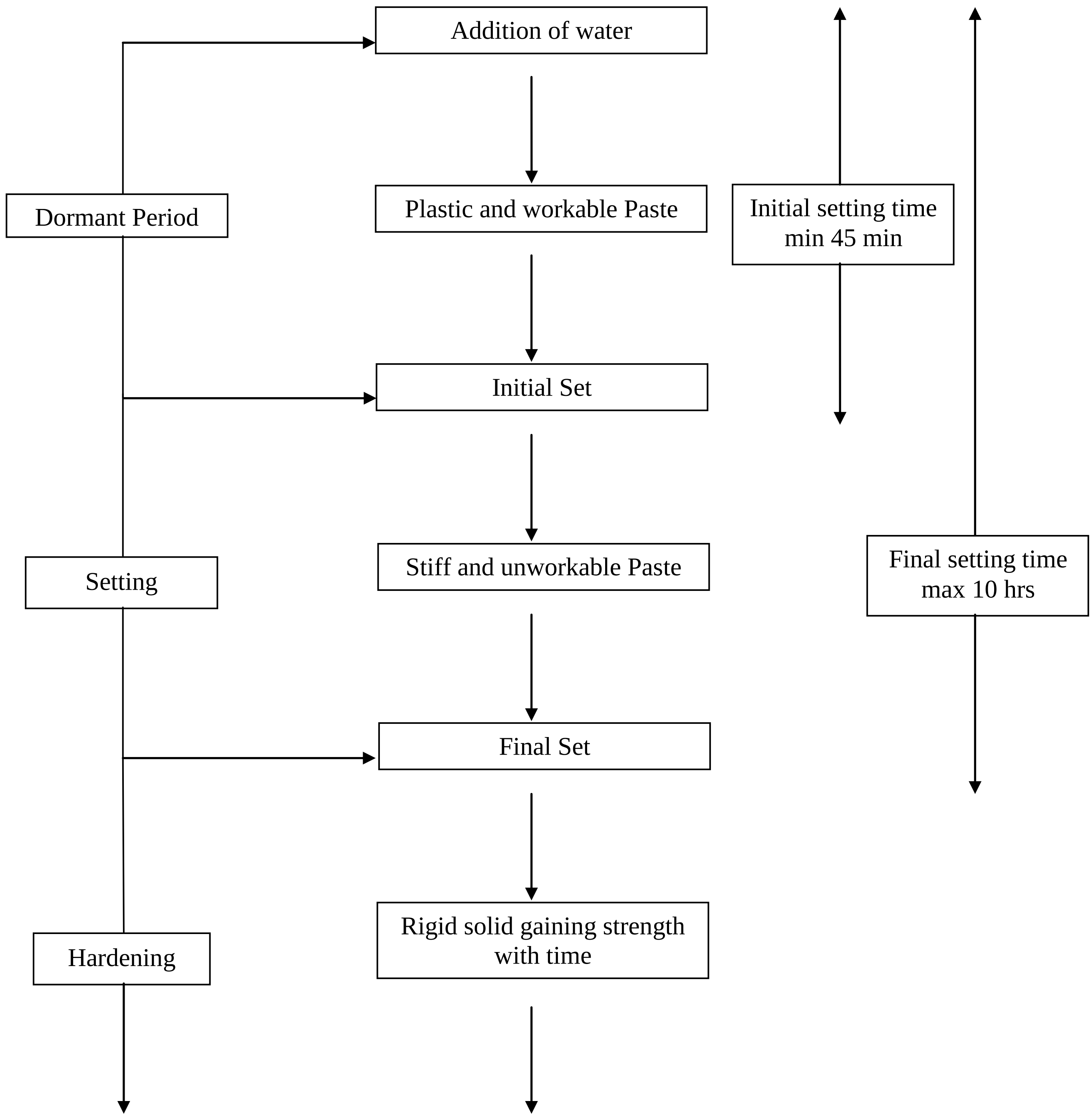


Fig 1.1 Schematic description of setting and hardening of a cement paste

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 1.1.**

1.3 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.

1.4 Various NDT Methods for Concrete

The following methods, with some typical applications, have been used for the NDT of concrete:

- **Visual inspection**, which is an essential precursor to any intended non-destructive test. An experienced civil or structural engineer may be able to establish the possible cause(s) of damage to a concrete structure and hence identify which of the various NDT methods available could be most useful for any further investigation of the problem.
- **Half-cell electrical potential method**, normally involves measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. The half-cell is usually a copper/copper sulphate or silver/silver chloride cell but other combinations are used. The concrete functions as an electrolyte and the risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to the measured potential difference. In some circumstances, useful measurements can be obtained between two half-cells on the concrete surface.
- **Schmidt/rebound hammer test**, is principally a surface hardness tester. It works on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges. There is little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer.
- **Carbonation depth measurement test**, used to determine whether moisture has reached the depth of the reinforcing bars and hence corrosion may be occurring. Carbonation of concrete occurs when the carbon dioxide, in the atmosphere in the presence of moisture, reacts with hydrated cement minerals to produce carbonates, e.g. calcium carbonate. The carbonation process is also called depassivation. Carbonation penetrates below the exposed surface of concrete extremely slowly.

  The significance of carbonation is that the usual protection of the reinforcing steel generally present in concrete due to the alkaline conditions caused by hydrated cement paste is neutralized by carbonation. Thus, if the entire concrete cover over the reinforcing steel is carbonated, corrosion of the steel would occur if moisture and oxygen could reach the steel.
- **Permeability test**, used to measure the flow of water through the concrete. Permeability of concrete is important when dealing with durability of concrete particularly in concrete used for water retaining structures or watertight sub-structures. Structures exposed to harsh environmental conditions also require low porosity as well as permeability. Such adverse elements can result in degradation of reinforced concrete, for example, corrosion of steel leading to an increase in the volume of the steel, cracking and eventual spalling of the

concrete. Permeability tests measure the ease with which liquids, ions and gases can penetrate into the concrete. *In situ* tests are available for assessing the ease with which water, gas and deleterious matter such as chloride ions can penetrate into the concrete.

- **Penetration resistance or Windsor probe test**, like the rebound hammer, is a hardness tester, and its inventor's claim that the penetration of the probe reflects the precise compressive strength in a localized area is not strictly true. However, the probe penetration does relate to some property of the concrete below the surface, and, within limits, it has been possible to develop empirical correlations between strength properties and the penetration of the probe.
- **Covermeter testing**, used to measure the distance of steel reinforcing bars beneath the surface of the concrete and also possibly to measure the diameter of the reinforcing bars.
- **Radiographic testing**, used to detect voids in the concrete and the position of stressing ducts. As we know the intensity of a beam of X rays or gamma rays suffers a loss of intensity while passing through a material. This phenomenon is due to the absorption or scattering of the X or gamma rays by the object being exposed. The amount of radiation lost depends on the quality of radiation, the density of the material and the thickness traversed. The beam of radiation, which emerges from the material, is usually used to expose a radiation sensitive film so that different intensities of radiation are revealed as different densities on the film.
- **Ultrasonic pulse velocity testing**, mainly used to measure the sound velocity of the concrete by passing ultrasonic waves and hence the compressive strength of the concrete.
- **Ultrasonic methods** using an instrumented hammer or transducers to produce ultrasonic guided waves inside the concrete specimen or a wave guide providing both sonic echo and through transmission methods.

1.5 Thesis Objectives

The purpose of this research is to investigate the feasibility of using ultrasonic guided waves for characterizing the material properties of early age cementitious materials. The research is the first step forward in monitoring the setting and hardening of in-place concrete. The objective of this thesis can be summarized as follows:

- Relate results from experimental measurements to actual material properties.

- Provide an ultrasonic technique that can be implemented to monitor early age strength & hardening of cementitious materials.
- To relate the early age strength and hardening with UPV, Penetration Tests and destructive tests like compression, pull-out & split-tensile.
- Provide information that can be used to estimate and evaluate the strength development process of concrete for safe and efficient construction practices.

1.6 Closing Remarks

This chapter gives a general aspect and introduction about the early age strength and hardening of concrete. The motivation behind this report and physical background of monitoring young concrete has been emphasized. Various NDT techniques for monitoring concrete & main objective of thesis have also been highlighted.

The next chapter will throw light on the various details particularly to the use ultrasonic guided waves as a tool for NDT.

CHAPTER 2

ULTRASONICS AS NDT TOOL

2.1 Fundamentals of Ultrasonic Waves in Media

It is known that frequency range of sound audible to humans is approximately 20 to 20,000 Hz (cycles per second). Ultrasound is simply sound that are above the frequency range of human hearing. When a disturbance occurs at a portion in an elastic medium, it propagates through the medium in a finite time as a mechanical sound wave by the vibrations of molecules, atoms or any particles present. Such mechanical waves are also called elastic waves. Ultrasound waves or ultrasonic waves are the terms used to describe elastic waves with frequency greater than 20,000 Hz and normally exist in solids, liquids, and gases. A simple illustration of the ultrasonic waves produced in a solid is shown in **Fig. 2.1**, where distortion caused depending on whether a force is applied normal or parallel to the surface at one end of the solid can result in producing compression or shear vibrations, respectively, so that two types of ultrasonic waves, i.e. longitudinal waves or transverse waves, propagate through the solid. The energy of the wave is also carried with it.

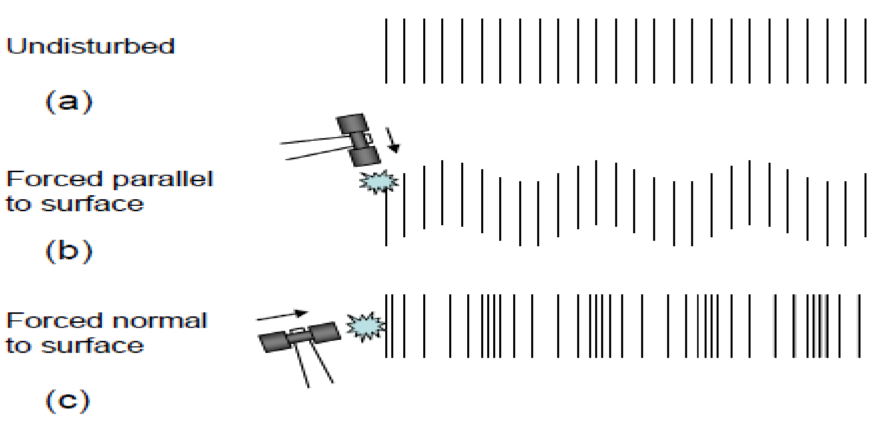


Fig. 2.1. Schematics of ultrasonic waves in a bulk specimen: (a)equilibrium state with no disturbance, (b)waves relating to shear (transverse) vibrations, (c)waves relating to longitudinal vibrations. [http://www.googleimages.com]

In a continuous medium, the behavior of ultrasonic waves is closely related to a balance between the forces of inertia and of elastic deformation. An ultrasonic wave moves at a velocity (the wave velocity) that is determined by the material properties and shape of the medium, and occasionally the frequency. The ultrasonic wave imparts motion to the material when it propagates. This is referred to as particle motion, to distinguish it from the wave motion. This particle motion is usually specified as a particle velocity v. It is noted in ultrasonic measurements that the particle velocity is much smaller than wave velocity. Also, one can understand that no ultrasonic wave propagates in vacuum because there are no particles that can vibrate in vacuum.

2.2 Basic Concepts of Wave Propagation

2.2.1 Some Common Terms Used:

• **Sound Waves: -** Sound waves are simply organized mechanical vibrations traveling through a medium, which may be a solid, a liquid, or a gas. These waves will travel through a given medium at a specific speed or velocity, in a predictable direction, and when they encounter a boundary with a different medium they will be reflected or transmitted according to simple rules. This is the principle of physics that underlies ultrasonic flaw detection.

• **Frequency: -** All sound waves oscillate at a specific frequency, or number of vibrations or cycles per second, which we experience as pitch in the familiar range of audible sound. Human hearing extends to a maximum frequency of about 20,000 cycles per second (20 KHz), while the majority of ultrasonic flaw detection applications utilize frequencies between 500 KHz to 10 MHz. At frequencies in the Megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and common engineering materials.

• **Wave Speed:** The speed of a sound wave varies depending on the medium through which it is travelling, affected by the medium’s density and elastic properties. Different types of sound waves will travel at different velocities.

• **Wavelength (λ)**: It is the distance between any two corresponding points in the wave cycle as it travels through a medium. Wavelength is related to frequency and velocity by the simple equation

$$\lambda = c/ \upsilon \qquad \textbf{....(2.1)}$$

Where, λ = wavelength, c = sound velocity, υ = frequency

In ultrasonic flaw detection, the generally accepted lower limit of detection for a small flaw is one-half wavelength, and anything smaller than that will be invisible. In ultrasonic thickness gauging, the theoretical minimum measurable thickness is one wavelength.

• **Attenuation**

When an ultrasonic wave propagates through a medium, ultrasonic attenuation is caused by a loss of energy in the ultrasonic wave and other reasons. The attenuation can be seen as a reduction of amplitude of the wave. There are some factors affecting the amplitude and waveform of the ultrasonic wave, such as ultrasonic beam spreading, energy absorption, dispersion, nonlinearity, transmission at interfaces, scattering by inclusions and defects, Doppler effect and so on. To characterize the ultrasonic attenuation quantitatively, attenuation coefficient α is defined as follows;

$$A = A_0 \cdot e^{-\alpha x} \qquad \textbf{....(2.2)}$$

where A is the peak amplitude of the wave at propagation distance x, A_0 is the initial peak amplitude.

The attenuation coefficient α is experimentally determined from the variation of the peak amplitude with the propagation distance, and it can be given in decibel per meter (dB/m) or in neper per meter (Np/m). In general, the attenuation coefficient highly depends on frequency. Since this frequency dependence reflects microstructures of materials, it can be used for characterizing microscopic material properties relating to chemical reactions and mechanical processes.

• **Acoustic impedance (Z):** Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid. The Acoustic impedance (Z) of a material is defined as the product of its density (ρ) and acoustic speed in medium

$$Z = \rho V \qquad \textbf{....(2.3)}$$

Acoustic impedance is important in determining acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.

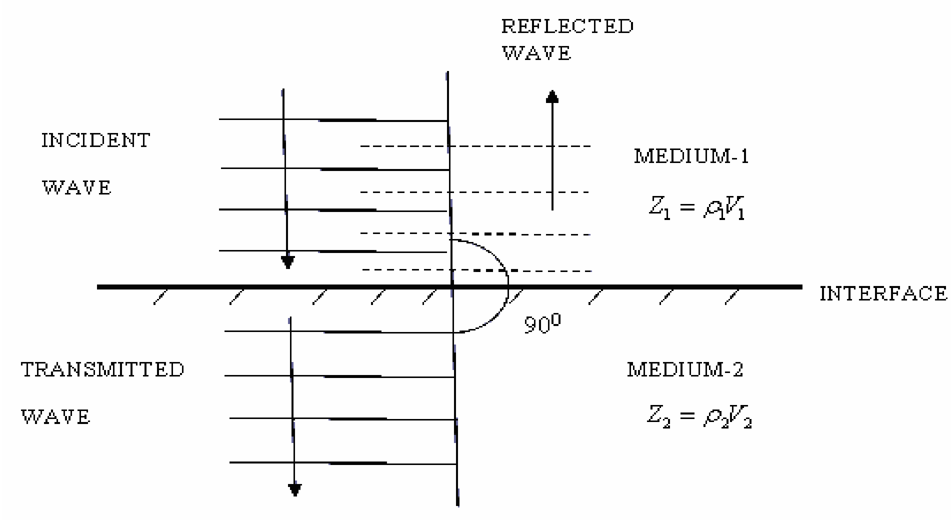


Fig 2.2 Reflection and Transmission of sound wave at normal incidence [Bindal, 1999]

• **Reflection and Transmission Coefficients:** Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary as shown in the **Fig. 2.2**. This difference in Z is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another. The fraction of the incident wave intensity that is refracted can be derived because particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with the equation below. The value produced is known as the reflection coefficient.

$$\text{Reflection coefficient,}\quad R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \qquad \textbf{....(2.4)}$$

$$\text{Transmission coefficient,}\quad T = \frac{2Z_2}{Z_2 + Z_1} = \frac{2\rho_2 V_2}{\rho_2 V_2 + \rho_1 V_1} \qquad \textbf{....(2.5)}$$

-

2.2.2 Reflection, Refraction and Mode Conversion of Waves

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal wave hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. Mode conversion occurs when a wave encounters an interface between materials of different acoustic impedances and the incident angle is not normal to the interface.

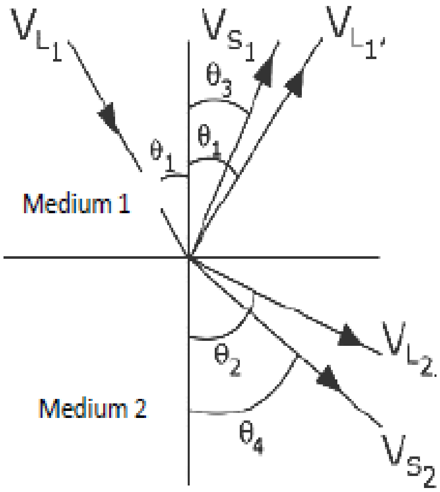
When sound waves pass through an interface between materials having different acoustic velocities, refraction takes place at the interface. The larger the difference in acoustic velocities between the two materials, the more the sound is refracted. Notice that the shear wave is not refracted as much as the longitudinal wave. This occurs because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as longitudinal waves but it is between the incident and refracted longitudinal waves. Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave (ref. **Fig.2.3**). This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material. Snell's Law holds true for shear waves as well as longitudinal waves and can be written as

$$\frac{\sin\,\theta_1}{\mathrm{VL}_1} = \frac{\sin\,\theta_2}{\mathrm{VL}_2} = \frac{\sin\,\theta_3}{\mathrm{VS}_3} = \frac{\sin\,\theta_4}{\mathrm{VS}_4} \qquad \textbf{....(2.6)}$$

2.2.3 Use of Critical Angles for NDT

For small angles of incidence sound waves travelling at an angle from medium 1give rise to the longitudinal as well as shear waves, in the medium 2. Such a situation is very confusing for NDT inspection, as both of these waves present in the medium 2, travel at different velocities and give rise to separate on the flaw detector screen.

As a solution to this problem the longitudinal wave is not allowed to enter the test piece and is eliminated by total internal reflection. Therefore, a clear knowledge about the formation of critical angles becomes important, especially in the case of designing of angle beam transducers.



$$\frac{\sin\,\theta_1}{VL_1} = \frac{\sin\,\theta_2}{VL_2} = \frac{\sin\,\theta_3}{VS_3} = \frac{\sin\,\theta_4}{VS_4} \qquad \textbf{….(2.7)}$$

Where:

VL_1 – is the longitudinal wave velocity in medium 1.

VL_2 – is the longitudinal wave velocity in medium 2.

VS_1 – is the shear wave velocity in medium 1.

VS_2 – is the shear wave velocity in medium 2.

Fig 2.3 Snell's Law [Bindal. 1999]

2.2.3.1 First Critical Angle (A_1)

If the angle of incidence A is increased in the particular case when c2 > c1, angle B of the refraction longitudinal wave also increases till, for some specific value of angle A, the angle B becomes equal to 90^o. At this angle A1, (**Fig 2.4**) there would be no refraction longitudinal wave in the medium 2 and only the shear wave would be propagating. This value of angle A is called First Critical Angle (A1). Generally, the angle beyond the first critical angle is used for ultrasonic inspection at oblique incidence. Taking the refracted angle B for the longitudinal wave as 90^0, the Snell’s equation can be written as

$$\frac{\sin\,A_1}{C_1} = \frac{\sin\,90}{C_2(\text{Long})}$$

$$\text{or } A_1 = \sin^{-1}\frac{C_1}{C_2} \qquad \textbf{….(2.8)}$$

Where; C_1 and C_2 are longitudinal velocities in two media

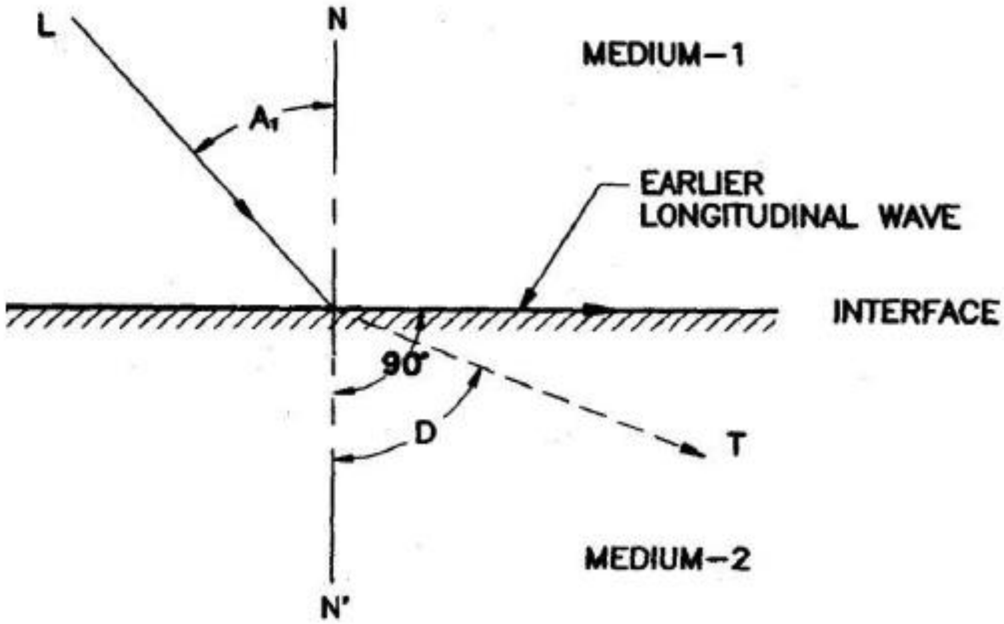


Fig 2.4 First Critical Angle [Bindal. 1999]

2.2.3.2 Second Critical Angle (A_2)

If the angle of incidence A is further increased beyond A1, a situation would arrive, when angle D of the refracted shear wave would be equal to 90^o. The value of angle A is now known as second critical Angle (A2) (**Fig 2.5**). At this position the Snell's equation can be written as

$$\frac{\sin A_2}{\mathrm{C_1(Long)}} = \frac{\sin 90}{\mathrm{C_2(Trans)}}$$

$$\text{or } \mathrm{A_2} = \sin^{-1}\frac{\mathrm{C_1(Long)}}{\mathrm{C_2(Trans)}} \qquad \textbf{....(2.9)}$$

The **Fig. 2.5** shows the formation of Second Critical Angle. At this position there would be no sound beam entering the medium 2 and the shear wave would appear as surface wave.

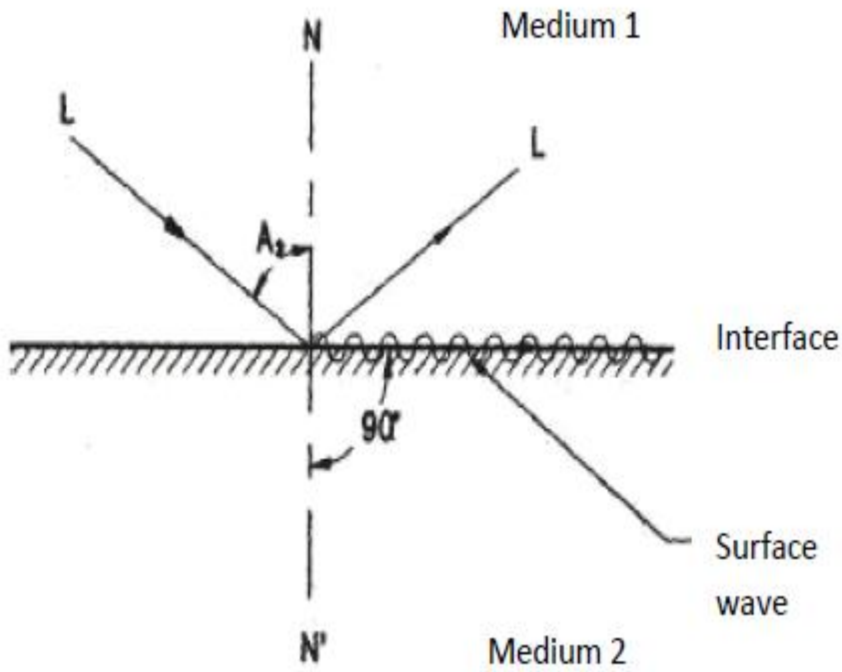


Fig 2.5 Second Critical Angle [Bindal. 1999]

2.2.4 Modes of Wave Propagation:

The ultrasonic waves propagate in a number of ways in a medium. On the basis of the mode of particle displacement, these waves can be classified as given in Table 2.1

a) Longitudinal or Compressional waves (L-waves)

b) Transverse or Shear waves (S-waves)

c) Surface or Rayleigh waves

d) Lamb or Plate waves

e) Creeping or Head waves

Out of these longitudinal and transverse wave propagations are most important and are extensively used in ultrasonic NDT applications for Civil structures. Surface waves and lamb waves are used for monitoring of thin plate geometries to locate surface defects.

Table 2.1 Types of Waves Propagation [http://www.ndt-ed.org]

Sr. no	Type of wave	Direction of motion of particles
1	Longitudinal or Compression waves (L-waves)	Parallel to wave direction
2	Transverse or Shear waves (S-waves)	Perpendicular to wave direction
3	Surface or Rayleigh waves	Elliptical orbit – symmetrical mode
4	Plate waves- Lamb	Component perpendicular to surface (extensional wave)
5	Plate waves- Love	Parallel to plane layer, perpendicular to wave direction
6	Stoneley (Leaky Rayleigh Waves)	Wave guided along interface
7	Sezawa	Anti symmetric mode

- **Longitudinal or Compressional waves**:

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compressional and dilatational forces are active in these waves, they are also called pressure or compressional waves. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements.

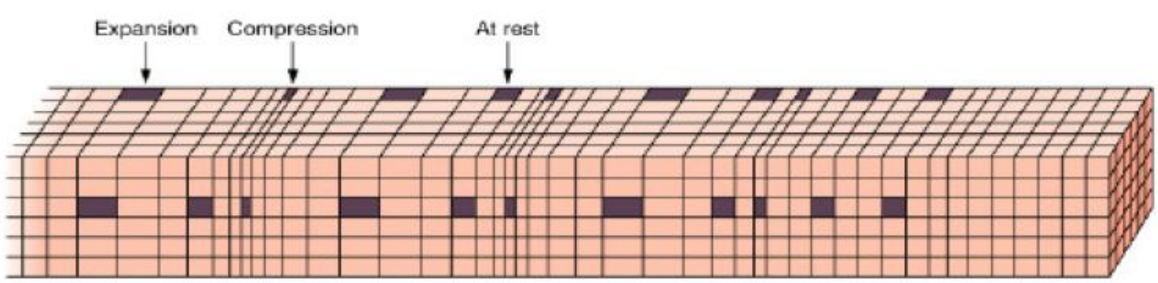


Fig 2.6 Propagation of Longitudinal waves [http://www.googleimages.com]

➢ **Transverse or Shear waves:**

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation.

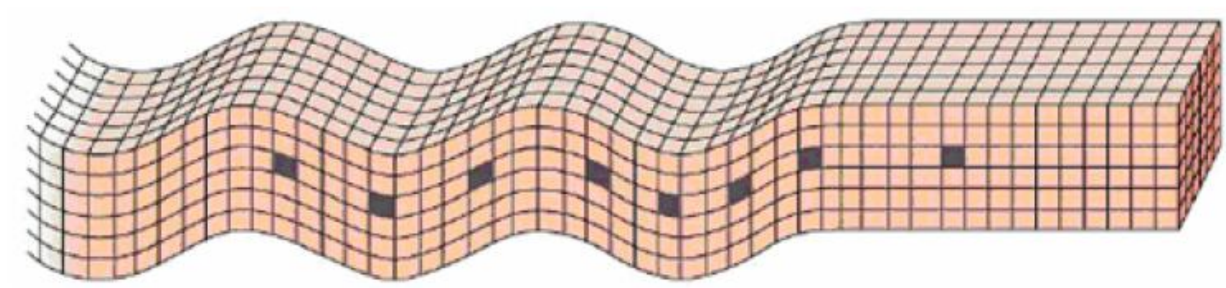


Fig 2.7 Propagation of Transverse or Shear waves [http://www.googleimages.com]

Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves.

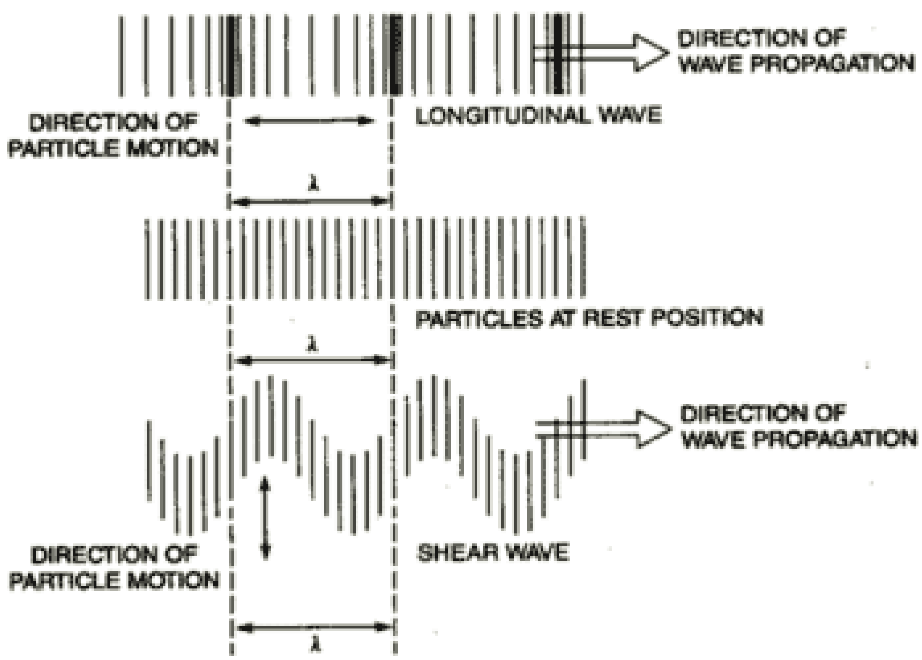


Fig 2.8 Particle Movement Showing the Propagation of Longitudinal and Shear Waves [http://www.ndt-ed.org]

➢ Surface (or Rayleigh) waves:

Surface (or Rayleigh) waves travel the surface of a relatively thick solid material penetrating to a depth of one wavelength. The particle movement has an elliptical orbit as shown in the image below. Rayleigh waves are useful because they are very sensitive to surface defects and they follow the surface around curves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

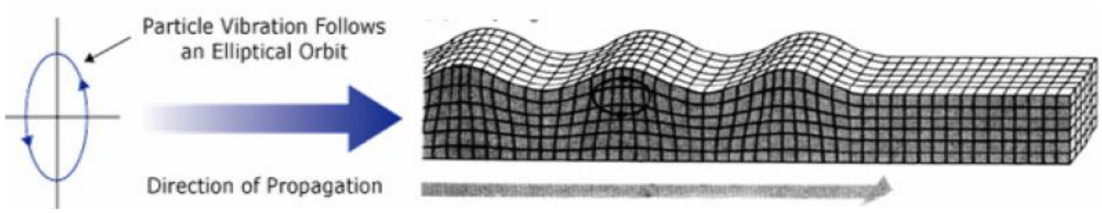


Fig 2.9 Propagation of Surface or Rayleigh Waves [http://www.googleimages.com]

➢ Lamb waves or Plate waves:

Plate waves can be propagated only in very thin metals. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that travel through the entire thickness of a material. Propagation of lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness.

With lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical. The complex motion of the particles is similar to the elliptical orbits for surface waves. Symmetrical lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is "stretching and compressing" the plate in the wave motion direction. Wave motion in the symmetrical mode is most efficiently produced when the exciting force is parallel to the plate. The asymmetrical lamb wave mode is often called the "flexural mode" because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

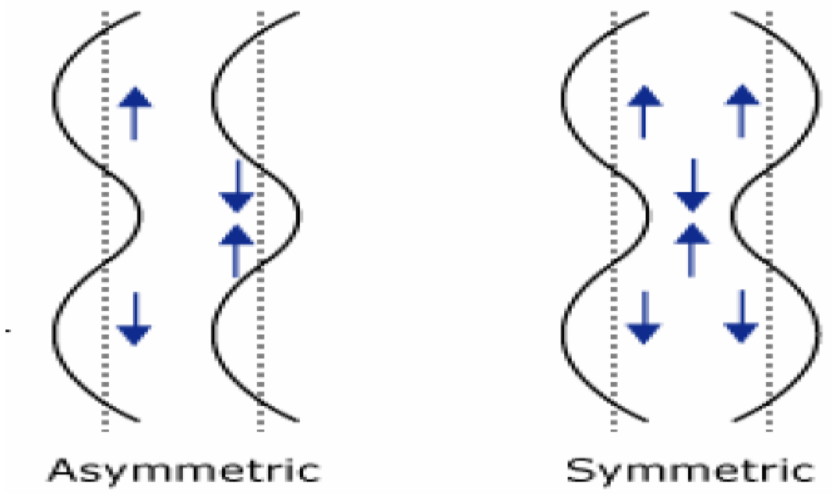


Fig 2.10 Lamb Waves Propagation (a) Symmetrical (Dilatational) and (b) Asymmetrical (Bending) waves [http://www.googleimages.com]

- **Creeping or Head waves:**

These waves are also called head waves. The behavior of creeping waves is similar to that of longitudinal waves. They travel as fast as longitudinal waves and the creeping waves should not be misunderstood as moving slowly. These are generated parallel to scanning surface, enabling detection of surface breaking defects. These have limited range and as these travel just below the surface and not on the surface, so the couplant has no influence.

2.3 Ultrasonic Testing

2.3.1 Basic Principles of Ultrasonic Testing

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 2.11** 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.

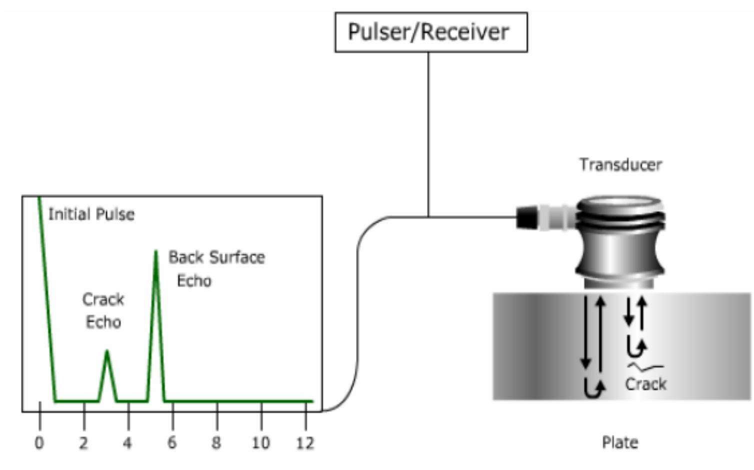


Fig 2.11 General (pulse echo method) ultrasonic Inspection Principle. [http://www.ndt-ed.org]

2.3.2 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. 2.12**, 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.

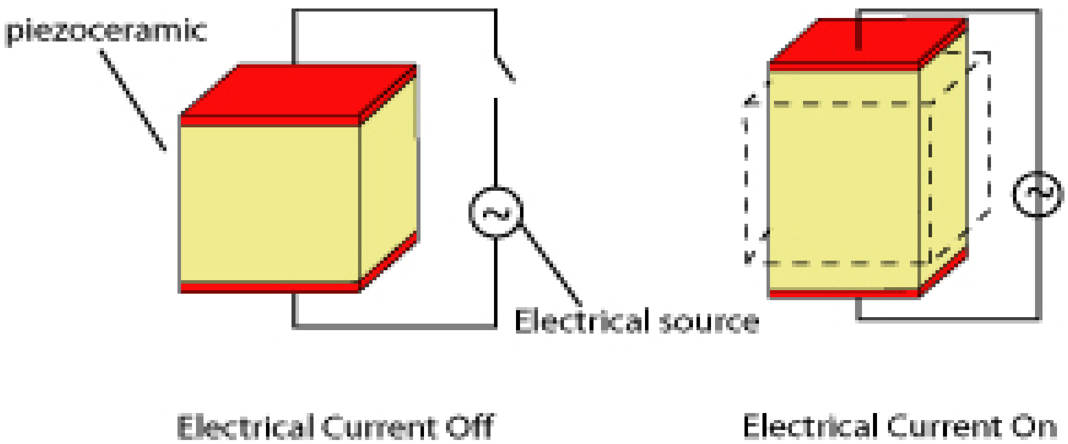


Fig. 2.12 Piezoelectric Crystal with Current Off and On [http://www.googleimages.com]

Main components of Transducer/Probe head as shown in **Fig 2.13** are;

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

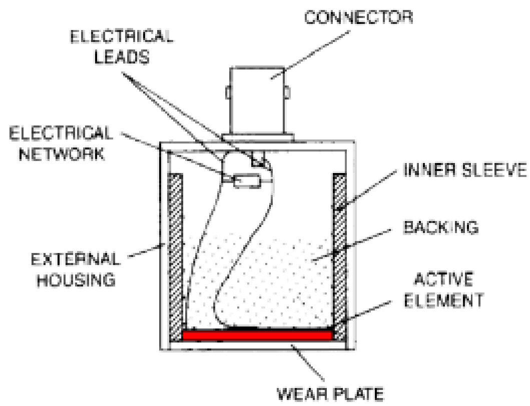


Fig. 2.13 Piezoelectric Transducer [http://www.googleimages.com]

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.

2.3.2.1 Components of Transducer

As shown in the **Fig. 2.14**, the components of the transducer and their functions are as follows:

The main purpose of the wear plate is simply to protect the piezoelectric transducer element from the environment. Wear plates are selected to generally protect against wear and corrosion. In an immersion-type transducer, the wear plate also serves as an acoustic transformer between the piezoelectric transducer element and water, wedge or delay line. [http://www.ndted.org]

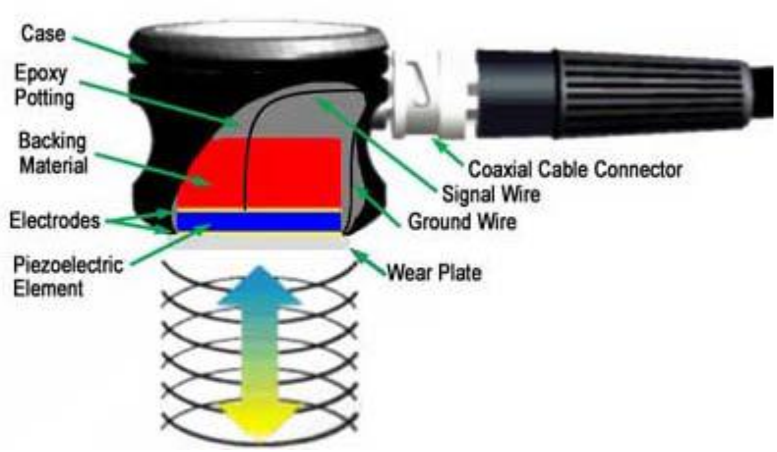


Fig. 2.14 Components of Transducer [http://www.googleimages.com]

The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with impedance similar to that of the active element will produce the most effective damping. Such transducer will have a narrow bandwidth resulting in higher sensitivity. As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced.

2.3.2.2 Radiated Fields of Ultrasonic Transducers

The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element. Round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer. The sound field from a typical piezoelectric transducer is shown below.

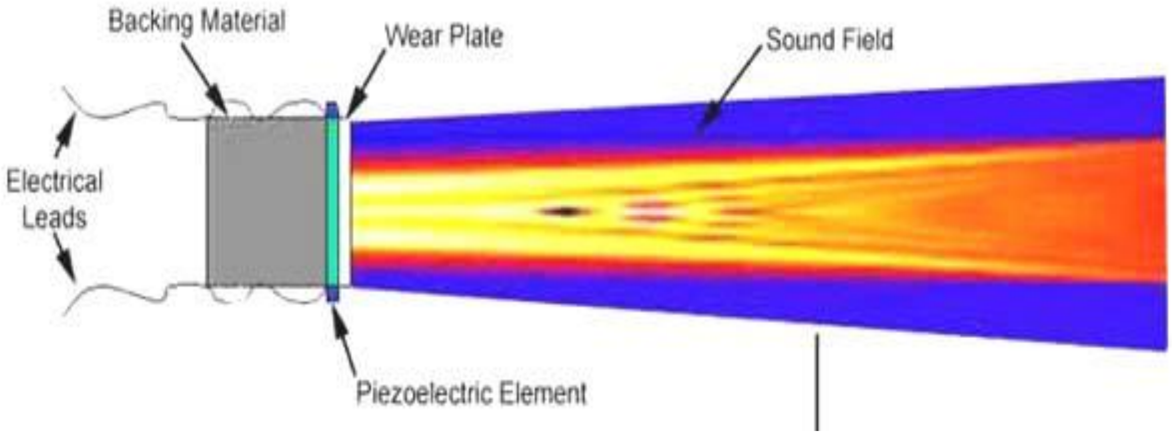


Fig. 2.15 Sound Field from a Typical Piezoelectric Transducer [http://www.googleimages.com]

The intensity of the sound in **Fig. 2.15** is indicated by colour, with lighter colours indicating higher intensity. Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference as discussed in a previous page on wave interference. These are sometimes also referred to as diffraction effects. This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the near field. Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.

2.3.2.3 Contact Transducers

Contact transducers are available in a variety of specifications to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

• **Dual element transducers** contain two independently operated elements in a single housing, as shown in **Fig. 2.16**. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of course grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience (when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function). Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.

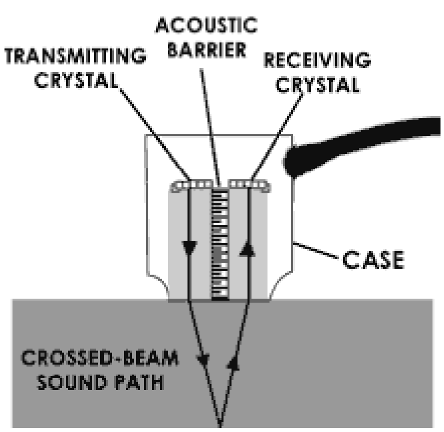


Fig. 2.16 Dual Element Transducers

[http://www.googleimages.com]

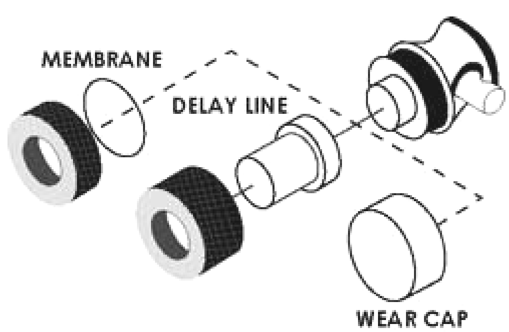


Fig. 2.17 Delay Line Transducers

[http://www.googleimages.com]

• **Delay line transducers** provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options, as shown in **Fig. 2.17** can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and de-lamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

• **Angle beam transducers** and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction. In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material, which is usually steel.

The angled sound path allows the sound beam to be reflected from the back wall to improve detect ability of flaws in and around welded areas. They are also used to generate surface waves for use in detecting defects on the surface of a component.

• **Normal incidence shear wave transducers** are unique because they allow the introduction of shear waves directly into a test piece without the use of an angle beam wedge. Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination. The ratio of the longitudinal to shear wave components is generally below -30dB.

• **Paint brush transducers** are used to scan wide areas. These long and narrow transducers are made up of an array of small crystals that are carefully matched to minimize variations in performance and maintain uniform sensitivity over the entire area of the transducer. Paint brush transducers make it possible to scan a larger area more rapidly for discontinuities. Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

2.3.3 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 2.18**. 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.

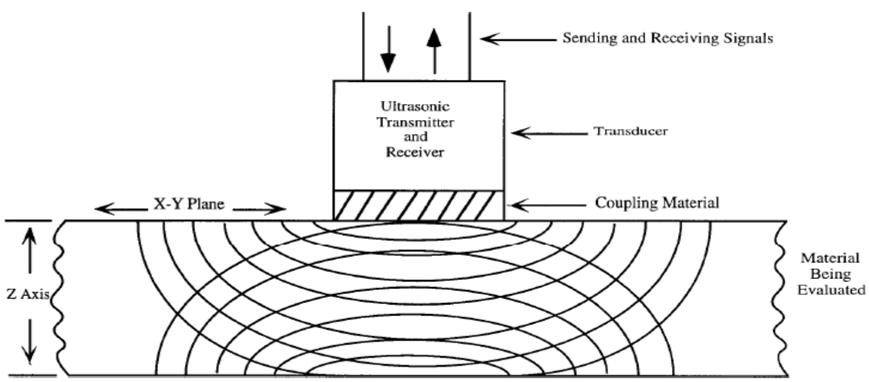


Fig 2.18 Principle of pulse echo method of inspection [Vermani, 2008].

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 2.19**. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

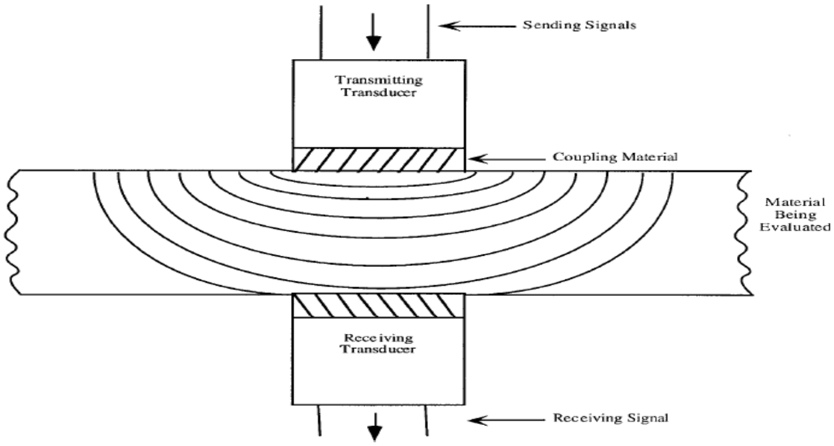


Fig 2.19 Principle of through transmission of ultrasonic testing [Vermani, 2008].

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 2.20** in which two transducers are placed on the same side of the plate at certain angle to detect the damage.

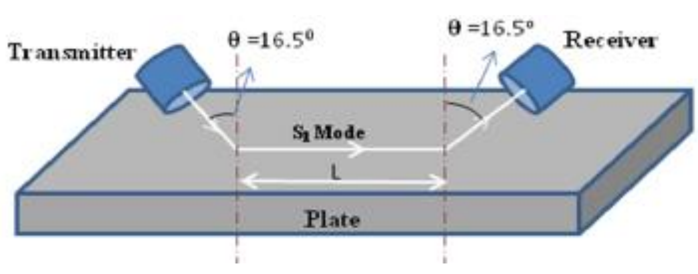


Fig 2.20 Transducers arranged at an angle to the Plate [http://www.googleimages.com]

2.4 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 2.21**. 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.

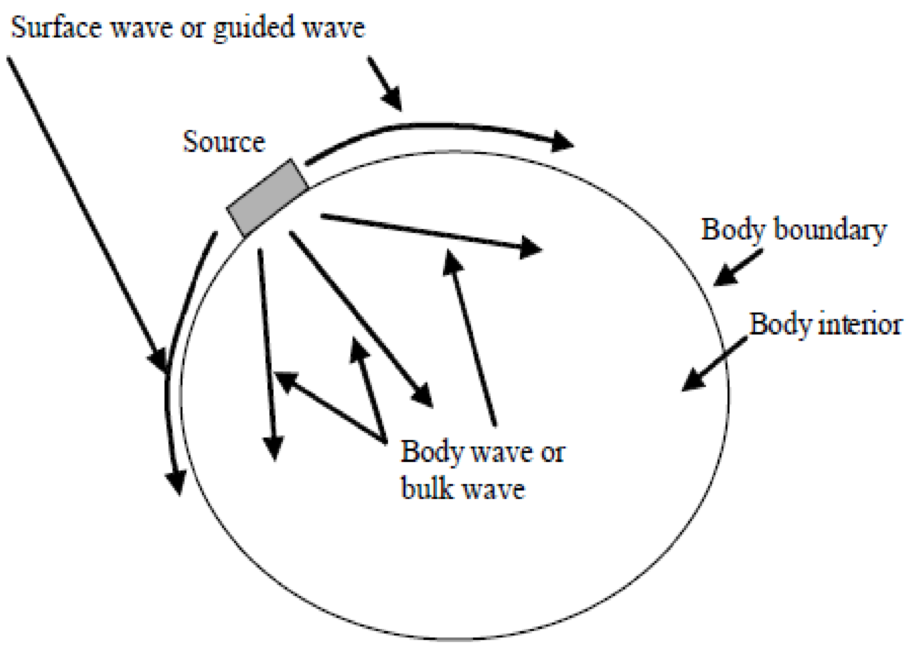


Fig 2.21 Body waves and surface waves generated by an ultrasonic source [Kundu, 2007]

Guided waves can further be classified into following types, as shown in **Fig 2.22**:

• Bar waves

• Cylindrical wave

• Rayleigh waves

• Lamb waves

• Rayleigh-Lamb waves

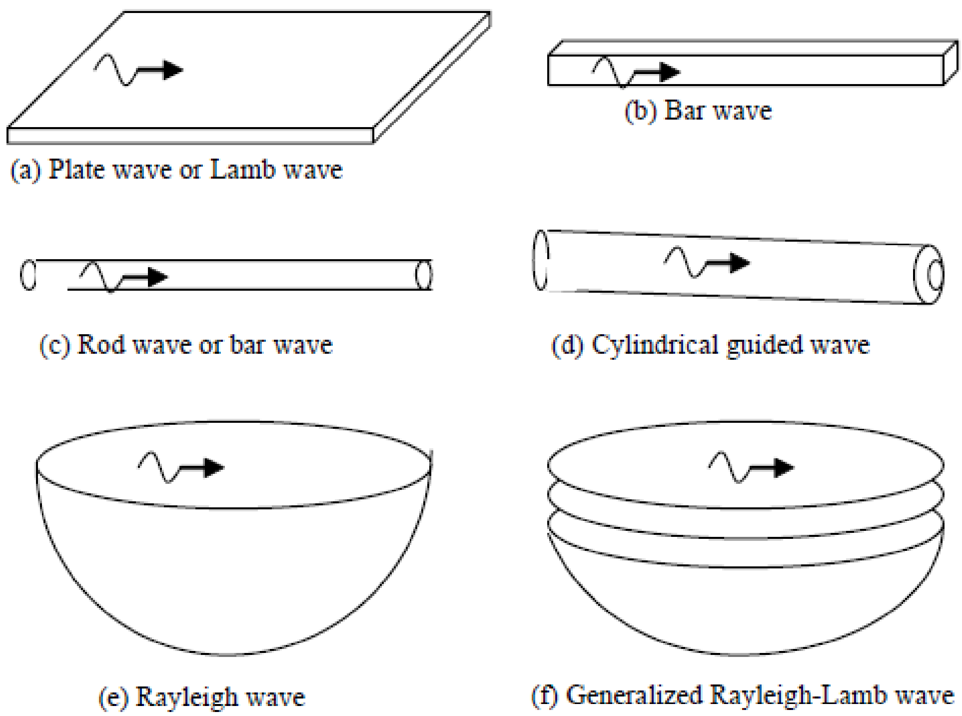


Fig 2.22 Different types of guided waves in various problem geometries [Kundu, 2007]

Cylindrical Guided Waves: Elastic waves propagating through a hollow cylinder or pipe are called cylindrical guided waves (**Fig 2.22(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 2.22(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 2.22(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 2.22(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 2.22(f))**.

2.5 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.

Table 2.2: 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

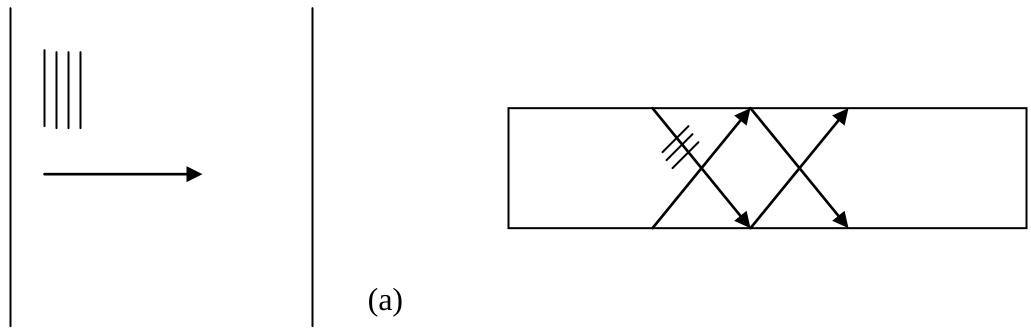
Table 2.3: Benefits of Guided Waves over Bulk waves [Rose, 2004]

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.

To think of the utilization of ultrasonic guided waves we can consider a variety of different natural wave guides as outlined in **Table 2.2**. 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.

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 2.3**. 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 2.23**. 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.



(a) (b)

Fig 2.23 Schematic of (a) bulk wave and (b) Guided wave propagation [Demma, 2003]

When the waveguide is imbedded in a solid, leakage by both longitudinal and shear waves can occur which leads to very high attenuation rates, especially when the acoustic impedances of the waveguide and the surrounding solid are similar. **Fig 2.24** shows two layers, layer one (bar) represent a finite layer and layer two (concrete) represents an infinite medium surrounding the cylinder. The partial waves (L±, SV±, SH±) combine to form a guided wave in the axisymmetric cylindrical structure.

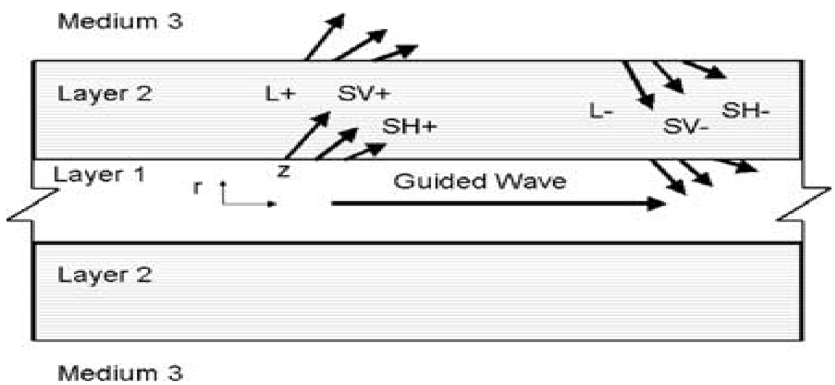


Fig 2.24 Schematic of a bar embedded in concrete [Kundu et al. 2002]

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.

2.6 Closing Remarks

This chapter highlights the various details of ultrasonic waves and discusses in detail the classifications of ultrasonic waves into Bulk and Surface Waves.

The principal advantage of guided or surface waves over bulk wave is that inspection over long distances with excellent sensitivity from a single probe position can be achieved and also enable one to inspect hidden structures and structures under water, coatings, insulations, and concrete.

The next chapter highlights the various details of using ultrasonic guided waves in early strength and hardening of concrete and emphasize on the work done on the same till date.

CHAPTER 3

LITREATURE REVIEW

It is proposed in this work to study setting and hardening properties of concrete using ultrasonic guided waves. This chapter presents a review of literature on various methods and techniques for monitoring early age strength i.e. first 24 hr of hydration and hardening i.e during curing of concrete specimen. This gives an idea of study carried out in this area up to this stage since last ten years.

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.

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.

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 .This paper shows 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.

Dhonde et al. (2006) studied Piezoelectric-based strength monitoring methods which provided an innovative experimental approach to conduct concrete strength monitoring at early ages. In this paper piezoelectric transducers in the form of 'smart aggregates' were embedded into the concrete specimen during casting. Piezoceramic materials were used as actuators to generate high frequency vibrating waves, which propagated within concrete structures; meanwhile, they were also used as sensors to detect the waves. The strength development of concrete structures was monitored by observing the development of harmonic response amplitude from the embedded piezoelectric sensor at early ages. From experimental results, it was found out that the amplitude of the harmonic response decreases with increasing concrete strength, as concrete strength increases at a fast rate during the first few days and at a decreasing rate after the first week. Concordantly, the amplitude of the harmonic response from the piezoelectric sensor drops rapidly for the first week and continues to drop slowly as hydration proceeds, matching the development of the concrete strength at early ages. In this paper, a fuzzy logic system is trained to correlate the harmonic amplitude with the concrete strength based on the experimental data. The experimental results showed that the concrete strength estimated by the trained fuzzy correlation system matches the experimental strength data. The proposed piezoelectric-based monitoring method had the potential to be applied to strength monitoring of concrete structures at early ages.

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.

Che-Way Chang and Hung-Sheng Lien (2008) utilized the impact pulse velocity nondestructive method to estimate the compressive strength of the concrete at early age. The results concerning the correlation between the compressive strength at early ages of concrete and that hardened under standard conditions. The relationship of pulse velocity and strength were established for concrete but they were controlled under various water-cement ratio. The result highlighted that Pulse velocity correlates well with strength at early ages but was insensitive to increases in compressive strength after concrete curing. This paper also discusses the influence of the curing time in concrete and water-cement ratio on the coefficients of variation of the compressive strength deduced both in a destructive and nondestructive methods. Lastly, it was concluded that accuracy of compressive strength estimation can be predicted by the impact method.

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.

Jinying Zhu & Seong-Hoon Kee (2010) noted that conventional ultrasonic setups typically measure longitudinal (P) waves in fresh cement pastes and need access two sides of the specimen. This type of setup was not suitable for in-situ field testing. In this study, embedded piezoelectric bender elements were used to generate and measure both P and shear (S) waves in fresh cement pastes. The shear waves were observed at very early age of the cement hydration. The velocities of P and S waves are obtained from B-scan images of a collection of recorded signals over time. Experimental results indicate that the shear wave velocity was closely related to the setting time of cement pastes and less affected by air contents than the P wave velocity. Shear modulus and Poisson's ratios of the cement pates were derived from the measured P and S wave velocities.

Lee .H.K. & Tawie R. (2010) studied the advances in piezoelectric materials to develop new nondestructive evaluation and monitoring techniques. In this study, piezoceramic (PZT) sensors were embedded in concrete by bonding the sensors on steel reinforcing bars to perform non-destructive monitoring. To evaluate the performance of the PZT sensors and electromechanical impedance (EMI) sensing technique, a series of experiments were carried out to monitor the bond development between steel rebar and concrete by measuring the electrical response of the PZT bonded to the steel rebar using an impedance analyzer. From the EMI measurements, the gradual adhesion between the steel rebar and fresh concrete was detected via the measured changes in the conductance spectra of the PZT sensor bonded to the steel rebar. The bond development could be attributed to the transformation of concrete from liquid to solid state controlled by the hydration of cement and by monitoring the hydration of concrete with respect to time, the status of bonding was estimated. The results showed that the early-age development of bonding between steel rebar and concrete is affected by various factors such as varying water–cement ratio, low curing temperature and poor compaction.

Pazdera et al. (2010) studied concrete properties during early age process. It was made clear that fissuring is mainly during early age. Some nondestructive testing methods such as Acoustic Emission Method and Nonlinear Spectroscopy were applied which indicate interesting results. The results concluded that Acoustic emission, Non-linear (ultrasonic) spectroscopy or Impedance spectroscopy are suitable tools for monitoring concrete structure over its lifetime. Using these methods simultaneously brought better evaluation of micro changes into concrete structure from its making.

3.1 Closing Remarks

This chapter throws light on recent works done in monitoring the early age strength development and hardening process of concrete using various approaches. The benefit of using other ultrasonic methods as a NDT tool in monitoring and comparing different properties of concrete was highlighted.

The literature of the work carried out till date in this field was also reviewed.

The following chapter discusses the experimental work carried out in this thesis report and various equipments used in experiment setup.

CHAPTER 4

EXPERIMENTAL STUDIES: MONITORING EARLY AGE STRENGTH & HARDENING OF CONCRETE

4.1 Introduction

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.

This chapter discusses about the guided wave approach that characterizes the early age setting/strength of concrete during the **first phase** i.e. first twenty-four hours of hydration and hardening of concrete during the **second phase** i.e. during curing of concrete i.e. upto 28 days in accordance with IS 516. Using a Pulse-transmission system, the method measures the energy leakage of the fundamental 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 various testing techniques, equipment, specimens, concrete mix used are also highlighted.

4.2 Experimental Program & Methodology

4.2.1 General

It is proposed in this work to use ultrasonic guided wave approach for monitoring strength and hardening of concrete in the two phases as mention above. The progression in the two phases is monitored by means of ultrasonic investigations. Along with the development of concrete setting and hardening is also studied with well established methods of UPV and Vicat Needle

Penetration tests. To characterize the phenomenon of early age setting and hardening of concrete, destructive tests like compressive tests & Pull-Out test were also conducted at different stages of the setting and hardening phases. Idea was to correlate the ultrasonic test results with other established strength development methods and also with in-situ strength of concrete.

4.2.2 Experimental Program

The experimental program in this work has been divided into two phases whose details are given in **Fig 4.1** and **Table 4.1** show the specimens used.

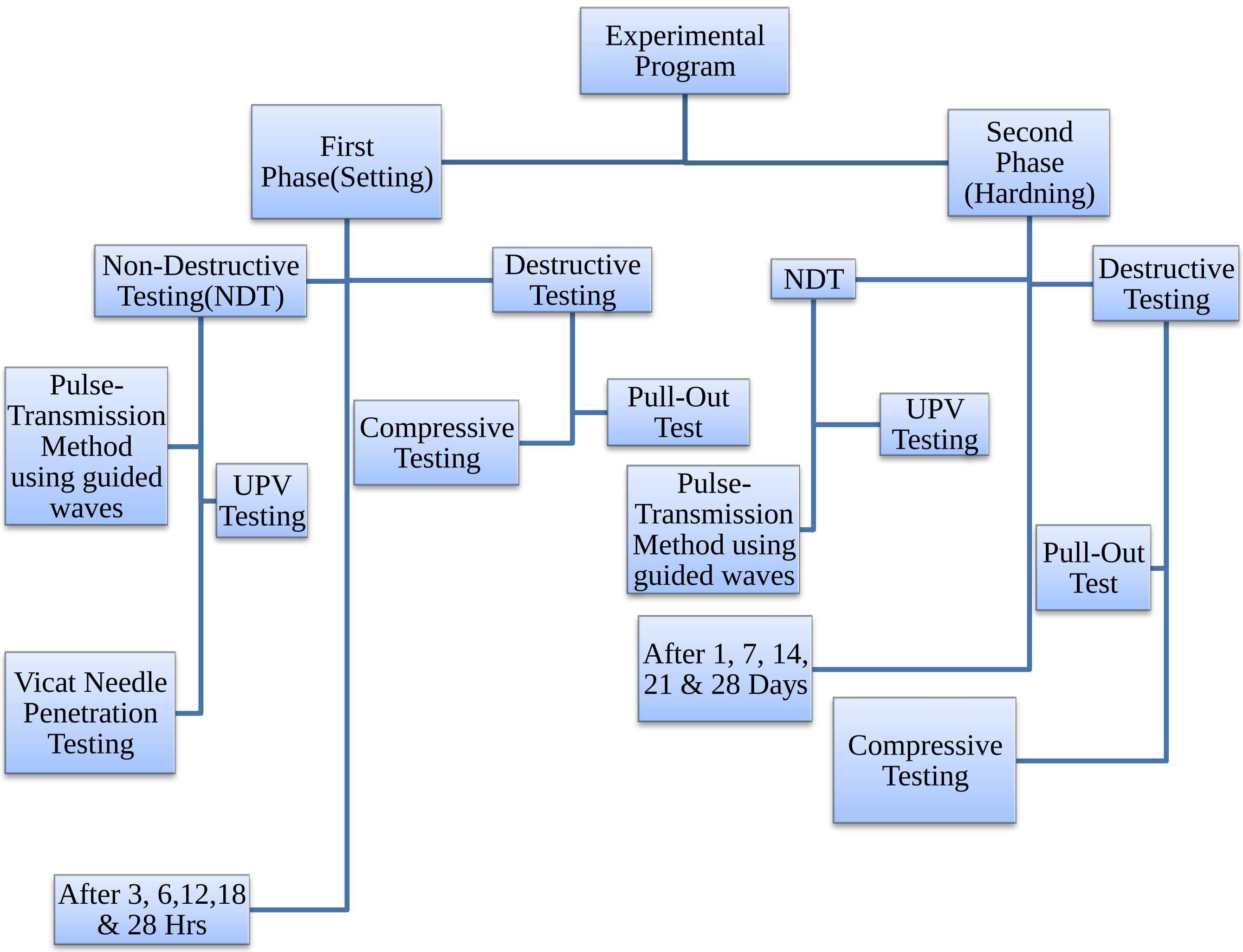


Fig 4.1 Experimental Program

Table 4.1 Specimens Used in the Experimental Program

Phase	Specimen	Specifications(mm)	Test Conducted	
			Non-Destructive	Destructive
First Phase (Setting)	Concrete Beam with embedded mild steel bar	Beam = 150x150x300 Steel Bar = 25 dia & 300 length	Ultrasonic Pulse transmission (UPT)	Pull-out and Compressive Tests
	Thin Cylinder	Diameter = 80 Height = 40	Penetration Test	
	Concrete cube	150x150x150	Ultrasonic Pulse Velocity(UPV)	Compressive Test
Second Phase (Hardening)	Concrete Beam with embedded mild steel bar	Beam = 150x150x300 Steel Bar = 25 dia & 300 length	Ultrasonic Pulse transmission (UPT)	Pull-Out Test
	Concrete cube	150x150x150	Ultrasonic Pulse Velocity(UPV)	Compressive Test
	Cylinder	Diameter = 150 Height = 300	Ultrasonic Pulse Velocity(UPV)	Compressive Test

4.2.3 Test Matrix

The Test matrix as the experimental program is also divided into two phases **(Fig 4.2)** as follows

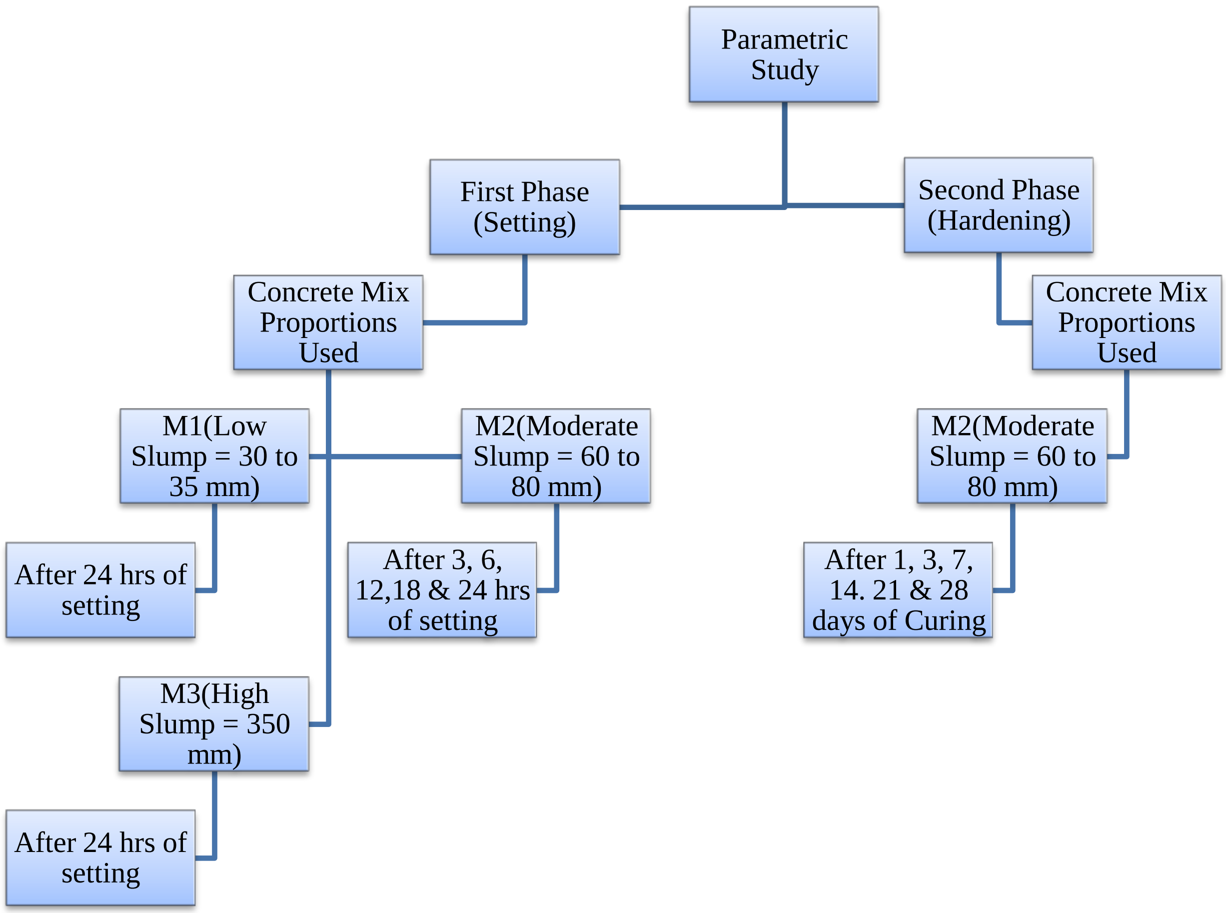


Fig 4.2 Parametric study carried out in the Experiment.

4.2.3.1 First/Initial Phase: Within first 24 Hrs of Hydration of Concrete Specimen

In the initial phase of the experiment various beams, cubes & thin cylinder of dimensions discussed earlier **(Table 4.1)** were casted using different mixes as shown in **Table 4.2**. The three different concrete mixes corresponds to various slumps levels which were taken named as $\mathbf{M_1}$ (Low slump), $\mathbf{M_2}$ (Moderate Slump) & $\mathbf{M_3}$ (High Slump).

For a moderate slump mix ($\mathbf{M_2}$), further test matrix was developed by considering different hrs of settings as 3hrs, 6hrs, 12hrs, 18hrs & 24hrs of setting. For all these cases non-destructive tests readings such as UPT, Penetration depth and UPV readings were taken throughout the duration of setting. After the completion of these tests destructive tests such as compressive test is performed on cubes while Pull-Out & Split-Tensile test is performed on beams. To obtain stability and check repeatability of data, minimum two samples were tested in each case.

Table 4.2 Concrete Mix Used

Concrete Mix No.	Mix Proportions			W/C Ratio	Water Reducing Admixture(FOSROC)	Slump(mm)
	Cement	Sand	Aggregate			
M_1	1	1.5	2.96	0.35 %	-----	Low (30 to 35)
M_2	1	1.5	2.96	0.45 %	-----	Moderate (60 to 80)
M_3	1	1.65	1.07	0.45 %	1.64 %	High (350)

4.2.3.2 Second/Final Phase: During curing of Concrete Specimen upto 28 Days

In this phase only one concrete mix i.e. $\mathbf{M_2}$ was used for casting beams, cubes & cylinder having dimensions mention earlier **(Table 4.1)**. For this mix, further test matrix was developed considering the different days of curing or hardening as 1day, 7 days, 14days, 21days and 28 days of curing.

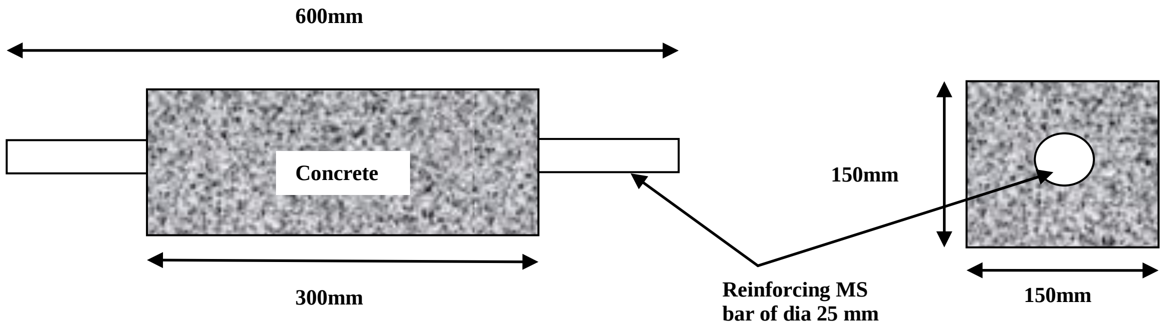
For all these cases same non-destructive tests as mention in first phase were performed except for Vicat Needle Penetration test throughout the curing process. After the completion of these tests destructive tests such as compressive test was performed on cubes and cylinder while only Pull-Out test was performed on beams. Similar to first phase, to obtain stability and check repeatability of data, minimum two samples were tested in each case here also.

4.3 Non-Destructive Testing

4.3.1 Experimental Detail: Ultrasonic Guided Wave Investigations

4.3.1.1 Set-Up & Specimen Detail

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 600mm length which is embedded in a concrete beam of size 150 mm x 150 mm x 300 mm **(Fig 4.3)** 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 4.4.**



(a) Side View **(b) Front view**

Fig 4.3 Concrete Beam specimen for ultrasonic investigations

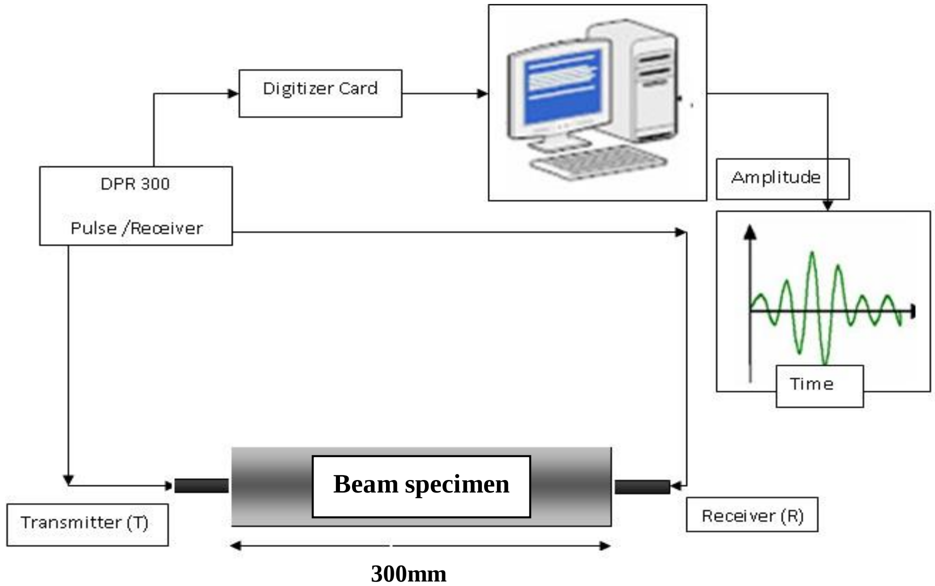


Fig 4.4 Experimental Set-Up

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:

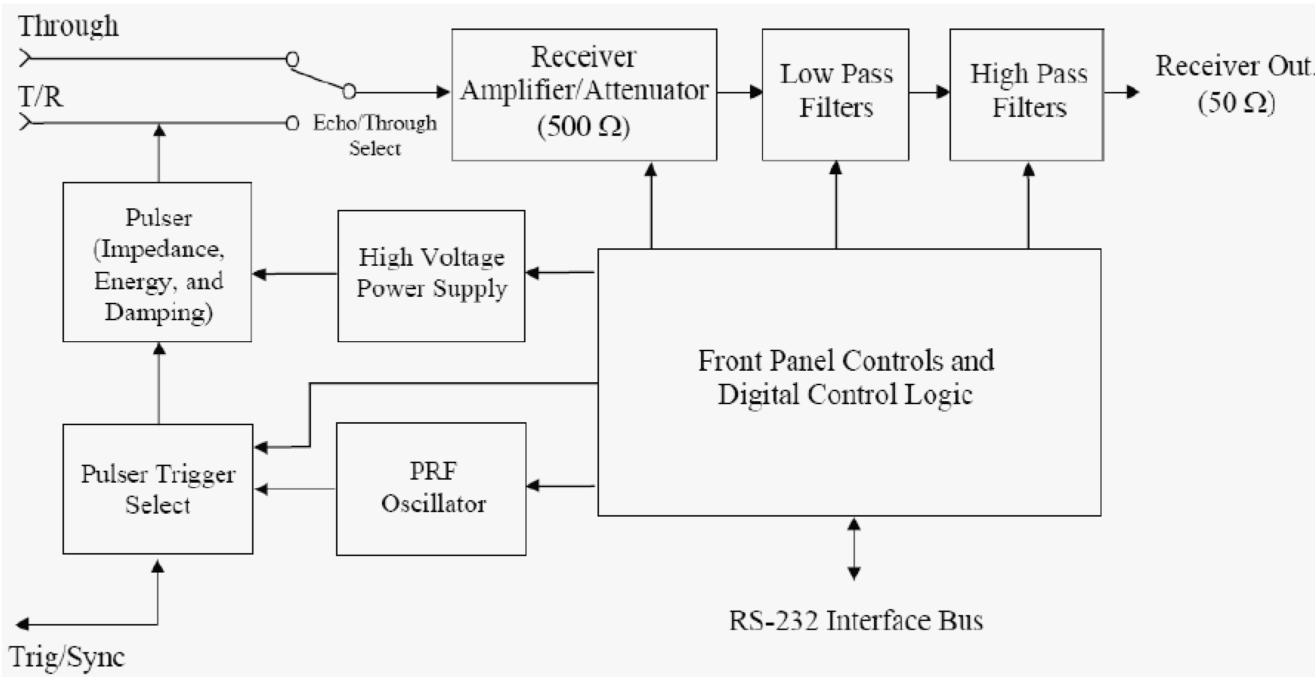


Fig 4.7 Detail circuit diagram of Pulser/Reciever system

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 4.3 gives the specifications of JSR pulse-receiver.

Table 4.3 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 4.4** gives the specifications of the Digitizer Card.

Table 4.4: 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

4.3.1.2 Methodology for ultrasonic guided wave testing

- **General**

Pulse-transmission method is used for characterizing the young concrete strength and hardening process. To produce guided waves in the bar of concrete beam two transducers (Karl Deutsch contact type) are attached at the two ends of the bar in projected beam. One transducer acting as a transmitter and the other acting as a receiver are attached parallel to the axis.

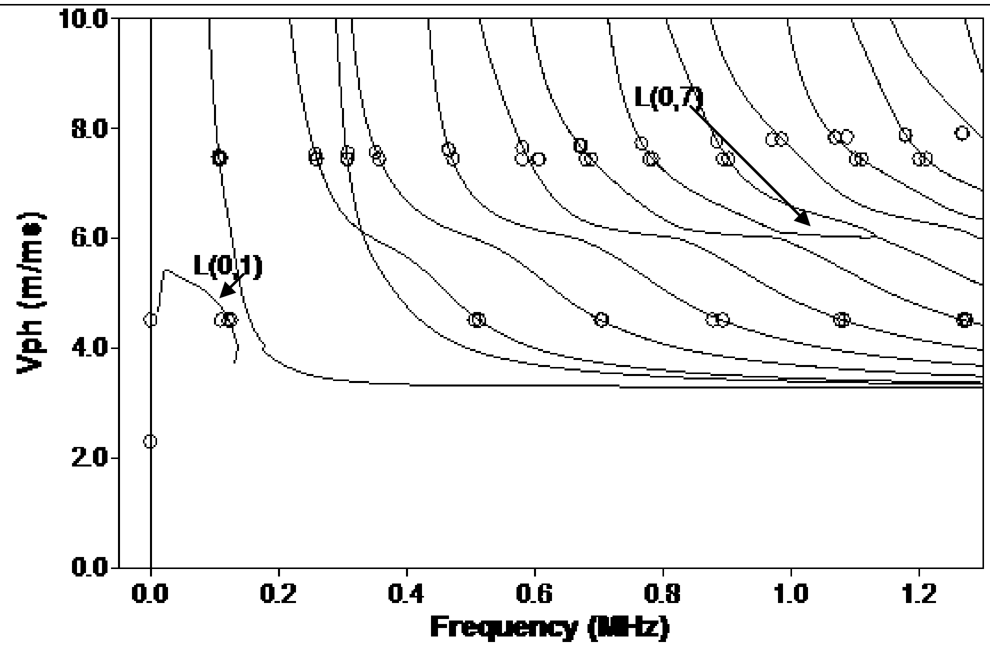
Transducers having longer wave form duration and a relatively narrow frequency bandwidth with centre frequency of 0.1 MHz (surface seeking mode) has been used because the main aim of the experiment was to monitor the bonding between the 25mm mild steel rod & the surrounding concrete in the beam.

- **Selection of Excitation Mode and Frequency**

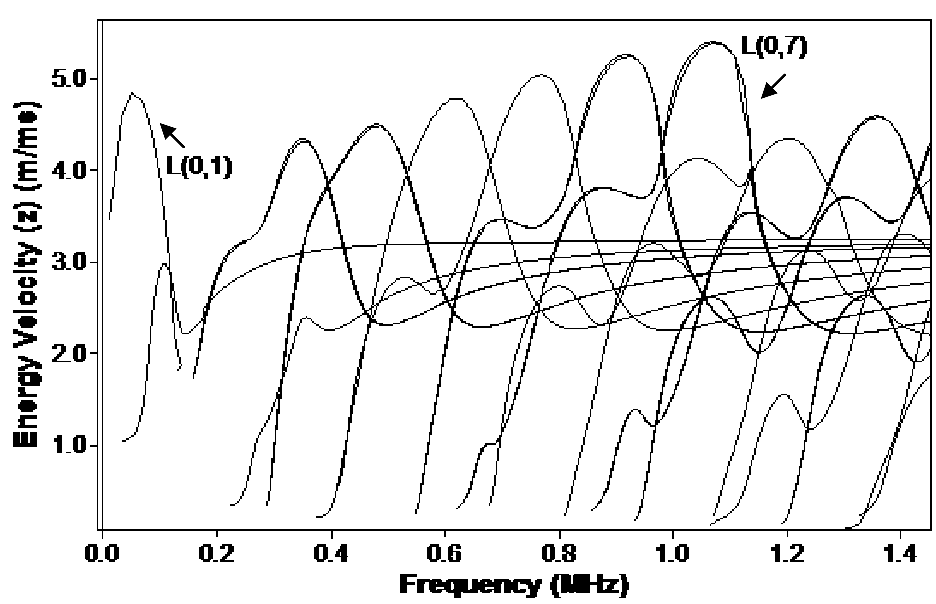
The selection of frequencies for testing is done using the software Disperse [Pavalakovic & Cawley, 2000]. The selection of a suitable test mode and frequency can be made by close examination of the dispersion curves. The modes that are easily distinguishable and have lowest signal attenuation are selected [Sharma & 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.

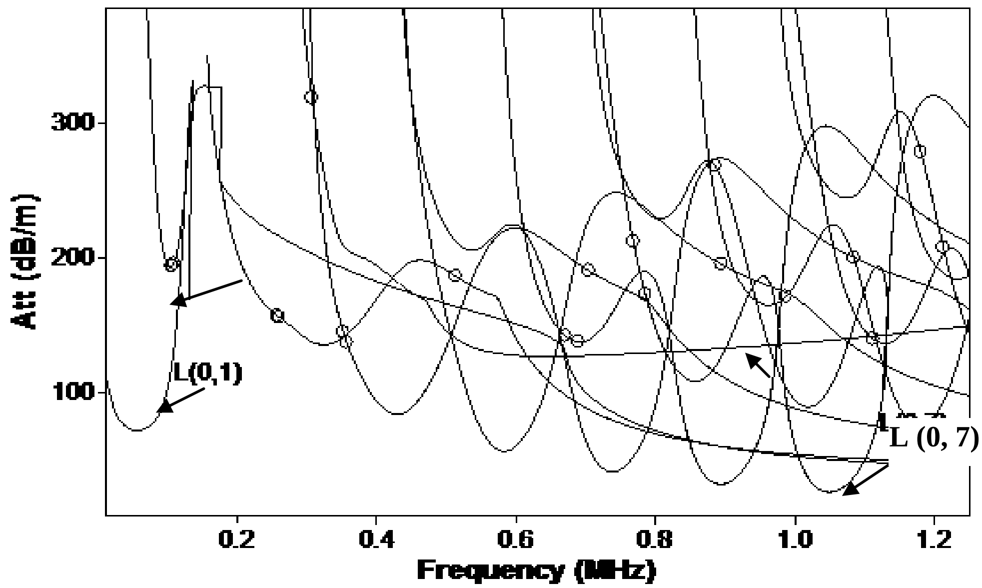
Another contributing factor to the selection of mode is the relative sensitivity of ultrasonic waves to setting of concrete. **Fig 4.9(b)** shows the displacement mode shape and radial strain energy density distribution for L (0, 7) mode not selected in the present investigation. The energy is concentrated 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. Thus, these two modes have been considered in an attempt to distinguish between the debond and area loss effect of chloride corrosion through ultrasonics. Also the two modes are the lowest attenuating modes as shown in **Fig 4.8(c)**.



(a) Phase velocity Vs Frequency

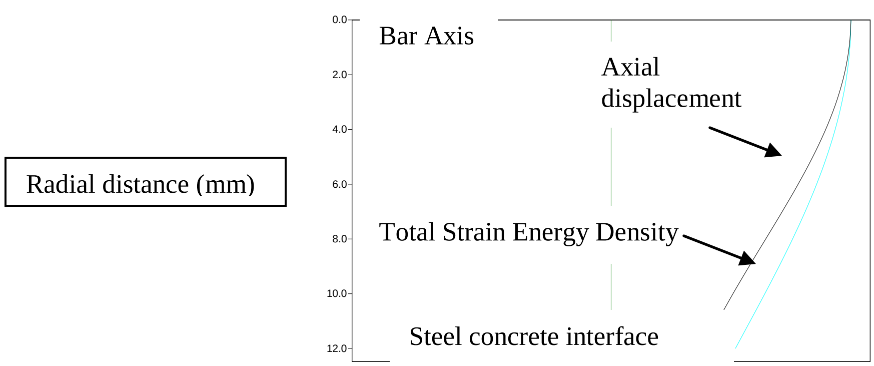


(b) Energy Velocity Vs Frequency

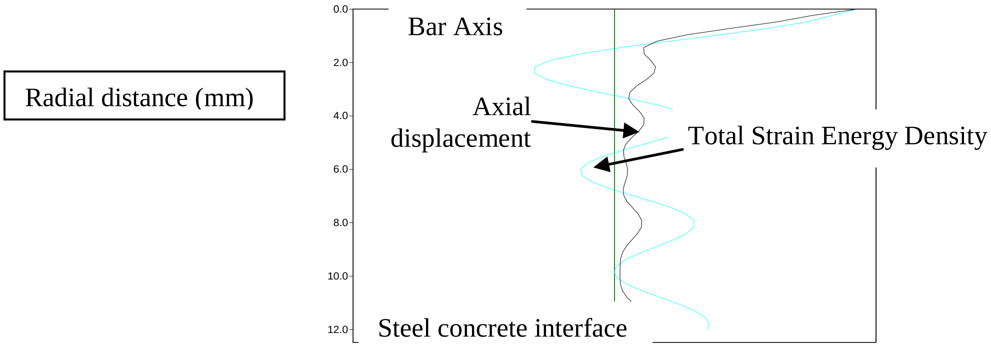


(c) Attenuation Vs Frequency

Fig 4.8 Dispersion curves for 25mm diameter bar [Sharma & 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 & Mukherjee, 2010]

4.3.2 Experimental Detail: Ultrasonic Pulse Velocity Investigations

4.3.2.1 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 strength during first phase (setting) and second phase(hardening).

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), while on the other hand in second phase the UPV test is performed on cube as well as on cylinder during the curing (days) process.

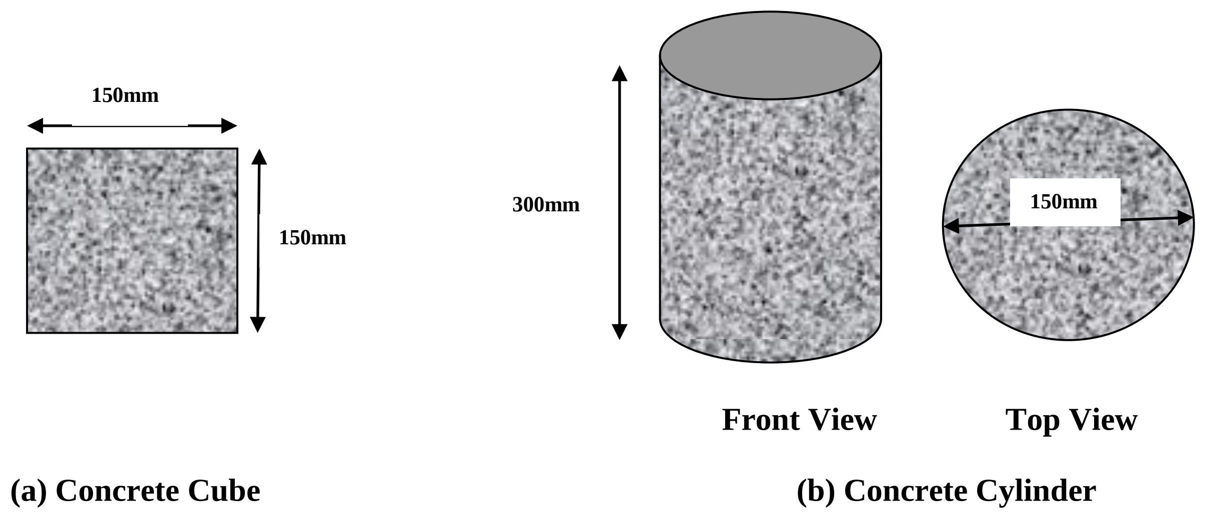


Fig 4.11 Concrete cube and cylinder specimen for UPV investigation

- **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.

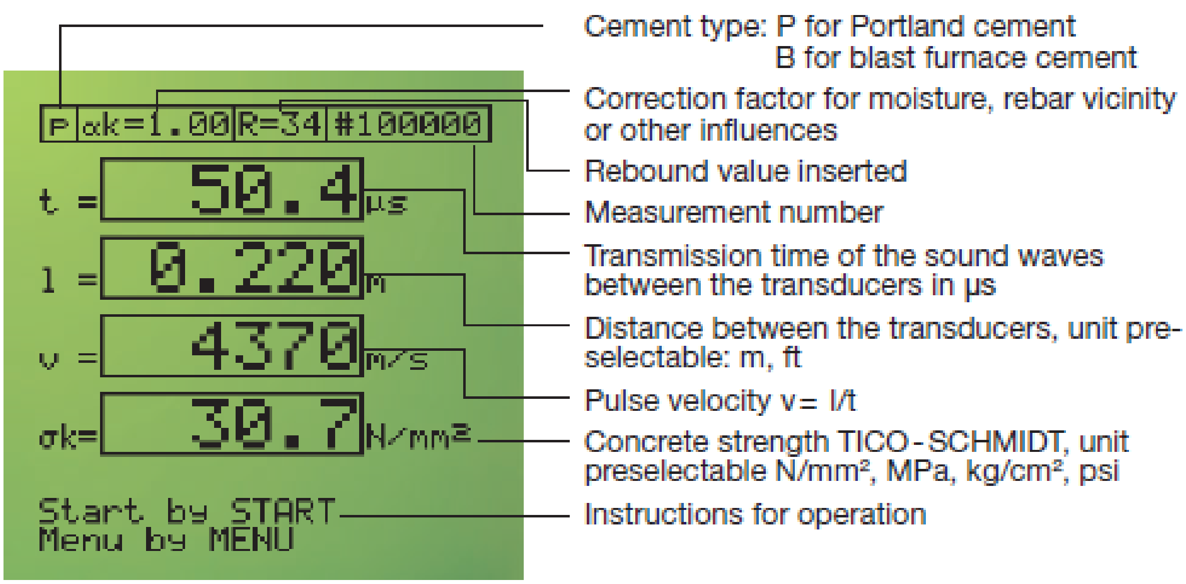


Fig 4.13 Display Unit of TICO Ultrasonic Instrument

The technical specifications of the display unit are given in **Table 4.5** as follows;

Table 4.5 Specifications of TICO Ultrasonic Instrument Display Unit

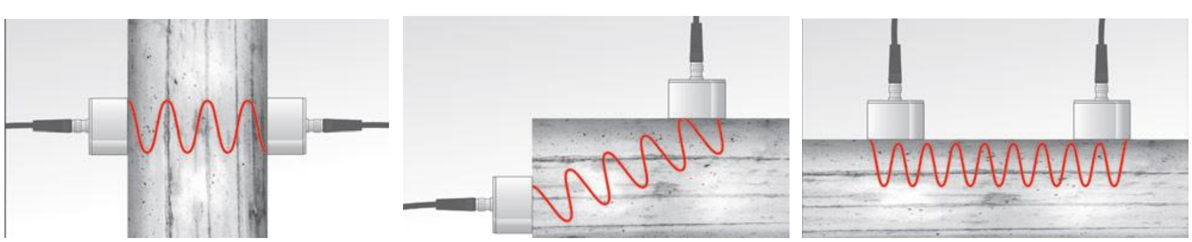
Display	128 x 128 graphic LCD
Interface	RS 232 or with adapter* to USB
Integrated software	for transmission of the measured values to PC
Measuring range	~15 to 6550 µs
Resolution	0.1 µs
Voltage pulse	1 KV
Pulse rate	3/s
Impedance at input	1MΩ
Temperature range	-10° to + 60°C for instrument
Recommended range for measurements	0°C to 50°C only
Battery	6 LR 6, 1.5 V (30 hours operation)

- **Transducer arrangement in UPV Testing**

The receiving transducer detects the arrival of that component of the pulse, which arrives earliest. This is generally the leading edge of the longitudinal vibration. Although the direction in which the maximum energy is propagated is at right angles to the face of the transmitting transducer, it is possible to detect pulses, which have travelled through the concrete in some other direction. It is possible, therefore, to make measurements of pulse velocity by placing the two transducers on either:

- opposite faces (direct transmission)
- adjacent faces (semi-direct transmission): or
- the same face (indirect or surface transmission).

These three arrangements are shown in Fig 4.14



(a) Direct Transmission (b) Semi-Direct Transmission (c) Indirect Transmission

Fig 4.14 Different Transducer arrangements in UPV Testing

4.3.2.2 Methodology for UPV Testing

In this research work, UPV measurements are taken by **direct transmission** arrangement of transducers in both early age setting (first phase) at different hrs (3, 6,12,18 & 24 hrs) and during the curing period (second phase) at different days of curing (1, 7, 14, 21 & 28 days) as shown in **Fig 4.15(a) and (b)**. 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 4.15(a) First phase i.e. early age setting or strength monitoring (during first 24 Hrs)

Fig 4.15(b) Second phase i.e. Hardening monitoring (During curing)

The above figures clearly show that during the first phase the concrete specimen need to be kept inside a special steel assembly in order to measure the velocity (m/sec). This is because the specimen is wet & can easily loosen its shape during its removal from the frame. This is not an issue during second phase when concrete has been cured for at least one day.

4.3.3 Experimental Detail: Penetration Test

Penetration testing was conducted using a Vicat Needle apparatus as shown in **Fig 4.16** 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 concrete cylinder as shown in **Fig 4.17** for different mixes used in the research work.

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

Fig 4.16 Penetration Testing Apparatus

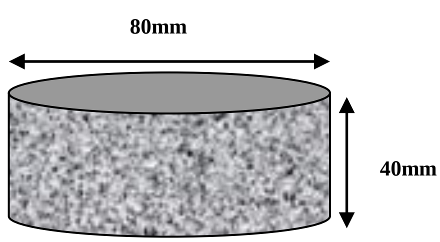
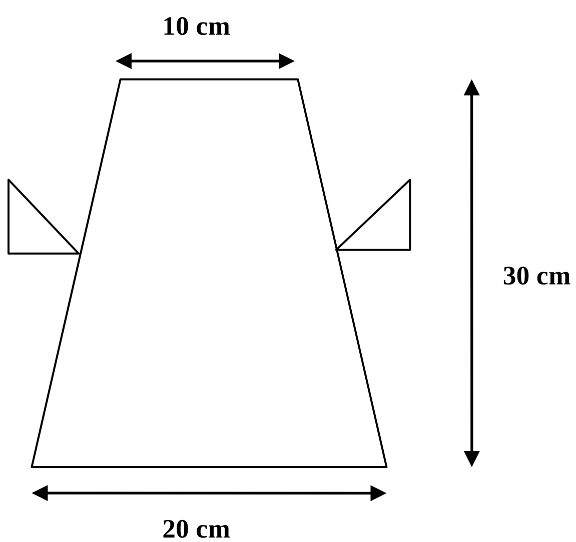


Fig 4.17 Concrete Cylinder for Penetration Test investigations

4.3.4 Experimental Detail: Slump Test

This test was also conducted during the initial phase i.e. within first 24 Hrs of concrete specimen casting. The main objective of this test was to know the workability or mobility of the different concrete mixes in hand, so that relation can be developed between early age strength or bond development and different values of slump.

The test was conducted with the help of slump cone having dimensions as shown in **Fig 4.18(a)**. The cone was filled with the concrete mix in hand upto 1/3rd of its height. Then with a help of a rod having 16mm diameter and 60 mm length, 20 to 30 strokes were given for ramming. This ramming procedure is repeated after cone if filled upto 2/3rd of its height. After this cone is completely filled and gradually raised vertically and removed. Then the concrete is allowed to subside and then, the height of concrete is measured. The slump of concrete is obtained by deducting height of concrete after subsidence from 30 cm. But in case of very high slump such as self compacting concrete diameter of the subside concrete is measured as shown in **Fig 4.18(b)**



(a) Slump Cone **(b) Measuring Diameter of subside Concrete**

Fig 4.18 Showing (a) Slump Cone Dimensions (b) Procedure of measuring very high slump

4.4 Destructive Testing

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

4.4.1 Pull-Out Test

This test was applied on the concrete beam specimens as shown in **Fig 4.3**. The main principle behind pull out test is to measure the bond strength development between the steel rod and the surrounding concrete. First step involves cutting the projected steel rod from one side of the beam. This cutting is done so that it can be fitted inside the custom made pull-out steel frame (**Fig 4.19**). Then test button is pressed from the control panel due to which tensile force get applied on the test specimen, resulting in the separation of steel rod from the surrounding concrete. The force applied during this test gets displayed in the digital display screen of the control panel in kN.

(a) Complete Setup **(b) Close-up View**

Fig 4.19 Pull out Test being conducted on UTM

4.4.2 Compressive Strength Testing

Compression test was carried out in order to determine the strength developed by the concrete specimen i.e. cubes in first phase i.e. during different setting times (3, 6, 12, 18 & 24 Hrs) whereas cube & cylinder in second phase during different curing times (1, 7, 14, 21 & 28 days) as shown in **Fig 4.20 & Fig 4.21.**

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

Fig 4.20 Compression Testing of Cube using UTM

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

Fig 4.21 Compression Testing of Cylinder using UTM

4.4.3 Compressive Beam Testing

Split Tensile Testing was conducted only on beam specimen of specifications shown in **Fig 4.3** belonging to initial phase i.e. within first 24 hr of hydration **(Fig 4.22)**. The purpose behind conducting this test was to study the bond development between concrete and aggregates during early age microbiological development of concrete specimen.

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

Fig 4.22 Compression Testing of Beam using UTM

4.5 Closing Remarks

This chapter discusses in detail the working, technical information & various components of different testing equipment used in this experimental study. Emphasis is also given on the different concrete mix, number and type of concrete specimens casted.

The next chapter discusses the results obtained under various test conducted in the two different phases.

CHAPTER 5

RESULTS AND DISCUSSIONS

This chapter discusses about the various results obtained by conducting different experiments on different concrete specimen as discussed in **Table 4.1** during two phases i.e. **early setting phase and Hardening phase**. Experiments as per the methodology discussed in last chapter have been carried out.

5.1 Early Setting Phase (First Phase)

5.1.1 Ultrasonic Pulse Transmission Investigations and Results

This test was conducted on a beam specimen of size 150 mm x 150 mm x 300 mm with an embedded mild steel rod of 25 mm diameter and 600 mm length **(Fig 4.3)**. First a healthy signature i.e. voltage vs time graph is captured **(Fig 5.1a and b)** and then compared with results signatures taken at different time intervals. Finally pk-pk voltage is measured and results are plotted as V-T (Voltage vs Time) graphs.

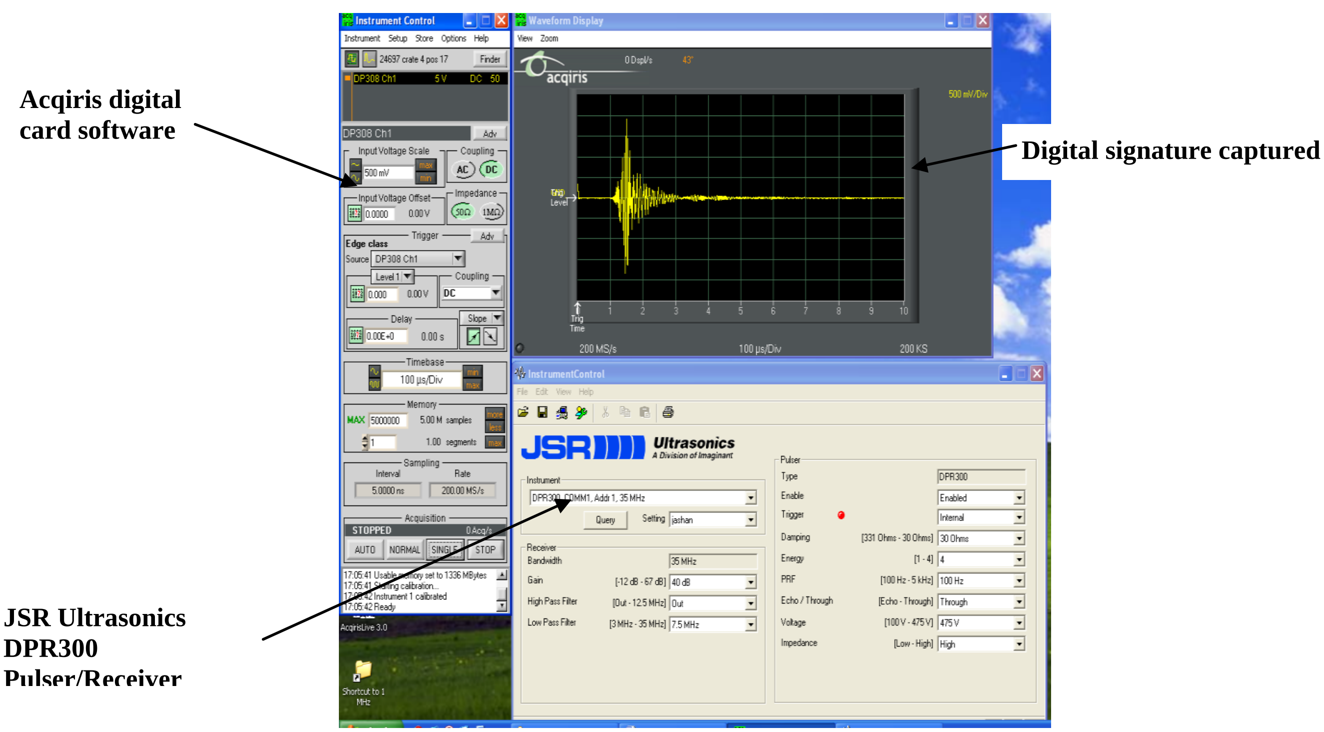


Fig 5.1(a) Image of waveform captured

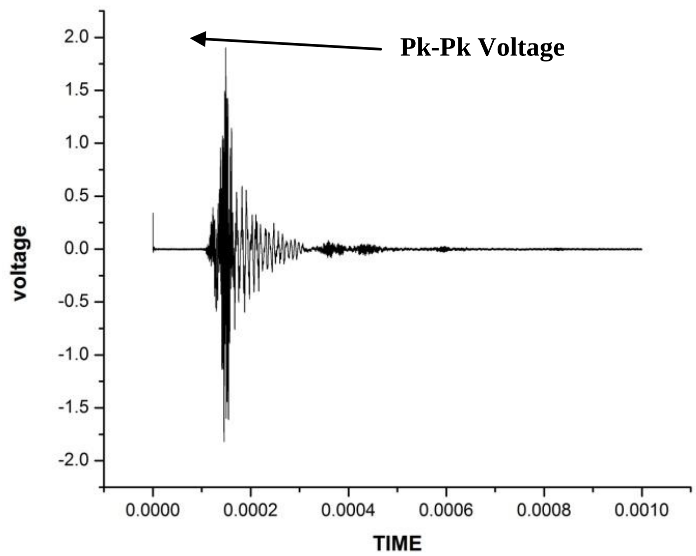


Fig 5.1 (b) Pk-Pk Voltage vs Time Signature (Plotted in Origin 8)

As concrete sets and hardens, Pk-Pk Voltage drops and hence the signature also drops. This is because of the surface seeking nature of the mode selected. This mode picks up the bond development between the reinforcing embedded mild steel and surrounding concrete.

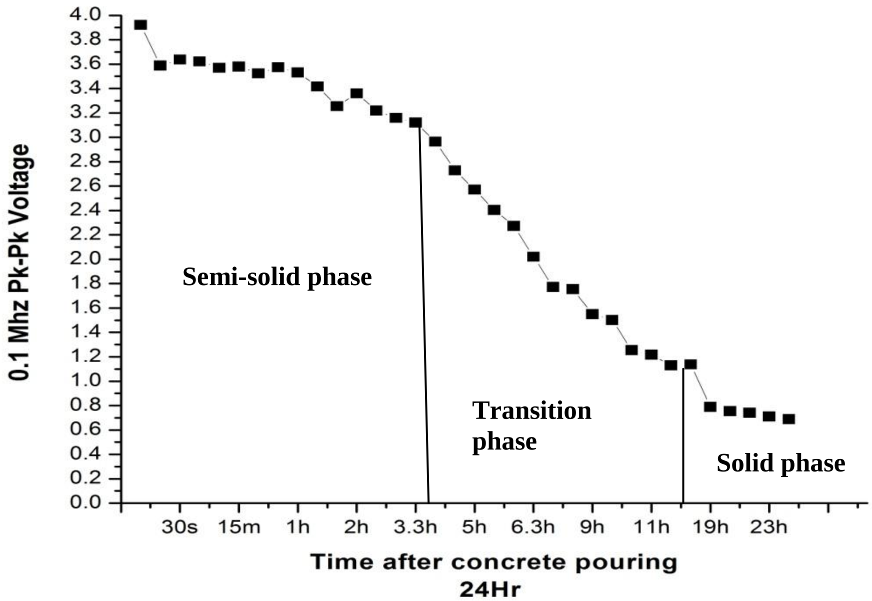
As the concrete sets, bond develops between steel and surrounding concrete indicating more energy leakage into the surrounding concrete thus causing drop in signal strength. Hence the fall in signal strength is a measure of development of bond and hence setting of concrete.

As outlined in chapter 4, the Ultrasonic Pulse-Transmission (UPT) readings are taken throughout 24 hrs of setting of concrete at regular time intervals. The ultrasonic measurements are made for concretes of different slumps categorized as $\mathbf{M_1}$ (low), $\mathbf{M_2}$ (moderate) & $\mathbf{M_3}$ (High) as shown in **Table 4.2**.

To correlate the ultrasonic investigation with in-situ strength of concrete, the test matrix was developed. For example, corresponding to 3hrs, 6hrs, 12hrs, 18hrs & 24hrs settings were monitored for $\mathbf{M_2}$ mix and destructive tests of Pull-out, Split-Tensile & compressive were conducted at the end of each duration along with the ultrasonic investigations. To obtain stability and check repeatability of data, minimum two samples were tested in each case and signatures plotted.

5.1.1.1 Study of setting properties of mix M_2 (Moderate slump= 60 to 80 mm)

The ultrasonic Pulse Transmission (UPT) and Penetration depth investigation of mix $\mathbf{M_2}$ is conducted for 24 hrs and results obtained are plotted as Voltage vs Time and Penetration depth vs Time graph as shown in **Fig 5.2.**



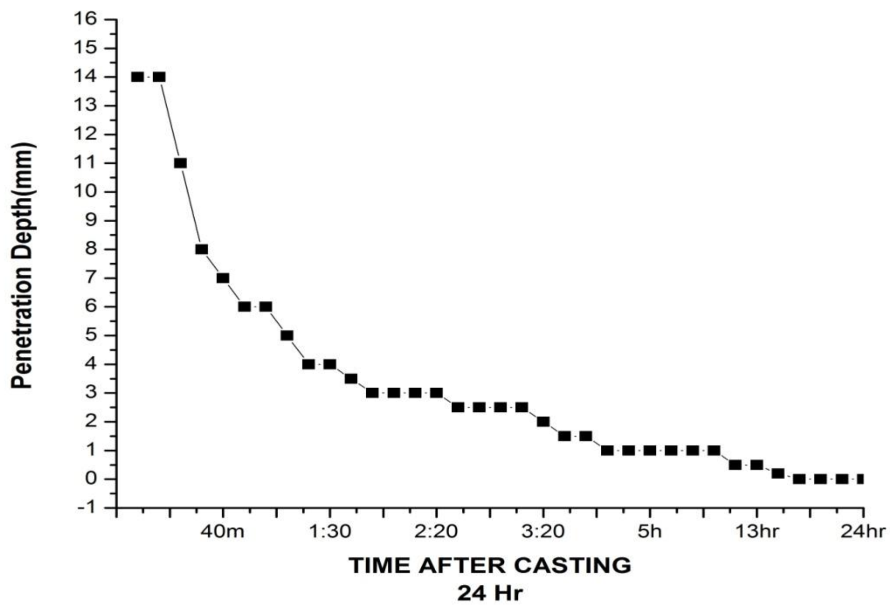


Fig 5.2 UPT and Penetration Test results after 24 Hrs for M_2 mix.

It is clear after seeing the UPT result graph that concrete was undergoing though three phases i.e. **Semi-Solid, Transition & Solid Phase(Fig 5.2).** In **Semi-solid Phase i.e. first 3 ½ hrs**, the concrete is still in semi-liquid phase & there is not heavy fall in Pk-Pk voltage. Thus indicating there is not significant setting or bonding between the mild steel bar and the surrounding concrete. This is also made clear with Penetration test results, as the max penetration depth is achieved till 3 ½ hrs when concrete is in semi-solid phase.

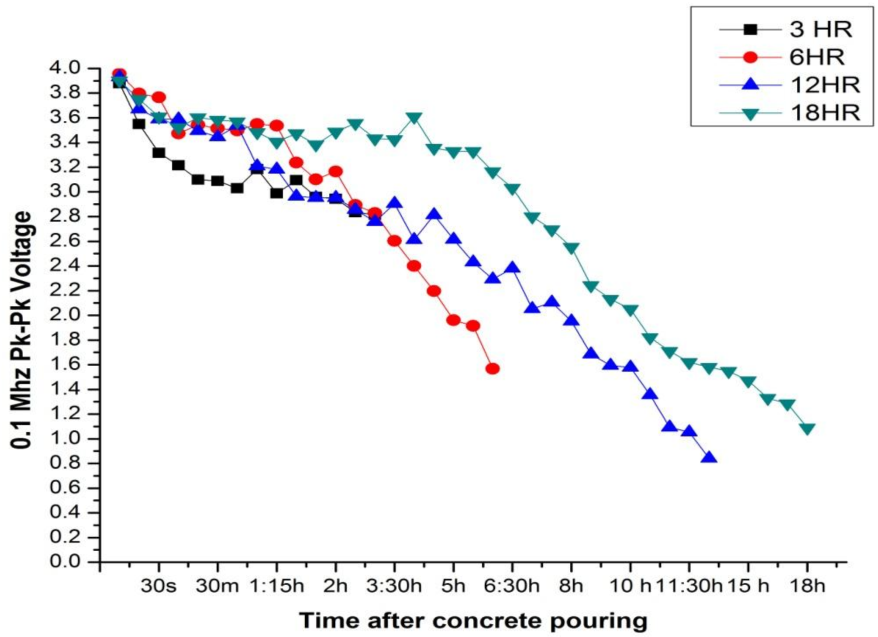
In **Transition Phase i.e. 3½ to 18hrs**, the concrete is undergoing a change from semi-soild to solid state or in other words we can say that the concrete is starting to set or making bond with the embedded mild steel bar. The max fall in Pk-Pk Voltage is observed in this phase. Whereas on the other hand there is hardly any increase in the Penetration depth, proving the concrete is setting.

Lastly in **Solid Phase i.e. 18hrs to 24 hrs**, there is very marginal fall in Pk-Pk voltage, indicating the concrete has become almost solid. There is hardly any setting or bonding occurring in this phase which shows that the max setting or bonding occur upto 18 hrs after casting.

In order to check the repeatability and accuracy of above 24hrs results in the three phases, a test matrix was developed in which 3hrs, 6hrs, 12hrs & 18 hrs beams were casted. The results obtained after conducting UPT and Penetration Tests are shown in **Fig 5.3.**

It is clear from **Fig 5.3**, all the UPT Test results done on various beams for different hrs i.e. 3hrs, 6hrs & 12 hrs follow the same pattern as the above 24hrs beam specimen except 18hrs beam. This is because 18 hrs beam specimen is monitored in much colder temperature (24^0 C) as compared to the other entire beam specimens which were monitored in hotter climate having temperature 36^0 C to 41^0 C. As a result, 18hr beam specimen was in **semi-solid phase** upto 5 ½ hrs instead of 3 ½ hrs and the Pk-Pk voltage drop value in **Transition Phase** (upto 18hrs) indicating setting or bond achieved by it was also also not significant as compared to other specimens.

After this, it is concluded that UPT technique is also successful in picking up the early changes in concrete as the environmental conditions changes & penetration test results are only feasible during the first 4 to 5 hrs when concrete is wet.



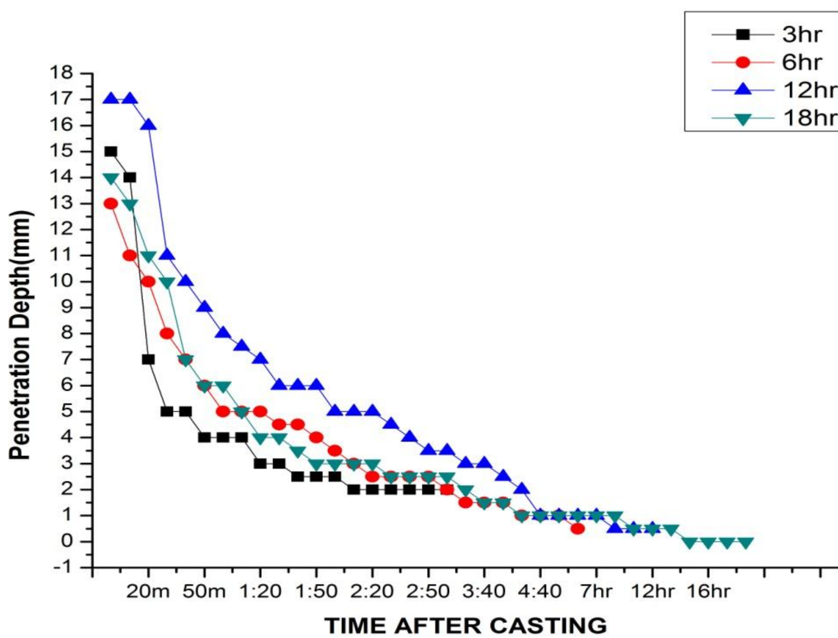


Fig 5.3 UPT and Penetration Test results after 3, 6, 12 & 18 Hrs for M_2 mix.

5.1.1.2 Comparison with UPV Test results

UPV tests were also conducted on cubes of size 150 mm x 150 mm x 150 mm alongside UPT tests for mix $\mathbf{M_2}$ in order to check the microstructure development of concrete during its early or setting phase. The results obtained are plotted as Velocity vs Time graphs for 24 Hrs **(Fig 5.4).**

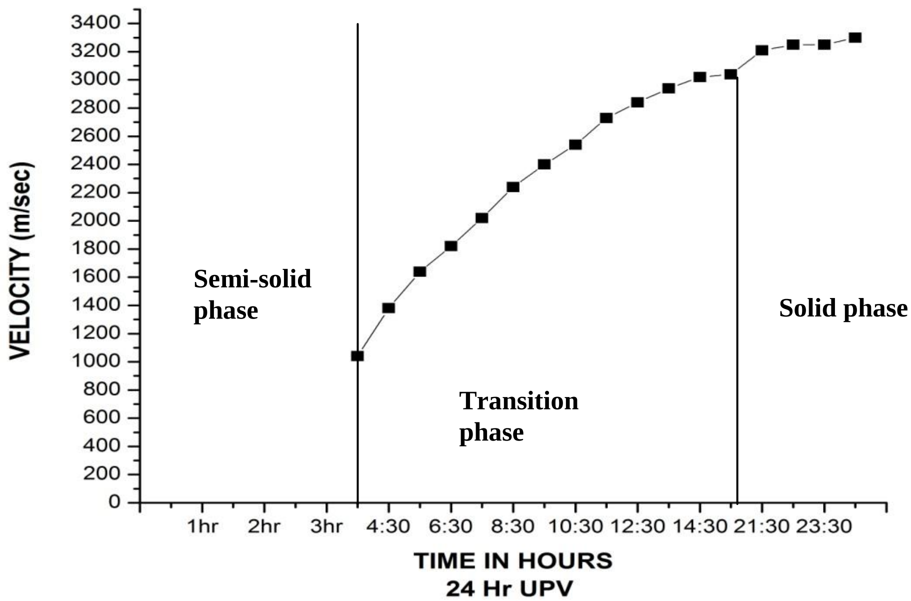


Fig 5.4 Velocity vs Time Graph for 24hrs cube specimen.

Above **Fig 5.4** clearly shows the velocity increases with time. This is because as the concrete starts to set the amount of ultrasonic wave attenuation i.e. loss of energy decreases and thus wave velocity increases.

But as we compare UPV with UPT technique we can clearly see that UPV method is unable to record the velocity during the semi-solid phase i.e. when concrete is wet, as the concrete start 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 and Solid phase,** the UPV results follow the same trend as UPT results, showing a max velocity gain during the transition phase and no significant increase in velocity during solid phase.

Similar to UPT, in order to check the repeatability and accuracy of above 24hrs results, a 3hrs, 6hrs, 12hrs & 18 hrs cubes were also casted. The results obtained after conducting UPV Test is shown in **Fig 5.5.**

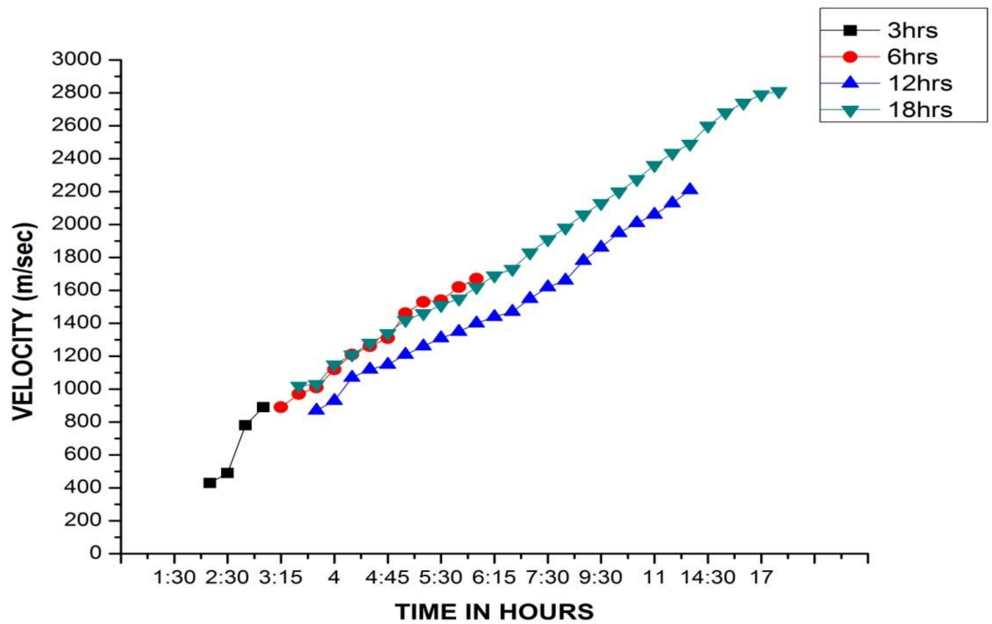


Fig 5.5 Velocity vs Time Graph for 3, 6, 12 & 18hrs cube specimens.

5.1.1.3 Comparison with Destructive Test results

Along with non-destructive tests like UPT and UPV various destructive tests like Pull-Out & Compressive Tests are also conducted on specimens of concrete mix **M_2** whose results are listed in **Table 5.1.**

Pull-Out test is conducted to know the measure of bond development, whereas Compressive tests are conducted to serve as parameters of in-situ strength development of concrete in this phase.

Table 5.1 Results of Destructive Tests in Early Setting for phase for M_2 mix.

Testing Duration(Hrs)	Pull-Out Strength (kN/m^2)	Compressive Beam Strength (kN/m^2)	Compressive Cube Strength (kN/m^2)
24	**166.66**	**12840.61**	**11149.12**
18	**103.34**	**6837.88**	**5333.34**
12	**74.23**	**3333.34**	**2160**
6	**27.56**	**2855.45**	**1398.89**
3	**Test could not be conducted**	**890**	**552.65**

In order to highlight the trend followed by the results of above tests **Fig 5.6(a), (b) & (c)** has been plotted.

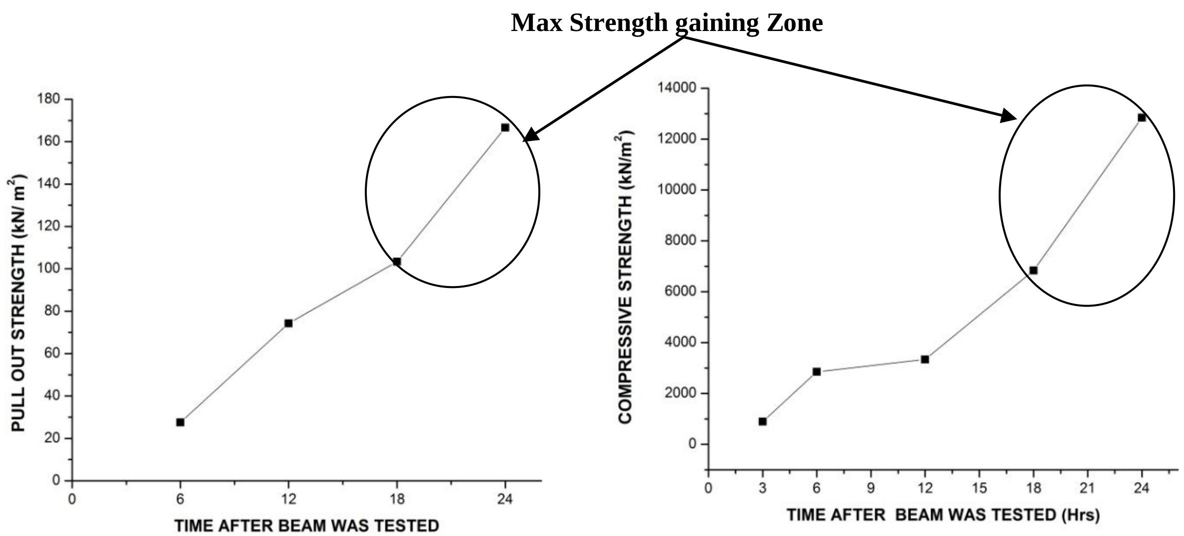


Fig 5.6 (a) Pull-Out & (b) Compressive Beam Strengths trends.

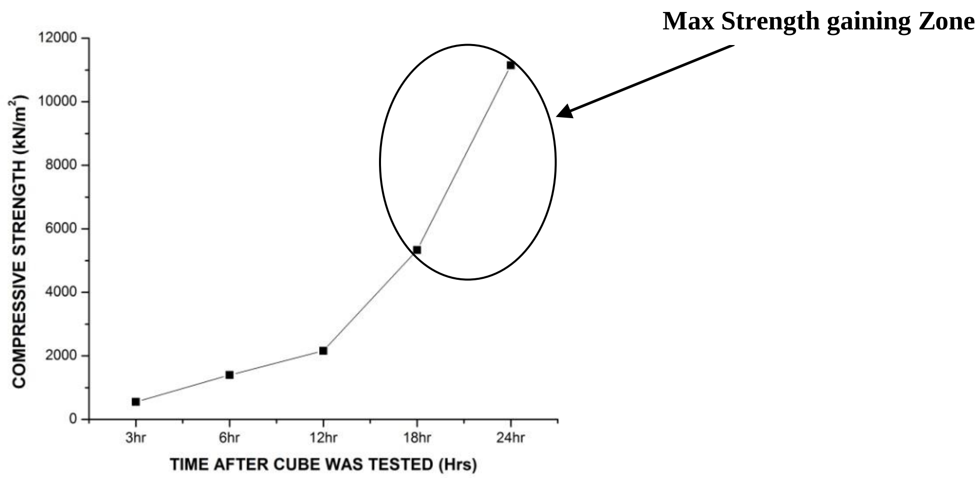


Fig 5.6 (c) Compressive Strength trend.

As highlighted in all the three destructive tests results shown in **Fig 5.6,** the max strength gaining zone occur between 18hrs to 24hrs. This max strength gaining zone occurs in the same period as the **Solid phase (**when concrete has almost set or become solid) occurs in UPT results discussed earlier, indicating as the attenuation of ultrasonic wave decreases the strength or bond of concrete increases.

5.1.1.4 Effect of Slump Value

In order to study the effect of slump on early age strength of concrete using ultrasonic guided waves three different mixes $\mathbf{M_1}$(Low slump), $\mathbf{M_2}$(Moderate Slump) & $\mathbf{M_3}$ (High Slump) as listed in **Table 4.2** were designed and the results obtained are shown in **Fig 5.7**

It can be clearly seen from the UPT test results (**Fig 5.7**) that mix's $\mathbf{M_1}$ and $\mathbf{M_2}$ have very similar Pk-Pk voltage readings in all the three phases, mix $\mathbf{M_1}$ being on the stiffer side as the slump value is less. Whereas mix $\mathbf{M_3}$**,** having very high slump value of 350mm showed a completely different or wrong pattern in all the three phases.

On investigation of $\mathbf{M_3}$ concrete mix beam sample, it was found that segregation has occurred. The lower portion of the beam was found to be heavier then the upper potion as shown in **Fig 5.8**, indicating settlement of aggregates or segregation.

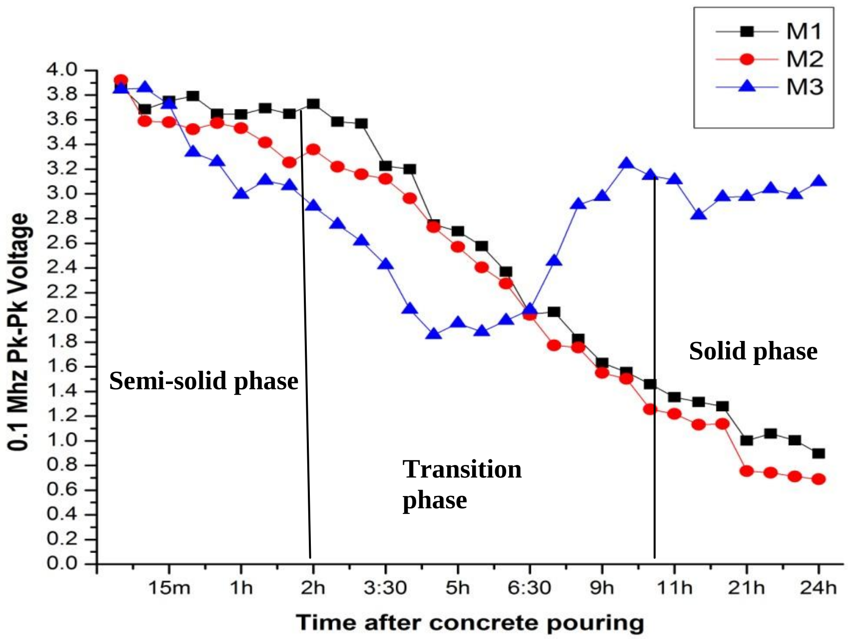
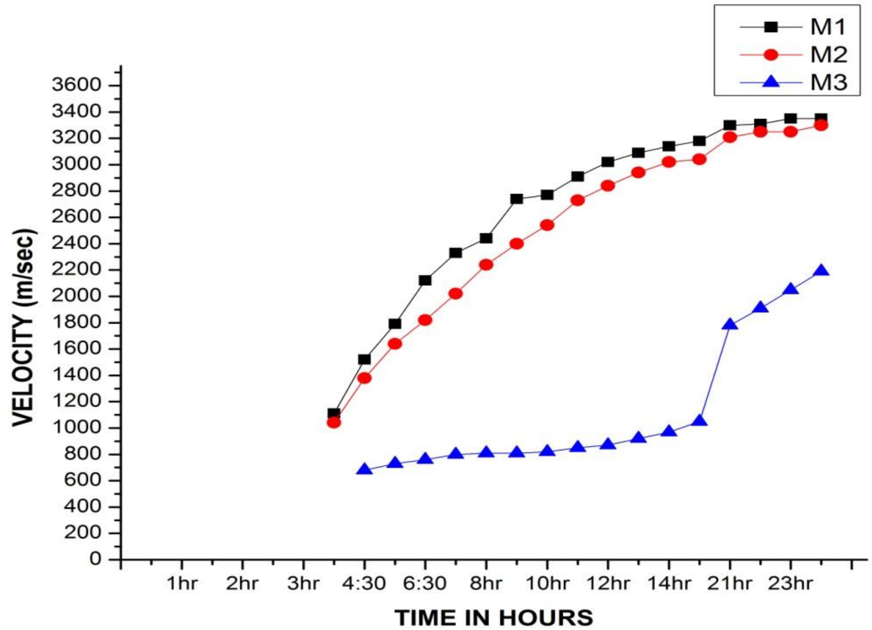


Fig 5.7 UPT Test results for concrete mix M_1, M_2 and M_3 having different slump values.

Fig 5.8 Two parts of segregated beam sample of M_3 mix.

Apart from UPT investigation, other non-destructive tests like UPV and penetration Test were also conducted alongside on cube and thin cylinder specimens for all the three concrete mixes i.e. **M_1, M_2** & **M_3** (**Fig 5.9**).



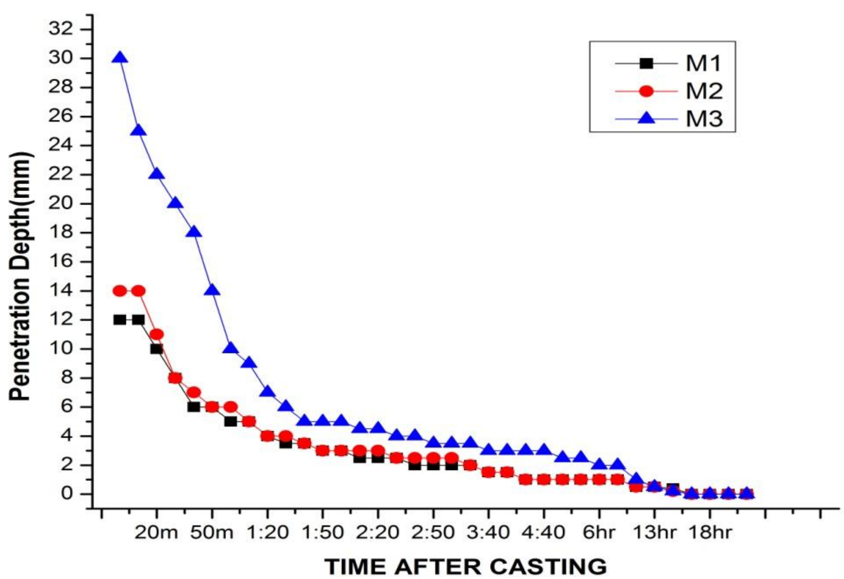


Fig 5.9 UPV and Penetration Tests results for concrete mix M_1, M_2 and M_3 having different slump values.

There is not much difference between the value of ultrasonic wave velocity & penetration depth in mixes **M_1** and **M_2**. Mix **M_1** offered slightly more resistance to the wave velocity & penetration depth, indicating the lower setting rate of the concrete. Mix **M_3** which is having the max slump value showed the lowest value of wave velocity and highest penetration depth. Mix **M_3** also showed almost very low constant like behavior upto 15^{th} hour as it is having max slump or mobility and sudden rise after that till the last 24^{th} hour, indicating an increase in the wave velocity as the water hydrate from concrete.

After conducting these non-destructive tests, destructive tests like Pull-Out & Compressive Tests are also conducted on specimens casted with different slump mixes **M_1**, **M_2** and **M_3** whose results are listed in **Table 5.2**

Table 5.2 Destructive Tests Results for M_1, M_2 and M_3 mixes.

Concrete Mix	Pull-Out Strength (kN/m^2)	Compressive Beam Strength (kN/m^2)	Compressive Cube Strength (kN/m^2)
M_1	**69.34**	**5848.48**	**7875.56**
M_2	**166.67**	**12840.61**	**11149.12**
M_3	**N.A**	**1903.95**	**1436.45**

Destructive test results highlight that the max strength gaining mix in all the three mixes is **M_2** having moderate slump of 60 to 80 mm & w/c ratio of 0.45%. This is because a min w/c ratio of 0.4 % is required to gain the sufficient strength according to IS:456(2000) as compared to 0.35% of mix **M_2**.On the other side mix **M_3** does not gain the required strength because the amount of water content inside the mix is so high that 24hrs are not sufficient for its complete hydration. Due to this the early age setting or bond development takes longer time.

5.2 Hardening i.e. During Curing Phase (Second Phase)

5.2.1 Ultrasonic Pulse Transmission Investigations and Results

In this phase only single mix M_2 (**Table 4.5**) was used. The beams were cured using transparent curing tank as shown in **Fig 5.10.** The beams were then taken out of the curing tank tested for 7, 14, 21 & 28 days in order to monitor the hardening of concrete. The results of UPT are shown in **Fig 5.11**. In order to check the repeatability and accuracy min two specimens were casted in each case.

Fig 5.10 Transparent Curing Tank

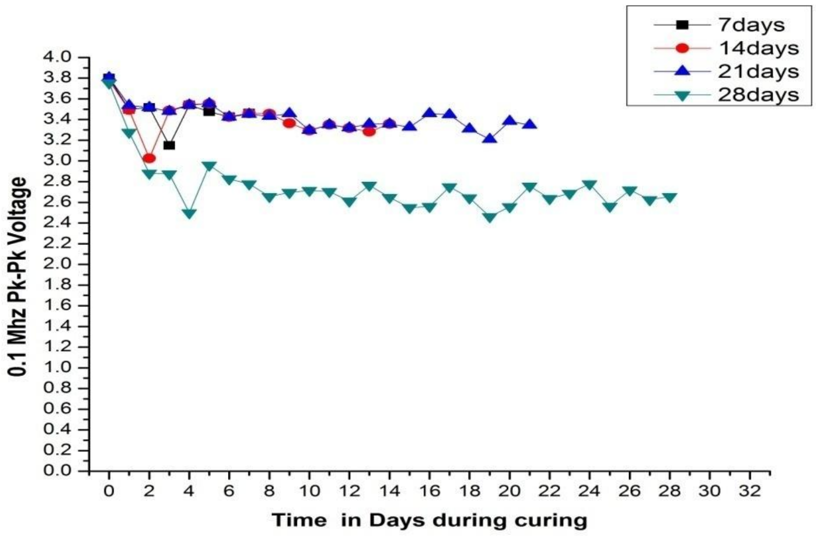


Fig 5.11 UPT Test results for Second phase.

From above results, it is clear that Pk-Pk voltage pattern shows a permanent pattern followed by all the concrete beam specimens cured for 7, 14 , 21 & 28 days. It is also quite obvious from **Fig 5.11**, that there is always a permanent drop in signal between 2 to 4 days and thereafter the signal rises again and remains almost constant throughout, indicating not significant bond or hardening development.

5.2.1.1 Comparison with UPV Test results

In this phase apart from UPT, other non- destructive test such as UPV test was also performed to study the microstructure development of concrete during curing. For repeatability and accuracy this test is conducted on 3 cubes and 3 cylinders after 1, 7, 14, 21 and 28 days and average result obtained is shown in **Fig 5.12**

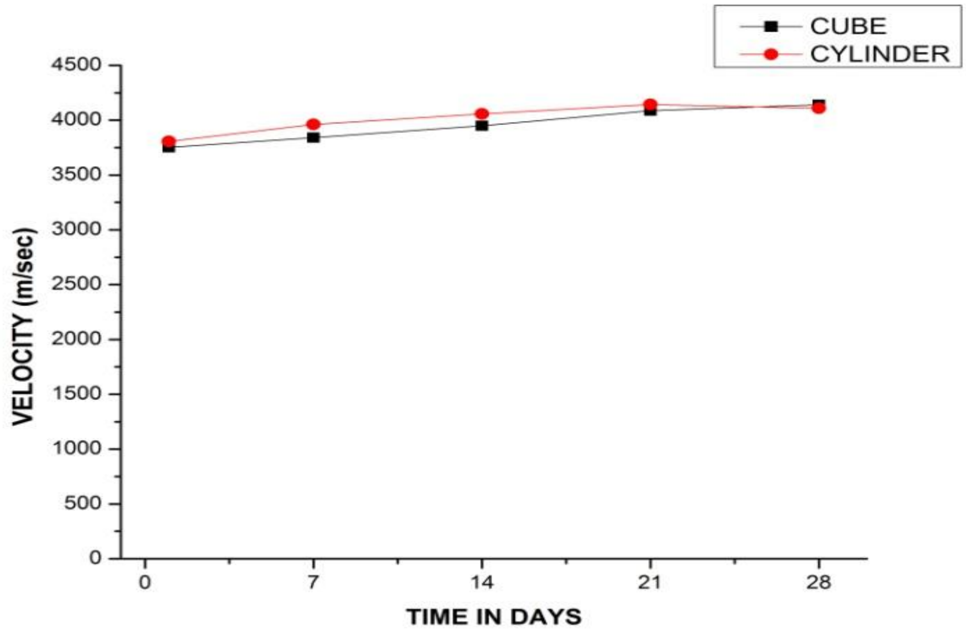
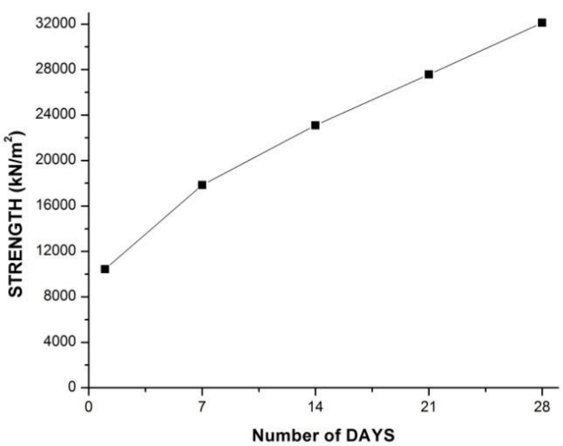


Fig 5.12 UPV tests results of cubes and cylinders during curing phase.

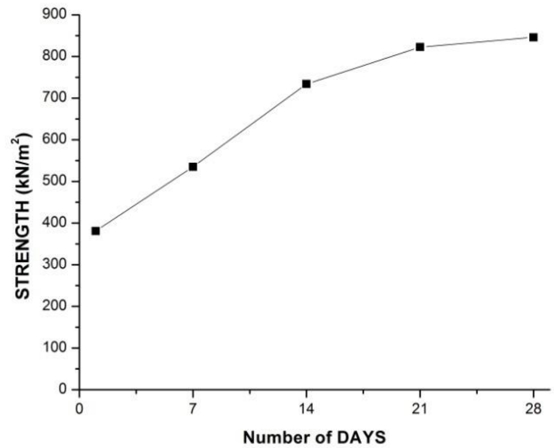
It is noted that both cube and cylinder UPV tests results are almost identical with hardly any change from beginning to the end day which is similar to UPT test conducted on beams, indicating not significant hardening or bonding between the mild steel bar and the surrounding concrete during curing.

5.2.1.2 Comparison with Destructive Test results

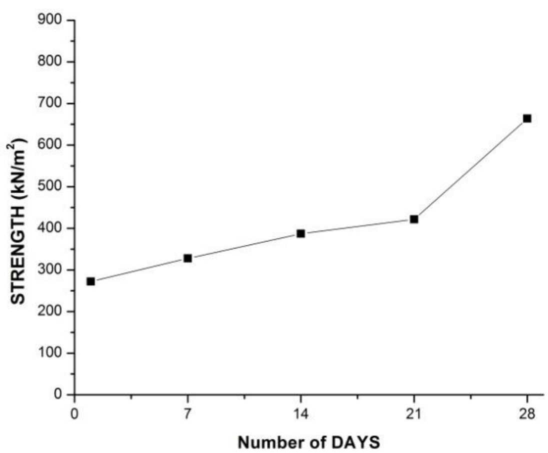
Similar to first phase apart from non-destructive tests, destructive tests like Pull-Out, Split Tensile & Compressive Tests are also conducted on specimens whose results are shown in **Fig 5.13 (a), (b) & (c).** The purpose behind these tests is to measure the development of bond and in-situ strength development of concrete during curing.



(a) Cube Compression Test Graph



(b) Cylinder Compression Test Graph



(c) Beam Pull-Out Test Graph

Fig 5.13 Pull-Out & Compression Test results for different Days during curing phase.

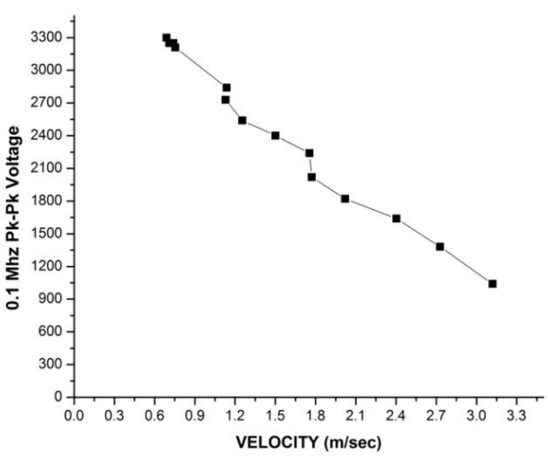
The Pull-out and compression results also show increase in strength with increase in time or days. The Pull-Out result conducted on beam show that there is not significant bond development between the mild steel bar & the surrounding concrete upto 21 days. But there is a sudden rise after 21 indicating the increase in bond strength. But overall there is hardly any bond making as indicated earlier by UPT results.

Compressive test shows a very gradual increase in strength during the 28 days time interval. This is true as concrete need minimum 28 days to achieve its full strength. In order to check the repeatability and accuracy min two samples are casted in each case.

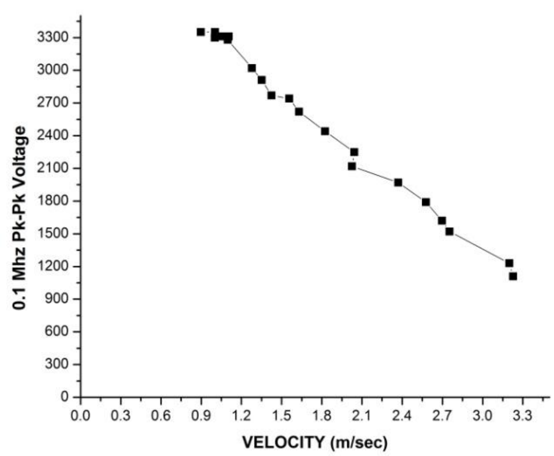
5.3 Comparing Early Setting Phase (First Phase) NDT Techniques

Here we have chosen to compare the graph results of only early setting phase i.e. within first 24 hrs of hydration of concrete because that is when max setting or bonding has taken place as compared to phase to. The different techniques compared are as follows:

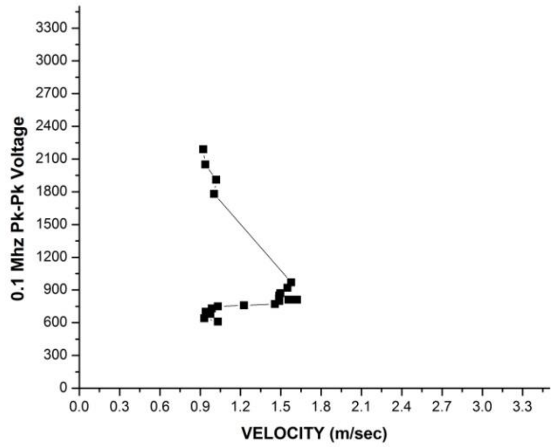
5.3.1 UPT (Pk-Pk voltage) vs UPV (velocity) graphs



(a) Concrete Mix 1



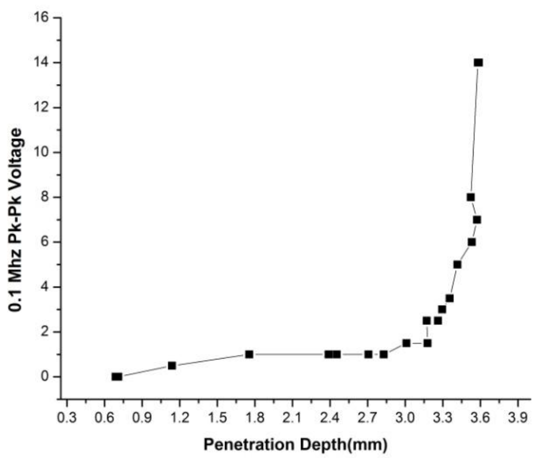
(b) Concrete Mix 2



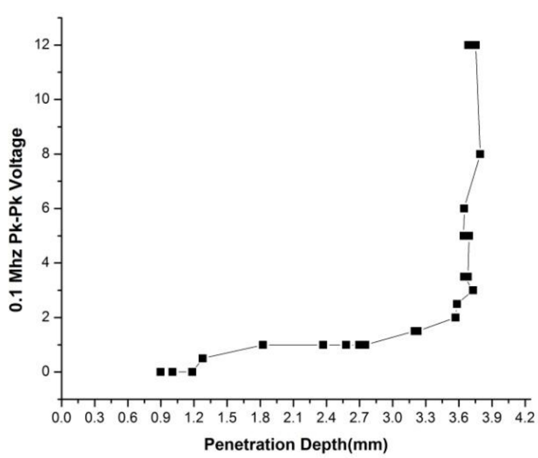
(c) Concrete Mix 3

Fig 5.14 Showing Pk-Pk Voltage Vs Velocity graphs for different mixes.

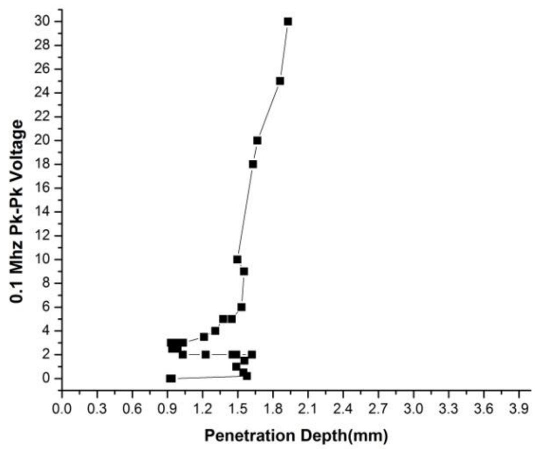
5.3.2 UPT (pk-pk voltage) vs Penetration test (Depth) graphs



(a) Concrete Mix 1



(b) Concrete Mix 2



(c) Concrete Mix 3

Fig 5.15 Showing Pk-Pk Voltage Vs Penetration Test graphs for different mixes.

5.4 Closing Remarks

This chapter shows the results obtained by Ultrasonic Pulse transmission method in the two phase's i.e. early setting and hardening phases. The UPT method is also compared with other well established non-destructive and destructive tests. Finally different techniques are compared with each other.

The next chapter discusses the various conclusions of this thesis report and scope of future work under this filed.

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) and hardening process (upto 28 days) of concrete.

Following conclusions can be drawn from the observations of **Early setting or First phase**:

- Maximum bond development or early setting is achieved during Transition Phase i.e. from 3 ½ hrs to 18hrs 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 method using ultrasonic guided waves.
- Variation in properties like slump value of concrete affects the test results.
- Segregation in concrete can also be monitored using ultrasonic methods.
- There is a linear variation between UPT vs UPV and UPT vs Penetration Test Graphs; except mix 3 where segregation occurred.

Conclusions which can be drawn from the observations of **Hardening i.e during curing or Second phase are**:

- There is not much fall in Pk-Pk voltage value in this phase as compared to first phase, indicating no significant hardening or bond development.
- There is not much development in hardening after first 4 days the value becomes almost constant, thus not solving our objective of finding the time required for economical removal of formwork.

- Significant bonding or hardening is also not shown by other well established NDT methods such as UPV and destructive methods such as Pull-Out and Compressive test results, indicating failure of these tests.

6.2 Scope of Future Work

The field of ultrasonic guided waves for monitoring early strength development and hardening of concrete constitutes important and challenging area of study, where wave propagation provides an efficient means of characterizing various microstructure developments in various ages of concrete. As the topic of ultrasonic guided wave propagation is very wide spread and has utilities in many areas of human endeavour, there is much scope for future work. The experimental methodology discussed in this work can be further extended for:

- Monitoring of special concretes like SCC, High performance concrete etc.
- By adding admixtures into normal grade concrete, to evaluate the effect caused by their presence.
- By conducting the experiments in various controlled environments.

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