IN-SITU MONITORING OF HPC USING ULTRASONIC GUIDED WAVES

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DECLARATION

I hereby declare that the work which is presented in this thesis report entitled **"IN-SITU MONITORING OF HPC 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 actual research carried out by her under the supervision of **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.

Rattan

Dated: 15-7-13

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

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ABSTRACT

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

In this study, apart from standardized methods like ultrasonic pulse velocity, vicat penetration and pull-out methods to study the setting of concrete, suitability of Ultrasonic Guided Waves (UGW) 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 purposes to use Ultrasonic Pulse Transmission (UPT) and Ultrasonic Pulse Echo (UPE) systems for monitoring setting and hardening phase change in High Performance Concrete (HPC). In UPT, a wave is 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. In UPE, a wave is transmitted on one end of an embedded waveguide and received on the same end of the propagating bar. 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 waves.

Experiments were performed on OPC with 0% fly ash and OPC with 20% fly ash for three w/cm ratios i.e. 0.50, 0.30 & 0.27 respectively. For UGW, slab specimens of size 300mm x 300mm x 100mm with embedded mild steel rod of 25mm diameter and 500mm length were used to monitor young concrete's strength, setting & hardening process. Ultrasonic Pulse Velocity was also carried out side by side on a standard cube of size 150mm x 150mm x 150mm of the same concrete mixtures to study the microstructure development of concrete.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most widely used construction material in India with annual consumption exceeding 100 million cubic meters. It is well known that conventional concrete designed on the basis of compressive strength does not meet many functional requirements such as impermeability, resistance to frost, thermal cracking adequately. Conventional Portland cement concrete is found deficient in respect of:

- Durability in severe environments (Shorter service life and require maintenance)
- Time of construction (longer release time of forms and slower gain of strength)
- Energy absorption capacity (for earthquake-resistant structures)
- Repair and retrofitting jobs

High performance concrete (HPC) successfully meets the above requirements.

HPC is an engineered concrete possessing the most desirable properties during fresh as well as hardened concrete stages. HPC is far superior to conventional cement concrete as the ingredients of HPC contribute most optimally and efficiently to the various properties. High performance concrete (HPC) is a specialized series of concrete designed to provide several benefits in the construction of concrete structures that cannot always be achieved routinely using conventional ingredients, normal mixing and curing practices. In the other words a high performance concrete is a concrete in which certain characteristics are developed for a particular application and environment, so that it will give excellent performance in the structure in which it will be placed, in the environment to which it will be exposed, and with the loads to which it will be subjected during its design life. It includes concrete that provides either substantially improved resistance to environmental influences (durability in service) or substantially increased structural capacity while maintaining adequate durability. It may also include concrete, which significantly reduces construction time without compromising long-term serviceability. While high strength concrete, aims at enhancing strength and consequent advantages owing to improved strength, the term high-performance concrete (HPC) is used to refer to concrete of required performance for the majority of construction applications.

The American Concrete Committee on HPC includes the following six criteria for material selections, mixing, placing, and curing procedures for concrete.

(1) Ease of placement
(2) Long term mechanical properties
(3) Early-age strength
(4) Toughness
(5) Life in severe environments
(6) Volumetric stability

The above-mentioned performance requirements can be grouped under the following three general categories:

(a) Attributes that benefit the construction process
(b) Attributes that lead to enhanced mechanical properties
(c) Attributes that enhance durability and long-term performance

Traditionally, **high performance concrete (HPC)** may be regarded as synonymous with high strength concrete (HSC). It is because lowering of water-to-cement ratio, which is needed to attain high strength, also generally improves other properties. However, it is now recognized that with the addition of mineral admixtures, HPC can be achieved by further lowering water-to-cement ratio, but without its certain adverse effects on the properties of the material. Hence, it is important to understand how concrete performance is linked to its microstructure and composition. In fact, performance can be related to any properties of concrete. It can mean excellent workability in fresh concrete, or low heat of hydration in case of mass concrete, or very quick setting and hardening of concrete in case of spray concrete which is used to repair roads and airfields, or very low imperviousness of storage vessels. However, from a structural point of view, one understands usually that high strength, high ductility and high durability, which are regarded as the most favorable factors of being a construction material, are the key attributes to HPC. Decades ago, HSC was only tested in laboratory without real applications because there were still many uncertainties on the structural behavior of HSC at that time. Up to the present, HPC has been widely used in tall building construction.

1.2 Definition of HPC

The performance requirements of concrete cannot be the same for different applications. Hence the specific definition of HPC required for each industrial application is likely to vary. The Strategic Highway Research Programme (SHRP) has defined HPC for highway application on the following strength, durability, and w/c ratio criteria:

(a) It should satisfy one of the following strength criteria:

24 hour strength ≥17.5 MPa
24 hour strength ≥35.0 MPa
28 days strength ≥ 70.0 MPa

(b) It should have a durability factor greater than 80% after 300 cycles of freezing and thawing.

(c) It should have a water-cement ratio of 0.35 or less.

In general, a **"High performance Concrete"** can be defined as that concrete which has the highest durability for any given strength class, and comparison between the concretes of different strength classes is not appropriate. This means that, with the available knowledge, one can always strive to achieve a better (most durable) concrete required for a particular application.

1.2.1 Paul Zia (http://elearning.vtu.ac.in)

HPC is a concrete, which meets special performance, and uniformity requirements that cannot be always achieved by using only the conventional materials and normal mixing, placing, and curing practices. The performance requirements may involve enhancement of placement and compaction without segregation and long term mechanical properties, early age strength, toughness, volume stability, service life.

1.2.2 Swamy, R.N. (http://elearning.vtu.ac.in)

A High Performance concrete element is that which is designed to give optimized performance characteristics for a given set of load, usage and exposure conditions, consistent with requirement of cost, service life and durability.

High Performance concrete has,

(a) Very low porosity through a tight and refined pore structure of the cement paste.
(b) Very low permeability of the concrete
(c) High resistance to chemical attack.
(d) Low heat of hydration

(e) High early strength and continued strength development
(f) High workability and control of slump
(g) Low water binder ratio
(h) Low bleeding and plastic shrinkage

1.2.3 Civil Engineering Research Foundation (CERP)

High performance construction materials and systems: An essential program for American and infrastructure. HPC is a concrete in which some or all of the following properties have been enhanced

(a) Ease of placement
(b) Long term mechanical properties
(c) Early age strength
(d) Toughness
(e) Volume stability
(f) Extended service life in severe environments

1.2.4 American Concrete Institute (ACI)

A more broad definition of HPC was adopted by the ACI. HPC was defined as concrete, which meets special performance and uniformity requirements that cannot be always be achieved routinely by using only conventional materials and normal mixing, placing and curing practices. The requirements may involve enhancement of placement and compaction without segregation, long term mechanical properties, early age strength, volume stability or service life in severe environments. Concretes possessing many of these characteristics often achieve higher strength. Therefore, HPC is often of high strength, but high strength concrete may not necessarily be of high performance.

1.3 Composition of High Performance Concrete

The composition of HPC usually consists of cement, water, fine sand, super plasticizer, fly ash and silica fumes. Sometimes, quartz flour and fiber are the components as well for HPC having ultra strength and ultra ductility, respectively. The key elements of high performance concrete can be summarized as follows:

- Low water-to-cement ratio,
- Large quantity of silica fume (and/or other fine mineral powders),

- Small aggregates and fine sand,
- High dosage of super plasticizers,
- Heat treatment and application of pressure which are necessary for ultra high strength concrete after mixing (at curing stage).

1.4 Research Significance and Objectives

Repeated failures of concrete structures during construction have shown that early age period is one of the most critical periods of life span of a concrete. Given this background, the availability of information about early age concrete properties is most essential. Normally, the compressive strength parameter is regarded as an important parameter that is used for quality control of concrete. However, compressive strength tests may not be helpful to evaluate the quality of concrete due to different curing conditions used in the quality control lab and the real in-situ condition. It is important to have a technique that can be used to perform in-situ evaluation of the quality of concrete or other cement-based materials. NDT methods can be a good option to satisfy this requirement, since these methods offer the possibility of direct measurement of in-situ concrete properties without causing significant damage to the structure.

In order to observe the property changes of a concrete at early age, an NDT method can continuously monitor the concrete behavior throughout its setting and hardening procedure is highly desired. Also, it is important to note that the technique can monitor other properties of a concrete besides the compressive strength. More details of hydration should be detected, since hydration is believed to be a key issue that relates to the evolution of microstructure that governs all the material properties. Besides the quality control issues , it is also necessary to have a simple and easily accessible equipment setup, so that the measurement can be easily applied to various structures, such as pavements, walls, columns, floor slabs, and ceilings.

A new NDT method, called the ultrasonic wave reflection (UWR) method, was developed by researchers at the Centre for Advanced Cement-Based Materials (ACBM) in the late 1990's (Boumiz et al. 1996). This method measures the energy loss of the reflected shear waves at the interface of a steel plate and cement paste. Reflection loss, the parameter that is obtained with the measurement, increases during hydration of cement. The major task of this study can be divided into several stages. First, it is important to evaluate the applicability and sensitivity of this technique to monitor the setting and hardening behavior of cementitious materials. Second, the possibility of this method to evaluate the mechanical properties, such as elastic moduli and compressive strength, is evaluated. This can benefit the in-situ quality control of civil infrastructure constructions. Third, the correlation between the micro structural and wave reflection measurements needs to be studied for the applicability of wave reflection technique.

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:

- Design of mix for High Performance Concrete (HPC).
- Develop a Non- Destructive Technique (NDT) in the form of Ultrasonic Guided Waves (UGW) that can be implemented to monitor early age strength and hardening of high performance concrete (HPC).
- To relate the early age strength and hardening with established non-destructive method (NDT) of Ultrasonic Pulse Velocity (UPV) and correlate with destructive tests like compression testing and split-tensile testing.
- Provide information that can be used to estimate and evaluate the strength development process of high performance concrete (HPC) for safe and efficient construction practices.

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1.5 Closing Remarks

This chapter gives a general aspect and introduction of High Performance Concrete (HPC) through various definitions. The motivation behind this report and physical background of monitoring young concrete has been emphasized. The main objective of this thesis have also been highlighted.

CHAPTER 2

HIGH PERFORMANCE CONCRETE (HPC)

2.1 General

High performance concrete (HPC) exceeds the properties and constructability of normal concrete. Normal and special materials are used to make these specially designed concrete that must meet a combination of performance requirements. Special mixing, placing and curing practices may be needed to produce and handle high- performance concrete.

High-performance concretes are made with carefully selected high quality ingredients and optimized mixture designs; these are batched mixed, placed and compacted and cured to the highest industry standards. Typically, such concretes will have a low water-cementing materials ratio of 0.20 to 0.45. Plasticizers are usually used to make these concretes fluid and workable. High-performance concretes always has a higher strength than normal concrete. However, strength is not always the primary required property. For example, a normal strength concrete with very high durability and very low permeability is considered to have high performance properties. **Table 2.1** lists properties that can be selected for high performance concrete. Not all properties can be achieved at the same time. High-performance concrete specifications ideally should be performance oriented. Unfortunately, many specifications are the combination of performance requirements (such as permeability or strength limits) and prescriptive requirements (such as air content limit or dosage of supplementary cementing material).

Table 2.1 Materials used in High-Performance Concrete (http://elearning.vtu.ac.in)

Material	Primary contribution/Desired property
Portland cement	Cementing material/durability
Blended cement	Cementing material/durability/high strength
Fly ash	Cementing material/durability/high strength
Slag	Cementing material/durability/high strength
Silica fume	Cementing material/durability/high strength
Calcined clay	Cementing material/durability/high strength
Metakaolin	Cementing material/durability/high strength

Calcined shale	Cementing material/durability/high strength
Super plasticizers	Flowability
High-range water reducers	Reduce water to cement ratio
Hydration control admixtures	Control setting
Retarders	Control setting
Accelerators	Accelerate setting
Corrosion inhibitors	Control steel corrosion
Water reducers	Reduce cement and water content
Shrinkage reducers	Reduce shrinkage
ASR inhibitors	Control alkali-silica reactivity
Polymer/latex modifiers	Durability
Optically graded aggregate	Improve workability and reduce paste demand

2.2 Requirements for High-performance Characteristics

Permeation is a major factor that causes premature deterioration of concrete structures. The provision of high-performance concrete must centre on minimizing permeation through proportioning methods and suitable construction procedures (curing) to ensure that the exposure conditions do not cause ingress of moisture and other agents responsible for deterioration. Permeation can be divided into three distinct but connected stages of transportation of moisture, vapour, air, gases, or dissolved ions. It is important to identify the dominant transport phenomenon and design the mix proportion with the aim of reducing that transport mechanism which is dominant to a predefined acceptable performance limit based on permeability. Like the requirement of permeation characteristics, there can be other performance characteristics which may become the specific need for which HPC is used. **Table 2.2** gives a list of such desired characteristics for which HPC has been used.

Table 2.2 Salient high-performance requirements(http://elearning.vtu.ac.in)

1	Compressive strength > 70 MPa
2	Very early strength (4h) > 17.5 MPa
3	Early Strength (24h) > 35 MPa

4	High degree of impermeability to prevent ingress of water/moisture/CO_2/SO_4/air/oxygen/chloride
5	High resistance to sulphate attack
6	Smooth fractured surface
7	Absence of micro-cracking
8	High level of corrosion resistance
9	High electrical resistivity
10	High chemical resistivity
11	High resistance to abrasion, erosion and cavitation

The parameter to be controlled for achieving the required performance criteria could be any of the following:

(1) Water/ (cement + mineral admixture) ratio

(2) Strength

(3) Densification of cement paste

(4) Elimination of bleeding

(5) Homogeneity of the mix

(6) Particle size distribution

(7) Dispersion of cement in the fresh mix

(8) Stronger transition zone

(9) Low free lime content

(10) Very little free water in hardened concrete

2.3 Material Selection

The main ingredients of HPC are almost the same as that of conventional concrete. These are:

1) Cement

2) Fine aggregate

3) Coarse aggregate

4) Water

5) Mineral admixtures (fine filler and/or pozzolonic supplementary cementitious materials)

6) Chemical admixtures (plasticizers, superplasticizers, retarders, air-entraining agents)

2.3.1 Cement

There are two important requirements for any cement: (a) strength development with time and (b) facilitating appropriate rheological characteristics when fresh. Till now, studies on HPC made in this field led to the following observations:

1) High C_3A content in cement generally leads to a rapid loss of flow in fresh concrete. Therefore, high C_3A content should be avoided in cements used for HPC.

2) The total amount of soluble sulphate present in cement is a fundamental consideration for the suitability of cement for HPC.

3) The fineness of cement is the critical parameter. Increasing fineness increases early strength development, but may lead to rheological deficiency.

4) The superplasticizer used in HPC should have long molecular chain in which the sulphonate group occupies the beta position in the poly condensate of formaldehyde and melamine sulphonate or that of naphthalene sulphonate.

5) The compatibility of cement with retarders, if used, is an important requirement.

2.3.2 Coarse Aggregate

The important parameters of coarse aggregate that influence the performance of concrete are its shape, texture and the maximum size. Since the aggregate is generally stronger than the paste, its strength is not a major factor for normal strength concrete, or for HES and VES concretes. However, the aggregate strength becomes important in the case of high performance concrete. Surface texture and mineralogy affect the bond between the aggregates and the paste as well as the stress level at which micro cracking begins. The surface texture, therefore, may also affect the modulus of elasticity, the shape of the stress-strain curve and to a lesser degree, the compressive strength of concrete. Since bond strength increases at a slower rate than compressive strength, these effects will be more pronounced in HES and VES concretes. Tensile strengths may be very sensitive to differences in aggregate surface texture and surface area per unit volume.

2.3.2.1 Effect of Aggregate Type

The intrinsic strength of coarse aggregate is not an important factor if water-cement ratio falls within the range of 0.50 to 0.70, primarily due to the fact that the cement-aggregate bond or the hydrated cement paste fails long before aggregates do.

It is, however, not true for very high strength concretes with very low water-cement ratio of 0.20 to 0.30. For such concretes, aggregates can assume the weaker-link role and fail in the form of transgranular fractures on the failure surface. However, the aggregate minerals must be strong, unaltered, and fine grained in order to be suitable for very high strength concrete. Intra- and inter-granular fissures partially decomposed coarse-grained minerals, and the presence of cleavages and lamination planes tend to weaken the aggregate, and therefore the ultimate strength of the concrete.

The compressive strength and elastic modulus of concrete are significantly influenced by the mineralogical characteristics of the aggregates. Crushed aggregates from fine-grained diabase and limestone give the best results. Concretes made from smooth river gravel and from crushed granite containing inclusions of a soft mineral are relatively weaker in strength. There exists a good correlation between the compressive strength of coarse aggregate and its soundness expressed in terms of weight loss. There exists a close correlation between the mean compressive strengths of the aggregate and the compressive strength of the concrete, ranging from 35 to 75 MPa, at both 7 days and 28 days of age.

2.3.2.2 Effect of Aggregate Size

The use of larger maximum nominal size of aggregate affects the strength in several ways. First, since larger aggregates have less specific surface area and the aggregate-paste bond strength is less, the compressive strength of concrete is reduced. Secondly, for a given volume of concrete, using larger aggregate results in a smaller volume of paste thereby providing more restraint to volume changes of the paste. This may induce additional stresses in the paste, resulting in micro cracks prior to application of load, which may be a critical factor in very high strength (VHS) concretes. Therefore, it is the general consensus that smaller size aggregate should be used to produce high performance concrete.

It is generally suggested that 10 to 12 mm is the appropriate maximum size of aggregates for making high strength concrete. However, adequate performance and economy can also be achieved with 20 to 25 mm maximum size graded aggregates by proportioning with a mid-range or high-range water reducer, high volume blended cements, and coarse ground Portland cement. Change in emphasis from water-cementitious material ratio versus strength relation to water-content versus durability relation will provide the incentive for much closer control of aggregate grading than in the current practices. A substantial reduction in water requirement can be achieved by using a well-graded aggregate.

2.3.3 Mineral Admixtures

Mineral admixtures form an essential part of the high-performance concrete mix. These are used for various purposes, depending upon their properties. The fly ash (FA), the ground granulated blast furnace slag (GGBS) and the silica fume (SF) has been used widely as supplementary cementitious materials in high performance concrete. These mineral admixtures, typically fly ash and silica fume (also called condensed silica or micro silica), reduce the permeability of concrete to carbon dioxide (CO2) and chloride-ion penetration without much change in the total porosity. The pozzolanas may also react with other alkalis such as sodium and potassium hydroxides present in the cement paste. These reactions reduce permeability, decrease the amounts of otherwise harmful free lime and other alkalis in the paste, decrease free water content, thus increase the strength and improve the durability.

Fly ash used as a partial replacement for cement in concrete, provides very good performance. Concrete is durable with continued increase in compressive strength beyond days. There is little evidence of carbonation, it has low to average permeability and good resistance to chloride-ion penetration. Chloride-ion penetration rating of high volume fly ash (HVFA) concrete is less than 2000 coulombs, which indicate a very low permeability concrete. It continues to improve because many fly ash particles react very slowly, pushing the coulomb value lower and lower.

Silica fume not only provides an extremely rapid pozzolanic reaction, but its very fine size also provides a beneficial contribution to concrete. Silica fume tends to improve both mechanical properties and durability. Silica fume concretes continue to gain strength under a variety of curing conditions, including unfavorable ones. Thus the concretes with silica fume appear to be more robust to early drying than similar concretes that do not contain silica fume. Silica fume is normally used in combination with high-range water reducers and increases achievable strength levels dramatically.

Since no interaction between silica fume, ground granulated blast-furnace slag and fly ash occurs, and each component manifests its own cementitious properties as hydration proceeds, higher strength and better flowability can be achieved by adding a combination of SF, FA and GGBFS to OPC which provides, a system with wider particle-size distribution. HVFA concrete incorporating SF exceeds performance of concrete with only FA. The key to developing OPC-FA-SF and OPC-GBSF-SF concretes without reduction in strength is to incorporate within the mixture adequate amounts of OPC and water.

2.3.4 Superplasticizers

The superplasticizers are extensively used in HPCs with very low water-cementitious material ratios.

The main objectives for using superplasticizers are the following.

(i) To produce highly dense concrete to ensure very low permeability with adequate resistance to freezing-hawing.

(ii) To minimize the effect of heat of hydration by lowering the cement content.

(iii) To produce concrete with low air content and high workability to ensure high bond strength.

(iv) To lower the water-cement ratio in order to keep the effect of creep and shrinkage to a minimum.

(v) To produce concrete of lowest possible porosity to protect it against external attacks.

(vi) To keep alkali content low enough for protection against alkali-aggregate reaction and to keep sulphate and chloride contents as low as possible for prevention of reinforcement corrosion.

(vii) To produce pumpable yet non-segregating type concrete.

(viii) To overcome the problems of reduced workability in fibre reinforce concrete and shotcrete.

(ix) To provide high degree of workability to the concretes having mineral additives with very low water-cementitious material ratios.

(x) To produce highly ductile and acid resistant polymer (acrylic latex) concrete with adequate workability and strength.

2.3.4.1 Superplastisizer Dosage

There is no a prior way of determining the required superplasticizer dosage; it must be determined by trial and error procedure. Basically, if strength is the primary criterion, then one should work with the lowest w/c ratio possible, and thus the highest superplasticizer dosage. However, if the rheological properties of the HPC are very important, then the highest w/c ratio possible consistent with the required strength should be used, with the superplasticizers dosage then adjusted to get the desired workability. In general, of course, some intermediate positions must be found, so that the combination of strength and rheological properties are optimized.

2.3.4.2 Retarders

Retarders are, generally, recommended for HSC to minimize the slump loss problem. However, it is difficult to maintain compatibility between the retarder and the superplasticizer. Therefore, the Retarders are recommended only as a last resort; the rheology is better controlled by the use of appropriate mineral admixture (supplementary cementing material) discussed before.

2.4 Mix Proportion

The main difference between mix designs of HPC and ordinary cement is the emphasis laid on performance aspect also (in fresh as well as hardened stages of concrete) besides strength, in case of HPC, whereas in design of ordinary cement mixes, strength of concrete is an important criterion. By imposing the limitations on maximum water–cement ratio, minimum cement content, workability (slum, flow table, compaction factor, Vee-Bee consistency), etc., it is sought to assure performance of ordinary cemnet; rarely any specific tests are conducted to measure the durability aspects of ordinary cement, during the mix design. In HPC, however, besides strength, durability considerations are given utmost importance. To achieve high durability of HPC, the mix design of HPC should be based on the following considerations **(**http://elearning.vtu.ac.in):

i) The water-binder (w/b) ratio should be as less as possible, preferably 0.3 and below.

ii) The workability of concrete mix should be enough to obtain good compaction (use suitable chemical admixtures such as superplasticizer (SP)).

iii) The transition zone between aggregate and cement paste should be strengthened (add fine fillers such as silica fume (SF)).

iv) The microstructure of cement concrete should be made dense and impermeable (add pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag powder (GGBFSP), SF, etc.)

v) Proper curing regime of concrete should be established (this is to overcome the problems associated with usual adoption of very low water content and high cement.

2.5 Properties of High Performance Concrete

2.5.1 Properties of Fresh Concrete

High performance concrete is characterized by special performance both short- and long-term and uniformity in behavior. Such requirements cannot always be achieved by using only conventional materials or applying conventional practices. It is wrong to believe that the mechanical properties of high performance concrete are simply those of a stronger concrete. It is also as wrong to consider that the mechanical properties of high-performance concrete can be deduced by extrapolating those of usual concretes as it would be wrong to consider that none of them are related. It is also wrong to apply blindly the relationships linking the mechanical properties of a usual concrete to its compressive strength that were developed through the years for usual concretes found in codes and text books.

2.5.1.1 Workability

The workability of HPC is normally good, even at low slumps, and HPC typically pumps very well, due to the ample volume of cementing material and the presence of chemical admixtures, particularly HRWR. Due to reduced water-cementing material ratio no bleeding occurs. In the flowing concrete bleeding is prevented by providing adequate fines in the concrete mix. The cohesiveness of superplastisized concrete is much better as a result of better dispersion of cement particles. Cohesion is a function of rheology of concrete mix, which is consequently improved. However, excessive dosages of superplastisizer can induce some segregation, but it has little effect on physical properties of hardened concrete.

2.5.1.2 Curing

The compressive strength of HPC is less sensitive to temperature and relative humidity than the normal strength concrete. However, tensile strength of HSC has been found to be more sensitive. The concrete containing very large quantities of ground granulated blast-furnace slag requires longer moist curing times to develop adequate strength and is more sensitive to drying than plain Portland cement concretes. The higher internal temperatures frequently found with high early strength HPC can lead to a rapid strength gain in concrete accompanied by a consequent gain in elastic modulus. The larger differential temperatures occurring within a stiffer concrete will create higher stresses and can cause more pronounced cracking than with normal concrete. These cracks will occur, regardless of the method of curing, due to stress caused by differential temperatures.

2.5.2 Properties of Hardened concrete

The behavior of hardened concrete can be characterized in terms of its short-term (essential instantaneous) and long-term properties. Short-term properties include strength in compression, tension and bond, and modulus of elasticity. The long-term properties include creep, shrinkage, behavior under fatigue, and durability characteristics such as porosity, permeability, freezing-thawing resistance, and abrasion resistance.

2.5.2.1 Strengths

Compressive, tensile and flexural strengths and modulus of elasticity of high performance concrete are much higher than those of the normal concrete of the same consistency. The enhancement in the mechanical properties is generally commensurate with reduction in water content when HRWR is used. In water reduced concrete the strength parameters can be generally increased by more than 20 percent. A strength of the order of normal concrete is achieved by superplastisized concrete with a reduced cement content.

The strength of the concrete depends on a number of factors including the properties and proportions of the constituent materials, degree of hydration, rate of loading, and method of testing and specimen geometry. The properties of the constituent materials which affect the strength are: the quality of fine and coarse aggregates, the cement paste and the paste-aggregate bond characteristics, i.e. properties of the interfacial transition zone. These, in turn, depend on the macro- and micro-scopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products, plus the bond between individual components.

2.5.2.2 Modulus of elasticity

It is generally agreed that the elastic modulus of concrete increases with its compressive strength. The modulus is greatly affected by the properties of the coarse aggregate; the larger the amount of coarse aggregate with a high elastic modulus, the higher would be the modulus of elasticity of concrete. The concrete in wet condition has about 15 percent higher elastic modulus than that in the dry condition. This is attributed to the effect of drying of transition zone between the aggregate and the paste. The modulus of elasticity increases with the strain rate. It also increases as the concrete is subjected to very low temperatures.

Addition of high volume of fly ash enhances elastic modulus significantly. The high elastic modulus of HVFA concrete is probably due to the fact that a considerable portion of the unreacted fly ash, consisting of glassy spherical particles, acts as a fine aggregate, and there is a strong interfacial bond between the paste and the aggregate.

2.5.2.3 Modulus of Rupture

For usual concrete modulus of rupture and splitting tensile strength are quite low and don’t vary much, because they are very much influenced by the tensile strength of the hydrated cement paste. However, this is no longer the case for high performance concrete, for which the water binder ratio and the compressive strength can vary over a wide range. The relationships that have been suggested between compressive strength and modulus of rupture for usual concrete lose some of their predictive value when going from usual concrete to high-performance concrete.

2.5.2.4 Splitting Tensile Strength

Dewar studied the relationship between the indirect tensile strength and the compressive strength of concretes having compressive strengths upto 83 MPa at 28 days. He concluded that at low strengths, the indirect tensile strengths may be as high as 10 percent of the compressive strength but at higher strengths it may reduce to 5 percent. He observed that the tensile splitting strength was about 8 percent higher for crushed rock aggregate concrete than for gravel aggregate concrete. He also found that the indirect tesile strength was about 70 percent of the flexural strength at 28 days.

2.6 Application of High Performance Concrete

Major applications of HPC have been in the areas of pavements, long-span bridges and high-rise buildings.

2.6.1 Pavements:

High Performance concrete is being increasingly used for highway pavements due to the potential economic benefits that can be derived from the early strength gain of high performance concrete, its reduced permeability, increased wear or abrasion resistance to steel studded tires and improved freeze-thaw durability. While the conventional normal strength concrete continue to be used in most cases of pavement construction, different types of high performance concretes are being considered for pavement repairs for early opening to traffic, bridge deck overlays, and special applications in rehabilitation of structures and other developments.

2.6.2 Bridges:

The use of high performance concrete would result in smaller loss pre-stress and consequently larger permissible stress and smaller cross-section being achieved, i.e. it would enable the standard pre-stressed concrete girders to span longer distances or to carry heavier loads. In addition, enhanced durability allow extended service life of the structure. In case of precast girders due to reduced weight the transportation and handling will be economical. Concrete structures are preferable for railway bridges to eliminate noise and vibration problems and minimize the maintenance cost.

In the construction of the concrete bridges and highway structures a general requirement of using a water-binder ratio of less than 0.40 combined with the use of silica fume so as to improve the chloride resistance against deicing agents and marine environment is recommended. This process improvement will provide the advantages of reduced weight, increased strength and enhanced durability.

2.6.3 High-rise Buildings

The reasons for using the high strength concrete in the area of high-rise buildings are to reduce the dead load, the deflection, the vibration and the noise, and the maintenance cost.

2.6.4 Miscellaneous Applications

Fibre reinforced concrete has been used with and without conventional reinforcement in many field applications. These include bridge deck overlays, floor slabs, pavements and pavement overlays, refractories, hydraulic structures, thin shells, rock slope stabilization, mine tunnel linings and many precast products. The addition of steel fibres is known to improve most of the mechanical properties of concrete, namely, its static and dynamic tensile strengths, energy abrasion and toughness, and fatigue resistance. Hence proper utilization of steel fibre-reinforced concrete depends on the skill of the engineer.

2.7 Concrete Properties at Early-Age

Concrete is one of the most heavily used materials for infrastructure construction in the world. In India, hundreds of crores spent on concrete structures every year, and this number is expected to increase with greater understandings of concrete properties by its users.

Concrete is a mixture of cement, water, aggregates, mineral and chemical admixtures. Hydration happens immediately after the mixing of cement and water, which produce a new material called cement paste. The cement paste serves as “glue” which binds aggregates to work together as a composite material. During hydration of cement, the physical state of the paste “glue” changes from liquid with suspensions to a complete solid. This period of physical change is called setting, which is followed by hardening that is defined as a period in which concrete strength is gained. The service life of a concrete depends very much on its durability. A good concrete can last for thousands of years. From the life cycle point of view, concrete life span consists of green period, early age and late age. However, there is no clear definition of each period. Generally speaking, the period of setting is called the green period. The first seven days of casting can be called early age, which is characterized by two important processes: setting and hardening. These properties play a deciding role in concrete properties and the performance of concrete during its service life. Between 7 and 28 days, the material is called “young concrete” and is called “matured concrete’ after that, since the concrete has attained most of its long term properties after 28 days.

The early age properties of concrete include workability, mechanical properties, and volume stability. Workability is a critical property when concrete is still in a liquid state. It determines the ease of casting and flow of material into the formwork. Mechanical properties include strength and elastic moduli. During the construction period of structure, there is a minimum requirement for compressive strength, since the material has to be strong enough to sustain the external loads. Volume stability includes creep and shrinkage; shrinkage of concrete at early age can effect the formation of micro-cracks inside the material, which reduces the durability and service life of material.

2.8 In-Situ Quality Control of Concrete at Early-Age

In-situ quality control of concrete plays an important role to guarantee the life time performance of structural members. If a good quality control system was applied in the field, the disasters can be avoided. Thus, efficient methods which can estimate the mechanical properties of concrete reliably and efficiently are urgently need.

In a large construction site, it is very difficult to estimate the strength of concrete accurately. Usually, concrete cylinders are cast on site with structural members then transferred to lab for curing under certain temperature and humidity conditions. The strength of concrete in the structural members is estimated by crushing a cylinders at certain required age. The big difference in curing conditions between the lab and the construction site leads to error in strength estimation. Over estimated field strength by lab measurement could be a reason for structural failure. In order to avoid error in strength estimation due to different curing conditions between the lab and construction site, the cast- in -place cylinder test can be used as an improved in-situ quality control method. In this method, mould is pre buried at the location where concrete does not sustain severe forces. When casting the structural member, the pre-buried mode is filled with exactly the same concrete as the other parts of the caste member. The concrete in pre-buried mode is considered as the concrete in other parts of the structural member. The pre-buried cylinder is taken out at a specific age and the compressive strength of this cylinder is regarded as the in-situ concrete strength.

Another popular method for strength estimation is temperature matched curing method. After casting the pre-cast member and testing cylinders at the same time, the testing cylinders are cured in the lab. A temperature control system is used to link the in-situ pre-cast member and the cylinder together, so that the temperature in the testing cylinder can be adjusted to be exactly the same as the temperature in the pre-cast member. Temperature match curing method can mimic the temperature condition but not the relative humidity condition. Although the cast-in –place cylinder method and the temperature matched curing method can be used to give good estimates of the in-situ strength of concrete, the pre-buring procedure and the temperature control system make the operation more complicated and sometimes may not be conducted in some plants. Also, the above mentioned, methods do not provide strength information continuously and are not suitable for concrete at early age. A continuous easy to apply method is necessary for in-situ quality control of concrete in the field at early age. Non-Destructive testing (NDT) techniques can be an option that satisfies the requirement of early age quality control for cementitious materials.

2.9 Setting and Hardening of Concrete

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 hydration process.

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

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.

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 2.1**

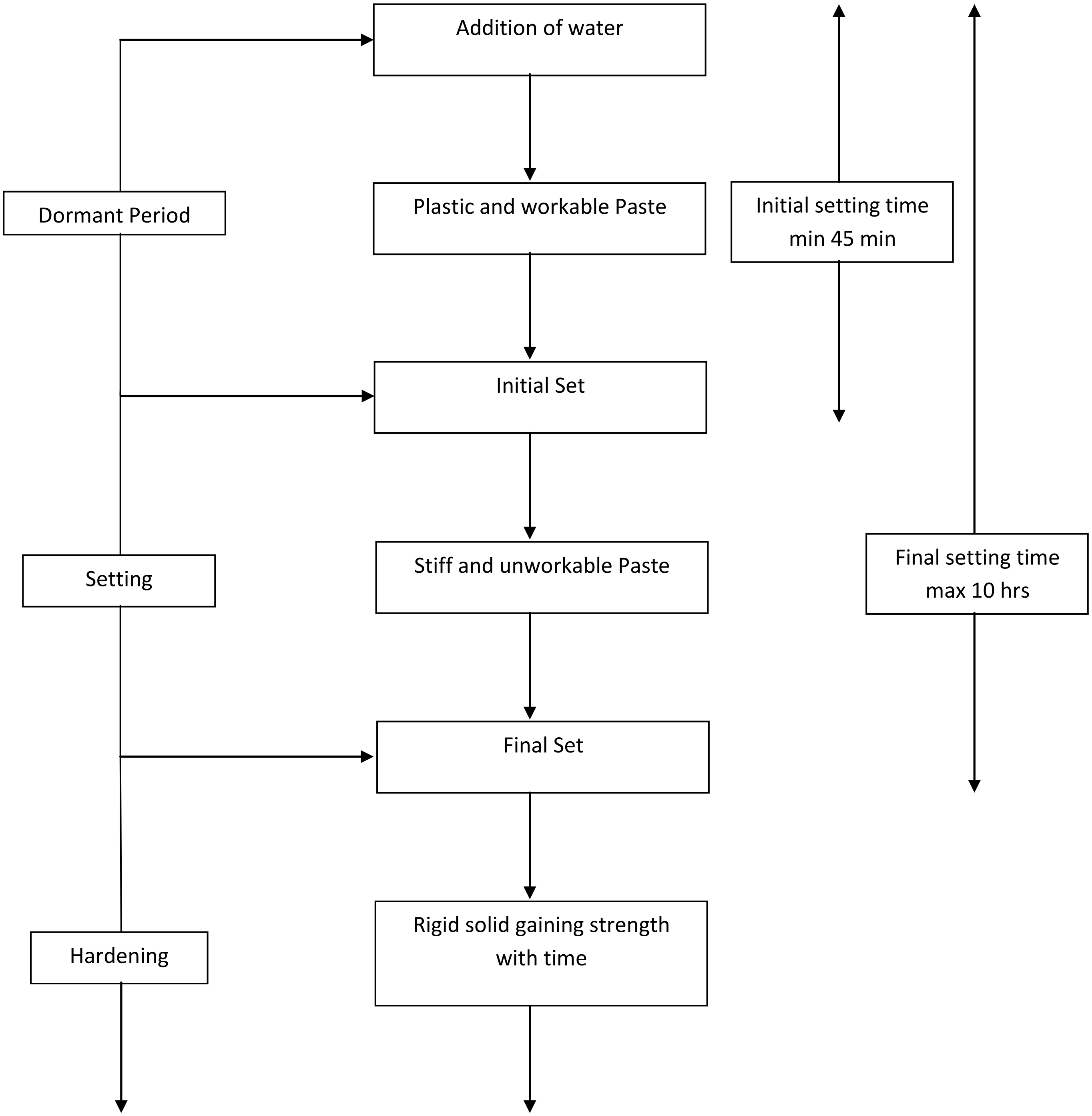


Fig 2.1 Schematic description of setting and hardening of a cement paste

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.

2.10 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-leveling 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 aggressive 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 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-Trans for 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.

2.11 Review of Literature Related to Setting and Hardening of Concrete

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

The results indicated that the ultrasonic pulse velocity largely depends on the water/cement ratio and state of hydration during the first 24 hours. The numerical cement hydration simulation model HYMOSTRUC 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 stages. Thus it was concluded that ultrasonic pulse velocity method is applicable in the recording and monitoring of the microstructure development and strength at early stages.

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

Reinhardt and Grosse et al. (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 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 is good for standard concrete mixtures but 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 hours 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 micro structural 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.

Mikulic et al. (2005) studied the importance of non-destructive test (NDT) methods like ultrasound methods for monitoring the young concrete's setting and hardening process which is the most critical phase during construction works. It showed that ultrasonic waves can propagate 0through media as transversal, longitudinal and rayleigh waves. With the help of ultrasonic methods, it is possible to determine the kinetics and degree of hydration, setting time, compressive strength and dynamic modulus of elasticity [Sekulic et al., 2004]. They performed measurements of longitudinal compressive wave velocity through concrete and mortar during hardening process. For mixtures preparation, different additives were used. The results obtained indicate the possibility for determining the hardening process and time of cementitous materials setting.

Toshiro et al. (2005) described the relationship between setting and hardening properties of cement paste and ultrasonic propagation characteristics from a macroscopic and microscopic point of view. The very first experimental series was aimed at evaluating changes in the physical properties of high early strength cement paste. A single cylinder rotational viscometer was used in the experiment for viscosity measurement. The experiments done in the second series of experiments was aimed at evaluating changes in the chemical properties of ultra rapid hardening cement paste. Scanning electron microscopy (SEM) and powder X-ray diffraction analysis were done in the experiment to investigate the generation of hydration products. The results confirmed that the maximum amplitude of the obtained waveform reflects the changes in shear resistance of cement paste adequately. The correlation was also established between the change in ultrasonic wave velocity and the formation of ettringite crystals as observed by SEM and powder X-ray diffraction analysis.

Dhonde et al. (2006) studied Piezoelectric based strength monitoring methods which provided an innovative experimental approach to conduct concrete strength monitoring at early ages. They used piezoelectric transducers in the form of smart aggregates which were embedded into the concrete specimen during casting. The Piezoceramic materials were also as actuators for generating the high frequency vibrating waves which propagate within concrete structures and 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. It was found out from the experimental results that the amplitude of the harmonic response decreases with increasing concrete strength, as the 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 dropped rapidly for the first week and continued dropping slowly as hydration proceeds, matching the development of the concrete strength at early ages. They trained a fuzzy logic system 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. They concluded that the proposed piezoelectric based monitoring method had the potential to be applied to strength monitoring of concrete structures at early ages.

Robeyst 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 monitored with the ultrasonic wave transmission method continuously.The revised measurement set-up 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 conclusion was drawn from the results that characteristic points in the graphs of penetration resistance and the ultrasonic velocity curves are correlated.

Chang and Lien et al. (2008) utilized the impact pulse velocity nondestructive method to estimate the compressive strength of the concrete at early age. The relationship of pulse velocity and strength were established for concrete but they were controlled under various water-cement ratios. The results highlighted that pulse velocity correlates well with strength at early ages but was insensitive to increases in compressive strength after concrete curing. They also discussed 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. They concluded at the end that the accuracy of compressive strength estimation can be predicted by the impact test method.

Darquennes et al. (2009) conducted three different techniques to study the evolution of the setting and hardening of concrete which were later compared are : (1) ultrasonic monitoring using the FreshCon system, (2) a resistivity method and (3) the mechanical Kelly-Bryant method. The experimental tests were conducted on two slag cement concretes in order to compare these methods and to evaluate their ability to monitor the setting and hardening process of concretes with different slag content in the cement continuously. 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.

Muhammad et al. (2009) studied the setting and hardening properties for understanding the green concretes behavior at early age. The setting and hardening behavior were monitored by applying non-destructive ultrasonic waves from the casting time of six green concrete mixtures containing high percentage of mineral additions. The ultrasonic velocity, the energy and the frequency spectrum (FFT algorithm) evolution as function of concrete age were computed during the test. The point corresponding to the first inflexion point on the velocity vs. age plot was related to the initial setting time. The tests were carried out at two temperatures at 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 and 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. The results also showed that initial temperature has an inverse effect on the setting of concrete, lower temperature delays the setting notably.

Nicolas and Nele et al. (2009) noted that research on ultrasonic methods to monitor the setting of concrete mainly focused on the wave velocity as a useful quantity. The application of wave energy as a parameter was investigated, the ultrasonic wave transmission technique was performed on several concrete and mortar samples in which 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 was retarded during setting if ordinary Portland cement was replaced by blast-furnace slag or fly ash. The final setting which is determined from 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 the 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.

Lee and Tawie et al. (2010) studied the advances in piezoelectric materials to develop new nondestructive evaluation and monitoring techniques. In this study, they embedded piezoceramic (PZT) sensors 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. The gradual adhesion between the steel rebar and fresh concrete was detected from the EMI measurements via 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. This was made clear that fissuring is mainly during early age. Some nondestructive testing methods- Acoustic Emission Method and Nonlinear Spectroscopy were applied which gave 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.

Zhu and Kee et al. (2010) noted that conventional ultrasonic set-ups measure typically the longitudinal waves (P-waves) in fresh cement pastes and need access from the two sides of the specimen. This type of set-up was not suitable for in-situ field testing. In this study, they used embedded piezoelectric bender elements to generate and measure both P and shear waves(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 indicated that the shear wave velocity is closely related to the setting time of cement pastes and is 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.

Dumoulin et al. (2012) noted the use of embedded piezoelectric transducers to monitor the ultrasonic P-wave velocity evolution during setting and hardening phases of concrete subsequent to casting time. The main advantage of this technique is that it overcomes the limitations of traditional methods which prevent the application of specific mechanical boundary conditions during the measurements. The embedded transducers are based on the concept of smart aggregates which was previously developed at University of Houston, Texas. After casting, the evolution of the P-wave velocity is recorded for the first 24 hours in concrete by embedding two embedding two piezoelectric transducers in a mold. The results showed a very good agreement with classical ultrasonic tests using external transducers.

Sanish et al. (2012) studied the application of ultrasonic methods to track the strength development on early age concrete. Ultrasonic non-destructive testing (NDT) was applied in various ways for assessing the condition of concrete in structures. The application ranges from determination of setting characteristics to studying damaged concrete. In the investigation, ultrasonic through-transmission signals were analyzed for the amplitude and pulse velocity. The changes in the amplitude of the ultrasonic signal passed through concrete specimen were observed when concrete changes from fresh fluid state to hardened solid state. The amplitude values are an indication of total energy passing through the test specimen, from which one can derive energy curves. When the concrete starts hardening, the amount of energy transmitted through concrete decreases and this change is related to the strength development in concrete. This methodology was applied in the investigation to a number of different concrete, with chemical and mineral admixtures. The conventional ultrasonic methods deal primarily with the analysis of pulse velocity. But the results from this study clearly indicated the velocity need not be the best indicator of strength development. The analysis of the entire ultrasonic signal, rather than just the time of flight, gave the useful details which are helpful in characterizing the early age strength in concrete. The amplitude of the ultrasonic transmitted pulse and transmitted energy presented the clear picture of the rate of change of strength in concrete as compared with the pulse velocity value.

2.12 Closing Remarks

This chapter thoroughly elaborates the details, properties of concrete as fresh and hardened concrete and various applications of HPC. It also discusses the setting and hardening, concrete properties and in-situ quality control of concrete at early age. In the end, motivation & physical background and the review of literature related to this has been reviewed. The next chapter highlights the various details particularly to ultrasonic waves as a tool for NDT.

CHAPTER 3

USE OF ULTRASONICS FOR NDT

3.1 Basic Principle

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below in **Fig 3.1** 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.

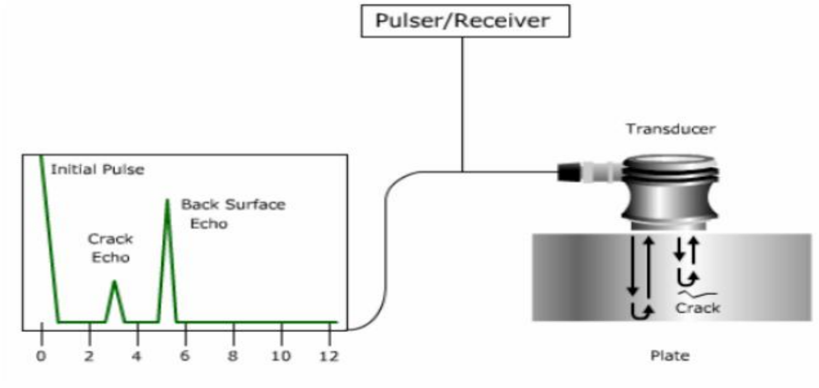


Fig 3.1 General (pulse echo method) Ultrasonic Inspection Principle (http://www.ndt-ed.org)

3.2 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 3.2**. 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.

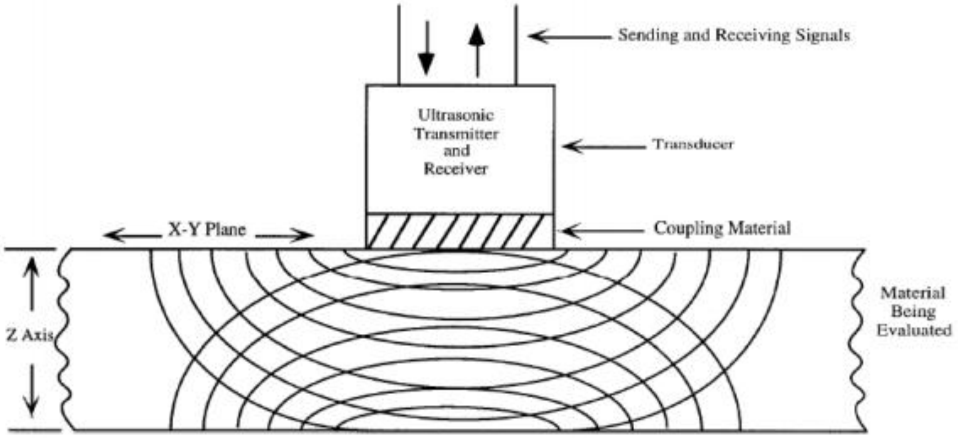


Fig 3.2 Principle of pulse echo method of inspection (Vermani, 2008)

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

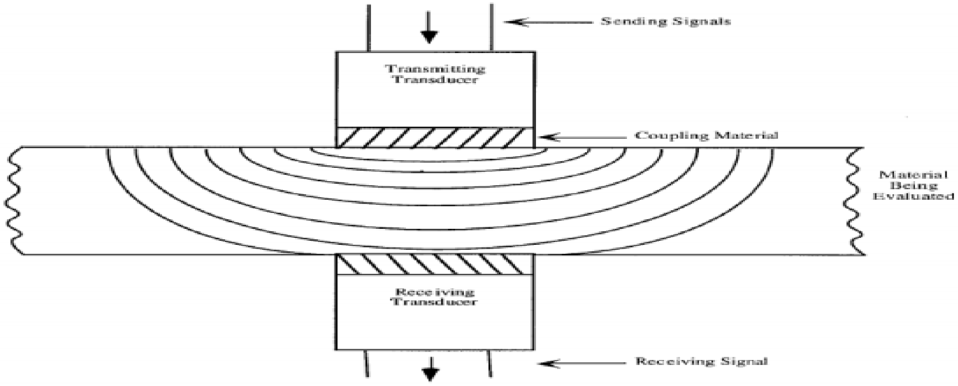


Fig 3.3 Principle of through transmission of ultrasonic testing (Vermani, 2008)

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

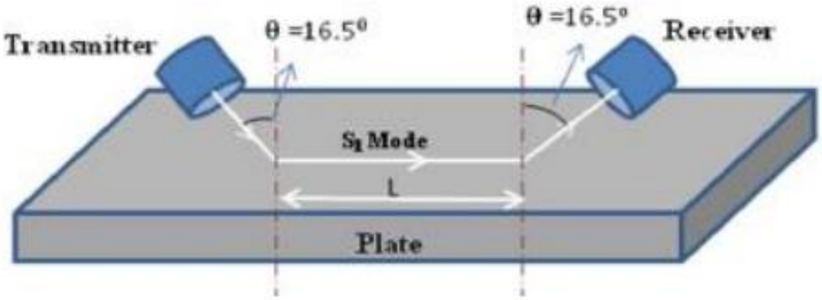


Fig 3.4 Transducers arranged at an angle to the Plate (http://www.googleimages.com)

3.3 Ultrasonic Pulse Velocity (UPV)

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

3.3.1 Pulse Velocity Test Instrument

The test instrument consists of a means of producing and introducing a wave pulse into the concrete (pulse generator and transmitter) and a means of sensing the arrival of the pulse (receiver) and accurately measuring the time taken by the pulse to travel through the concrete. The equipment may also be connected to an oscilloscope, or other display device, to observe the nature of the received pulse. A schematic diagram is shown in **Fig 3.5**

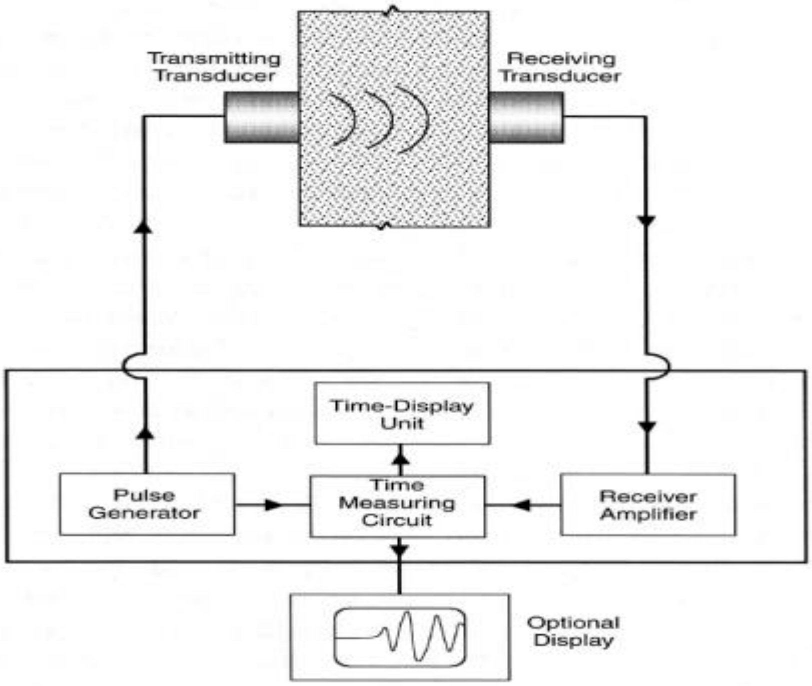


Fig 3.5 Schematic diagram of pulse velocity test circuit (http://www.googleimages.com)

Portable ultrasonic testing units are available worldwide. The equipment is portable, simple to operate, and may include a rechargeable battery and charging unit. Typically, pulse times of up to 6500 μs can be measured with 0.1-μs resolution. The measured travel time is prominently displayed. The instrument comes with a set of two transducers, one each for transmitting and receiving the ultrasonic pulse. Transducers with frequencies of 25 to 100 kHz are usually used for testing concrete. Transducer sets having different resonant frequencies are available for special applications: high-frequency transducers (above 100 kHz) are used for small-size specimens, relatively short path lengths, or high-strength concrete, Where as low-frequency transducers (below 25 kHz) are used for larger specimens and relatively longer path lengths, or concrete with larger size aggregates. These transducers primarily generate compressional waves at predominantly one frequency, with most of the wave energy directed along the axis normal to the transducer face. A commonly used instrument is shown in **Fig 3.6**

Fig 3.6 Pulse velocity instrument. (Courtesy of James Instruments, Inc.)

3.3.2 Pulse Velocity Method

The basic idea on which the pulse velocity method is established is that the velocity of a pulse of compressional waves through a medium depend on the elastic properties and density of the medium. The transmitting transducer of the pulse velocity instrument transmits a wave into the concrete and the receiving transducer, at a distance L, receives the pulse through the concrete at another point. The pulse velocity instrument display indicates the transit time, □t, it takes for the compressional wave pulse to travel through the concrete. The compressional wave pulse velocity V, therefore, is

$$V = \frac{l}{t}$$

The compressional pulse transmitted through the concrete undergoes scattering at various aggregate– mortar boundaries. By the time the pulse reaches the receiving transducer it becomes transformed into a complex waveform, which contains multiply reflected compressional waves and shear waves. Of course, compression waves traveling the fastest arrive first at the receiver. To transmit or receive the pulse, the transducers must be in full contact with the test object; otherwise an air pocket between the test object and transducer may introduce an error in the indicated transit time. This error is introduced because only a negligible amount of wave energy can be transmitted through air. Many couplants available in the market can be used to eliminate air pockets and to assure good contact; petroleum jelly has proved to be one of the superior couplants. Other couplants are grease, liquid soap, and kaolin-glycerol paste. The couplant layer should be as thin as possible. While applying constant pressure on the transducers, repeated readings at a particular location should be taken until a minimum value of transit time is obtained. The pulse velocity for ordinary concrete is typically 3700 to 4200 m/s. Therefore, for a 300-mm path length, the travel time is approximately 70 to 85 µs. It is obvious that the instrument must be very accurate to measure such a short transit time. The path length should also be carefully measured. Because the pulse velocity method is a wave propagation technique. There are three possible configurations in which the transducers may be arranged, as shown in **Fig3.7 (a) to (c).** These are (1) direct transmission; (2) semidirect transmission; and (3) indirect or surface transmission. The direct transmission method, **Fig 3.7 (a)**, is the most desirable and the most satisfactory.

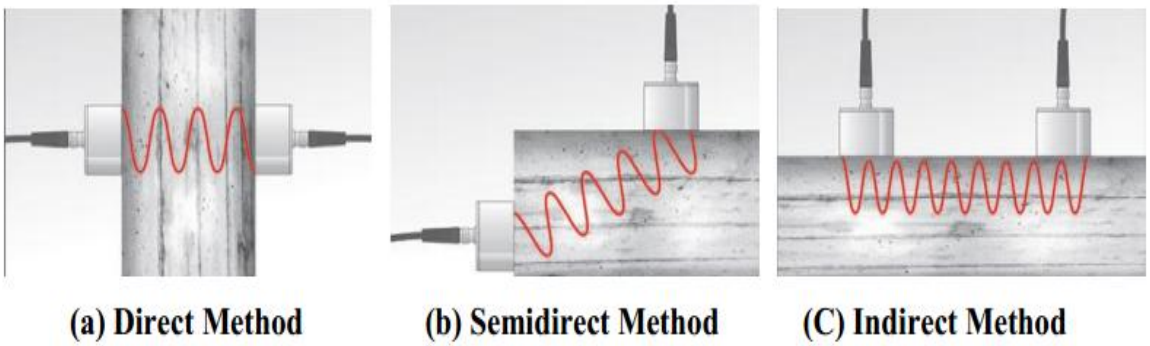

(a) Direct Method (b) Semidirect Method (C) Indirect Method

Fig 3.7 Ultrasonic pulse velocity testing transmission methods (Randhawa, J. (2011))

Arrangement because maximum energy of the pulse is transmitted and received with this arrangement. The semi direct transmission method**, Fig 3.7(b)**, can also be used quite satisfactorily. However, care should be exercised that the transducers are not too far apart; otherwise the transmitted pulse might attenuate and a pulse signal might not be detected. This method is useful in avoiding concentrations of reinforcements. The indirect or surface transmission method, **Fig3.7(c)**, is least satisfactory because the amplitude of the received signal is significantly lower than that received by the direct transmission method. This method is also more prone to errors and a special procedure may be necessary for determining the pulse velocity.

3.4 Advantages and Limitations

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

3.5 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 3.1: Natural Waveguides [Rose, 2004]

Plates (aircraft skin)
Rods (cylindrical, square, rail, etc.)
Hollow cylinder (pipes, tubing)
Multi-layer structures
Curved or flat surfaces on a half-space
Layer or multiple layers on a half-space
An interface

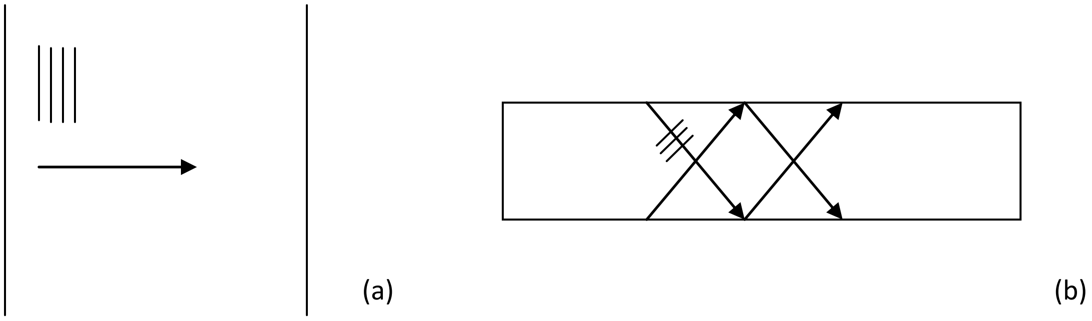
Table 3.2: Benefits of Guided Waves over Bulk waves [Rose, 2004]

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

To think of the utilization of ultrasonic guided waves we can consider a variety of different natural wave guides as outlined in **Table 3.2**. 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 3.3**. 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 3.8**. 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 3.8 Schematic of (a) bulk wave and (b) Guided wave propagation [Demma, 2003]

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.

3.6 Review of Literature Related to Use of Ultrasonic Waves

Lobkis et al. (1997) examined the behavior of guided elastic waves in the presence of rough surfaces. These investigations lead to a broader understanding of the phenomenon of rough-surface interactions with elastic guided waves. Extensive measurements in immersion, contact mode, and with a knife-edge coupler demonstrated the wide range of physical behaviour of elastic guided waves and their dependence on the condition of the guiding surfaces. Author configured experimental conditions to maximize the rough-surface damping contrast, by measuring below and above the Compressional critical angle.

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

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

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

Kundu et al. (2002 a) studied the feasibility of detecting and quantifying delamination at the interface between steel bar and concrete using ultrasonic guided waves was investigated in this paper. These waves can propagate a long distance along the reinforcing steel bar or concrete beam as guided waves are sensitive to interface bonding condition between the steel bar and concrete. The traditional ultrasonic methods are good for detecting large voids in concrete but are not efficient for detecting delamination at the interface between concrete and steel bar since they use reflection, transmission and scattering of longitudinal waves by internal discontinuities. In this study, special solid couplers between the steel bars (or concrete beam) and ultrasonic transducers have been used to launch flexural cylindrical guided waves (or lamb waves) in steel bar (or concrete). This investigation showed that the guided wave testing technique was an efficient and effective tool for health monitoring of reinforced concrete structures.

Kundu et al. (2002 b) applied the ultrasonic guided wave technique to concrete beams reinforced by glass fiber reinforced polymer bars to investigate the effect of high attenuation. Experiment setup has been shown in **Fig 3.9**.

This study showed that ultrasonic guided wave testing technique has potential for both glass fiber reinforced polymer/concrete and steel/concrete interface testing.

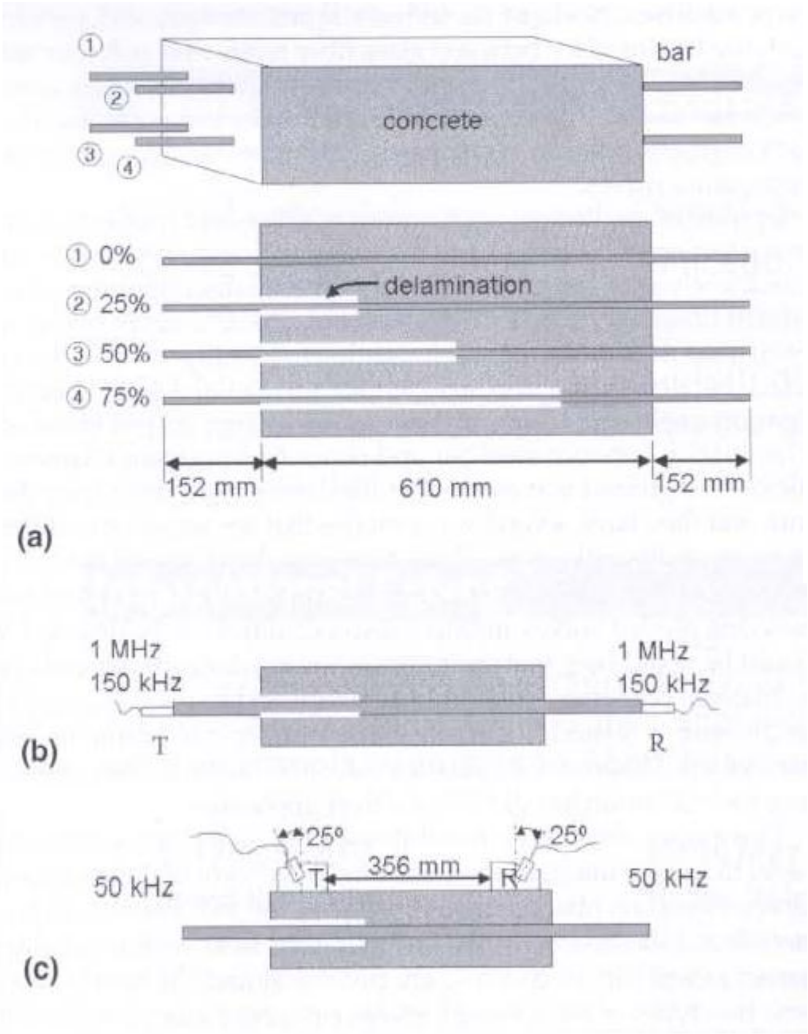


Fig 3.9 Experiment setup [Kundu et al. 2002 b]

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

Lindenb et al. (2003) described about the online monitoring of fatigue cracks using ultrasonic waves. Most of the currently available non-destructive testing methods are off-line, i.e. the operational loading and the inspection were considered as two distinct stages. In this article, an experimental methodology based on ultrasonic surface waves was developed to continuously inspect a structure during its operation. The proposed method used spectral information of transmitted surface waves at several working points of the operational load. Simple statistical indicators of the transmitted wave energy during loading were introduced in order to be able to monitor the structural health on-line. As a validation experiment, a propagating fatigue crack in a sinusoidal loaded beam was considered.

Reis et al. (2005) studied the development of a wireless embedded sensor system to monitor and assess corrosion damage in reinforced concrete; reinforced mortar specimens were manufactured with seeded defects to simulate corrosion damage. Taking advantage of waveguide effects of the reinforcing bars, these specimens were then tested using an ultrasonic approach. Using the same ultrasonic approach, specimens without seeded defects were also monitored during accelerated corrosion tests. Both the ultrasonic sending and the receiving transducers were mounted on the steel rebar. Advantage was taken of the lower frequency (<250 kHz) fundamental flexural propagation mode because of its relatively large displacements at the interface between the reinforcing steel and the surrounding mortar. Waveform energy (indicative of attenuation) was presented and discussed in terms of corrosion damage. Current results indicated that the loss of bond strength between the reinforcing steel and the surrounding concrete can be detected and evaluated.

Reis et al. (2005) studied the development of a wireless embedded sensor system to monitor and assess corrosion damage in reinforced concrete, reinforced mortar specimens were manufactured with seeded defects to simulate corrosion damage. Taking advantage of waveguide effects of the reinforcing bars, these specimens were then tested using an ultrasonic approach. Using the same ultrasonic approach, specimens without seeded defects were also monitored during accelerated corrosion tests. Both the ultrasonic sending and the receiving transducers were mounted on the steel rebar. Advantage was taken of the lower frequency (<250 kHz) fundamental flexural propagation mode because of its relatively large displacements at the interface between the reinforcing steel and the surrounding mortar. Waveform energy (indicative of attenuation) was presented and discussed in terms of corrosion damage. Current results indicated that the loss of bond strength between the reinforcing steel and the surrounding concrete can be detected and evaluated.

Rokhlin et al. (2007) discussed about the sizing and locating of internal defects in fatigue samples. For the monitoring of crack initiation and evolution ultrasonic Lamb waves were excited and acquired in the sample continuously during fatigue tests at different levels of fatigue load using a high-speed data acquisition system. The cracks were localized and sized using the vertical C-scanning technique (VC-scan). The scanned ultrasonic images were compared with micro radiographic images and were found to be in good agreement. Data fusion from three NDE techniques enables one to determine the initiation times, shapes, orientations and sizes of fatigue cracks.

Sharma et al. (2009 a) studied towards the use of ultrasonic waves for damage detection in bars in air, which will be further extended to bar embedded in concrete. Minimum intrusion was effected by exciting one end of the bar with an ultrasonic pulse and recording its propagation at the other end using the bar as a waveguide. Ultrasonic guided waves with frequencies in the range of 1-4 MHz were generated in healthy and damage bars by varying the input frequencies of an ultrasonic transducer. Bar diameter of 12mm was used and damages were inflicted in the form of symmetrical area reduction in reinforcing bars. Two ultrasonic testing techniques, pulse echo and pulse transmission, were used to monitor healthy as well as damaged bars. Time of flight measurement in pulse echo indicated the damage location accurately. Amplitude of received signal in both pulse echo and pulse transmission was a measure of extent of damage. The two techniques when used in combination can predict the existence, location as well as the extent of damage in steel bars in air. The same methodology was then extended to steel bars embedded in concrete.

Sharma et al. (2009 b) studied a nonintrusive corrosion monitoring technique for early detection of damages in steel embedded in concrete. Corrosion manifests itself in debond and pitting steel bars. Guided ultrasonic waves offer a potentially attractive solution for this problem. But it is imperative to excite the right mode for detection of a particular type of corrosion. In this study, longitudinal guided ultrasonic waves were utilized to monitor notch and debond defects in steel bars in concrete simulating pitting and delamination phenomena caused by corrosion. Two ultrasonic techniques of pulse transmission and pulse echo were used to monitor the healthy and damaged specimens. The developed methodology was successfully applied for real time monitoring of RC beam specimens undergoing accelerated chloride corrosion. The ultrasonic signals effectively relate to the state of reinforcing bars.

In the experiment concrete with proportions of cement, sand, and stone aggregates as 1:1.5:2.96 was taken. The water cement ratio was 0.45. RC beam specimens of dimensions 150mm_150mm_700mm were cast. 25mm diameter plain mild steel bar of 1.2m length was embedded in the center of cross section of the beam at the time of casting. The bar projected out by 250mm on each side of beam. Bars were subjected to two different types of damages, simulating different aspects of corrosion phenomenon in the form of notches representing pits and debonding representing delamination between steel and surrounding concrete. In one set of specimens, notches with symmetrical 0%, 20%, 40%, and 60% diameter reduction are introduced in the middle of the bar before casting them in concrete. Two samples of each specimen were tested to examine the repeatability and precision of the results. In another set of specimens, delamination is simulated by wrapping a double sided tape on the steel bar to different extents of 0%, 6.25%, 12.5%, 25%, 50%, and 75% representing different extents of debonds and then embedded in concrete. The notch specimens were ultrasonically monitored in the pulse echo as well as pulse transmission modes using the set-up shown in **Fig 3.10.**

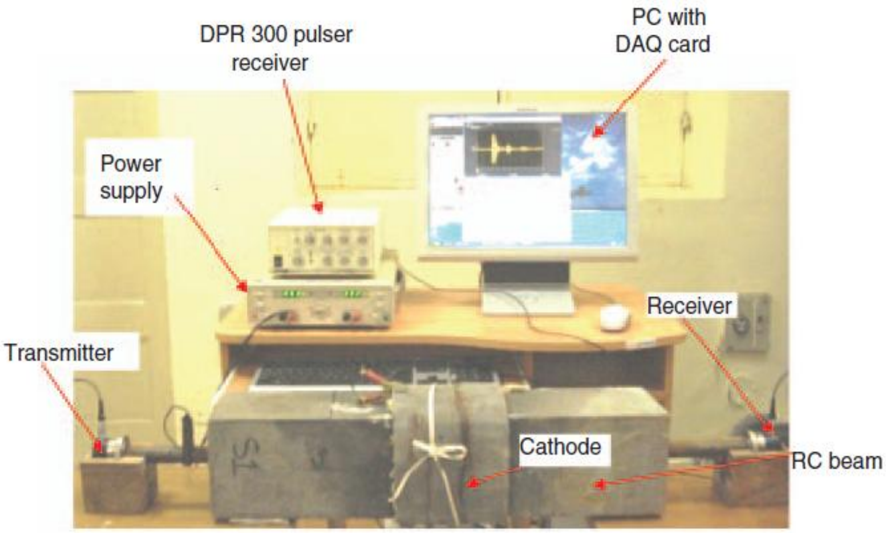


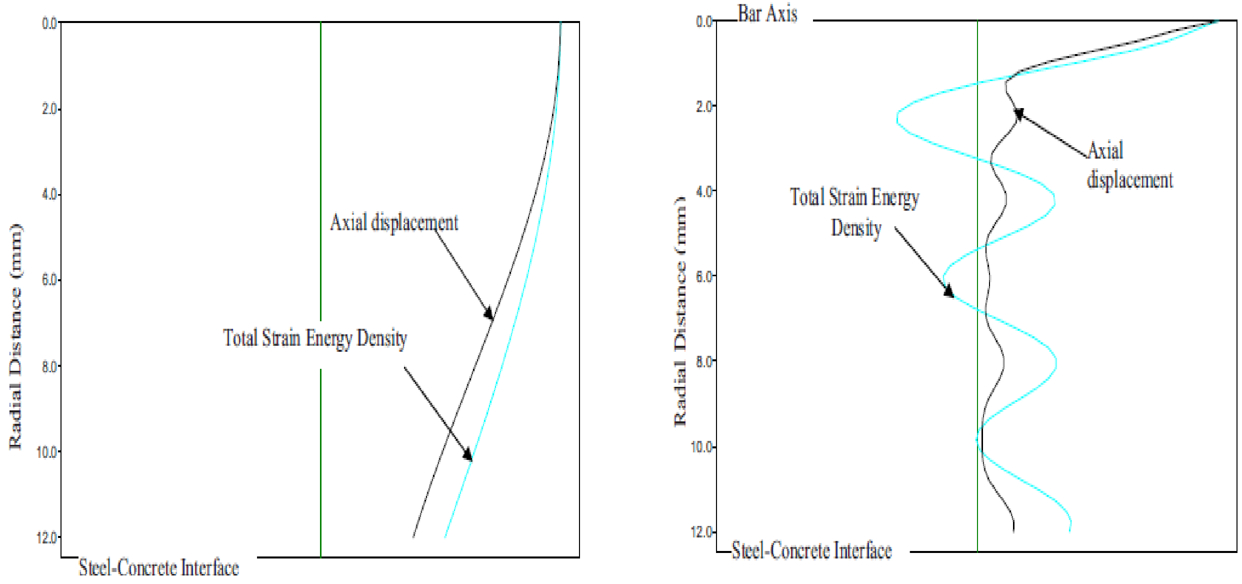
Fig 3.10 Experimental set up for ultrasonic monitoring of RC beams [Sharma et al. 2009 b]

The following conclusions were drawn;

- Ultrasonic pulse echo and pulse transmission techniques on simulated notch and debond damages can be applied for in situ corrosion monitoring of embedded reinforcements in RC beams.
- These techniques not only indicate the presence of damage but also give the exact location and magnitude of damage.
- By proper selection of ultrasonic modes the complete corrosion mechanism in RC structures can be successfully identified.

Sharma et al. (2010 a) used high frequency ultrasonic guided waves to develop a damage detection methodology for steel bars embedded in concrete with simulated notch and debond defects. Both pulse transmission and pulse echo techniques were adopted and the time of flight and signal attenuation was observed to locate and quantify damages accurately. The method is then successfully applied to reinforced concrete beam specimens undergoing accelerated chloride corrosion. The simulated and actual corrosion results were compared. The ultrasonic signals effectively relate to the state of reinforcing bar undergoing actual corrosion.

Sharma et al. (2010 c) used ultrasonic guided wave for monitoring progression of rebar corrosion concrete in chloride and oxide environments. The effect of rates of corrosion in the two environments on the ultrasonic signals was reported. Surface and core seeking guided wave modes were used **(Fig 3.11)** to monitor beams undergoing accelerated impressed current corrosion in the presence (chloride corrosion) and absence of chlorides (oxide corrosion). Effective combination of guided wave modes could relate to the differences in corrosion mechanisms and rates in the two environments. It was found that Ultrasonic test results correlated well with that of the destructive tests.



(a) **(b)**

Fig 3.11 Mode shapes: (a) surface seeking mode L (0, 1) at 100 kHZ; (b) core seeking mode L (0, 7) at 1 MHz [Sharma et al. 2010 c]

The main conclusions were;

- Initiation of corrosion was well picked up by electrochemical measurements.
- Sudden change or fall in corrosion potential (Ecorr) and change or rise corrosion current (Icorr) values indicates corrosion initiation.
- The initiation of corrosion was observed in all the beam specimens, 2-Bar Beam and 3-Bar Beam specimens, for accelerated as well as non-accelerated beams.
- In order to monitor the corrosion progression, ultrasonic measurements have proved to be a reliable method. It was found that topmost bar corrodes in lesser time whereas, the other bars at the bottom corrodes slowly and takes more time.

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

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

3.7 Closing Remarks

This chapter highlights the basic details of ultrasonic testing and discusses in detail the various methods of ultrasonic’s (i.e. UPT, UPE & UPV). It also discusses a part of Ultrasonic Guided Waves (UGW).

The following chapter discusses the experimental work carried out in this thesis report and the various equipment used in experimental set-up.

CHAPTER 4
EXPERIMENTAL STUDIES

4.1 Introduction

Setting and hardening of fresh concrete are the most critical phases during the construction works, on which properties of concrete structure depends during its service life. During setting process, concrete mixture transforms from fluid state to solid state whose properties are important for placing formworks into solid and 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 for **High Performance Concrete (with and without fly ash)** prepared at **three w/cm ratios (i.e. 0.5, 0.30, 0.27) .** Using a **Pulse-transmission system and Pulse-echo system**, the methods 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 development of concrete (both with and without fly ash) setting with different w/cm ratios is also studied with well established method of UPV.

Two different types of concrete are prepared with three different w/cm ratios. The various testing techniques, equipment, specimens, concrete mix used are also discussed in detail in the following sections.

4.2 Experimental Details: High Performance Concrete (HPC)

The use of ultrasonic guided waves for in-situ monitoring of high performance concrete (HPC) is proposed in this thesis work. It is also studied with well established method of ultrasonic pulse velocity (UPV) and destructive tests like compressive testing and split tensile testing.

4.2.1 Mix Design Details and Test Matrix

The test matrix and details of mix proportion for HPC are given below in **Fig 4.1** and **Table 4.1**.

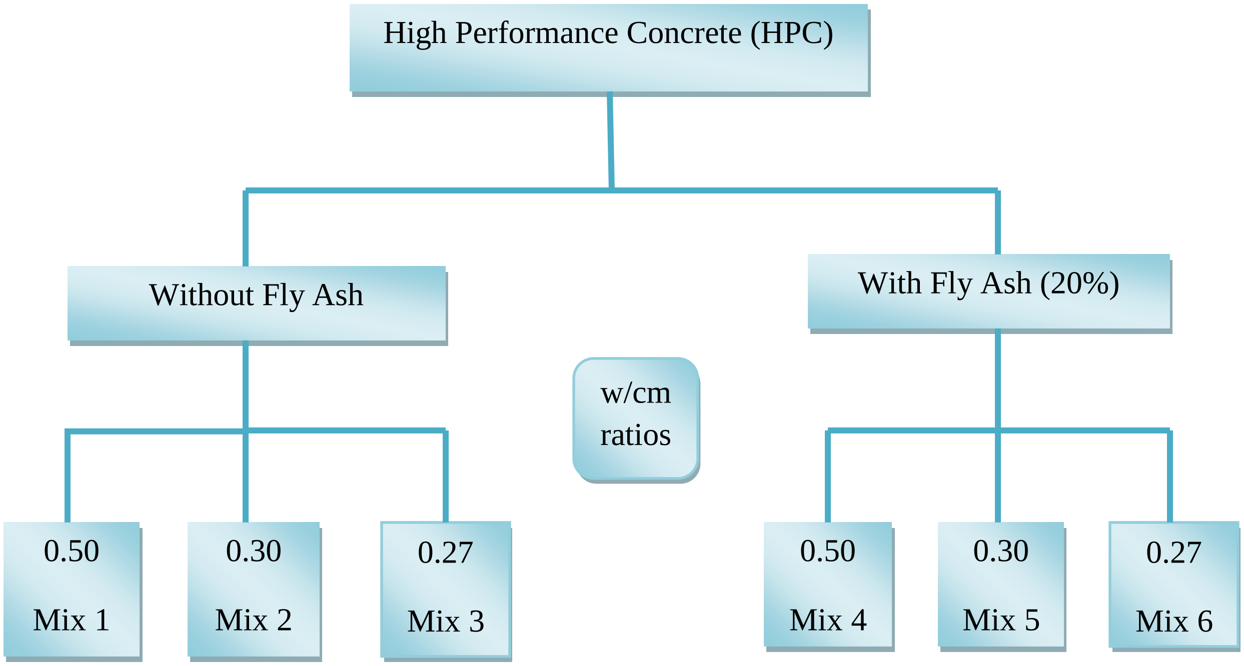


Fig 4.1 Test Matrix for HPC

Table 4.1 Mix Proportions for HPC

Mix proportions of concrete per cubic meter

Mix no.	Water (kg)	Cement (kg)	Fly Ash (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Admixture (cm x wt%)	w/cm
1	186	372	-	789.36	1023.96	-	0.50
2	186	620	-	580.94	966.08	2	0.30
3	186	688.88	-	576	957.87	2.4	0.27
4	186	297.6	74.40	633.30	1053.16	-	0.50
5	186	496	124	518.69	862.57	2	0.30
6	186	551.11	137.77	488.07	811.63	2.4	0.27

w/cm (cement + FA) ratio.

Mixes 1-3 = OPC series, Mixes 4-6 = FA series

4.2.2 Physical Properties of Materials Used for Making HPC

4.2.2.1 Cement

Ordinary Portland Cement (OPC) of 43 grade from a single lot was used throughout the course of investigation. The properties match with requirements of specification given by IS: 8112-1989. The physical properties of PPC are shown in Table 4.2.

Table 4.2 Physical Properties of OPC

Characteristics/ Properties	**Observed Value**		
Initial Setting Time	95 minutes		
Final Setting Time	185 minutes		
Specific Gravity	3.01		
Normal Consistency	27%		
Compressive Strength (MPa)	3 days	7 days	28 days
	19.01	30.20	41.45

4.2.2.2 Fine Aggregate

Sand made of crushed aggregates was used as fine aggregates. The properties match with requirement of specifications given by IS: 383-1970. The sieve analysis and physical characteristics of fine aggregate is discussed in **Table 4.3** and **Table 4.4** respectively.

Table 4.3 Sieve Analysis of Fine Aggregate

SNo.	Sieve Size	Percent Passing
1	4.75mm	99.4
2	2.36mm	93.5
3	1.18mm	71.5
4	600µ	55.6
5	300µ	23.95
6	150µ	4.3
7	Pan	0

Total Weight taken = 1000gm

Fineness Modulus of Fine Aggregate = 2.51

Table 4.4 Physical Characteristics of Fine Aggregate

SNo.	Characteristics	Values
1	Specific Gravity	2.6
2	Fineness Modulus	2.51

3	Water Absorption	0.8%
4	Grading Zone	Zone III
5	Bulk Modulus	1.4

4.2.2.3 Coarse Aggregate

Locally available crushed stone aggregates of 10mm and 20mm nominal were used as coarse aggregates. The aggregates were first sieved through 50 micron sieve in order to remove the dirt and other impurities. The sieve analysis of coarse aggregate is discussed below in **Table 4.5** and **Table 4.6.**

Table 4.5 Sieve Analysis of 20mm Coarse Aggregate

SNo.	**Sieve Size**	**Percent Passing**
1	20mm	99.4
2	10mm	93.5
3	4.75mm	71.5

Total Weight taken = 1000gm

Fineness Modulus of Coarse Aggregate = 7.01

Table 4.6 Sieve Analysis of 10mm Coarse Aggregate

S.No.	Sieve Size	Percent Passing
1	20mm	100
2	10mm	21.1
3	4.75mm	0.7

Total Weight taken = 1000gm

Fineness Modulus of Coarse Aggregate = 6.78

Specific Gravity of Coarse Aggregates = 2.65

4.2.2.4 Water

Portable tap water is used in the entire study.

4.2.2.5 Superplastisizer

Conplast SP430 complies with IS: 9103:1973 and BS:5075 part3 and ASTM-C-494 Type 'F' as a high range water reducing admixture. Conplast is based on sulphonated napthalene formaldehyde condensate ploymers . It is supplied as brown liquid instantly dispersible in water and specially formulated to give high water reduction up to 25% without loss of workability with specific gravity ranging from 1.22 to 1.225 at 30^0C. Physical properties of SP430 are discussed in the Table 4.7.

Table 4.7 Physical properties of SP430

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

4.2.3 Methodology for Studying Setting of High Performance Concrete (HPC)

It is proposed in this work to use ultrasonic guided waves approach for studying setting properties of high performance concrete. The progression of setting process is monitored by means of ultrasonic investigations. The development of concrete is also studied with well established method of UPV. To characterize the phenomenon of hardening of concrete, destructive tests like compressive test and split-tensile test were also conducted at different stages of hardening of concrete. Idea was to correlate the ultrasonic test results with other established strength development methods and also with in-situ strength of concrete.

4.2.3.1 Experimental Program

The experimental program of this thesis work is given in **Fig 4.2** and **Table 4.8** show the specimens used.

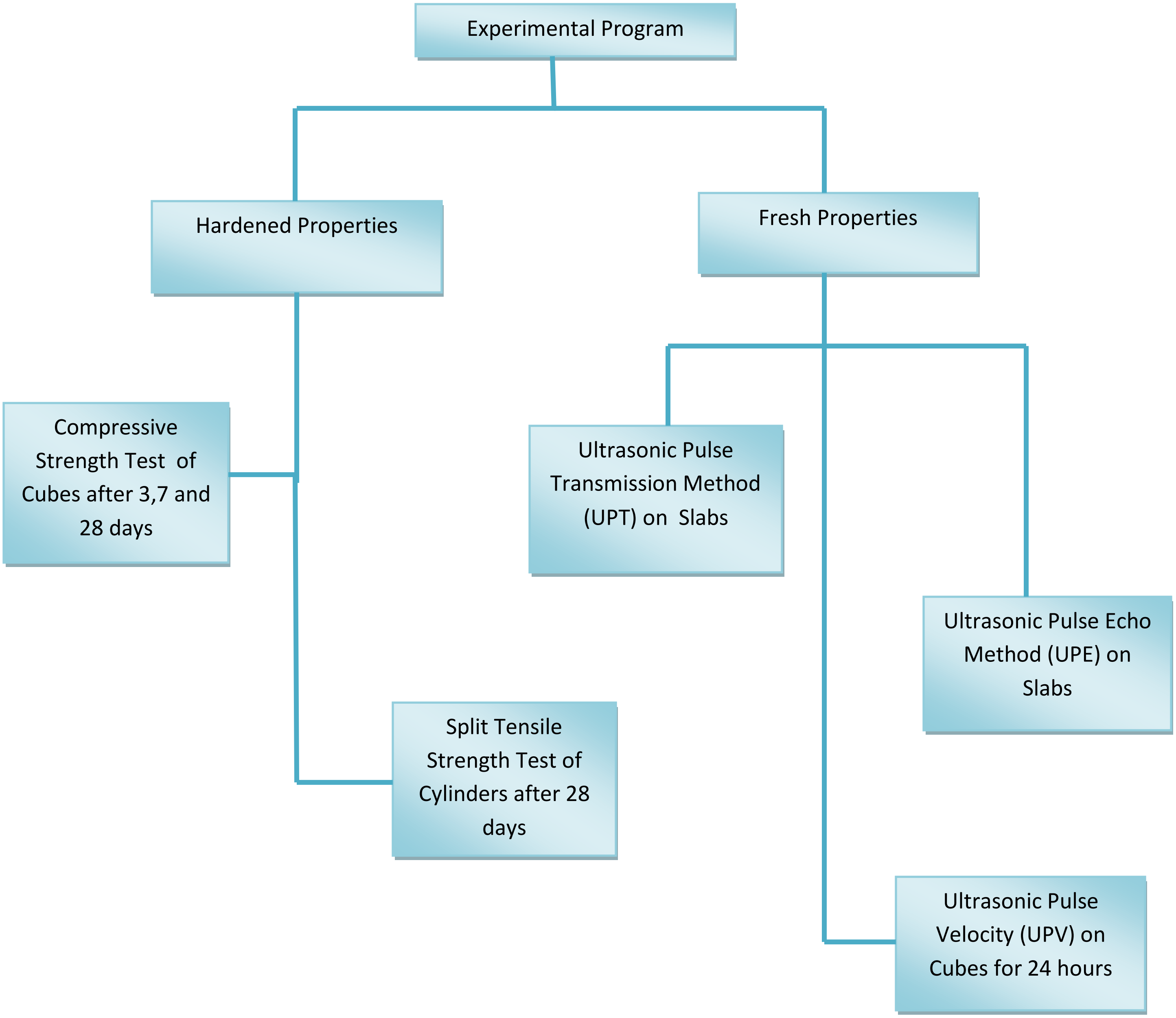


Fig 4.2 Experimental Program

Table 4.8 Specimens Used in the Experimental Program

Specimen	Specifications(mm)	Test Conducted	
		Non-Destructive (Fresh Property)	Destructive (Hardened Property)
Concrete Slab with embedded mild steel bar	Beam = 300 x 300 x 100 Steel Bar = 25 dia & 500 length	Ultrasonic Pulse transmission (UPT), Ultrasonic Pulse Echo (UPE)	
Concrete Cube	150x150x150	Ultrasonic Pulse Velocity(UPV)	Compressive Strength Test
Cylinder	Diameter = 150 Height = 300		Split Tensile Strength Test

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

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

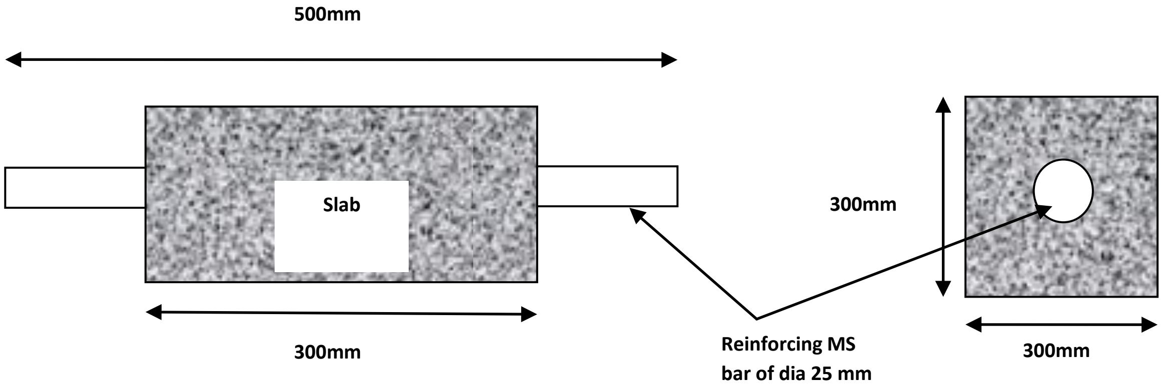
4.3 Ultrasonic Guided Waves Studies

4.3.1 General

It is proposed in this work to use ultrasonic guided wave approach for monitoring strength and hardening of concrete on two different types of concrete with three different w/cm ratios as mentioned above. The progression 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 test. To characterize the phenomenon of early age setting and hardening of concrete, destructive tests like compressive test & split tensile 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.

4.3.2 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 500mm length which is embedded in a concrete slab of size 300 mm x 300 mm x 100 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 & Fig 4.5.**



(a) Side View (b) Front view

Fig 4.3 Concrete Slab specimen for guided wave investigations

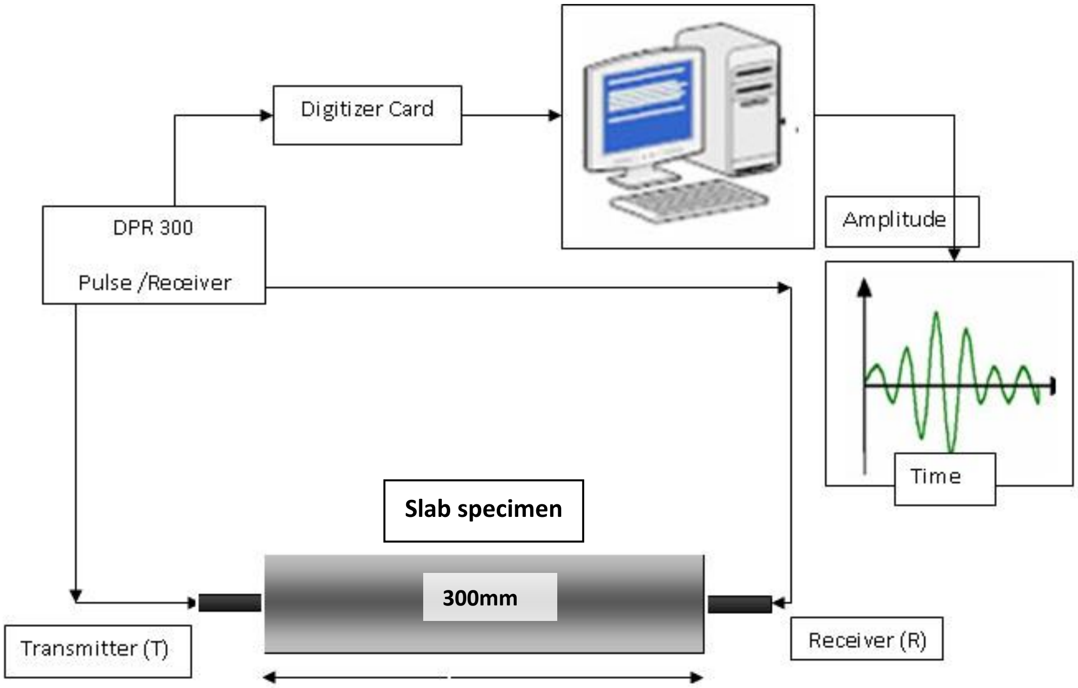


Fig 4.4 Schematic details of Set-Up

Fig 4.5 Actual Set-Up in Use

Driven by the pulser/receiver, the compressional transducer generates ultrasonic pulse that propagates through the steel bar in the form of guided waves. When concrete start setting the surrounding concrete begins making bond with the embedded steel rod which result in attenuation i.e. loss of wave energy occurs. This attenuation is due to material absorption and energy leakage into the surrounding concrete. This attenuation energy is picked up by the receiver transducer and then converted into an electrical signal which has been processesd 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. 4.6.**

Fig. 4.6 Standard KARL DEUTSCH transducer

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

JSR Ultrasonics DPR300 pulser shown in **Fig 4.7** 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 4.7 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. 4.8 gives the details of the inside layout of the JSR pulse generator. The sub-units of the JSR pulse-receiver are as given below:

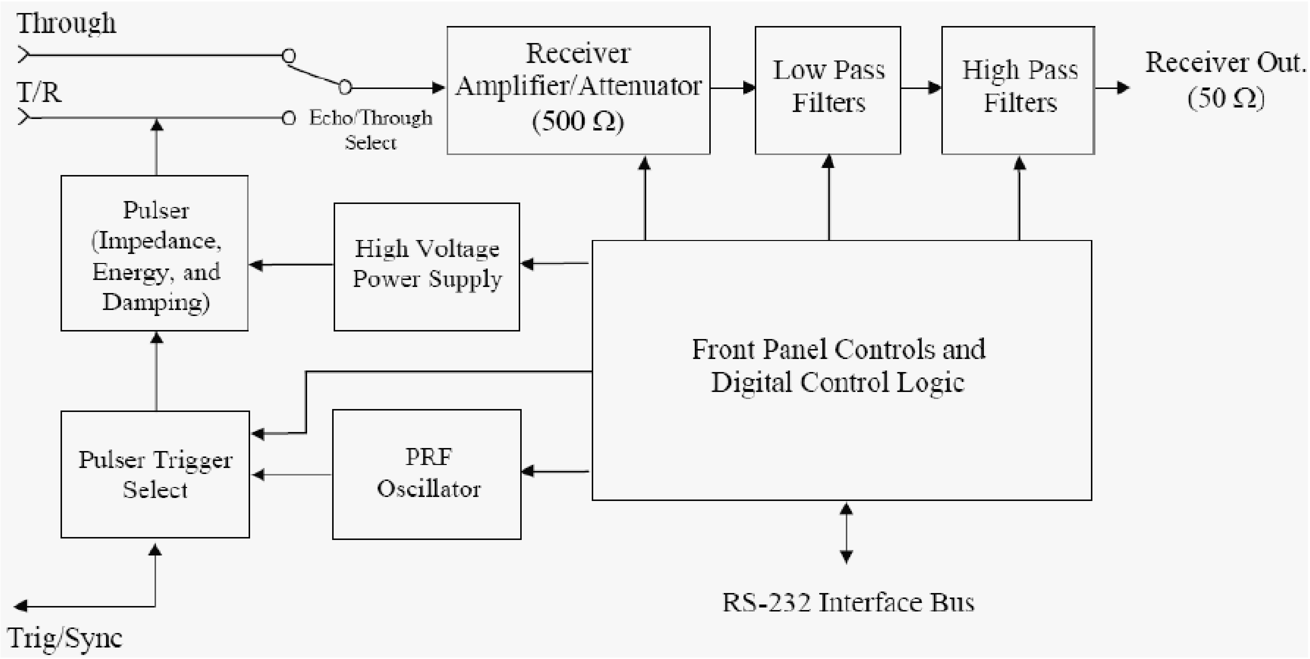


Fig 4.8 Detail circuit diagram of Pulser/Reciever system

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 4.9 gives the specifications of JSR pulse-receiver.

Table 4.9 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 4.10** gives the specifications of the Digitizer Card.

Table 4.10 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

4.4 Methodology for Ultrasonic Guided Wave Testing

4.4.1 General

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

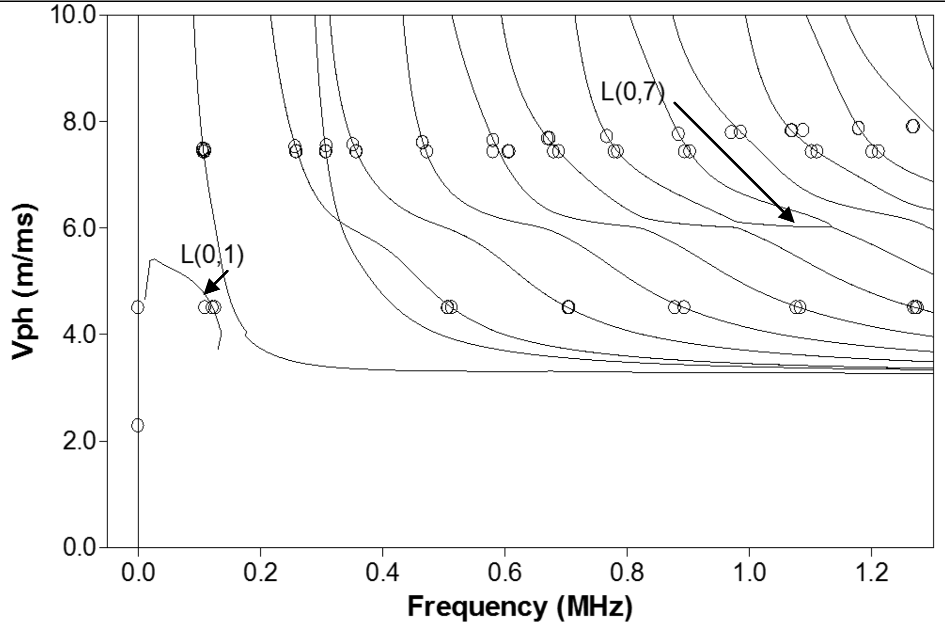
Similarly Pulse echo method is used for characterizing the young concrete strength and hardening process. To produce guided waves in the bar of concrete slab and cube one transducer (Karl Deutsch contact type) is attached to the bar which is acting perpendicular to the axis of slab and cube. Transducers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

4.4.2 Selection of Excitation Mode and Frequency

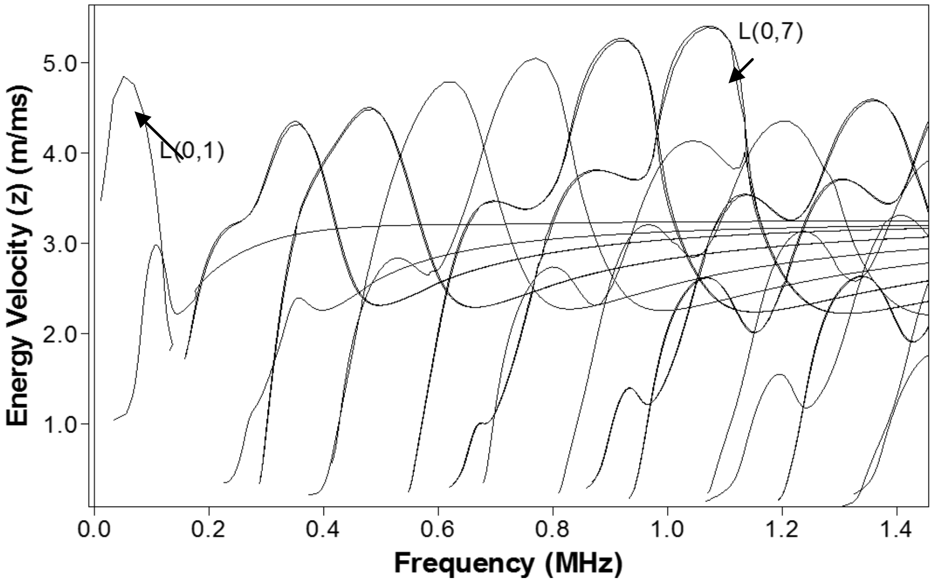
The selection of frequencies for testing is done using the software Disperse [Pavalakovic & Cawley, 2000]. The selection of a suitable test mode and frequency can be made by close examination of the dispersion curves. The modes that are easily distinguishable and have lowest signal attenuation are selected [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 4.9**. 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 4.9(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.

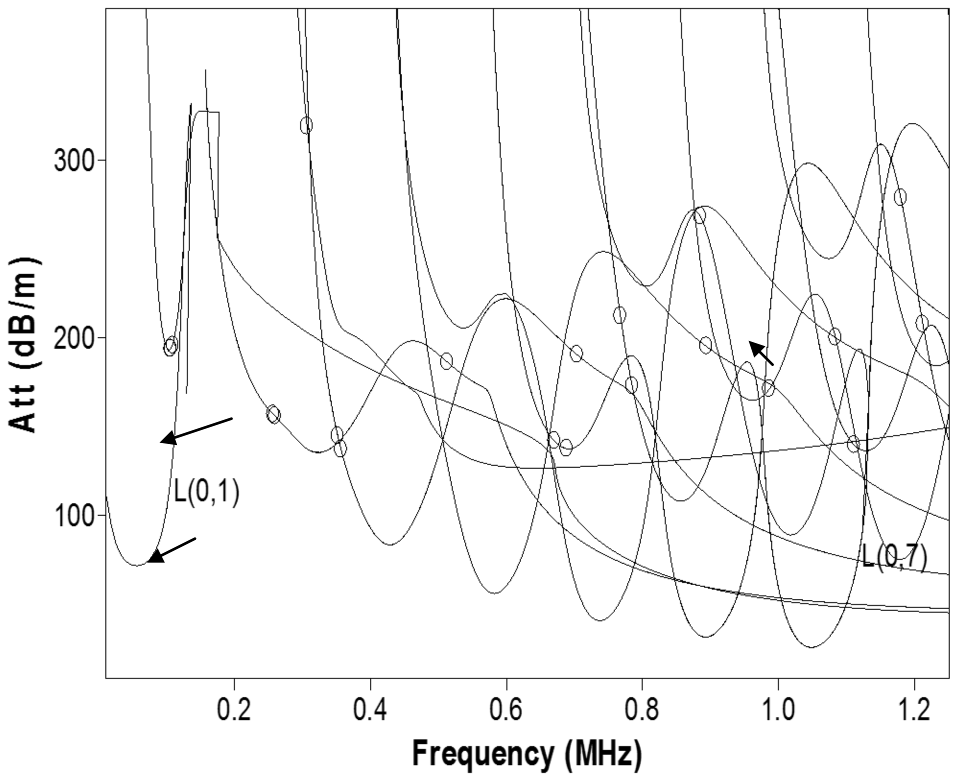
Another contributing factor to the selection of mode is the relative sensitivity of ultrasonic waves to setting of concrete. **Fig 4.10(b)** shows the displacement mode shape and radial strain energy density distribution for L (0, 7) mode not selected in the present investigation. The energy is concentrated 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 4.10(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 4.9(c)**.



(a) Phase velocity Vs Frequency

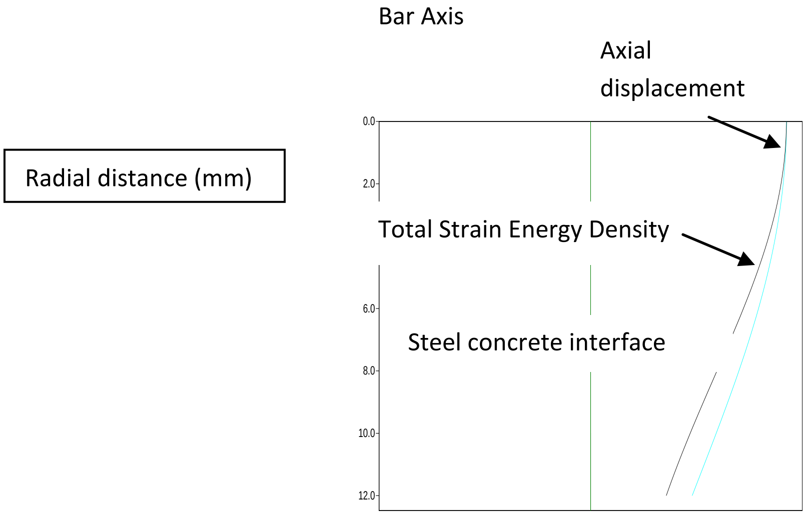


(b) Energy Velocity Vs Frequency

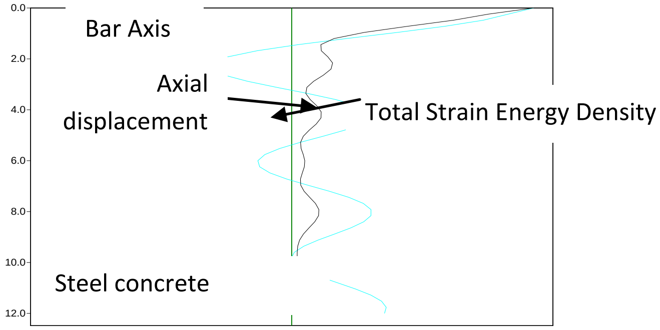


(c) Attenuation Vs Frequency

Fig 4.9 Dispersion curves for 25mm diameter bar (Sharma & Mukherjee, 2010)



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



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

Fig 4.10 Mode Shapes (Sharma & Mukherjee, 2010)

4.5 Experimental Detail: Ultrasonic Pulse Velocity Investigations

4.5.1 Set-Up & Specimen Detail

TICO Ultrasonic Instrument: ZI 10006 as shown in **Fig 4.11** was used to measure the velocity (m/sec) of the ultrasonic wave as it passes from concrete specimen as it gain its strength during setting and hardening.

Fig 4.11 TICO Ultrasonic Instrument: ZI 10006

The concrete specimens used in UPV testing are shown in **Fig 4.12**. UPV test is performed on cube during the whole setting and hardening process (hrs).

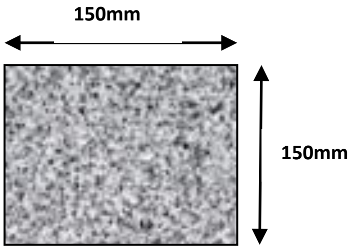


Fig 4.12 Concrete cube specimen for UPV investigation

Components of TICO Ultrasonic Instrument

The various components of TICO UPV Instrument have been shown in Fig 4.13.

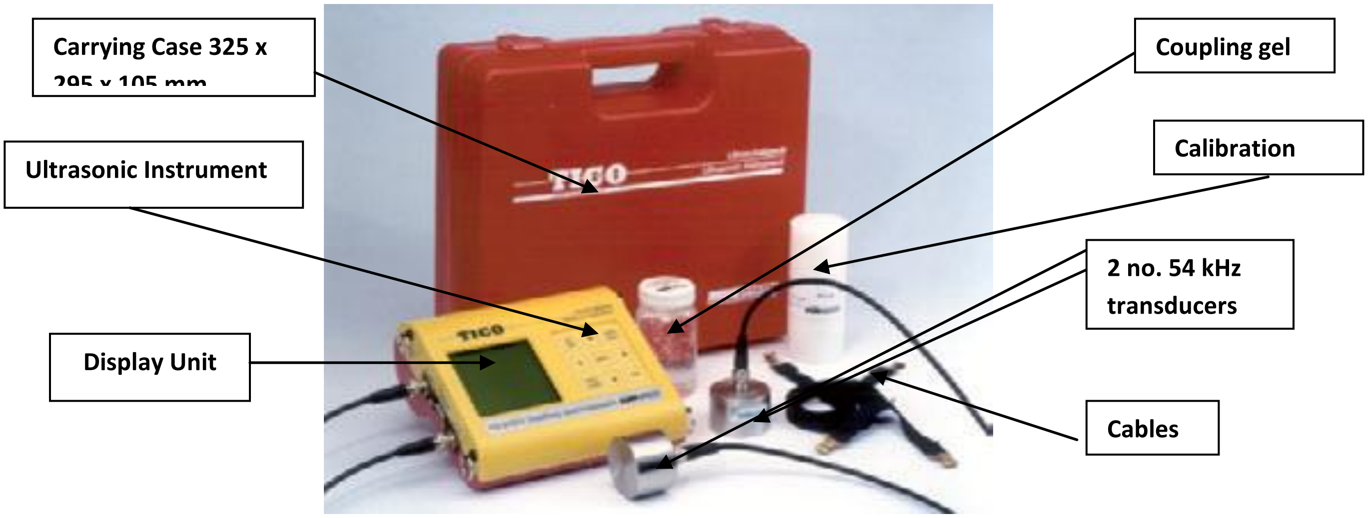


Fig 4.13 Components of TICO Ultrasonic Instrument

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 b

a second transducer and displayed in the digital display unit as shown in **Fig 4.14**. 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.

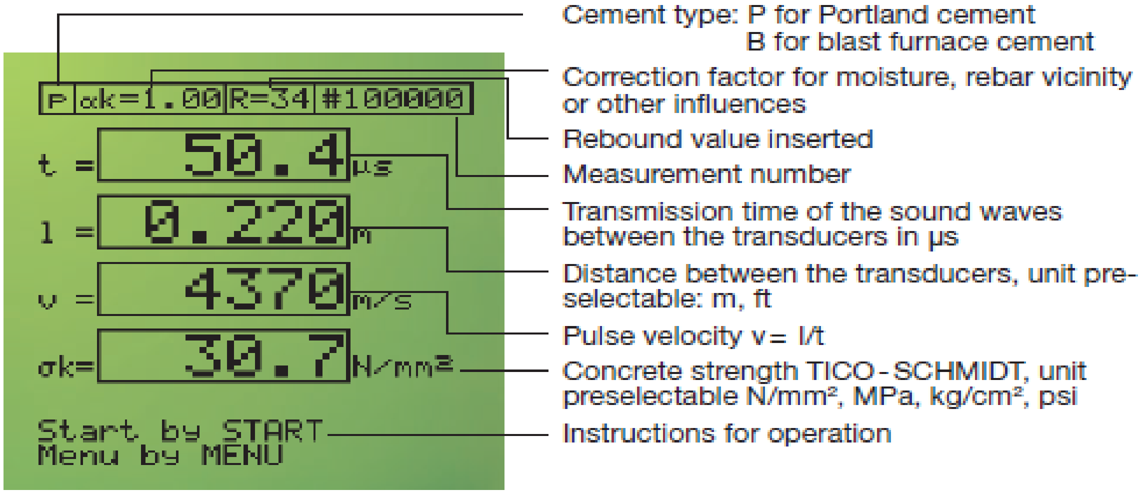


Fig 4.14 Display Unit of TICO Ultrasonic Instrument

The technical specifications of the display unit are given in Table 4.11 as follows;

Table 4.11 Specifications of TICO Ultrasonic Instrument Display Unit

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

Battery	6 LR 6, 1.5 V (30 hours operation)

4.5.2 Methodology

In this research work, UPV measurements are taken by **direct transmission** arrangement of transducers in early age setting at every hour after 3 hrs of casting upto 24 hrs continuously for both with fly ash and without fly ash concrete specimen as shown in **Fig 4.15.** 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 Early Age Setting or Strength Monitoring

The above figure clearly show that during setting and hardening, 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.

4.6 Destructive Testing

Compression Testing Machine of capacity 3000kN was used to conduct various destructive tests on different concrete specimens in the hardening phase. The various tests performed on machine are as follows:

4.6.1 Compressive Strength Testing

Compression test was carried out in order to determine the strength developed by HPC at different curing times (3, 7& 28 days) as shown in Fig 4.16.

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

Fig 4.16 Compression Testing of Cube

4.6.2 Split Tensile Testing

Split tensile strength test was carried out in order to determine the strength developed by the cylinder specimen (both fly ash and non-fly ash) at curing time of 28 days as shown in Fig 4.17.

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

Fig 4.17 Split Tensile Testing of Cylinder

4.7 Concluding Remarks

This chapter gives the physical characteristics of materials used for making high performance concrete. The outline of the experimental program with details of the specimens and tests to be conducted for determining the setting properties of HPC to draw the comparison between the two types of concrete (with & without fly ash) is done.

+

CHAPTER 5

RESULTS AND DISSCUSSIONS

5.1 General

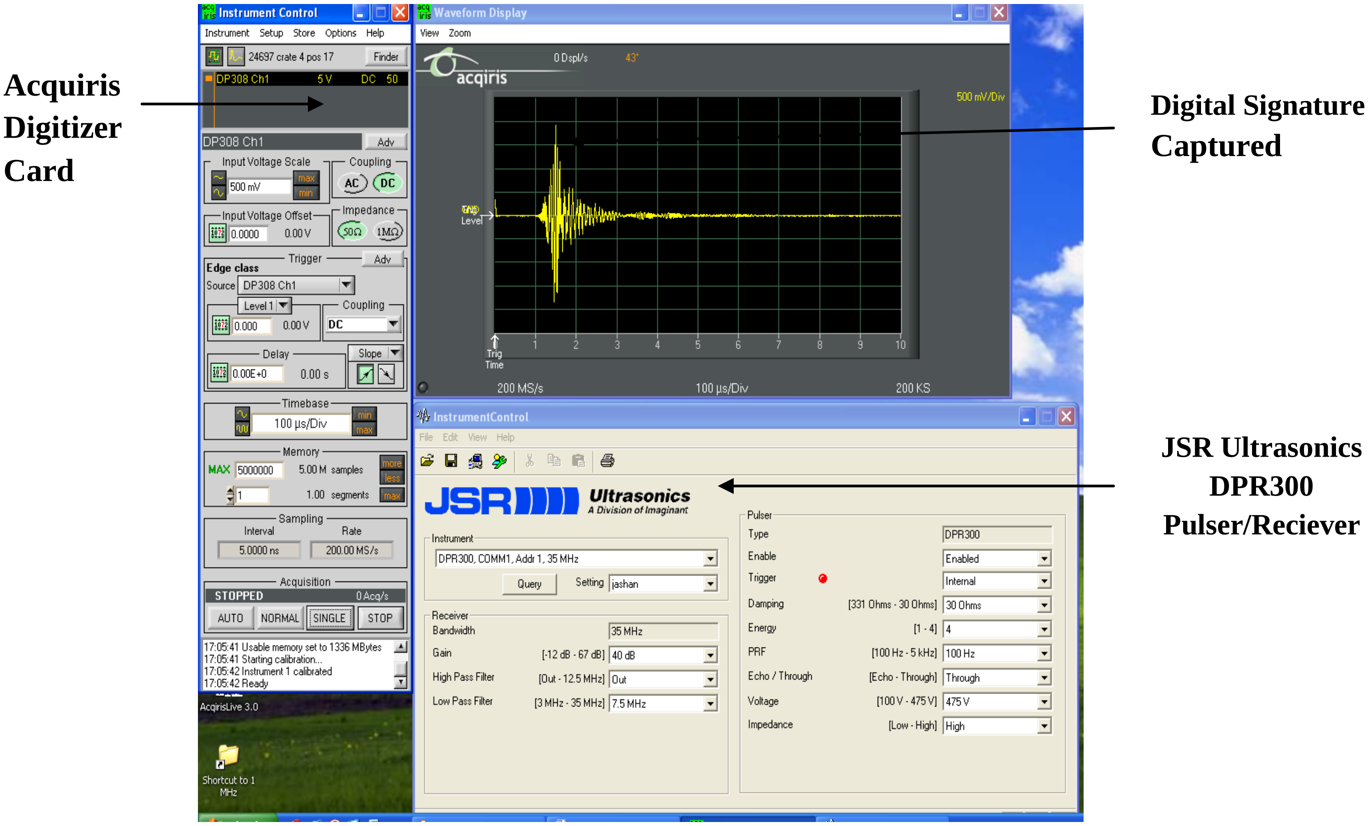
This Chapter discusses the results obtained by conducting different experiments on HPC prepared with (0% and 20%) fly ash using three different water-cementitious ratios to determine the setting characteristics and phenomenon. The schedule and test method of the experiment is given in Chapter 4.

5.2 Strength Characteristics of HPC

The Ultrasonic Pulse Transmission (UPT) and Ultrasonic Pulse Echo (UPE) tests were conducted by using frequency of 0.1 MHz and 1MHz on different specimens of slab of size 300mm x 300 mm x 100mm with an embedded mild steel rod of 25 mm diameter and 500mm length.

The conventional Ultrasonic Pulse Velocity (UPV) was also conducted on different cube specimens of size 150mm x 150mm x 150mm (Fig 4.12). The different specimens are based on three water-cementitious ratios of 0.50,0.30 & 0.27 with 0% and 20% Fly Ash replacement in OPC. The ultrasonic signatures were taken at regular time intervals during first 48 hours of setting of concrete. First a healthy signature i.e. voltage vs time graph is captured 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.

Two such images of waveform captured by digitizer card (i.e. for UPT and UPE) and their graphs (plotted in Origin 8) are shown in Fig 5.1(a), (b), (c) and (d) below.



24697 crate 4 pos 17

DP308 Ch1 5 V DC 50

DP308 Ch1

Input Voltage Scale: 500 mV

Coupling: DC

Input Voltage Offset: 0.0000 0.00 V

Impedance: 50Ω

Trigger

Source: DP308 Ch1

Level 1: 0.000 0.00 V

Coupling: DC

Delay: 0.00E+0 0.00 s

Timebase: 100 µs/Div

Memory: MAX 5000000 5.00 M samples

1 1.00 segments

Sampling: Interval 5.0000 ns Rate 200.00 MS/s

Acquisition: STOPPED 0 Acq/s

17:05:41 Usable memory set to 1336 MBytes
17:05:41 Starting calibration...
17:05:42 Instrument 1 calibrated
17:05:42 Ready

200 MS/s 100 µs/Div 200 KS

Instrument: DPR300, COMM1, Addr 1, 35 MHz

Setting: jashan

Receiver

Bandwidth: 35 MHz

Gain [-12 dB - 67 dB]: 40 dB

High Pass Filter [Out - 12.5 MHz]: Out

Low Pass Filter [3 MHz - 35 MHz]: 7.5 MHz

Pulser

Type: DPR300

Enable: Enabled

Trigger: Internal

Damping [331 Ohms - 30 Ohms]: 30 Ohms

Energy [1 - 4]: 4

PRF [100 Hz - 5 kHz]: 100 Hz

Echo / Through [Echo - Through]: Through

Voltage [100 V - 475 V]: 475 V

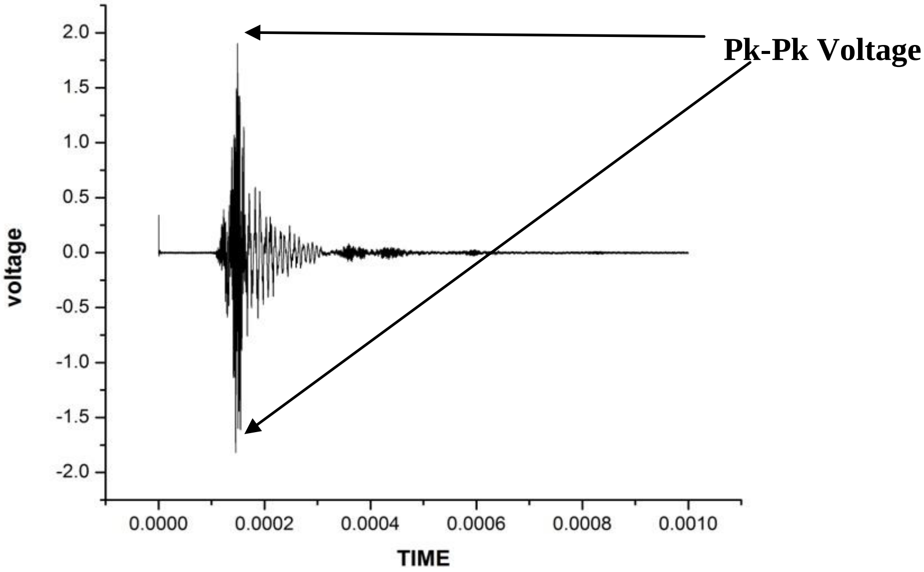
Impedance [Low - High]: High

Acquiris Digitizer Card

Digital Signature Captured

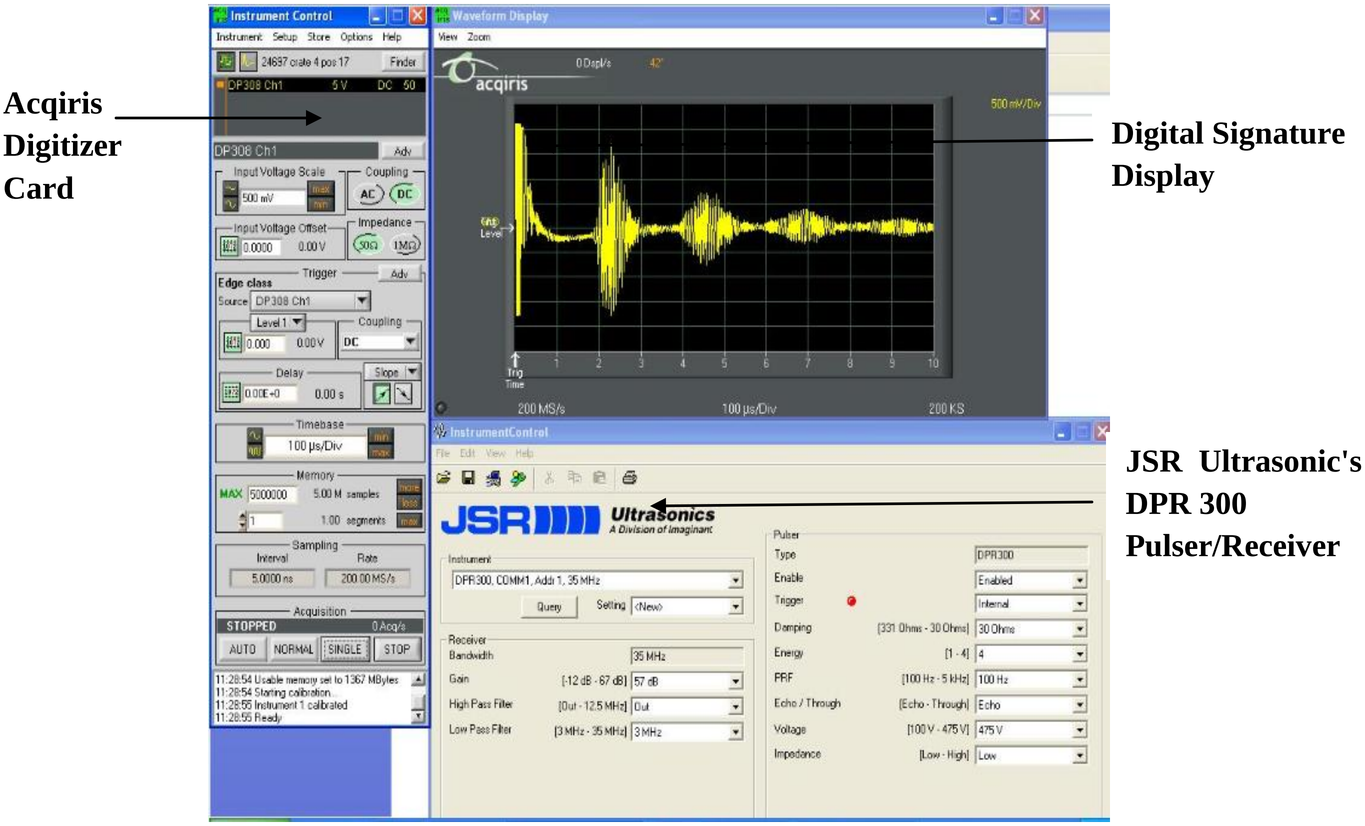
JSR Ultrasonics DPR300 Pulser/Reciever

Fig 5.1(a) Image of waveform captured in Pulse Transmission (UPT)



Pk-Pk Voltage

Fig 5.1(b) Typical UPT Signature (Plotted in Origin 8)



24697 crate 4 pos 17

DP308 Ch1 5 V DC 50

Input Voltage Scale: 500 mV

Coupling: DC

Input Voltage Offset: 0.0000 0.00 V

Impedance: 50Ω

Trigger: Edge class

Source: DP308 Ch1

Level 1: 0.000 0.00 V

Coupling: DC

Delay: 0.00E+0 0.00 s

Timebase: 100 µs/Div

Memory: MAX 5000000 5.00 M samples

1 1.00 segments

Sampling: Interval 5.0000 ns, Rate 200.00 MS/s

Acquisition: STOPPED 0 Acq/s

```
11:28:54 Usable memory set to 1367 MBytes
11:28:54 Starting calibration...
11:28:55 Instrument 1 calibrated
11:28:55 Ready
```

Instrument: DPR300, COMM1, Addr 1, 35 MHz

Setting: <New>

Receiver

Bandwidth: 35 MHz

Gain [-12 dB - 67 dB]: 57 dB

High Pass Filter [Out - 12.5 MHz]: Out

Low Pass Filter [3 MHz - 35 MHz]: 3 MHz

Pulser

Type: DPR300

Enable: Enabled

Trigger: Internal

Damping [331 Ohms - 30 Ohms]: 30 Ohms

Energy [1 - 4]: 4

PRF [100 Hz - 5 kHz]: 100 Hz

Echo / Through [Echo - Through]: Echo

Voltage [100 V - 475 V]: 475 V

Impedance [Low - High]: Low

Fig 5.1(c) Image of waveform captured in Pulse Echo (UPE)

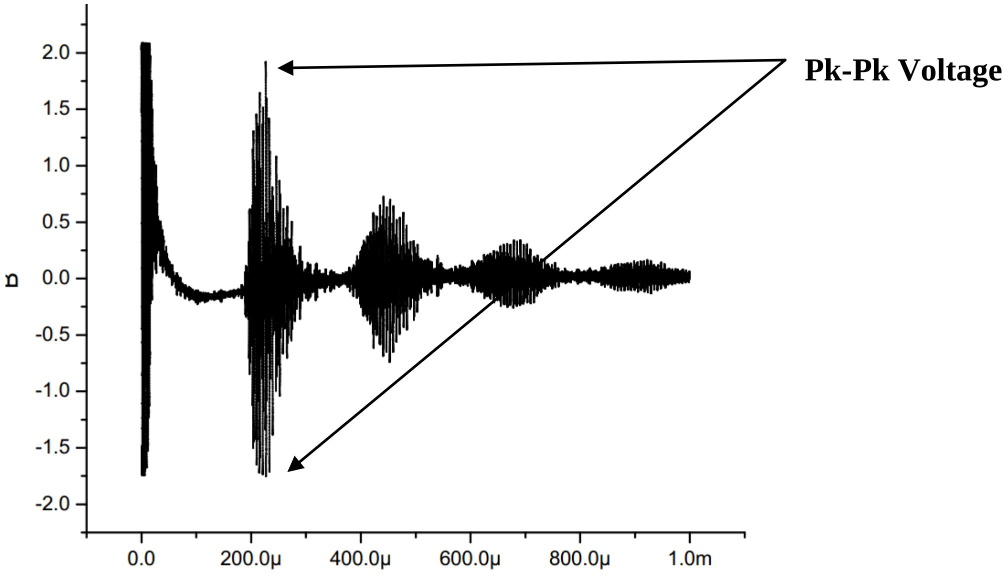


Fig 5.1(d) Typical UPE Signature (Plotted in Origin 8)

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. The bond development indicates more energy leakage into the surrounding concrete hence causing drop in signal strength. Thus the fall in signal strength is a measure of development of bond between bonding rebar and concrete and hence relates to the setting of concrete.

As outlined in Chapter 4, the Ultrasonic Pulse-Transmission (UPT) readings and Ultrasonic Pulse- Echo (UPE) are taken for HPC with 0% and 20 % fly ash for three w/cm ratios on different concrete specimens throughout first 48 hrs of setting of concrete at regular time intervals respectively. To obtain stability and check repeatability of data, minimum two samples were tested in each case and signatures plotted.

5.3 Study of Setting of HPC using Guided Waves

5.3.1 General

The signature plotted for UPT and UPE in slab and UPV in cube are used to compute pk-pk voltage trends throughout the setting process of HPC. This is done for first 48 hours regularly till the signal vanish. The first reading was taken within 15mins of casting, then after 30mins, 1 hr, 2 hr and so on till 40 hrs. The results obtained are plotted as Voltage v/s Time graphs.

In the investigation, HPC was prepared in two ways: **one with using OPC with 0% fly ash at three w/cm ratios 0.50, 0.30 and 0.27 (Mix 1, Mix 2 and Mix 3)** and second with using OPC with 20% fly ash **at three w/cm ratios 0.50, 0.30 and 0.27 (Mix 4, Mix 5 and Mix 6).** Ultrasonic investigations were carried out using both UPE and UPT. Three types of comparisons were made for UPE and UPT:

(1) Comparison between different w/cm ratios for two types of HPC (with and without fly ash) in UPT and UPE

(2) Comparison between two types of HPC for each w/cm ratio in UPT and UPE

(3) Comparison between two types of HPC for each w/cm ratio in UPV

The above two comparisons are done for slab specimens and last one is for cube specimens.

5.3.2 Comparison between Conventional Concrete and HPC

For comparison only UPT results using 1MHz frequency have been illustrated in **Fig 5.2** and **Fig 5.3.**

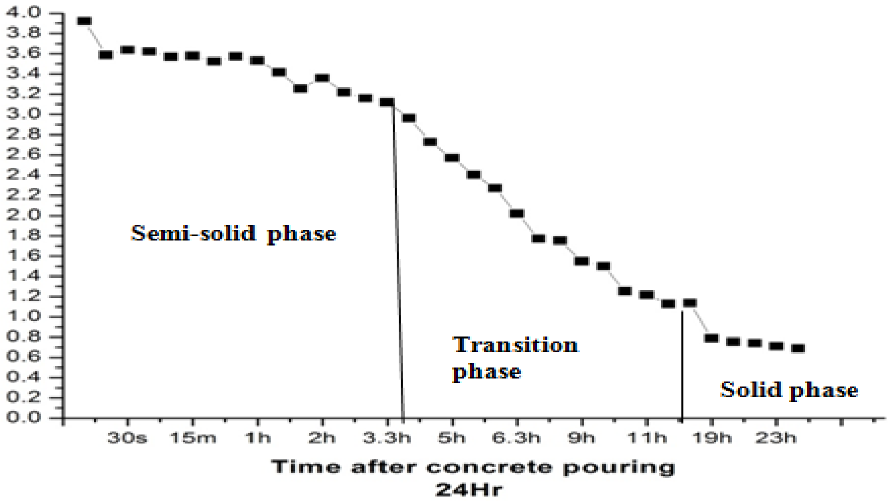


Fig 5.2 UPT Test results after 24 Hrs for Conventional Concrete Mix (Randhawa,J., 2011)

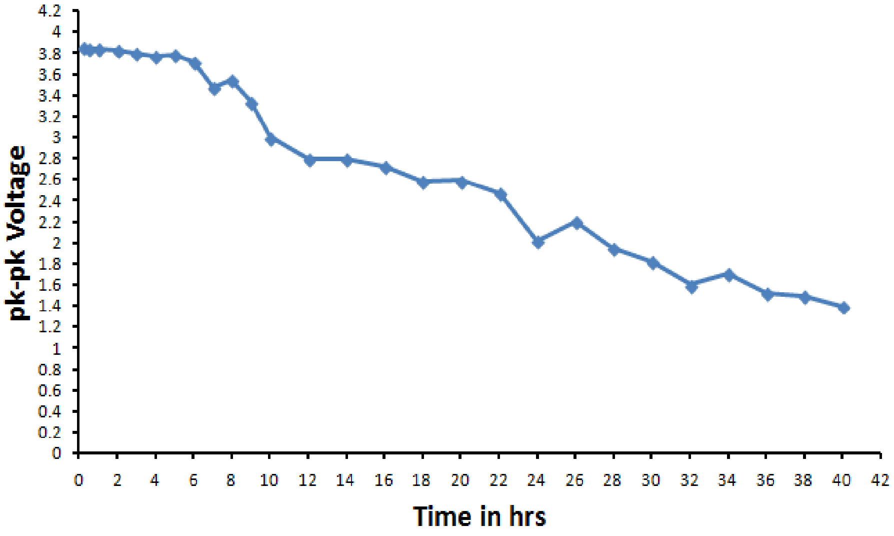


Fig 5.3 UPT Test results after 40 Hrs for HPC

Major observations can be summarized as:

In conventional concrete mix at w/cm = 0.45, there is sharp fall in pk-pk voltage and the reading is almost died at 24 hours of setting of concrete.

In HPC at w/cm = 0.30 with 20% fly ash, the pk-pk voltage fall is slow and the reading was not vanished. Solid phase was not obtained in 40 hours.

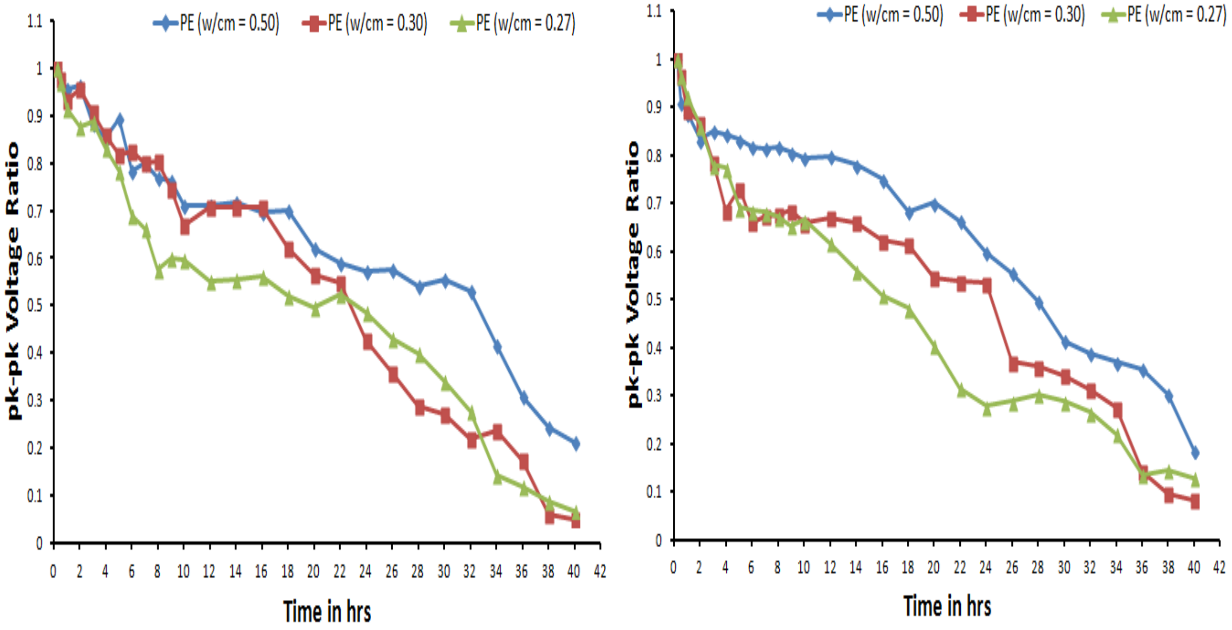
The slow setting of HPC as compared with conventional concrete because replacing cement with fly ash retards the hydration reaction. The cement particles in the lower w/cm cases (in HPC) may connect at early ages because of the shorter distances between them, but hydration is delayed due to the superplasticisers, admixtures used. That's why this delay of hydration is more in case HPC than conventional concrete.

Basic advantage is that UGW using UPT can successfully differentiate between setting of conventional concrete and HPC. It indicates that guided waves can be used for successful monitoring of early age properties of any kind of concrete.

5.4 Ultrasonic Guided Wave (UGW) Studies for HPC

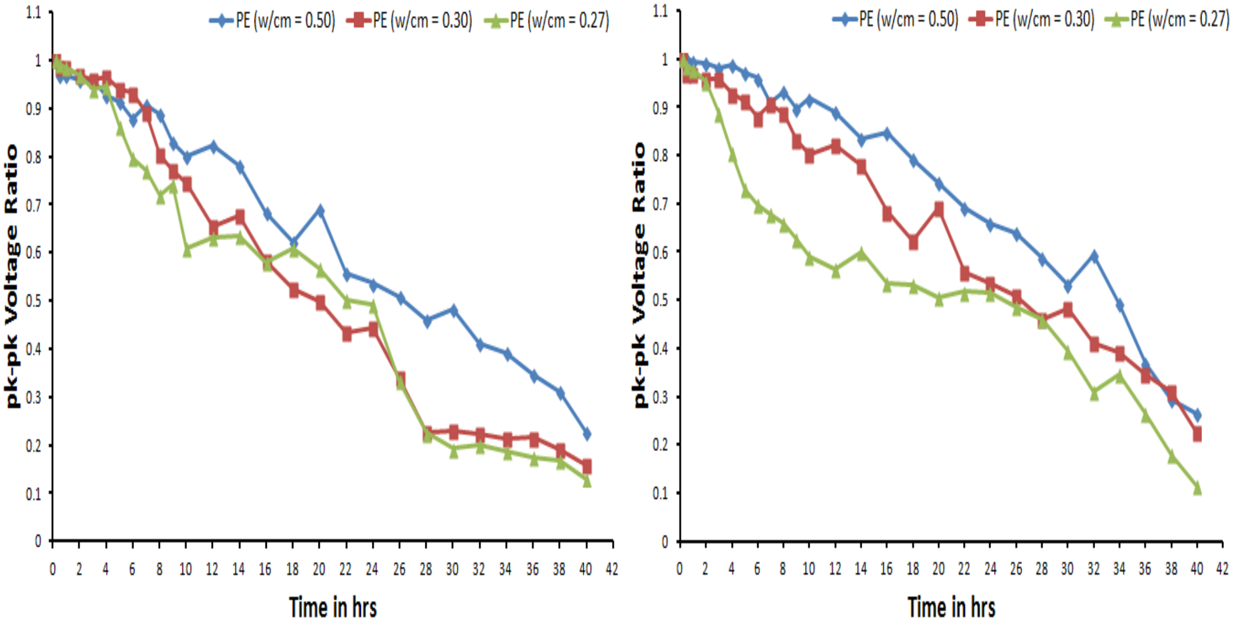
5.4.1 Pulse Echo Investigations

Following graphs shows the trends of variation of pk-pk voltage ratio of PE signals with 0% fly ash as well as 20% fly ash obtained at different hours of setting of HPC. In fig 5.4(a),(b) and fig 5.5(a), (b) shows the graphs taken for HPC with 0% fly ash and 20% fly ash respectively at three selected w/cm ratios at 0.1MHz (Surface seeking mode) and 1 MHz (Core seeking mode).



(a) 0% Fly Ash (b) 20% Fly Ash

Fig 5.4 (a) & (b) UPE Test results for HPC for Surface Seeking Mode



(a) 0% Fly Ash (b) 20% Fly Ash

Fig 5.5 (a) & (b) UPE Test results for HPC for Core Seeking Mode

From the graphs, the following observations are made:

Drop in pk-pk voltage is observed throughout the duration indicating the development of bond and hence setting of concrete using both surface and core seeking mode. As setting increases more energy leaks into concrete causing fall in signal voltage. The phenomenon of attenuation signals a measure of setting of concrete.

The surface seeking mode shows immediate falling (Fig 5.4(a) & (b)) as compared to consistent signals to core seeking mode (Fig 5.5(a) & (b))

In general, surface seeking mode (0.1 MHz) is a better indicator of setting of HPC than core seeking mode (1 MHz).

UPE graphs shows that concrete setting process can be divided into 2 phases i.e. semi—solid and transition.

In HPC with fly ash, semi-solid phase i.e. first 4,6 and 7 hours in case of w/cm = 0.50, 0.30 & 0.27 of concrete is almost fluid and there is slow fall in pk-pk voltage is observed. It indicates slow setting or bond development between the mild steel bar and the surrounding concrete during the phases of pouring concrete in mould. In HPC without fly ash, further after 4, 6 and 7 hours upto 40 hours concrete undergoes change from semi-solid state to solid state. It is termed as transition phase. The fall in pk-pk voltage is drastic as observed in this phase. This indicates that concrete is starting to set or making bond with embedded steel bar.

In HPC with fly ash, semi-solid state runs upto more time in comparison to HPC without fly ash upto 5,9 and 10 hours in relation to 4,6 and 7 hours in HPC without fly ash. It indicates that setting of HPC with fly ash is slow and needs more time to make bond with surrounding concrete. In HPC with fly ash, rate of fall is slow in comparison to HPC without fly ash.

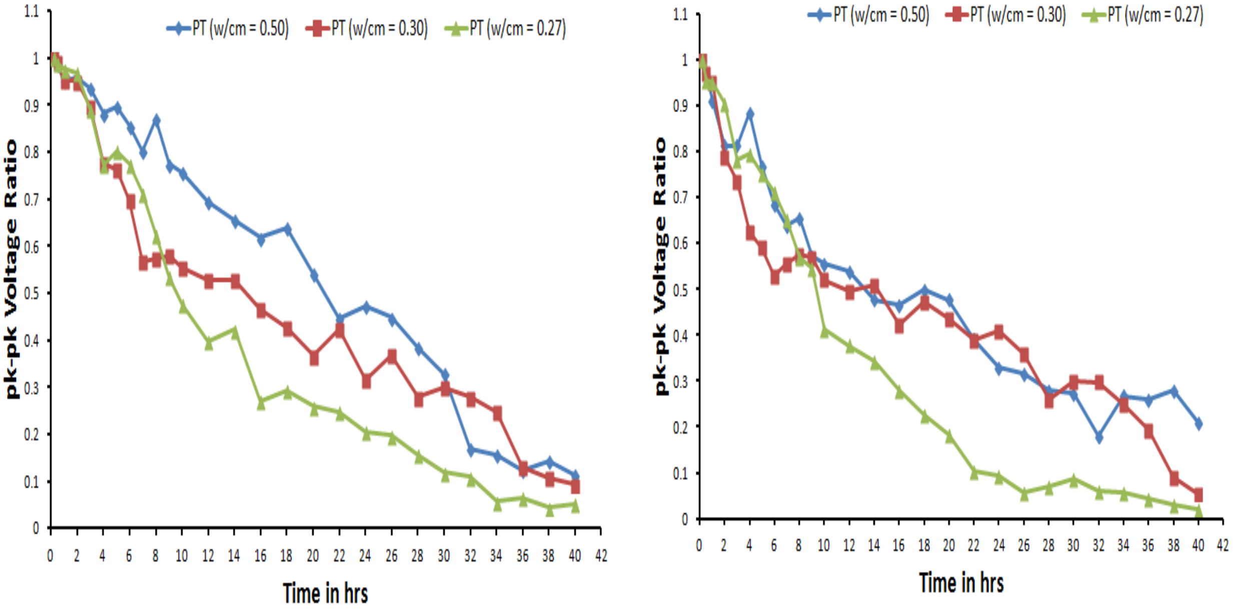
Irrespective of the type of HPC, with the reduction in w/cm ratio 0.50, 0.30 to 0.27, it is observed that setting rate is faster as with reducing the w/cm ratio, rate of fall increases. It is due to the fact that with reduction in w/cm ratio, mixes have faster bond and strength development causing faster rate of fall of signal.

So, it is concluded that UPE technique is successful in picking the early changes in HPC. At particular w/cm ratio, HPC made 0% fly ash takes more time in setting as seen easily from fig 5.4 and 5.5. Similarly, HPC made with fly ash takes less time in completion of setting of concrete as seen from the same above figures.

In OPC 0% and 20% fly ash, the falling pattern closes with decrease in w/cm ratio in UPE well as in UPT. But the lines (falling pattern) are closer in UPE than in UPT.

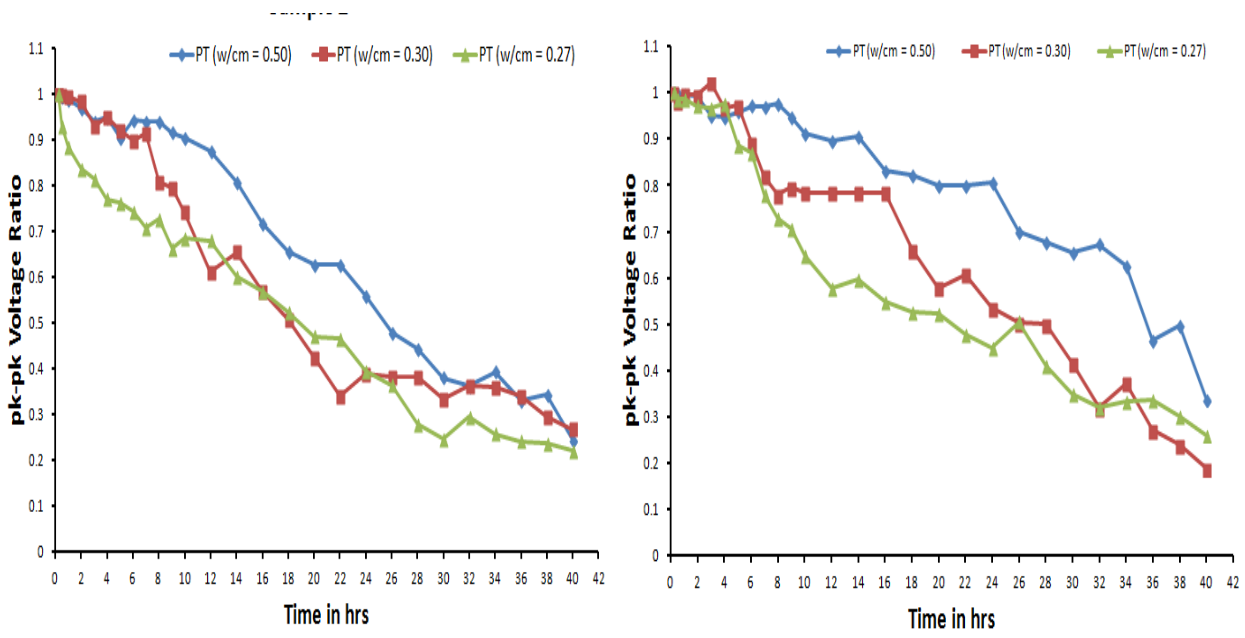
5.4.2 Pulse Transmission Investigations

Following graphs shows the trends of variation of pk-pk voltage ratio of PT signals with 0% fly ash as well as 20% fly ash obtained at different hours of setting of HPC. In fig 5.6(a),(b) and fig 5.7(a), (b) shows the graphs taken for HPC with 0% fly ash and 20% fly ash respectively at three selected w/cm ratios at 0.1MHz (Surface seeking mode) and 1 MHz (Core seeking mode).



(a) 0% Fly Ash (b) 20% Fly Ash

Fig 5.6 (a) & (b) UPT Test results for HPC for Surface Seeking Mode



(a) 0% Fly Ash (b) 20% Fly Ash

Fig 5.7 (a) & (b) UPT Test results for HPC for Core Seeking Mode

From the graphs, the following observations are made:

Drop in pk-pk voltage is observed throughout the duration indicating the development of bond and hence setting of concrete using both surface and core seeking mode. As setting increases more energy leaks into concrete causing fall in signal voltage. The phenomenon of attenuation signals a measure of setting of concrete.

The surface seeking mode shows immediate falling (Fig 5.6(a) & (b)) as compared to consistent signals to core seeking mode (Fig 5.7(a) & (b)).

In general, surface seeking mode (0.1 MHz) is a better indicator of setting of HPC than core seeking mode (1 MHz).

UPE graphs shows that concrete setting process can be divided into 2 phases i.e. semi—solid and transition.

In HPC with fly ash, semi-solid phase i.e. first 4,5 and 6 hours in case of w/cm = 0.50, 0.30 & 0.27 of concrete is almost fluid and there is slow fall in pk-pk voltage is observed. It indicates slow setting or bond development between the mild steel bar and the surrounding concrete during the phases of pouring concrete in mould. In HPC without fly ash, further after 4, 5 and 6 hours upto 40 hours concrete undergoes change from semi-solid state to solid state. It is termed as transition phase. The fall in pk-pk voltage is drastic as observed in this phase. This indicates that concrete is starting to set or making bond with embedded steel bar.

In HPC with fly ash, semi-solid state runs upto more time in comparison to HPC without fly ash upto 5,9 and 10 hours in relation to 4,6 and 7 hours in HPC without fly ash. It indicates that setting of HPC with fly ash is slow and needs more time to make bond with surrounding concrete. In HPC with fly ash, rate of fall is slow in comparison to HPC without fly ash.

Irrespective of the type of HPC, with the reduction in w/cm ratio 0.50, 0.30 to 0.27, it is observed that setting rate is faster as with reducing the w/cm ratio, rate of fall increases. It is due to the fact that with reduction in w/cm ratio, mixes have faster bond and strength development causing faster rate of fall of signal.

So, it is concluded that UPT technique is successful in picking the early changes in HPC.

At particular w/cm ratio, HPC made 0% fly ash takes more time in setting as seen easily from fig 5.6 and 5.7. Similarly, HPC made with fly ash takes less time in completion of setting of concrete as seen from the same above figures.

The pattern of fall rate of concrete in the above normalized graphs is more in HPC with 20% fly ash than in HPC with 0% fly ash. In OPC 0% and 20% fly ash, the falling pattern closes with decrease in w/cm ratio in UPE well as in UPT. But the lines (falling pattern) are closer in UPE than in UPT as the readings are almost died.

5.4.3 UPE Vs UPT

Both the techniques can be used for monitoring setting of concrete falls. Fall in signal relates to setting. But fall is faster in UPE as expected because signal travels double length as against UPT.

Duration of UPT is more as signal travels signal length of bar.

UPE is better technique because single side access is required.

5.5 Results and Discussions: UPV

UPV test was also conducted on cubes of size 150 mm x 150 mm x 150 mm alongside UPT and UPE for HPC with 0% & 20% fly ash at various w/cm ratios of 0.50, 0.30 and 0.27 in order to check the microstructure development of concrete using its early setting phase. The results obtained are plotted as velocity vs time graphs for 24 hrs shown in **Fig 5.8** below.

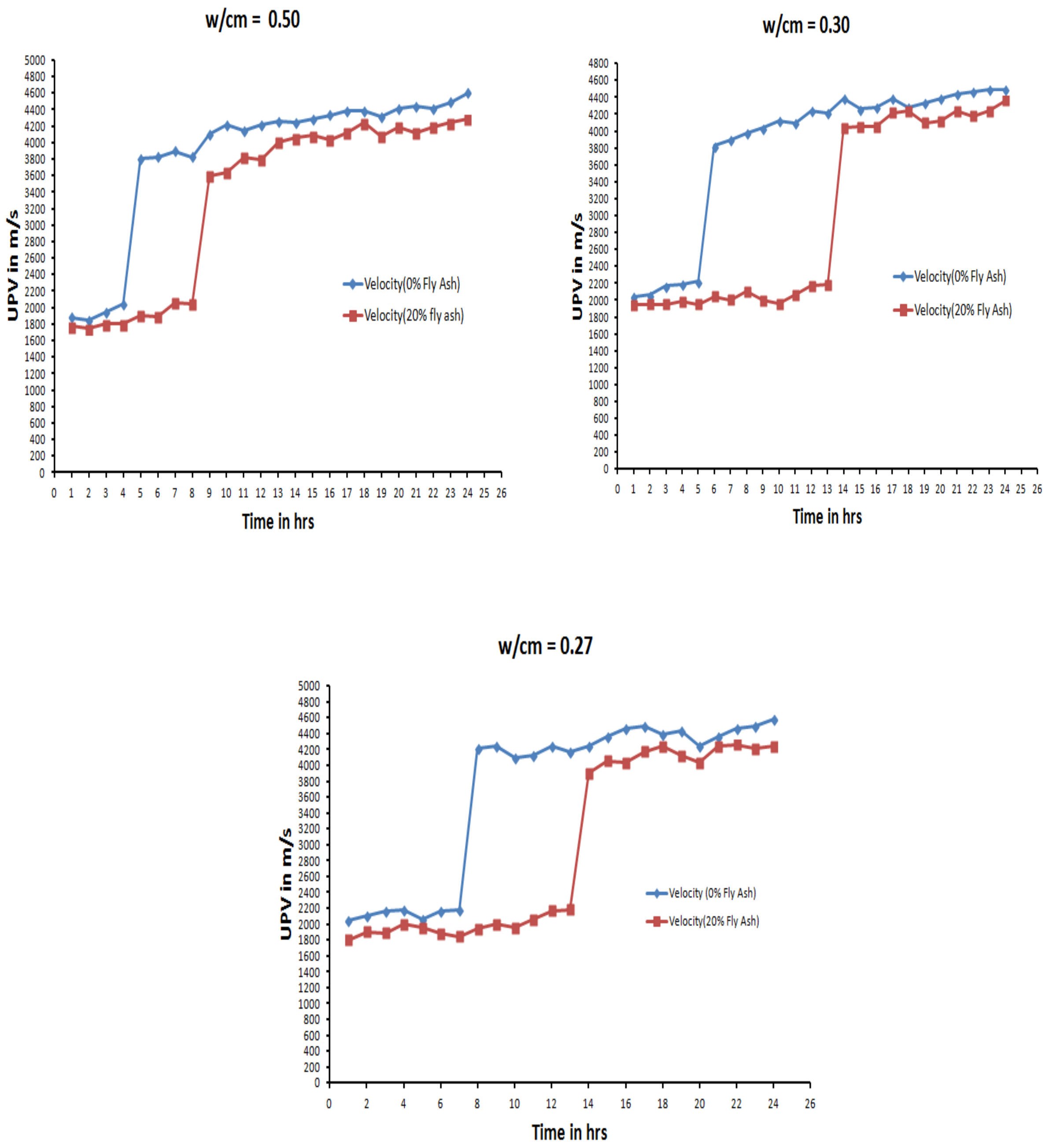


Fig 5.8 UPV Test Results

From the UPV testing the following observations were made:

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

- The earliest setting of concrete is seen in case of w/cm ratio of 0.5, i.e. 4 hours and 9 hours in case of HPC with 0% and 20%. When w/cm ratio is 0.30, the setting occurs at 5 and 13 hours while the late setting is seen in case 0.27 w/cm, i.e. 7 and 14 hours respectively.

- The cause of this early and prolonged increase of UPV with low w/cm ratio is that the cement particles in the low w/cm ratios may get connected at relatively early ages because of the relatively short distances between them, but massive hydration is delayed due to various admixtures used. This delay of massive hydration is more significant in HPC with 20% fly ash than in HPC with 0% fly ash which is due to the presence of the fly ash in addition to the admixture effects.

- UPVs of HPC with 0% fly ash case are greater than HPC with 20% fly ash case. This is due to the higher stiffness of coarse aggregates and retarding effects of fly ash.

- But as we compare UPV with UPT and UPE technique we can clearly see that UPV method is unable to record the velocity during the semi-solid Phase i.e. first 4 hrs for w/cm ratio of 0.5 and first 3 hrs for w/cm ratios of 0.30 and 0.27 as concrete is wet and starts sticking to the transducers. To overcome this problem special frame arrangement has to be made, thus making it unpractical during the in-situ monitoring of concrete.

- In transition and solid phase, the UPV results follow the same trend as UPT results, showing a maximum velocity gain during transition phase as there is no significant increase in velocity and the graph shows steep rise in velocity during solid phase.

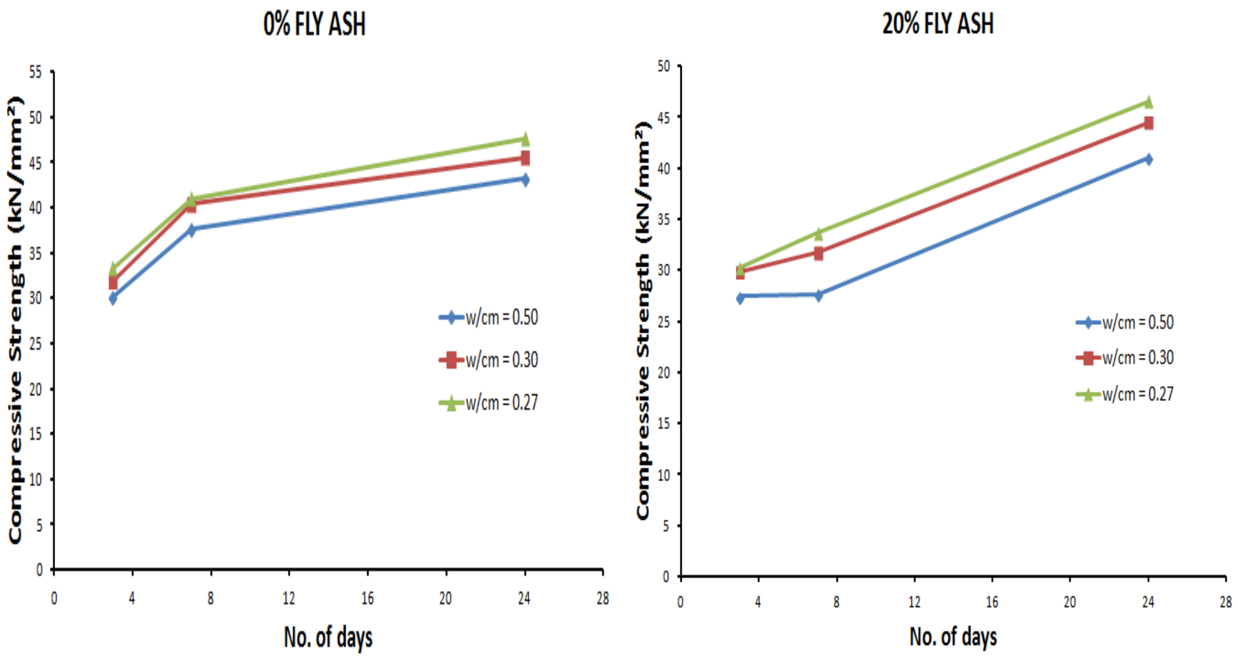
- The values of UPV are not reliable as there is no homogeneity in the values of UPV. This is due to variable properties of concrete as UPV is directly conducted on concrete and the concrete properties are not stable every time.

5.6 Destructive Testing

In destructive tests like Compressive Strength Test and Split tensile test were conducted on the specimens of HPC with 0% & 20% fly ash for w/cm ratios of 0.50, 0.30 & 0.27. The purpose behind these tests is to ensure that adequate strength development has been achieved in concrete during curing. The results of these tests are shown below in **Table 5.1 and Fig (5.9(a) & (b), & 5.10).**

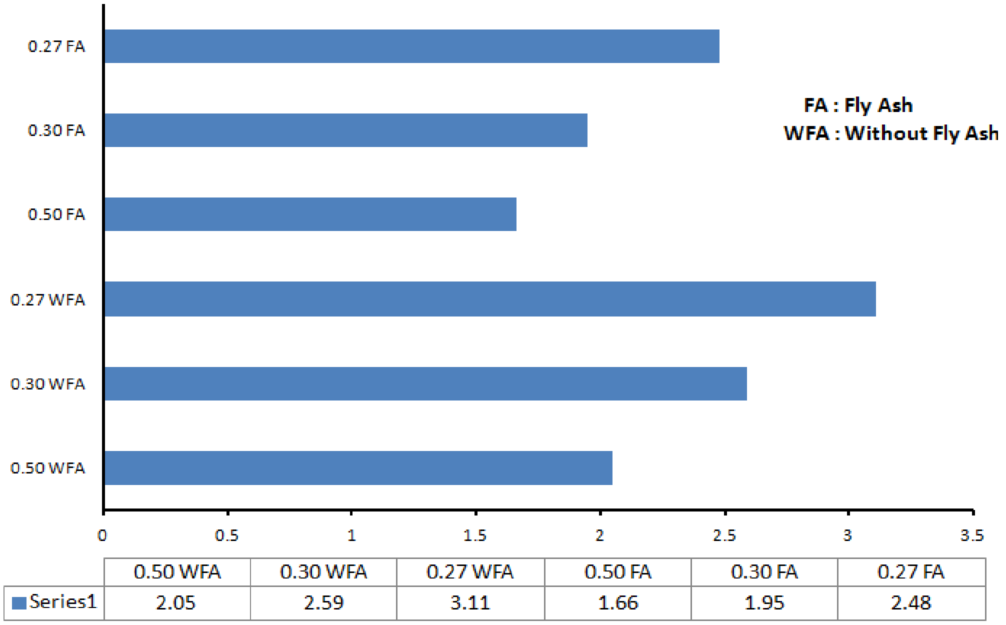
Table 5.1: Material properties of concrete

Mix No.	Compressive strength of Cube (kN/mm²)			Split tensile strength of Cylinder (kN/mm²)
	3 days	**7 days**	**28 days**	**28 days**
1	30.22	37.67	43.15	2.05
2	31.91	40.39	45.58	2.59
3	33.34	41.03	47.63	3.11
4	27.43	27.66	40.94	1.66
5	29.79	31.76	44.46	1.95
6	30.26	33.72	46.55	2.48



(a) 0% Fly Ash **(b) 20% Fly Ash**

Fig 5.9 Compressive Strength of Cubes for OPC with 20% Fly Ash



	0.50 WFA	0.30 WFA	0.27 WFA	0.50 FA	0.30 FA	0.27 FA
Series1	2.05	2.59	3.11	1.66	1.95	2.48

Fig 5.10 Split Tensile Strength of Cylinder

Following the observations obtained from these graphs:

- Both the compressive strength and split tensile strength values are higher in OPC with 0% fly ash when compared to OPC with 20% fly ash.

- The highest value of compressive strength and split tensile strength showed by w/cm = 0.27 and lowest value showed by w/cm = 0.50 in both OPC’s.

- The strength showed by OPC with 0% fly ash is more than OPC with 20% fly ash. This is because the higher stiffness of coarse aggregates and the retarding effects of fly ash.

5.7 Closing Remarks

This chapter discusses the results obtained from Ultrasonic Pulse Transmission , Ultrasonic Pulse Echo and Ultrasonic Pulse Velocity for OPC with 0% and 20% fly ash at three w/cm ratios (i.e. 0.50, 0.30 & 0.27) in early setting phase. The UPT and UPE method is also compared with the other well established methods of UPV and destructive tests like compressive test and split tensile test.

CHAPTER 6

CONCLUSIONS AND SCOPE OF FUTURE WORK

6.1 General

The experimental study carried out on various concrete specimens for HPC with 0% & 20% fly ash at three w/cm ratios during the setting and hardening phases indicates 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 :**

- NDT technique can go a long way in determining the time of formwork removal and putting the structure to use.
- Early setting is achieved during semi-solid phase and maximum bond development is achieved during transition phase i.e. till 48 hrs, when concrete is changing from semi-solid to solid.
- The early age behavior may be because waves propagating through the common phase of viscous suspension. The later age behavior is because replacing cement by fly ash retards the hydration reaction, thus the setting retardation depends on the fly ash content.
- The other well established NDT and destructive tests methods are not capable of monitoring continuously early age strength of concrete during the first 48 hrs as compared to UPT and UPE method using Ultrasonic Guided Waves.
- Variation in properties like w/cm of concrete affects the test results.
- The use of fly ash decreases the values of results as compared with without fly ash concrete due to the retarding effects of fly ash.
- The values of w/cm = 0.27 are not reliable as they vary a lot. This means that very low w/cm ratios for high performance concrete are not suitable because of its high viscosity.
- UPVs of OPC with 0% fly ash case are greater than OPC with 20% fly ash case. This is due to the higher stiffness of coarse aggregates and retarding effects of fly ash.

- The cause of early and prolonged increase of UPV with low w/cm ratio is that the cement particles in the low w/cm ratios may get connected at relatively early ages because of the relatively short distances between them, but massive hydration is delayed due to the HRWR.
- The UPT and UPE method is also compared with the other well established methods of UPV and destructive tests like compressive test and split tensile test in hardening phases.
- But as we compare UPV with UPT and UPE technique, UPV method is unable to record the velocity during the semi-solid phase, as concrete is wet and starts sticking to the transducers. To overcome this problem special frame arrangement has to be made, thus making it unpractical during the in-situ monitoring of concrete.
- In transition and solid phase, the UPV results follow the same trend as UPT results, showing a maximum velocity gain during transition phase and no significant increase in velocity the graph shows steep rise in velocity during solid phase.
- The values of UPV are not reliable as there is no homogeneity in the values of UPV. This is due to variable properties of concrete as UPV is directly conducted on concrete and the concrete properties are not stable every time.

Conclusions which can be drawn from the observations of **Destructive Testing :**

- Both the compressive strength and split tensile strength are higher in OPC with 0% fly ash when compared to OPC with 20% fly ash.
- In 0% & 20% fly ash series, the highest value of compressive strength and split tensile strength showed by w/cm = 0.27 and lowest value showed by w/cm = 0.50.
- The strength showed by OPC with 0% fly ash is more than OPC with 20% fly ash. This is because the higher stiffness of coarse aggregates and the retarding effects of fly ash.
- There is not much fall in pk-pk voltage value in hardening phase as compared to setting phase, indicating no significant hardening or bond development.
- There is not much development in hardening after first few hrs the value becomes almost constant.

- Significant bonding or hardening is also not shown by other well established NDT methods such as UPV and destructive methods such as Compressive test and Split Tensile Strength 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 endeavor, there is much scope for future work. The experimental methodology discussed in this work can be further extended for:

- Setting properties of various concrete High strength concrete etc. with different mineral admixtures.
- Ultrasonic monitoring of SCC/non-vibrated concrete was done for 48 hrs only. The study can be extended for another 1or 2 days to understand complete process.
- Correlations of ultrasonic voltages with destructive tests can be established.
- By conducting the experiments in various controlled environments.

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