Study of fresh and hardened properties of concrete modified with recycled concrete aggregates

A thesis report submitted in the partial fulfillment of the requirements for the award of degree of

MASTERS OF ENGINEERING
IN
STRUCTURAL ENGINEERING

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DECLARATION

I hereby declare that the work presented in this thesis report titled **"Study of fresh and hardened properties of concrete modified with recycled concrete aggregates"** in partial fulfillment of requirements for the award of the **MASTER IN ENGINEERING IN STRUCTURAL ENGINEERING**,submitted in the**Department of Civil Engineering, Thapar University, Patiala,** is an authentic record of initial research carried out by me under the supervision of **Dr.Shruti Sharma, Assistant Professor,Department of Civil Engineering and Mr. Sandeep Sharma, Assistant Professor, 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.

Date: 15.07.2013

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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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ACKNOWLEDGEMENT

I take this opportunity to thank first of all my supervisor Dr. Shruti Sharma for her patience and valuable suggestions without which this thesis report would not have seen the light of day. I would also thank the entire faculty of Civil Engineering especially Dr. Naveen Kwatra, Dr. Prem Pal Bansal, Dr. Shweta Goyal, Dr. Rafat Siddique and Dr. Reema Goyal, whose lessons have invariably created great interest in the subject matter of Civil/Structural Engineering. I would also like to express my heartfelt gratitude to Shri Ram Sumiran, without whom the experiments would not have been possible.

I would like to express sincere thanks and admiration for Dr. Abhijit Mukherjee whose lessons have taught me to think beyond the ambit of subjects taught at the university. His suggestions have helped create a more seeking mind.

In the end, I express my heartfelt gratitude to my mother whose constant support has helped me keep going at the most challenging times. In addition to this, I thank my father and my brother for their support.

ABSTRACT

The rapid urbanization and industrialization of the world in the last few decades has led to the ever rising demand of construction materials especially aggregates. Mining of these aggregates has led to a strain on the environment and in serious ecological damagae. Thus mining has been banned in some states by the government. The shortfall of construction aggregates is a serious problem and necessitates the use of other recycled aggregates as its replacement.

Recycled aggregates are obtained from old demolished construction waste. Usually they are transported to a landfill site where they are disposed. The expansion of cities in the past decades has not only made landfill sites farther but also at the same time made the transportation of these aggregates costlier. The solution is to use these as a replacement for natural aggregates in concrete mixes. This has the potential to significantly reduce the need for mining new aggregates and also at the same time reduce disposing costs.

This paper deals with the study of Recycled aggregate concrete with varying percentages of recycled aggregate as a replacement for natural aggregates. In addition to this, this paper also investigates the efficacy of using the 'Ultrasonic Guided wave' method for measuring the strength and fresh properties of concrete mixes over the more common Ultrasonic Pulse Velocity method. It will be demonstrated in the course of this work, as to what advantages the Ultrasonic Guided wave method has over other conventional methods such as the 'Ultrasonic Pulse velocity' method.

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CHAPTER 1

INTRODUCTION

1.0 GENERAL:

With greater emphasis on reducing carbon footprint for construction, recycling concrete from old demolished structures is now coming into practice. It is estimated that close to 16 billion tons of concrete was produced in 2009. Earlier the demolished concrete used to be disposed in landfills, now it is being used as a replacement for aggregate in new concrete and also in mass concreting applications. Reducing the consumption of energy and raw materials is a major concern for the world at present. The recycling of materials or waste has gained considerable attention in industry over the past few decades. The use of Recycled Concrete Aggregate or RCA offers considerable potential in the field of waste recycling and also reduces the need for disposal land.

1.1 OBJECTIVE OF THESIS:

There has been significant research on the use of RCA in last few decades, especially after the world war in Europe, when a number of buildings although new, were badly damaged. Most research shows that the strength of Recycled Aggregate Concrete (RAC) is comparatively weaker than that of conventional concrete made with natural aggregates. Some researchers have found RAC to be stronger than that of conventional concrete which leaves considerable space to study the strength of RAC. There are many reasons for the varying behavior of RAC primarily due to the origin, strength and proportion of the RCA in the concrete mix. Also, it is difficult to maintain the standard or quality or type of the recyclable waste aggregates being procured.

The use of RCA internationally has led to a large pool of data on the mechanical and durability properties of concrete containing RCA. In many countries, RCA has been found suitable for large-scale non-structural applications such as in the base and sub-base layers of new road pavements, but when used in structural concrete the tendency is to blend RCA and NA and to limit the proportion of RCA. The limit varies internationally from 10% to 30% and even up to 45% for specific applications.

The aim of this study is divided into two parts. The first part is to determine the suitability of using the RCA in structural concrete based on the proportion of RCA in the concrete mix by studying the hardened properties of specimens. The second part is to determine the suitability of the Ultrasonic Guided Wave method as tool for monitoring the fresh properties of RAC. In this study four types of RCA designated RCA0, RCA30, RCA 60 and RCA100 were investigated. Their specimens were tested to establish their mechanical characteristics for use as aggregates in concrete. In the experimental program RCA was used at replacement percentages of 0%, 30%, 60% and 100% to replace Natural Aggregates (NA) in order to study its suitability as aggregate in concrete, and to what level of NA replacement satisfactory for structural application

1.2 METHODOLOGY:

The experimental program has been divided into two parts as explained in Section 1.1. In the first part, cube and cylinder specimens of RAC with varying proportions of NA and RCA were cast and tested subsequently for strength properties to estimate the suitability of these methods for determining setting of concretes produced with RCA. In the second part nondestructive techniques of UPV and UGW were performed on specimens of RAC. The results obtained from these experiments were compared with the results of concrete made from natural aggregates. Slump values were also compared for the different specimens as a measure for application of RAC in pumpable concrete.

2.0 RECYCLED AGGREGATE CONCRETE (RAC):

Recycled concrete aggregate is a broad term used to denote both fine and coarse aggregate reused in various engineering applications. These aggregates are obtained from a multitude of sources pertaining to industrial waste, construction and demolition waste. The properties of these recycled aggregates vary on many factors such as characteristic strength of old concrete, the size of gravel used, the percentage of sand and gravel fraction in the concrete mix, amount of lime in the sand fraction of the old mix, etc. They can be substituted with varying percentages of replacement for fine and coarse aggregates in new mixes. The use of recycled concrete aggregate started early in west but is still not very common in India. The potential of using recycled concrete aggregate as a way to mitigate environmental pollution is tremendous. In the subsequent text relevant topics on waste concrete aggregate will be discussed in detail.

Figure 1.1 shows RCA just prior to their use in concrete mixing. Figure 1.2 shows the supply demand diagram of recycled concrete aggregate. In the diagram it is shown how natural and recycled concrete aggregates can be used together for better cost optimization as well as satisfy good environmental practices.

Figure 1.1 Recycled concrete aggregate size 10-30mm

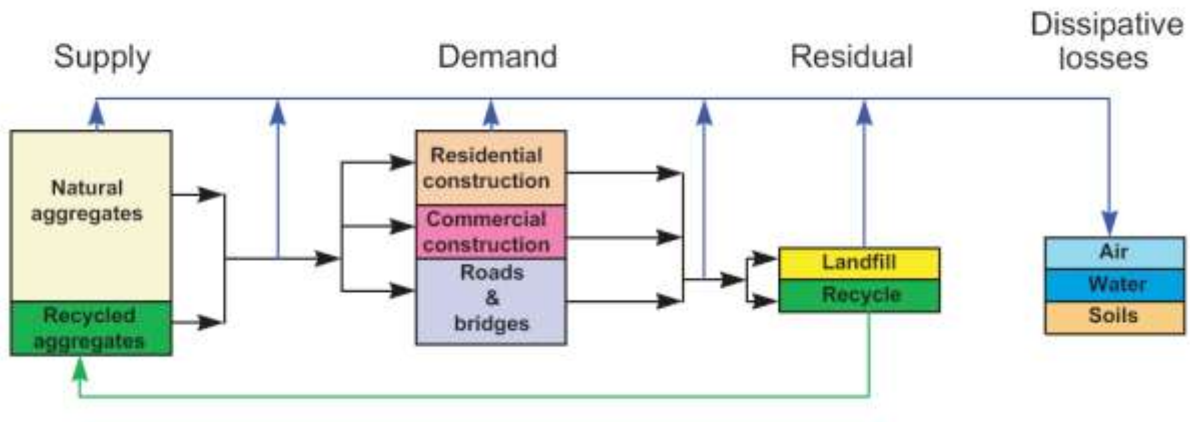

Figure 1.2 Supply demand diagram of recycled concrete aggregate [Waste de brito(2013]

3.0 TYPES OF RCA:

The types of recycled aggregates have been broadly classified according to their sources. They are:

a) Industrial waste aggregates: These include plastic waste, e-plastic waste, rubber tire waste, mining waste, industrial slag, organic waste, glass, ceramic waste. etc.

The use of industrial waste in the 21st century is steadily growing as a result of growing environmental concerns. Alternate aggregate materials such as blast furnace slag, glass waste such as fiber glass waste or float glass waste, mining waste such as aggregate particles which are otherwise not used. The construction industry has a great potential to absorb much of the industrial waste coming out of metals industry as a major quantity can directly be used as concrete aggregates. This use of industrial waste aggregates can significantly reduce the cost of waste disposal of the metals industry and at the same time reduce the cost of concrete production.

b) Construction and demolition waste aggregates:

Construction and demolition waste aggregates: these include aggregates obtained from existing concrete forms such as building or other structures. These kinds of wastes are obtained from old structures made of reinforced or plain concrete. Concrete used as aggregate from sources such as these have the potential to tremendously reduce the carbon footprint of the construction industry.

It is important to clean the old demolished concrete of impurities such as plastics, organic matter, metals and other impurities before use. The demolished concrete is then processed in a grading machine which separates the matter according to size. Since there is a considerable expenditure in transporting demolished concrete to landfills, using demolished concrete brings down the transportation cost. Figure 1.1 shows a picture of recycled concrete aggregate in the range of 10-30mm. According to **www.concreterecycling.org** , upto 140 million tons of concrete is recycled in the United States of America each year.

4.0 PRODUCTION OF RECYCLED AGGREGATE:

The basic principle behind using recycled concrete is to crush the debris to produce a granular product of a specific size and also screen it for impurities. The common recycling plants active in industry are illustrated below.

a) Stationary recycling plants: This process involves two stage crushing and screening for removing the impurities in the recycled aggregate. Figure 1.3 shows the work flow in a stationary recycling plant.

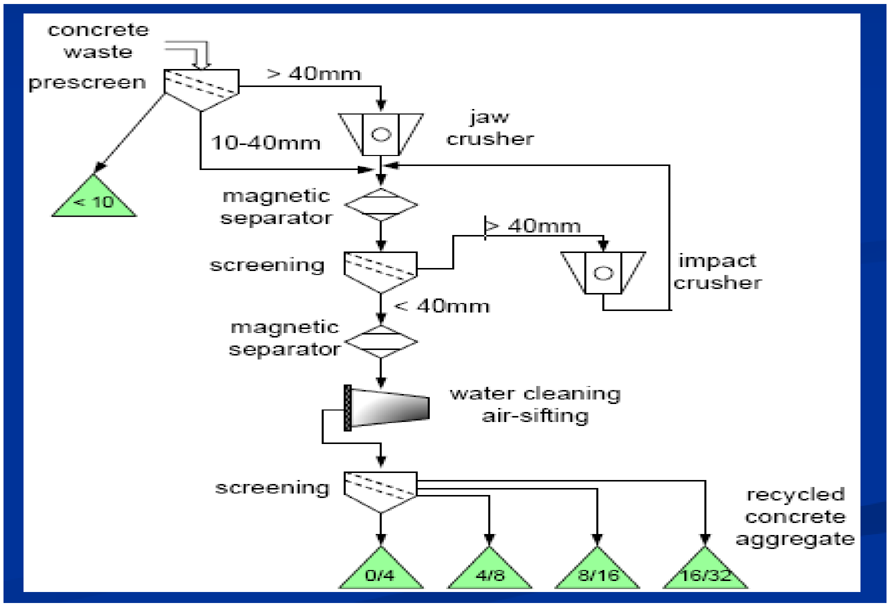

Figure 1.3 Stationary recycling[Marinkovic (2002)]

b) ***Mobile recycling plants:*** These plants are used when the demolished sites are huge and have largely homogeneous waste. A good example where this kind of plant can be used is a township made of same kind of concrete. Figure 1.4 shows a typical mobile recycling plant.[2]

Figure 1.4 Mobile recycling plant[Marinkovic (2002)]

In addition to this, there is not much difference between the production process of recycled aggregate and nominal aggregate (Hansen 1992).The common machines used in the production process are jaw crushers, screens for removing impurities and mixing machines. The first stage in the production process is sorting of demolition debris. One of the primary concerns in the initial research on sorting of recycled concrete was removal of steel from the debris. There was a concern that steel would damage the crushers but later it was found to be exaggerated.

The storage and handling of the recycled aggregates is another important area. The Japanese standard for the use of recycled aggregate and recycled aggregate concrete states the following:

a) Recycled aggregates produced from original concretes of distinctly different quality and recycled aggregates produced by means of different production methods shall be stored separately.

b) Recycled coarse aggregate and recycled fine aggregates shall be stored separately.

c) Recycled aggregate shall be stored and transported in a manner to prevent breakage and segregation or otherwise cause change in quality of the recycled aggregate concerned.

d) Water absorption of the recycled aggregates in large, therefore such aggregates should normally be used in a saturated and surface dry condition.

e) Recycled aggregates shall be stored separate from other types of aggregates.

f) If different types and qualities of recycled aggregate are produced, the plant should not process colored material such as brick rubble together with concrete rubble because of the extra cost involved in the cleaning of the processing units.

5.0 WHY RECYCLE OLD CONCRETE:

Due to the rapid development of commercial and residential properties in the past 50 years there are a lot of concrete structures which are now either obsolete or are on the verge of becoming obsolete. This old concrete if used in the construction of new structures can bring down the cost of production of new concrete and also reduce the transportation cost of exporting demolished concrete to a landfill site. Figure 1.5 shows the schematic diagram of concrete recycling in an urban dwelling area. The diagram explains the transportation of old concrete to growth areas.

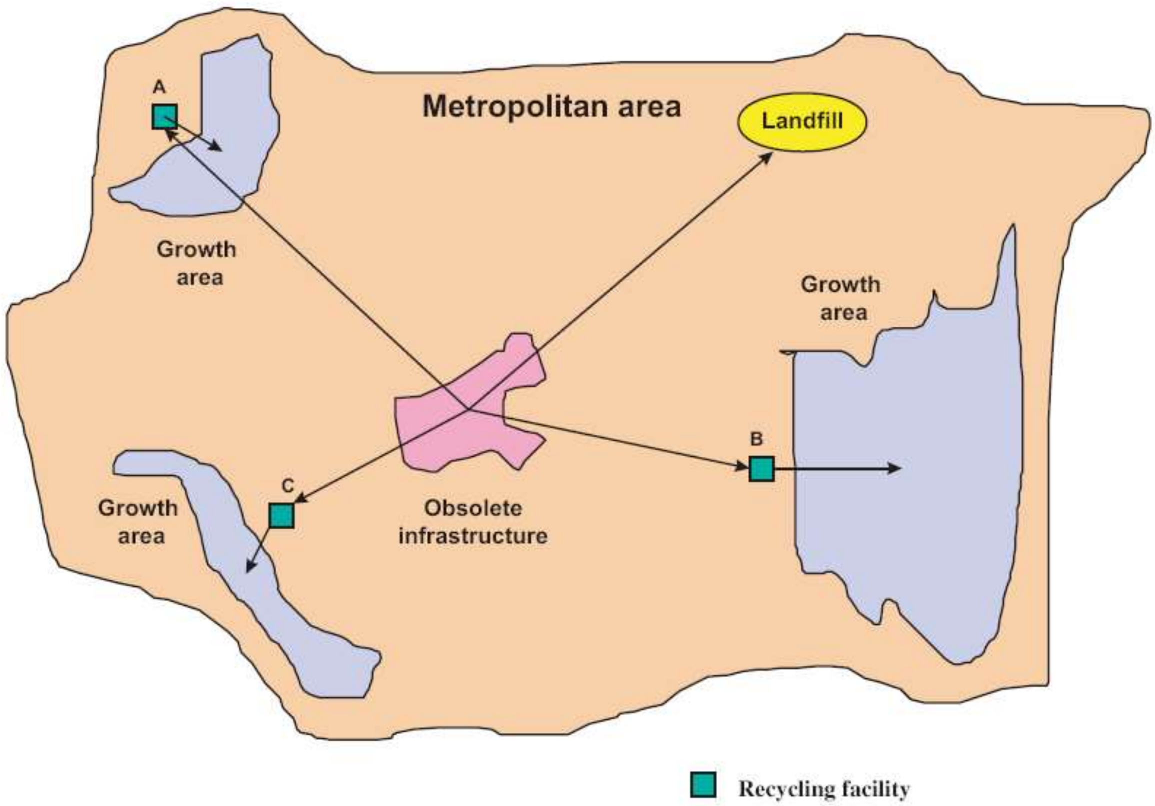

Figure 1.5 : Concrete recycling in urban areas[Wate de brito(2013)]

6.0 PROPERTIES OF RECYLCED CONCRETE AGGREGATE(RCA):

Some reported properties of RCA in literature can be summarized as below:

- Recycled concrete aggregates have lower density as compared to nominal aggregates. This is due to the presence of mortar on the surface of these aggregates, since the mortar has a relatively high volume of porosity. So in essence, the properties of recycled aggregates are influenced by the type and amount of adhered mortar on their surface. Also it is important to remember that recycled aggregates contain not just the hydrated mortar but also nominal aggregates present in the old concrete.

- Recycled concrete aggregates are used both as coarse and fine aggregates. They are also crushed using different methods as explained in section 5.0.
- Buck (1977) concluded that recycled concrete has low specific gravity and high water absorption.
- Topcu (2002) reported that Los Angeles abrasion percentage and crushing values are also much higher compared to nominal aggregates.
- Workability of recycled concrete aggregate is low compared to concrete produced from nominal aggregates. The reason for this could be attributed to the presence of lime on the surface of the concrete aggregates which absorbs water.
- Nixon(1977) was the first to compile a report on the properties of recycled aggregates and stated that there is not much correlation between loss in strength of recycled aggregate concrete and the water cement ratio of the new concrete.
- Hansen(1992) stated that the weakest link in recycled aggregate concrete is the adhered mortar during the crushing of concrete. The use of recycled fine aggregates in concrete does not affect the strength of the new concrete much but has a considerable influence over the workability of the mix.

7.0 CURRENT TRENDS OF APPLICATION:

Recycled aggregates in concrete have been used in several building projects around the world. Here are some examples:

a) Vilbeler Weg Office Building, Darmstadt, Germany (1997/98): In this project, the water quantity in concrete production was kept constant which led to variable workability due to changing weather conditions and unsheltered storage of aggregate fractions. Grubl, Nealen and Schmidt (1998) reported the standard deviation of the compressive strength between 3.01 N/mm^2 and 4.23 N/mm^2. There were two concrete mixes mostly used in this project. Figure 1.6 shows a side view of this building.

i) Concrete sort 590321: Used for foundations

ii) Concrete sort 540423: Used for walls, pillars, ceilings, etc.

The table below shows the mix proportions of these two mixtures:

Concrete sort	540423	590321
Compressive strength	M25	M25
Water (kg/m^3)	190	180
Fly ash	50	40
Water cement ratio	0.59	0.59
Sand (kg/m^3)	616	615
Nominal aggregate(2/8) (kg/m^3)	530	290
Recycled aggregates(8/16) (kg/m^3)	569	334
Nominal aggregate(16/32) (kg/m^3)	-	544
Water reducing agent(kg/m^3)	1.5	-
CEM I 42.5 R(kg/m^3) Portland cement	-	290
CEM III/A 32.5 R(kg/m^3) Portland cement	300	-
Initial consistency (cm)	40-42	36-38

Table 1.1 Mix proportions of RAC used as structural concrete[Grubl, Radonjanin and Schmidt (1998)}

Figure 1.6 Vilbeler Beg office building, Darmstadt, Germany[Marinkovic (2002)]

b) BRE office building, Gartson, Watford, UK (1995/96):

In this project, a M-25 mix with OPC = 350 kg/m^3 and water cement ratio equal to 0.50was used for foundations. For the floor slabs, a M-35 mix with a 75 mm slump was used. Figure 1.7 shows all the features of this environmentally green building.

Figure 1.7: BRE office building features[www.bre.co.uk]

8.0 ENVIRONMENTAL IMPACT:

The benefits of using recycled aggregate are tremendous. It is well known that concrete production consumes a lot of energy right from production of cement to production of aggregates, the carbon footprint is high. Also because of the rapid urbanization of the world in the last 50 years has led to mining. Aggregate for construction is one of the largest mined products in the world. Mining not only damages the habitat of living creatures but also contaminates the surroundings, ground water and most often leaves the soil unfit for agriculture. In certain parts of India, the huge demand for aggregates has led to illegal mining which has no regard for the ecology of the area. Over a period of time there is a considerable damage to the environment from mining of aggregates. In summary, the various advantages of using recycled aggregates in concrete production are:

a) Reuse of waste concrete

b) Reduction of fuel use (which would have been used for new nominal aggregates)

c) Reduction in transportation

d) Optimum use of non renewable resources

In addition to this, there can be certain disadvantages in the usage of recycled aggregates but these are not significant. The potential disadvantages are dust and noise which are location specific.

9.0 CLOSING REMARKS:

With rising global population and the ever rising demand for construction materials increasing at the same rate it is necessary to use demolished concrete from old structures. It is still a common practice in many countries such as India to dump this waste on landfill sites, which occupied large areas of land. A lot of research has been carried in the past few decades to find a way to utilize these waste materials in construction. This practice not only saves our environment but also saves costs and energy in many ways. Total replacement of NA by RCA may not be suitable for all kinds of construction work but a certain amount of RCA will be suitable for new construction as it does not significantly change the properties of the final product.

CHAPTER 2

ULTRASONICS AS A MONITORING TOOL

2.0 General :

The application of ultrasonics to measure the fresh and hardened properties of concrete has been in practice for some years now. The basic emphasis in this mode of experiment is to measure the variation in the velocity of ultrasonic waves passing through a medium. Since it is known that the velocity of sound differs for solids, liquids and gases and concrete being a multi phase medium, this variation of velocity is studied to investigate phase changes in concrete from the point of mixing ingredients to produce concrete till it hardens.

Ultrasonic testing has been in use for metals, employing the reflective pulse technique with higher frequencies but its application to concrete poses several problems due to scattering occurring at matrix-aggregate interface and micro-cracks. The two types of ultrasonic approaches are Ultrasonic pulse velocity measurement and Ultrasonic guided wave measurements

i) Ultrasonic pulse velocity: The variation in the velocity of sound waves when passing through different mediums is investigated in this method. There are several manufacturers of light weight UPV instruments, the better known being PUNDIT(portable ultrasonic non destructive digital indicating tester) developed in UK, V-meter developed in the USA.

ii) Ultrasonic guided wave **:** This kind of testing on concrete is done using through and echo transmission techniques. The sound waves are made to pass through a good conducting medium (structural steel embedded in concrete) and the resulting amplitudes are studied in detail.

The brief description of these methods is given in the following sections.

2.1 Ultrasonic Testing:

2.1.1Basic Principles of Ultrasonic Testing:

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below in **Fig 2.1** 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.

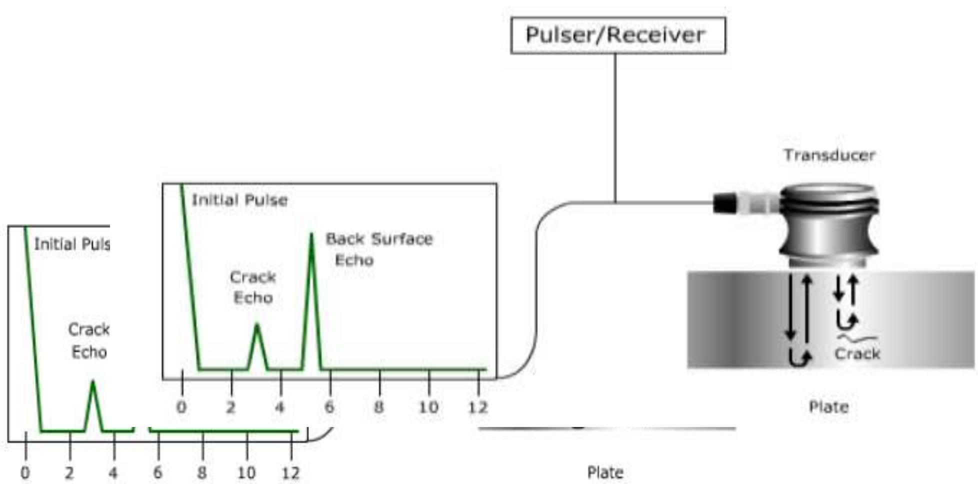

Fig 2.1 General (pulse echo method) ultrasonic Inspection Principle. [www.images.google.com]

The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material with electrodes attached to two of its opposite faces. When an electric field is applied across the material, as shown in **Fig. 2.2**, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction.

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

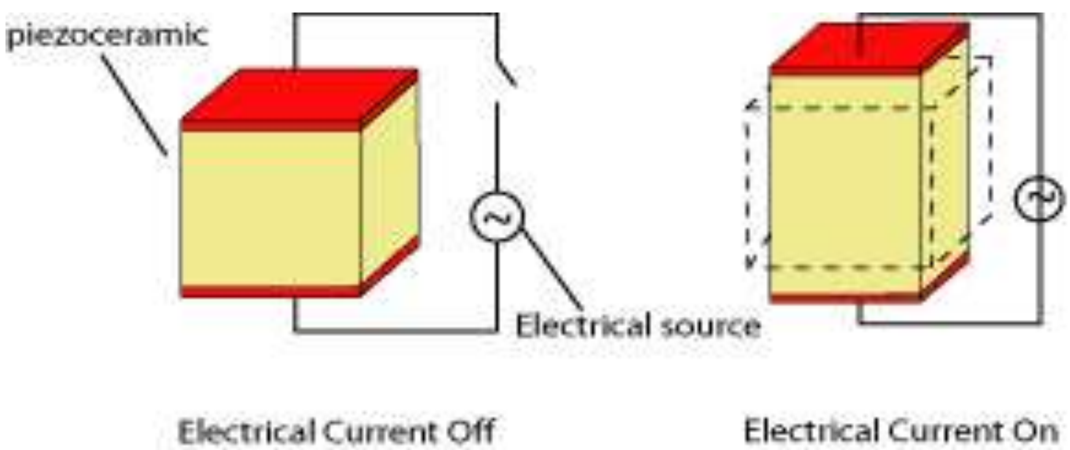

Fig. 2.2 Piezoelectric Crystal with Current Off and On [www.images.google.com]

2.1.2 Components of Transducer

Main components of Transducer/Probe head as shown in **Fig 2.3** are;

1. Active element

2. Backing material

3. Matching layer

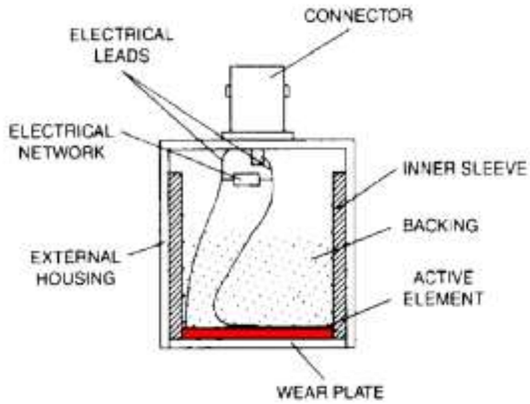

Fig. 2.3 Piezoelectric Transducer [www.images.google.com]

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

As shown in the **Fig. 2.4**, the components of the transducer and their functions are as follows:
The main purpose of the wear plate is simply to protect the piezoelectric transducer element from the environment. Wear plates are selected to generally protect against wear and corrosion. In an immersion-type transducer, the wear plate also serves as an acoustic transformer between the piezoelectric transducer element and water, wedge or delay line. [http://www.ndted.org]

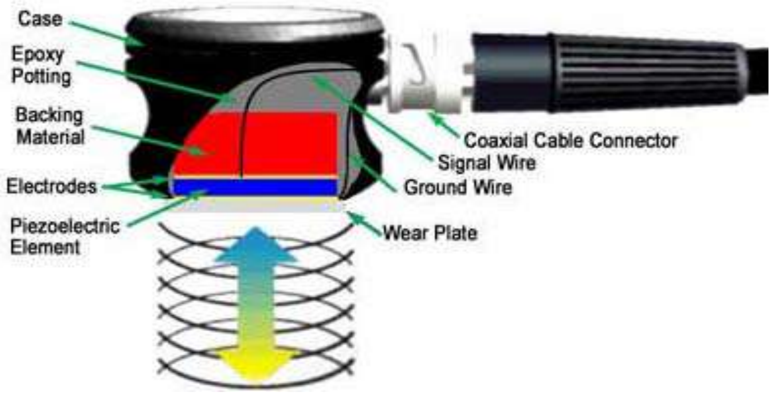

Fig. 2.4 Components of Transducer [www.images.google.com]

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

2.1.3 Radiated Fields of Ultrasonic Transducers

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

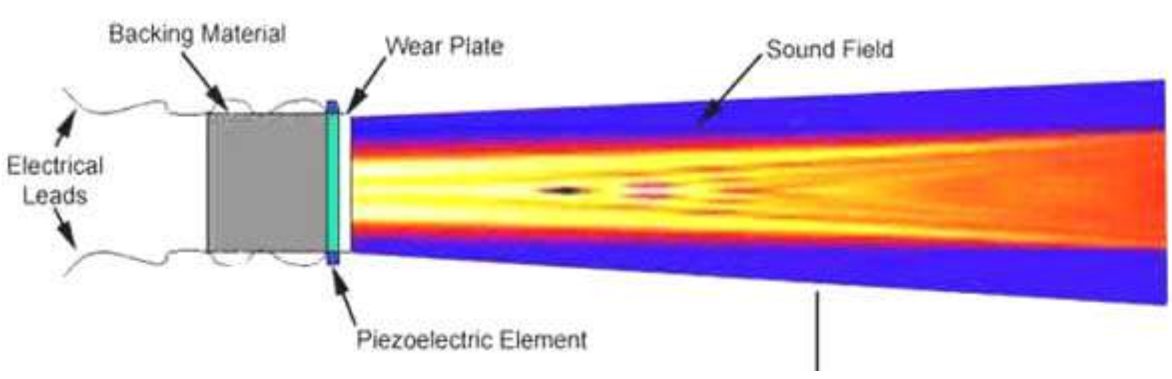

Fig. 2.5 Sound Field from a Typical Piezoelectric Transducer [www.images.google.com]

The intensity of the sound in **Fig. 2.5** is indicated by colour, with lighter colours indicating higher intensity. Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference as discussed in a previous page on wave interference. These are sometimes also referred to as diffraction effects. This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the near field. Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.

2.1.4 Various types of Transducers:

- **Contact transducers** are available in a variety of specifications to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.
- **Dual element transducers** contain two independently operated elements in a single housing, as shown in **Fig. 2.6**. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of course grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience (when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function). Dual element transducers

are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.

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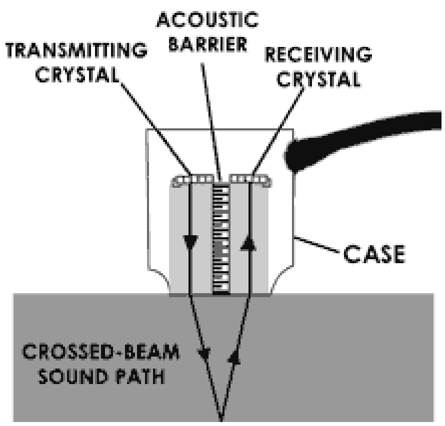

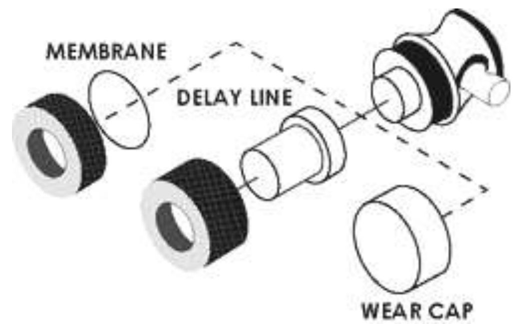

Fig. 2.6 Dual Element Transducers **Fig. 2.7 Delay Line Transducers**

[www.images.google.com]

[www.images.google.com]

• **Delay line transducers** provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options, as shown in **Fig. 2.7** can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and de-lamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

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

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

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

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

2.1.5 Various methods of Ultrasonic Testing can be classified as:

1. Pulse echo method

2. Pulse transmission method

3. Two Transducer Method

1. Pulse echo method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy as shown in **Fig 2.8**. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer where the reflected energy is converted into an electrical signal. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

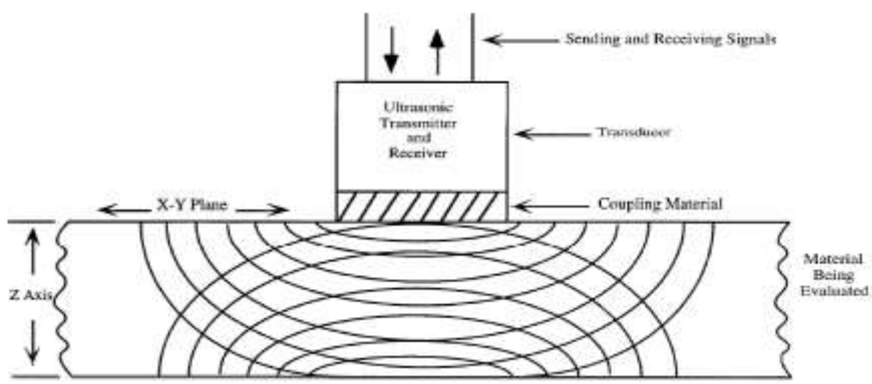

Fig 2.8 Principle of pulse echo method of inspection [Vermani(2008)]

2. Pulse-Transmission Method

In the pulse-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed as shown in **Fig 2.9**. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

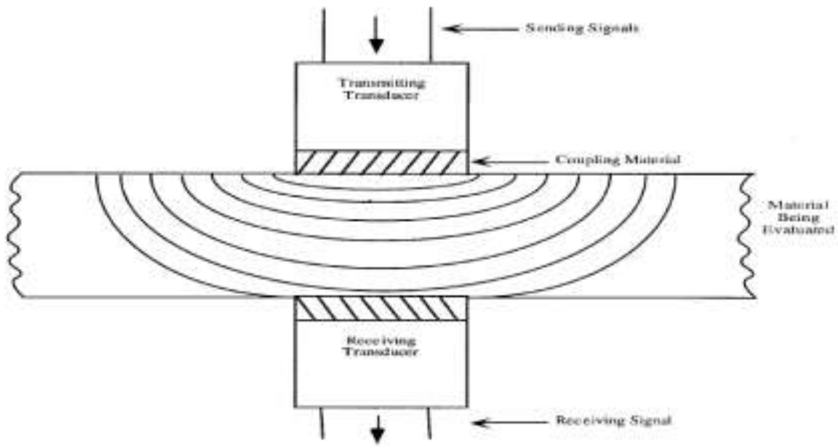

Fig 2.9 Principle of through transmission of ultrasonic testing [Vermani(2008)]

3. Two Transducer Method

The pulse echo method can be used with either single or double crystal unit in single transducer unit the probe acts as both transmitter and receiver .In two transducer arrangement, one transmits and other receives the ultrasonic waves .These are placed on same side of specimen and pulse wave is send in to the specimen by the transducer T (Transmitter) and the echoes reflected from the back surface or any defect are received by the transducer R (Receiver) and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used .These transducers are popularly known as ‘twin’ or T-R probes. For example, **Fig 2.10** in which two transducers are placed on the same side of the plate at certain angle to detect the damage.

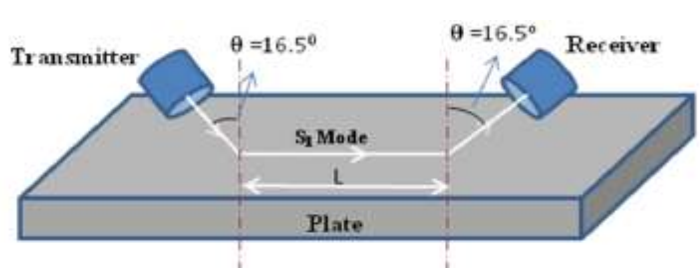

Fig 2.10 Transducers arranged at an angle to the Plate [www.images.google.com]

2.2 Classification of Ultrasonic Waves for NDT Applications:

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

• Body waves or bulk waves

• Surface waves or guided waves.

Body waves propagate through a bulk material, hence attenuate, while the surface waves propagate along the surface of a body as shown in **Fig 2.11**. The inspection of large structures using conventional ultrasonic bulk wave (*longitudinal and shear waves)* techniques is slow because scanning is required if the whole structure is to be tested.

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

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

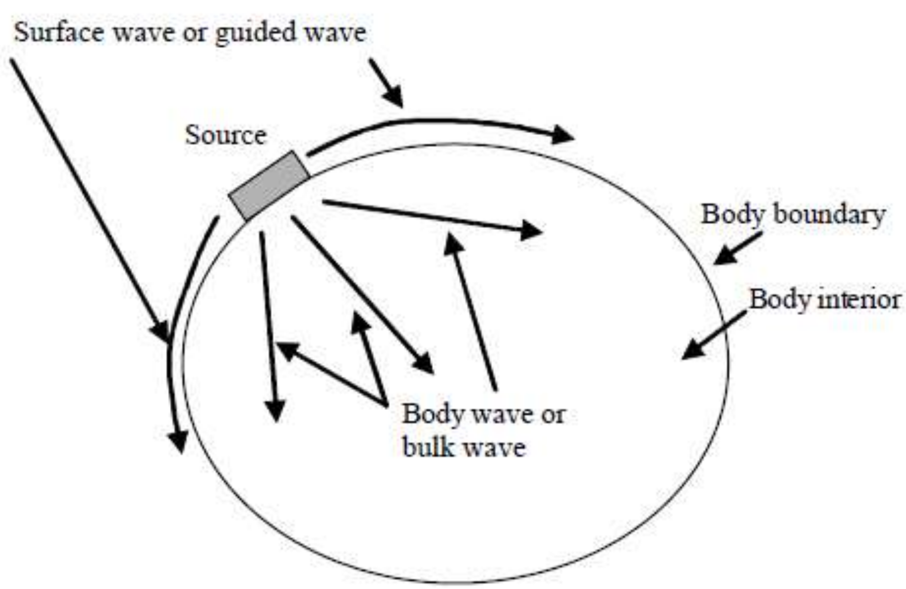

Fig 2.11 Body waves and surface waves generated by an ultrasonic source [Kundu et al (2002)]

2.2.1Guided waves:

The wave is termed “guided” because it travels along the medium guided by the geometric boundaries of the medium. Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave [Redwood et al., 1960 and Achenbach, 1975]. In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of the guided waves varies significantly with the wave frequency and the geometry of the medium. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders [Sang-Young Kim et al., 2001]. Guided waves travel either at boundaries (Surface Waves) or between the boundaries (Lamb Waves) as shown in **Fig 2.13**. 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

Guided waves can further be classified into following types, as shown in **Fig 2.12**:

• Bar waves

• Cylindrical wave

• Rayleigh waves

• Lamb waves

• Rayleigh-Lamb waves

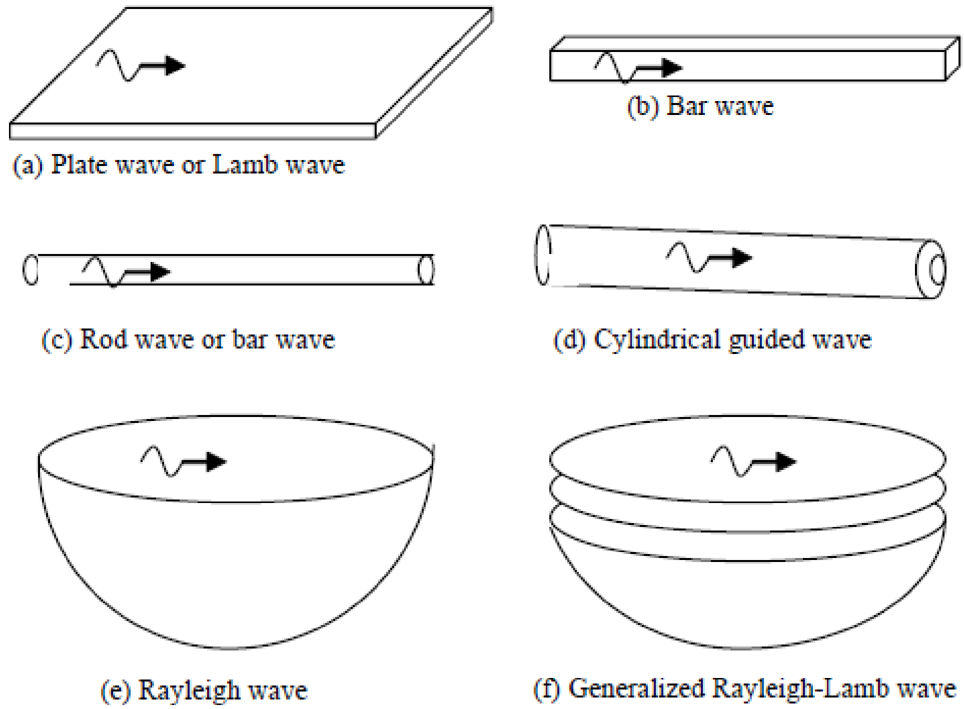

Fig 2.12 Different types of guided waves in various problem geometries [Vermani (2008)]

Cylindrical Guided Waves: Elastic waves propagating through a hollow cylinder or pipe are called cylindrical guided waves (**Fig 2.12(d))**. Since for a cylinder the two stress-free surfaces-inner and outer surfaces – are parallel to each other as in a plate, sometimes the cylindrical guided waves are also called Lamb waves.

Bar waves: When guided waves propagate through a rod or bar they are known as bar waves (**Fig 2.12(c))**.

Rayleigh wave: If the structure is a homogenous half-space then the guided wave propagating along the surface of the half-space is called Rayleigh wave (**Fig 2.12(e))**.

Lamb waves: Waves propagating through a plate type structure with two parallel stress-free boundaries are known as Lamb waves, again named after its inventor. Lamb waves are also known as plate waves because they propagate through plates (**Fig 2.12(a))**.

Rayleigh-Lamb waves: Waves propagating parallel to the free surface of a multilayered solid half-space are known as generalized Rayleigh-Lamb waves or simply Rayleigh waves (**Fig 2.12(f))**.

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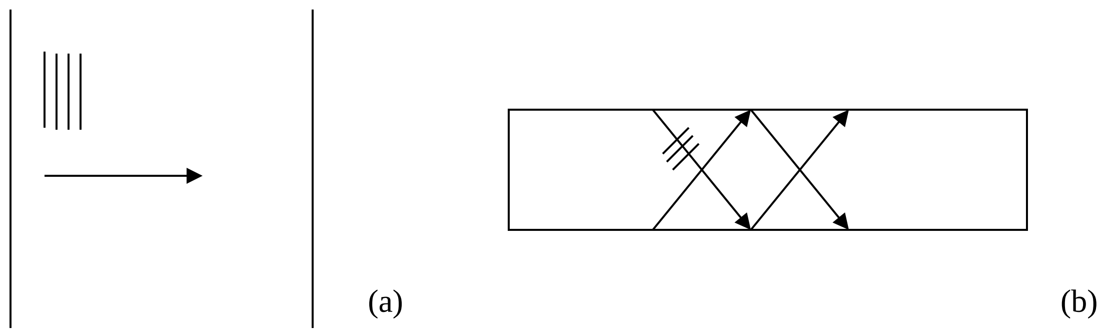


Fig 2.13 Schematic of (a) bulk wave and (b) Guided wave propagation [Kundu et al (2002)]

Guided waves in reinforcing bars in concrete by both longitudinal and shear waves can occur which leads to very high attenuation rates, especially when the acoustic impedances of the waveguide and the surrounding solid are similar. **Fig 2.14** shows two layers, layer one (bar) represent a finite layer and layer two (concrete) represents an infinite medium surrounding the cylinder. The partial waves (L±, SV±, SH±) combine to form a guided wave in the axisymmetric cylindrical structure.

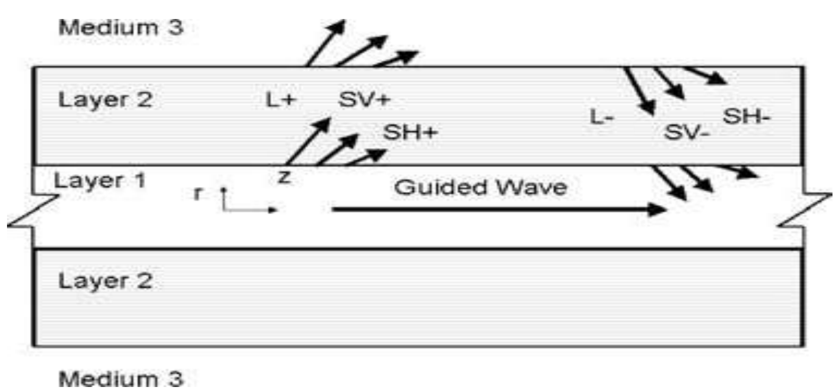


Fig 2.14 Schematic of a bar embedded in concrete [Kundu et al (2002)]

For a layered system, the solution includes phase velocity, frequency and attenuation. Attenuation is due to material absorption and energy leakage into the surrounding concrete. The waves propagate in longitudinal, flexural and torsional modes due to complex effect of boundaries and they have frequency dependent 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. Table 2.1 shows the benefits of Guided waves over bulk waves.

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.

Table 2.1: Benefits of Guided Waves over Bulk waves [Rose (2005)]

2.3 Ultrasonic Pulse Velocity:

2.3.1 Apparatus:

The apparatus for Ultrasonic Pulse Velocity tests usually consists of the following: Figure 2.1 shows the components of UPV testing.

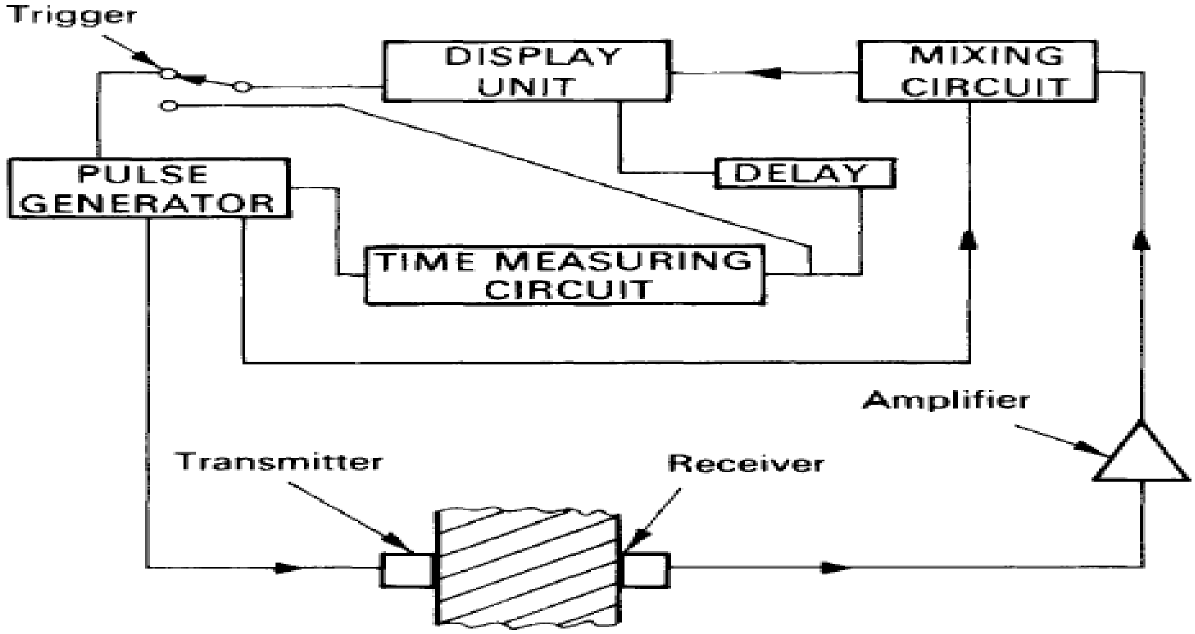


Figure 2.15: Components of UPV apparatus[www.ndt.org]

2.3.1.1 Electrical Pulse generator: A pulse generator is either an electronic circuit or a piece of electronic test equipment used to generate rectangular pulses. In the UPV tests apparatus, repetitive voltage pulses are generated electronically. The pulse to the transmitter must have a rise time of less than one quarter of its natural period so as to ensure a sharp pulse onset. The repetition frequency of the pulse must be low enough to avoid interference between consecutive pulses, and the performance must be maintained over a reasonable range of climatic and operating conditions.

2.3.1.2 Transducer-Transmitter and Receiver: A device that converts signals from one type to another (for example, a light signal in photons to a DC signal in amperes) is a transducer, however this does not amplify power. The pulses from the electrical pulse generator are transformed into wave bursts of mechanical energy through a connecting medium. As per the guidelines of IS:13311-I, any suitable transducer in the frequency range of 20 kHz to 150 kHz may be used. Piezoelectric crystal and magneto-strictive are also used, magneto-strictive being used for lower frequency ranges.

The following Table 2.2 specifies the natural frequency of transducers for different path lengths

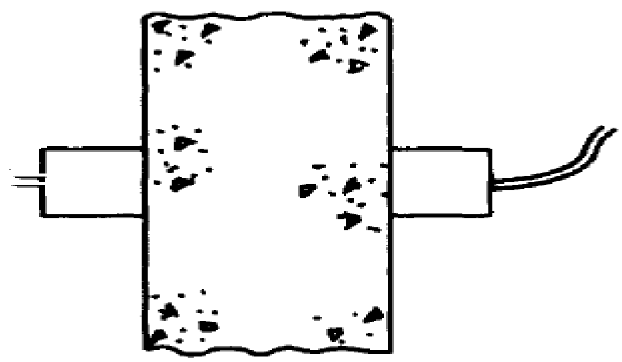
Path Length(mm)	Natural frequency of transducer(kHz)	Minimum transverse dimensions of members(mm)
Upto 500	150	25
500-700	>60	70
700-1500	>40	150
Above 1500	>20	300

Table 2.2 Natural frequency of transducers[IS:13311-1992]

Exponential probe transducers are also available in the market. These make direct contact with the concrete surface, and are preferred when testing rough and curved surfaces.

Arrangement of Transducers: There are three basic ways in which a transducer can be arranged.

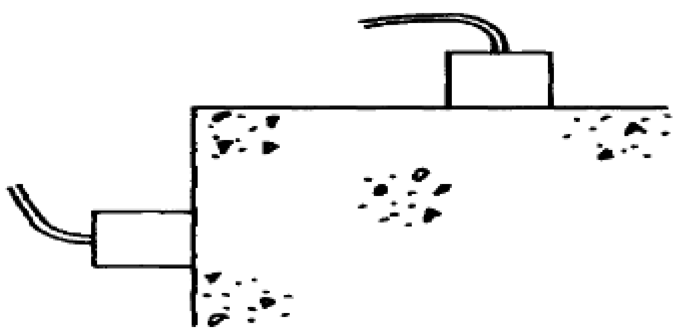
a) Opposite faces (direct transmission): The direct method is the most reliable from the point of view of transit time measurement since the maximum pulse energy is transmitted at right angles to the face of the transmitter. In addition to this, the path is clearly defined and can be measured accurately. This approach is recommended for use wherever possible for assessing concrete quality. **Figures 2.16, 2.17 and 2.18** shows the modes of measurement.



(a)

Figure 2.16 DIRECT TRANSMISSION[Jashan (2011)]

b) Adjacent faces (semi direct transmission): This method is sometimes used when the path length is not too large and the angle between the transducers isn't also very great. The sensitivity is comparatively smaller and if the above mentioned requirements are not met, no clear signal is received because of attenuation of the transmitted pulse. Due to the finite transducer size, the path length is also less clearly defined. The path length is generally assumed to be the centre to centre distance from the transducer faces.



(b)

Figure 2.17 SEMI DIRECT TRANSMISSION[Jashan (2011)]

c) Same face (indirect transmission): This method is the least satisfactory as the received signal amplitude may be less than 3% compared to a direct transmission signal. The received signal is dependent on the scattering of the pulse by discontinuities and is highly probable to errors. The pulse velocity will be predominantly influenced by the surface zone concrete, which may not be representative of the body, and the exact path length is uncertain.

A special procedure is necessary to account for this lack of precision of path length, requiring a series of readings with the transmitter fixed and the receiver located at a series of fixed incremental points along a chosen radial line (mean pulse velocity is given by the slope of the best straight line. If there is a discontinuity in this plot it is likely that either surface cracking or an inferior surface layer is present. Unless measurements are being taken to detect such features, this method should be avoided if at all possible and only used where just one surface is available.

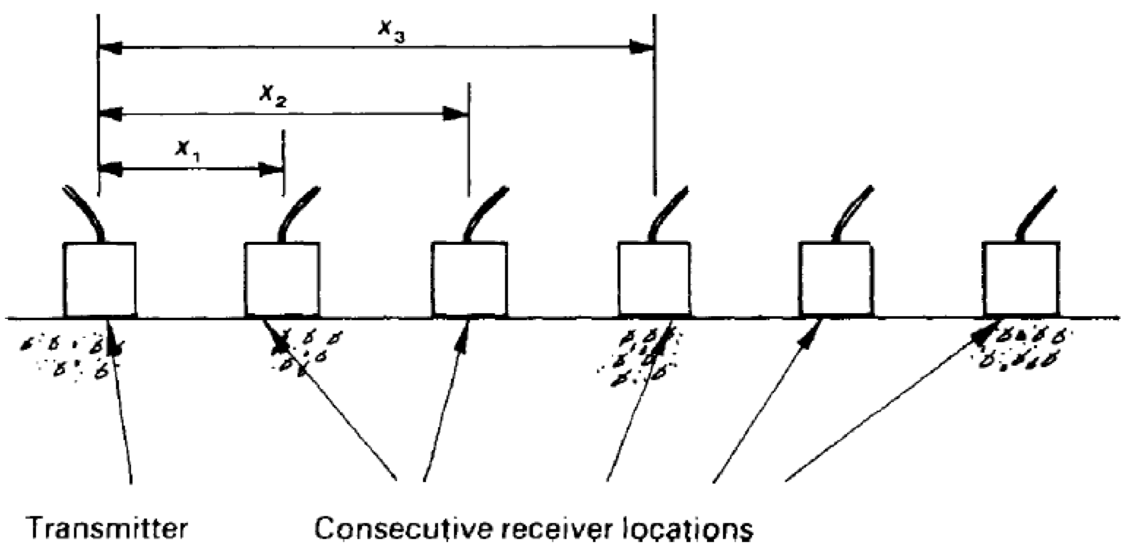


Figure 2.18 INDIRECT TRANSMISSION[Jashan (2011)]

2.3.1.3 Amplifier: An amplifier is a device for increasing the power of a signal by use of an external energy source.

In an electronic amplifier, the input "signal" is usually a voltage or a current. Other types exist; a fluidic amplifier increases the power of signals represented as flow of gas or liquid, for example. Amplifiers may be classified in a variety of ways depending on their application, the frequency range they cover, or the active devices used. Ideally an amplifier increases the power of a signal without otherwise altering it; practical amplifiers have finite distortion and noise which they invariably add to the signal.

2.3.1.4 Electronic timing device: The electronic timing device measures the interval between the onset and reception of the pulse and this is displayed either on an oscilloscope or as a digital readout. The equipment must be able to measure the transit time to an accuracy of ±1%. To ensure a sharp pulse onset, the electronic pulse to the transmitter must have rise time of less than one-quarter of its natural period.

The repetition frequency of the pulse must be low enough to avoid interference between consecutive pulses, and the performance must be maintained over a reasonable range of climatic and operating conditions.

According to IS:13311-I, two kinds of this apparatus can be used, the first one which uses a cathode ray tube on which the leading edge of the pulse is displayed in relation to the suitable time scale, the other uses an interval timer with a direct reading digital display. If both the forms of timing apparatus are available, the interpretation of results becomes more reliable.

2.4 Measurement Procedure:

The ultrasonic pulse is produced by the transducer which is held in contact with one surface of the concrete member under test. Operation is relatively straightforward but requires great care if reliable results are to be obtained. One essential is good acoustical coupling between the concrete surface and the face of the transducer, and this is provided by a medium such as petroleum jelly, liquid soap or grease. Air pockets must be eliminated, and it is important that only a thin separating layer exists—any surplus must be squeezed out. A light medium, such as petroleum jelly or liquid soap, has been found to be the best for smooth surfaces, but a thicker grease is recommended for rougher surfaces which have not been cast against smooth shutters. If the surface is very rough or uneven, grinding or preparation with plaster of Paris or quick-setting mortar may be necessary to provide a smooth surface for transducer application.

As per IS:13311-I guidelines, after traversing a known path length in the concrete, the pulse of vibrations is converted into an electrical signal by the second transducer held in contact with the other surface of the concrete member and an electronic timing circuit enables the transit time (T) of the pulse to be measured.

The pulse velocity (V) is given by: V = L/T (2.1)

Once the ultrasonic pulse impinges on the surface of the material, the maximum energy is propagated at right angles to the face of the transmitting transducer and best results are, therefore, obtained when the receiving transducer is placed on the opposite face of the concrete member (direct transmission or cross probing). However, in many situations two opposite faces of the structural member may not be accessible for measurements. In such cases, the receiving transducer is also placed on the same face of the concrete members (surface probing). Surface probing is not so efficient as cross probing, because the signal produced at the receiving transducer has an amplitude of only 2 to 3 percent of that produced by cross probing and the test results are greatly influenced by the surface layers of concrete which may have different properties from that of concrete inside the structural member. The indirect velocity is invariably lower than the direct velocity on the same concrete element. This difference may vary from 5 to 20 percent depending largely on the quality of the concrete under test. For good quality concrete, a difference of about 0.5 km/s may generally be encountered.

To ensure that the ultrasonic pulses generated at the transmitting transducer pass into the concrete and are then detected by the receiving transducer, it is essential that there be adequate acoustical coupling between the concrete and the face of each transducer. Typical couplants are petroleum jelly, grease, liquid soap and kaolin glycerol paste. If there is very rough concrete surface, it is required to smoothen and level an area of the surface where the transducer is to be placed. If it is necessary to work on concrete surfaces formed by other means, for example trowelling, it is desirable to measure pulse velocity over a longer path length than would normally be used. A minimum path length of 150 mm is recommended for the direct transmission method involving one unmoulded surface and a minimum of 400 mm for the surface probing method along an unmoulded surface.

The natural frequency of transducers should preferably be within the range of 20 to 150 kHz. Generally, high frequency transducers are preferable for short path lengths and low frequency transducers for long path lengths. Transducers with a frequency of 50 to 60 kHz are useful for most all-round applications.

Since size of aggregates influences the pulse velocity measurement, it is recommended that the minimum path length should be 100 mm for concrete in which the nominal maximum size of aggregate is 20 mm or less and 150 mm for concrete in which the nominal maximum size of aggregate is between 20 to 40 mm.

In view of the inherent variability in the test results, sufficient number of readings are taken by dividing the entire structure in suitable grid markings of 30 x 30 cm or even smaller. Each junction point of the grid becomes a point of observation. Transducers are held on corresponding points of observation on opposite faces of a structural element to measure the ultrasonic pulse velocity by direct transmission, i.e., cross probing. If one

of the faces is not- accessible, ultrasonic pulse velocity is measured on one face of the structural member by surface probing. Surface, probing in general gives lower pulse velocity than in case of cross probing and depending on number of parameters, the difference could be of the order of about 1 km/s.

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2.5 Interpretation of Results: The ultrasonic pulse velocity of concrete is mainly related to its density and modulus of elasticity. This in turn, depends upon the materials and mix proportions used in making concrete as well as the method of placing, compaction and curing of concrete. For example, if the concrete is not compacted as thoroughly as possible, or if there is segregation of concrete during placing or there are internal cracks or flaws, the pulse velocity will be lower, although the same materials and mix proportions are used.

The quality of concrete in terms of uniformity, incidence or absence of internal flaws,cracks and segregation, etc, indicative of the level of workmanship employed; can thus be assessed using the guidelines given in **Table 2.3**, which have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.

Serial No.	Pulse velocity by cross probing(km/sec)	Concrete quality grading
1	Above 4.5	Excellent
2	3.5-4.5	Good
3	3.0-3.5	Medium
4	Below 3.0	Doubtful

Table 2.3 Probe results and quality of concrete for UPV[IS:13311 (1992)]

In case of doubtful quality, it may be necessary to carry out further tests.

Since actual values of the pulse velocity obtained, depend on a number of parameters, any criterion for assessing the quality of concrete on the basis of pulse velocity as given in Table 2 can be held as satisfactory only to a general extent. However, when the comparison is made amongst different parts of a structure, which have been built at the same time with supposedly similar materials, construction practices and supervision, the assessment of quality becomes more meaningful and reliable.

The assessment of compressive strength of concrete from ultrasonic pulse velocity values is not adequate because the statistical confidence of the correlation between ultrasonic pulse velocity and the compressive strength of concrete is not very high. The reason is that a large number of parameters are involved, which influence the pulse velocity and compressive strength of concrete to different extents. However if actual concrete materials ’ and mix proportions adopted in a particular structure are available, then estimate of concrete strength can be made by establishing suitable correlation between the pulse velocity and the compressive strength of concrete specimens made with such materials and mix proportions, under environmental conditions similar to that in the structure. The estimated strength may vary from the actual strength by +/- 20 percent. The correlation so obtained may not be applicable for concrete of another grade or made with different types of materials.

2.6 Concluding Remarks

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

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

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

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CHAPTER 3

LITREATURE REVIEW

3.1 General:

The objective of this work is to study the efficacy of using RCA as a replacement for natural aggregates in structural concrete applications. In addition to this, the objective is also to understand the benefits of ultrasonic guided wave experiments over the more common ultrasonic pulse velocity test in studying fresh properties of concrete made with replaced RCA for characterization at young age. In this chapter, results obtained by research on strength tests as well as ultrasonic monitoring on concrete containing partial to full replacement of RAC will be analysed in detail. The mentioned research literature is a record of works done earlier in the same field of recycled concrete aggregate.

3.2 Literature review:

This section is divided into two parts, the first part 3.2.1 deals with research already done in the field of hardened properties of Recycled aggregate concrete. The second part 3.2.1 deals with ultrasonic investigations done on both RAC and NAC.

3.2.1 Review of previous work on hardened properties of RAC:

Ammon, K. (2002) in his paper titled *"Properties of concrete made with recycled aggregate from partially hydrated old concrete"* investigated the effects of partially hydrated waste concrete on the properties of aggregate made from it and the resulting properties of new concrete made with these recycled aggregates. The overall experimental program consisted of two stages: (1) a comprehensive study of the properties of new concrete made with recycled aggregate that was prepared by crushing partially hydrated old concrete; (2) a study of the effect of recycled fines only on the properties of new concrete, but this paper only reported stage 1 of the experimental program. 100mm cubes and 70x70x280mm prisms were prepared and tested.

The results indicated that concretes made with 100% recycled aggregates was weaker than concrete made with natural aggregates at the same water to cement ratio. When the new concrete was made from the same type of OPC and the same water to cement ratio as the old concrete from which old concretes, the strength reduction was upto 25% regardless of the crushing age of the old concrete. With white cement the reduction was 30-405 depending on the crushing age of the old concrete. Other properties such as flexural and splitting strengths, absorption, drying shrinkage and depth of carbonation exhibited similar trends.

The properties of recycled WPC concrete made with recycled aggregate crushed at age 3 days were significantly better than those of concretes made with aggregate crushed at age 1 or 28 days. Opposing trends were seen in recycled OPC concrete in which the new cement matrix was weaker than that of the WPC concrete at the same water to cement ratio. Two opposing mechanisms seem to affect the properties of the new concrete: the physical properties of the old concrete and the presence of unhydrated cement in the recycled aggregate. These effects are prominent when the new cement matrix is significantly stronger than the one in the old concrete.

In such concrete, the combination of strength and cementing capacity of the recycled aggregates crushed at 3 days provides better strength over crushing ages of 1 or 28 days. In a weaker new cement matrix, this effect is reversed and the new concrete made from recycled aggregates crushed at 3 days was slightly weaker than concrete made from aggregates crushed at 1 or 28 days.

Topcu, I. and Selim, S. (2003) in their paper titled *"Properties of concrete produced with waste concrete aggreagate"* investigated the physical and mechanical properties along with their freeze-thaw durability of recycled aggregate concrete. While experimenting with fresh and hardened concrete, mixtures containing recycled concrete aggregates in amounts of 30%, 50%, 70% and 100% were prepared. The authors used two mixes M-16 and M-20 and varied the amount of coarse aggregates in the proportions mentioned above. The main purpose was to determine the optimum amount of recycled concrete aggregates in the mix.

The results indicated that specific gravity of RCA's was lower than that of natural aggregates. This was because of the presence of mortar over the surface of the recycled aggregates. It was also found that the water absorption ratio was much higher for recycled aggregates. Compressive strength decreased in both control concrete and concrete with RCA in parallel to w/c ratio. However, compressive strength decreased in proportion to low w/c ratio in concrete with RCA's. The major point reported was that workability of concrete significantly reduces when proportion of recycled aggregate in the mix exceeds 30% conventional concrete to maintain the same slump without the use of admixtures. This affects the quality and strength of the concrete, resulting in lower concrete strength.

Tsung-Yueh, Yuen-Yuen and Hwang Chao-Lung (2005) in their paper titled *"Properties of HPC with recycled aggregates"* examined the properties of HPC produced from recycled aggregates originating from demolished construction wastes. The authors presented the different characteristics of recycled concrete aggregates compared to those of normal aggregates. The properties of both fresh and hardened concrete were illustrated and further analyses of the influence of recycled coarse and fine aggregates was done. The authors also proposed a new mix proportion design and procedure for incorporating recycled concrete aggregates into HPC. A set of ten mixes with varying proportions of aggregates were studied in this research for 0 to 91 days.

Etxeberria, M., Vazquez, E., Mari, A. and Barra, M. (2005) in their paper titled *"Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete*" investigated four different recycled concretes made with 0%, 25%, 50% and 100% of recycled coarse aggregates. The mix proportions of the four concretes were designed in order to achieve the same compressive strengths. Recycled aggregates were used in wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The influence of the order of materials used in concrete production9made with recycled aggregates) with respect to improving its splitting tensile strength was analysed. The lower modulus of elasticity of recycled coarse aggregates concrete with respect to conventional concretes was measured verifying the numerical models proposed by several researchers.

The results indicated that absorption capacity and the humidity level of recycled aggregates must be considered for concrete production. The humidity content in recycled coarse aggregates must be high and they should be used in concrete production with little absorption capacity in order to produce controlled quality concrete. In addition to this, concrete made with 100% recycled coarse aggregates has 20-25% less compression strength than conventional concrete at 28 days with same w/c ratio. Medium compression strength (30-45 MPa) concrete made with 25% of recycled coarse aggregates achieves the same mechanical properties as that of conventional concrete having the same w/c ratio.

Li Xuping (2008) in the paper titled *"Recycling and reuse of waste concrete in China, Part 1. Material behavior of recycled aggregate concrete"* studied the background information for the recycling of waste concrete in China and also material behavior of RAC. The focus of this research was mainly on: the production of RAC, the mechanical behavior of RAC(both strength and deformation characteristics) and the durability aspects of RAC.

The results in this research was a collection of numerous tests and analyses performed in the recent years. Although there are unavoidable discrepancies amongst the results, there is still a lot in common. The tests focused in the research were compressive strength, tensile strength and flexural strength, uniaxial compression, shrinkage, freeze thaw resistance, carbonation resistance, sulfate resistance, chloride ion penetration resistance, air permeability resistance and fire resistance.

Tabsh ,S and Abdelfatah ,A (2008) in their paper titled *"Influence of recycled concrete aggregates on strength properties of concrete"* investigated the strength of concretes made with recycled coarse aggregate with variables being the source of recycled aggregate and target strength. The focus of the study was to investigate the quality of crushed old concrete(either with predetermined or unknown strength) and determine the factors that influence the compressive and tensile strengths of concrete. The scope of the investigation covered two different concrete mix designs, one that results in low strength and another that yields moderate strength. The tests done were of soundness, toughness, concrete compressive strength, concrete tensile strength on two mixes.

The results indicated that the percentage loss in compressive or tensile strength due to the use of recycled concrete aggregate is more significant in a weak concrete than in a strong one. The authors also reported that the use of coarse aggregate made from recycled concrete with strength equal to 50MPa will result in concrete compressive and tensile strengths comparable with that achieved when using natural coarse aggregate. Recycled concrete mixes require more water than conventional concrete mixes.

Kou Shi-cong, Poon Chi-sun and Agrela, F (2010) in their paper titled *"Comparisons of natural and recycled concrete aggregates prepared with addition of different mineral admixtures"* performed a systematic study on the effect of different mineral admixtures in the strength, drying shrinkage, chloride ion penetration and UPV of recycled concrete aggregate. In the concrete mixtures the replacement levels of cement were chosen at 10% silica fume, 15% metakaoline, 35% fly ash and 55% GGBS. There were a total of 22 mixes in addition to one control mix used in the experiment with varying values of mineral admixtures and these mixes were subjected to destructive tests(compressive and tensile splitting tensile strength test), drying shrinkage tests, chloride ion penetration tests and UPV tests.

The results indicated that the compressive strength of concrete containing recycled aggregate at 1,4,7,28 and 90 days was lower than that of the control specimen, but could be compensated by the use of 10% silica fume or 15% metakaoline. However, it was reported that the use of 30% fly ash or 55% GGBS lowered the strength. The tensile splitting strength of natural and recycled aggregate concrete made with SF and MK was higher than that of the corresponding concrete at all test ages, whereas fly ash and GGBS decreased the tensile splitting strength of the concretes. The test results show that SF and MK can improve both mechanical and durability properties of recycled aggregate concrete. The results show that the contributions of the mineral admixtures to performance improvement of recycled aggregate concrete are higher than that of natural aggregate concrete

Paul (2011) in his research titled *"Mechanical behavior and durability performance of concrete containing Recycled Concrete Aggregate"* investigated durability properties of RAC with varying proportions of RCA. The author also investigated hardened properties such as compressive strength and split tensile strength. The compressive strength and split tensile strength of RAC Came out to be marginally higher than that of NAC.Table 3.1 gives the summary of RAC compressive strength results from previous research based on varying proportions of RCA in the concrete mixes.

Source	Year	% Replacement	Compressive strength
Fernando Branco	2004	100	Same
Bordelon et al.	2009	100 100	10.9% lower (7 days) 3.1% lower
Poon et al.	2004	50 20	7.45% lower 7% lower
Xiao et al.	2005	100 70 50 30	26.63% lower 15.6% lower 21.28% lower 5.28% lower
Mirjana at al.	2010	100 50	5.1% higher 13.61% lower
Folarin Olorunsogo	1999	100 70 50 30	11.66% lower 11.66% lower 6.66% lower 8.33% lower
Nishibayashi and Yamura	1988	100	15-30% lower
Yong & Teo	2009	100 50	15.5% higher same

Gomez	2002	100 60 30 15	11.53% lower 8.2% lower 5.1% lower 2.3% lower
Limbachiya et al.	2004	100 50 30	2.27% higher 2.27% lower 2.27% lower

Table 3.1 Summary of RCA performance from previous research[Paul and Van (2010)]

The various durability tests performed were Oxygen permeability test, Chloride conductivity test and water soprivity test. The research showed that NAC performed much better than RAC in all durability tests. The durability of RAC was much lower than NAC after 180 Days and subsequent periods.

3.2.2 Review of previous work on ultrasonics applied to concrete testing:

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

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

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

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

Obtained results indicate possibility for hardening process monitoring and time of cementitous materials setting determination.

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

The results indicated that basic characteristics such as specific gravity, the absorption capacity, gradation, dry-loose density, soundness and wear resistance of recycled aggregates are lower compared to normal aggregates due to the existence of residual mortar and impurities. In addition to this, it was reported that whatever recycled aggregate is used to manufacture HPC, the trend of properties such as concrete resistivity, UPV and CP are very similar to those of normal HPC. However a 20-30% reduction in strength in compressive strength was reported when compared to normal HPC. It was suggested to not to utilize recycled aggregate got high concrete strength applications due to long term durability problems. Durability can be further enhanced by the addition of natural aggregates in the mixes.

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

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

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

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

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

Latif, A and Fried, A.N (2012) in their paper titled " The early age non-destructive testing of concrete made with recycled concrete aggregate" extended the application of ultrasonic pulse velocity to the very early age of concrete, starting from the period immediately after mixing to 28 days. Non- destructive tests were performed on concrete made with recycled aggregates and then confirmed with concrete made from normal aggregates. Concretes of four different water cement ratios (0.4, 0.5, 0.6 & 0.7) were tested for compressive strength measurements, rebound hammer tests as well as UPV measurements.

The results indicated that RCA concrete shows similar behavior with age to normal concrete using strength, UPV and rebound number measurements. For any particular mix the compressive strength and UPV are higher for normal concretes than RCA ones, but surface hardness for RCA concretes are higher for normal ones. Expressions have been obtained for the RCA and normal concretes that would enable the evaluation of compressive strength of concrete using early age UPV measurements. In addition to this, the paper concluded that UPV can be a reliable method for determining the setting time of concrete which has been established to be 2 h after the point of maximum increase in the UPV measurements.

3.3 Concluding Remarks

Recent work done in using Waste concrete aggregates to produce concrete was studied. The emphasis of the literature review was to find out the response of WCA Concrete to various strength tests and ultrasonic monitoring tests. The following chapter explains the experimental work in detail.

CHAPTER 4

EXPERIMENTAL PROGRAM & INVESTIGATIONS

4.1 General:

The objective of this work was to establish and study the efficacy and efficiency of replacing natural aggregates with RAC and verify it for use in RAC. In addition to this, the other objective of this work was to verify the suitability of monitoring fresh properties of RAC by using Ultrasonic Guided Wave over the more common Ultrasonic Pulse velocity testing. To achieve this goal various strength tests during the hardened phase and ultrasonic monitoring during the fresh stage were conducted. Four mixes were prepared with varying proportions of RAC. One of these mixes was the control mix in which there was no replacement with RCA. The test results of the other mixes were then compared with the values obtained for RAC 0. The following chapter describes all of these tests in addition to explaining the choice of the mix, the testing of the constituent materials, conformity to Indian standard codes and the sources of these materials. **Figure 4.1** explains the flowchart of the experimental program.

4.2 Experimental program:

The experimental program is divided into two phases:

i) Hardened Properties: The test specimens were subjected to compressive strength and split tensile strength testing. In addition to this, their slump value was also noted in this phase.

ii) Fresh properties: The test specimens were subjected to the ultrasonic pulse velocity test and the ultrasonic guided wave test.

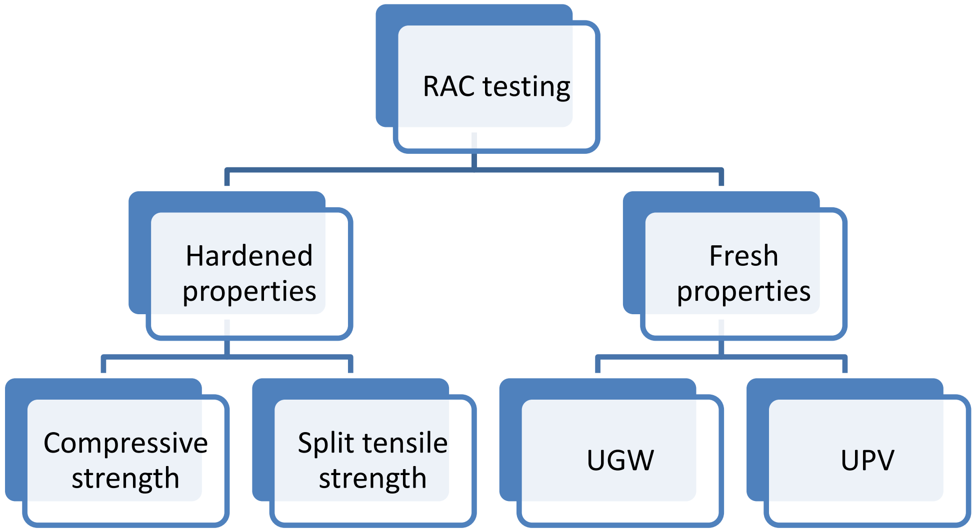


Figure 4.1 Flowchart of experimental program

The test program was to conduct both destructive and non destructive testing on specimens made with replacement of with varying proportions of recycled concrete aggregate and compare them with the results of the standard mix. There were four mixes chosen with varying proportions of recycled concrete aggregate in them. The replacement percentages were chosen as 30%, 60% and 90%. The emphasis of the testing is to compare the results of Compressive strength, split tensile strength, ultrasonic guided wave and ultrasonic pulse velocity of the mixes with replacement of recycled aggregate. Mentioned below are the constituent proportions of cement, sand, aggreagate, etc in all of the four mixes chosen for this experiment. Table 4.1 shows the varying proportions of RCA and natural aggregates for all the four mixes.

The RCA was procured from M50 cubes which were at least 56 to 90 days old. The M 50 cubes were broken down by hammering and then the aggregates were made to pass through the following set of sieves. 20mm-12mm-10mm-4.75mm-PAN.For choosing 20 mm aggregates, the criterion was 20 passing and retained on 10 sieve. For 10 mm aggregates, the criterion was 10 passing and retained on 4.75 sieve. The RCA were hence, kept and named as RCA 20 and RCA 10 for replacement of coarse aggregates in concrete.

4.3 Mix design:

The mix design process chosen was adapted from the Indian standard code IS:10262-2009.

4.3.1 Stipulations for mix design:

a) Grade designation : M 25
b) Type of cement : OPC 43
c) Type of mineral admixture : Fly ash
d) Maximum nominal size of aggregate : 20 mm
e) Minimum cement content :320kg/m^3

4.3.2 Target strength for mix proportioning:

According to IS:10262-2009, page 8, $f_t = f_{ck} + 1.65s$

Where, f_t is target average compressive strength at 28 days

(f_{ck}) = characteristic compressive strength at 28 days

(s) = standard deviation

From table 1 of this code, we get standard deviation for M25 as 4.0

Therefore, target strength = f_t = 25 + 1.65 x 4 = 31.60 N/mm^2

4.3.3 Selection of water-cement ratio:

From table 5 of IS:456, we get maximum water cement ratio as equal to 0.50. Choose water cement ratio equal to 0. 48.

0.48 < 0.50, hence O.K

W/C = 0.48

4.3.4 Selection of water content:

From Table 2 of IS:10262-2009, we get the maximum water content per cubic metre of concrete for nominal maximum size of aggregate:

For nominal size = 20mm, max water content = 186 kg/m^3. Since we are using superplasticizer, water content can be reduced upto 30%. Hence, adopt **water content = 160 kg.**

4.3.5 Calculation of cement and fly ash content:

Water cement ratio = 0.48

Therefore, cementitious material (cement + fly ash) content = 160/0.48 = 333.34 kg/m^3

From Table 5 of IS:456-2000, minimum cement content for 'severe' exposure conditions = 320 kg/m^3.

Since, 333.34 kg/m^3 > 320 kg/m^3, hence OK.

4.3.6 Proportioning of cement and fly ash in the mix:

Fly ash to be used is 20% of total cementitious matter.

Fly ash @ 20% of total cementitious matter = 334 x 20% = 67 kg/m^3

Cement (OPC) = 334 – 67 = 267 kg/m^3

4.3.7 Mix calculations:

The mix calculations are as follows:

a) Volume of concrete = 1 m^3

b) Volume of cement = (Mass of cement/Sp. Gravity of cement) x (1/1000)

   = (267/3.15) x (1/1000)

   = 0.084 m^3

c) Volume of fly ash = (Mass of fly ash/ Sp. Gravity of fly ash) x (1/1000)

   = (67/1) x (1/1000)

   =0.067 m^3

d) Volume of water = (Mass of water/Sp. Gravity of water) x (1/1000)

   = (160/1) x (1/1000)

   = 0.160 m^3

e) Volume of superplasticizer @ 1% by mass of cementitious material =

   (Mass of admixture/Sp. Gravity of admixture) x (1/1000)

   = (3.34/1.55) x (1/1000)

= 0.002 m^3

f) Volume of all in aggregate: = [a – (b+c+d+e)]

= 1 – (0.084 + 0.067 + 0.160 + 0.002)

= 0.687 m^3

g) Mass of coarse aggregate = f x volume of coarse aggregate x sp. Gravity of coarse aggregate x 1000

= 642.95 kg for 20 mm size & 526.05 kg for 10 mm size

Mass of fine aggregate = 717 kg

Coarse aggregate to fine aggregate ratio = 0.55:0.45

Therefore, the mix proportions for control mix are given in Table 4.1.

OPC cement 43	267 kg/m^3
FLY ASH	67 kg/m^3
WATER	160 kg/m^3
SAND	717 kg/m^3
20 mm AGG	642.95 kg/m^3
10 mm AGG	526.05 kg/m^3
Admixture % to weight of cementitous material	3.34
% of superplasticizer dose	1 %
W/c	0.48
Target Strength	M25

Table 4.1 Mix design quantities

	RAC 0	**RAC 30**	**RAC 60**	**RAC 100**
w/c ratio	0.48	0.48	0.48	0.48
OPC cement 43	267 kg/m^3	267 kg/m^3	267 kg/m^3	267 kg/m^3
SP	1.35 ltr.	1.45 ltr.	1.6 ltr.	1.6 ltr.
FLY ASH	67 kg/m^3	67 kg/m^3	67 kg/m^3	67 kg/m^3
WATER	160 kg/m^3	160 kg/m^3	160 kg/m^3	160 kg/m^3
COARSE SAND	726 kg/m^3	726 kg/m^3	726 kg/m^3	726 kg/m^3
CA 20	714 kg/m^3	499.8 kg/m^3	285.6 kg/m^3	0
CA 10	476 kg/m^3	333.2 kg/m^3	190.4 kg/m^3	0
RCA 20	0	214.2 kg/m^3	428.4 kg/m^3	714 kg/m^3
RCA 10	0	142.8 kg/m^3	285.6 kg/m^3	476 kg/m^3

Table 4.2 Proportions of constituents in all mixes.

4.4 Accelerated Curing Test (ACT) ASTM C684-99(2003)

The accelerated curing procedures provide, at the earliest practical time, an indication of the potential strength of a specific concrete mixture. These procedures also provide information on the variability of the production process for use in quality control. The accelerated early strength obtained from any of the procedures in this test method can be used to evaluate concrete strengths in the same way conventional 28-day strengths have been used in the past, with suitable changes in the expected strength values. Since the practice of using strength values obtained from standard-cured cylinders at 28 days is long established and widespread, the results of accelerated strength tests are often used to estimate the later-age strength under standard curing. Such estimates should be limited to concretes using the same materials and mixture proportions as those used for establishing the correlation.

This test conforms to ASTM C684-99(2003). Three cubes of the trial mix are cast and put in accelerated curing tank for a period of 24 hours. During the period of 24 hours, steam produced by heating water to boiling temperature in the tank. After 24 hours, the samples are checked for their compressive strength. If the cubes pass this test, the trial mix is selected.

Table 4.3: ACT test values

Peak Load(kN)	Absolute stress(N/mm^2)	Average stress(N/mm^2)
451.125	20.05	
480.375	21.35	19.85
408.375	18.15	

For trial mixes the Calculated strength given by (4.1) should be greater than 1.5(target strength)

Calculated Strength = Average stress (ACT Test) x 1.64 + 8.09 (4.1)

From Table 4.3, average stress obtained was 19.85 x 1.64 + 8.09 = 40.64 > 1.5 x 25 = 37.5 MPa

Hence Ok.

4.4 Hardened properties of concrete

The destructive tests used in this procedure were compressive strength and splitting tensile strength.

4.4.1 Compression strength test

In total 36 cubes of size 150 mm x 150 mm x 150mm were cast for compression strength testing. The apparatus used for measuring compressive strength was Universal Testing Machine(UTM).

4.4.2 Splitting tensile strength test

In total 36 cylinders of size 150mm diameter and height 300 mm were cast. These cylinders were tested on the 3rd, 7th and 28th day after casting. Given below is the diagram of the splitting test apparatus followed by a photograph. Figure 4.2 shows the setup and loading pattern of the split tensile test. Figure 4.3 shows the test cylinder undergoing split tensile test.

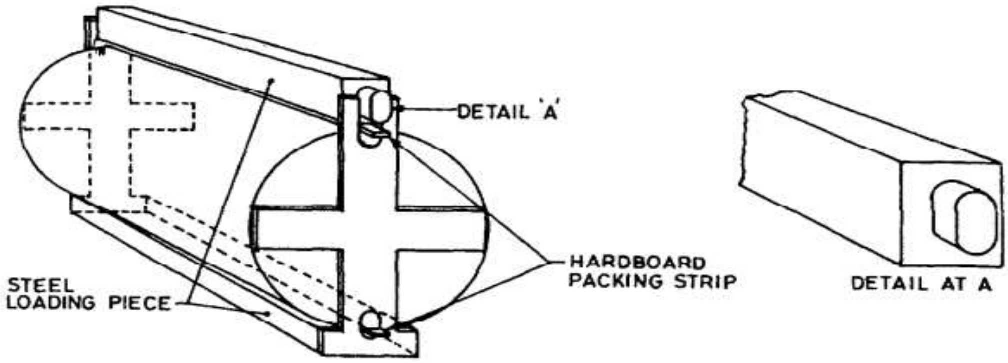


Figure 4.2 Splitting tensile test apparatus [IS 5816-1996]

Figure 4.3 Split tensile test in laboratory

Calculations for splitting tensile strength:

According to IS:5816-1999, the measures splitting tensile strength f_{ct} of the specimen shall be calculated to the nearest 0.05 N/mm^2 using the equation:

$f_{ct} = 2P/\pi lD$ (4.2)

Where

P is max load applied to the specimen in (N)

L is length of the specimen

D is diameter of the specimen.

4.5 Fresh properties of concrete

For determining the fresh properties of concrete made with RCA the ultrasonic pulse velocity test and the ultrasonic guided wave test were used.

4.5.1 Ultrasonic guided wave testing

In all 8 slabs of size 30 cm x 30 cm x 10cm were cast(two slabs for each mix type). A mild steel bar of diameter 25mm was embedded in each slab at the centre position(15cm,15cm,5cm in global coordinates).

The testing apparatus consisted of a DPR 300 pulser/receiver which generates pulses for a specified time interval. This pulse after generation is sent to a transducer which converts the signal to an ultrasonic wave. Figure 4.4 shows the experimental setup.

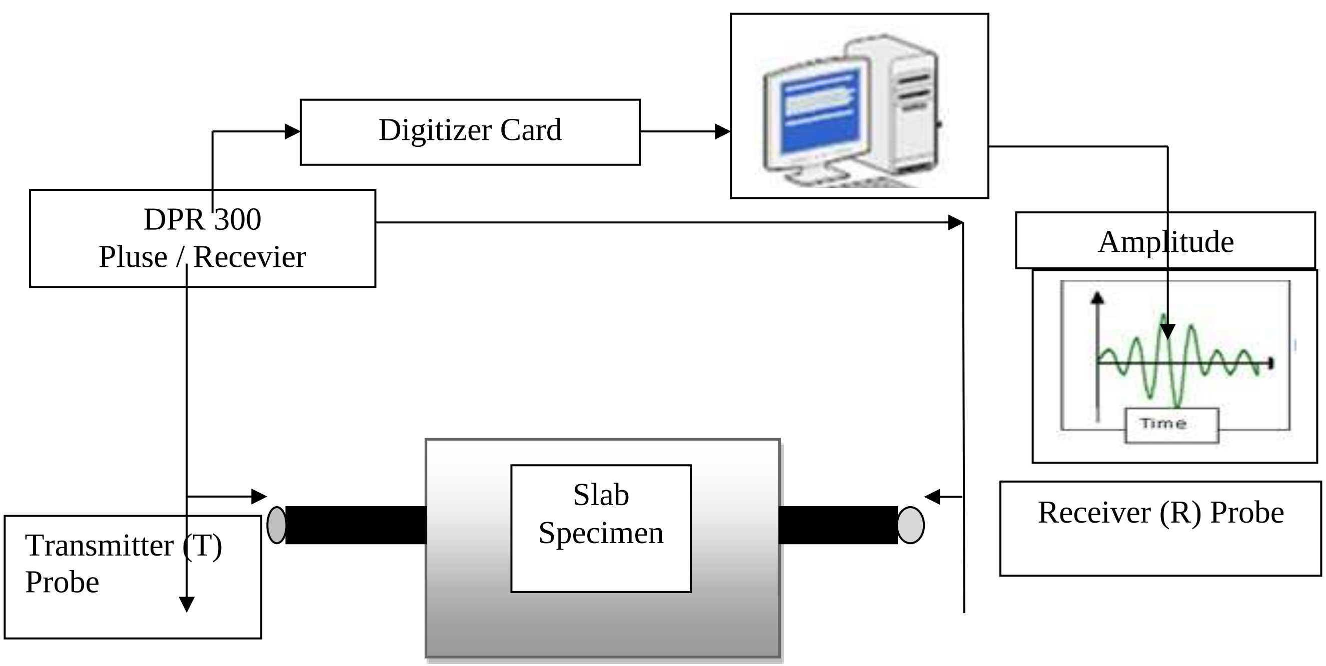


Figure 4.4 Experimental setup of UGW

The ultrasonic pulse propagates through the mild steel bar in form of guided waves. After the concrete setting process starts, the concrete surrounding the mild steel bar begins to bond with the bar thus resulting in attenuation, that is, loss of wave energy. This wave energy loss is due to the absorption of the wave energy by the material and energy leakage into surrounding concrete. Finally, the receiver transducer picks up the wave signal after attenuation and converts it to an electrical signal to be processed by software. Figure 4.5 gives the work flow diagram of the UGW test method.

The key elements of the apparatus were:

a) Transducers: S 24 HB 0.1 S and S 24 HB 0.1E (KARL DEUTSCH) were the standard transducers of 0.1 MHz frequency and 24 mm diameter used in this experiment. The transducers are given in Fig 4.5.

Figure 4.5: Standard KARL DEUTSCH transducers

Figure 4.6: Transducers and the specimen

b) JSR Ultrasonics DPR 300 Pulser/receiver system:

This device can produce a high voltage electrical excitation pulse upto 475V and transfers this pulse to the instrument's T/R connector. Figure 4.6 shows a sample of the slab while testing.

Figure 4.7: JSR Ultrasonic DPR 300 front

This device can be configured for both pulse echo and through operations using the computer software. During the echo mode, signals reflected from interfaces or defects within the specimen are converted into electrical signals. The DPR 300 amplifies the signals before these are passed through adjustable high pass and low pass filters. Figure 4.7 shows the picture of the receiver system.

Table 4.4 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

4.6.1.1 Excitation mode and frequency:

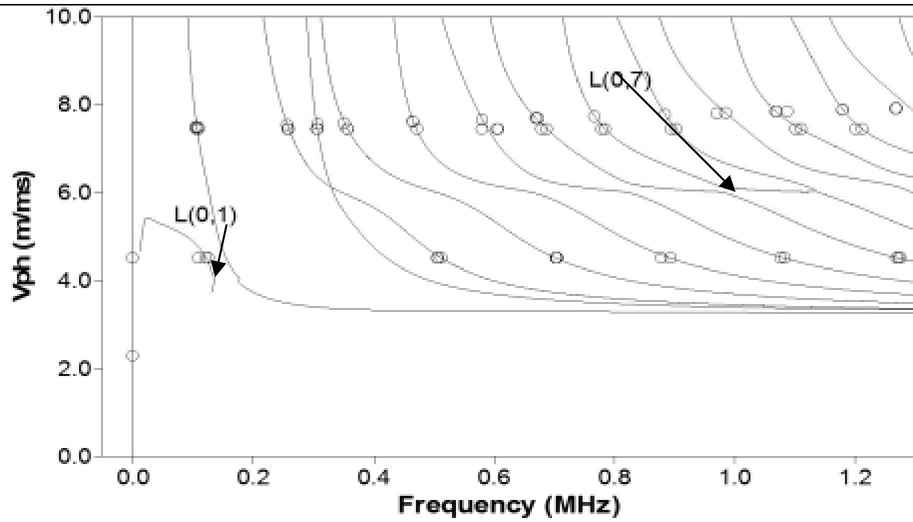
The selection of a suitable test mode and frequency is done after analyzing the dispersion curves using the software Disperse. According to Sharma and Mukherjee, 2010, modes that have lowest signal attenuation and at the same time are easily distinguishable are selected. Generally, modes at low attenuation are used to maximize the inspection range and at the same time to minimize the effects of dispersion and also minimize the interference of other modes in the received signal. Dispersion curves for a mild steel bar of 25mm diameter are shown in figure 4.8.

4.6.1.2 Testing procedure:

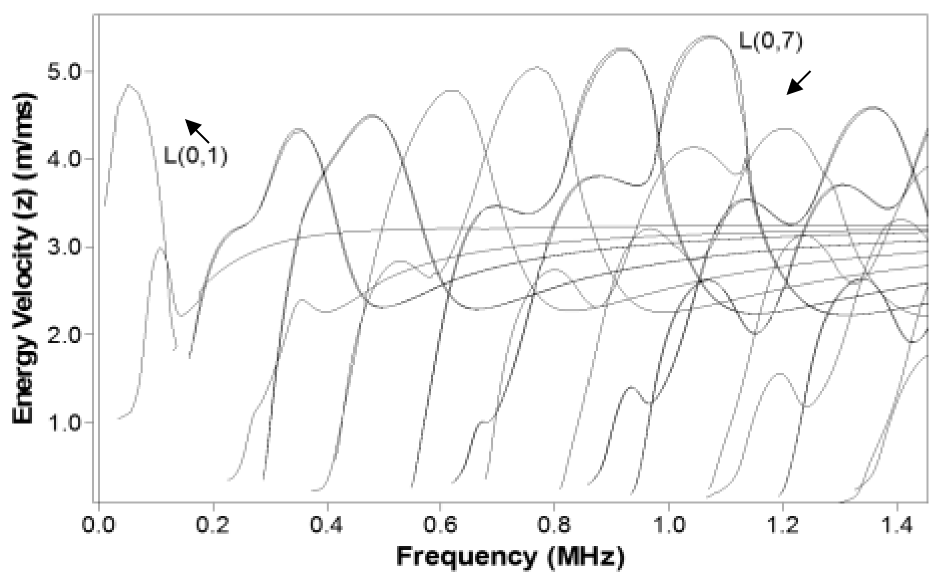
The two KARL DEUTSCH transducers surfaces are first applied Ultrasonic gel. This gel helps to make the surface smooth. The transducers are then connected to the ends of the mild steel bar embedded in the concrete slab. One transducer acts as a transmitter and the other as a receiver. The transducers used had longer wave form duration and a relatively narrow frequency bandwidth with central frequency of 0.1 megahertz as the objective was to monitor bonding between the mild steel bar and the surrounding concrete in the slab.

Another contributing factor to the selection of mode is the relative sensitivity of ultrasonic waves to setting of concrete. **Fig 4.8(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 4.8(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 4.8c)**.

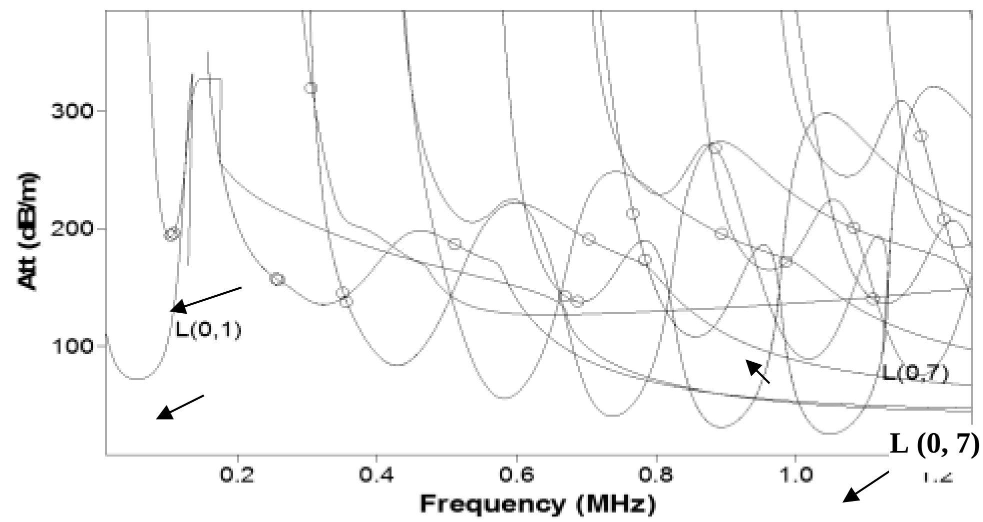


(a) Phase velocity Vs Frequency



(b) Energy Velocity Vs Frequency

Figure 4.8 Dispersion curves for a 25mm mild steel bar[39]



(c) Attenuation Vs Frequency

Fig 4.8c)Dispersion curves for 25mm dia bar[Sharma & Mukherjee, 2010]

Longitudinal modes are studied alone as other modes of flexure and torsion show high attenuation. Figure 4.9 shows the specimen details for UGW tests.

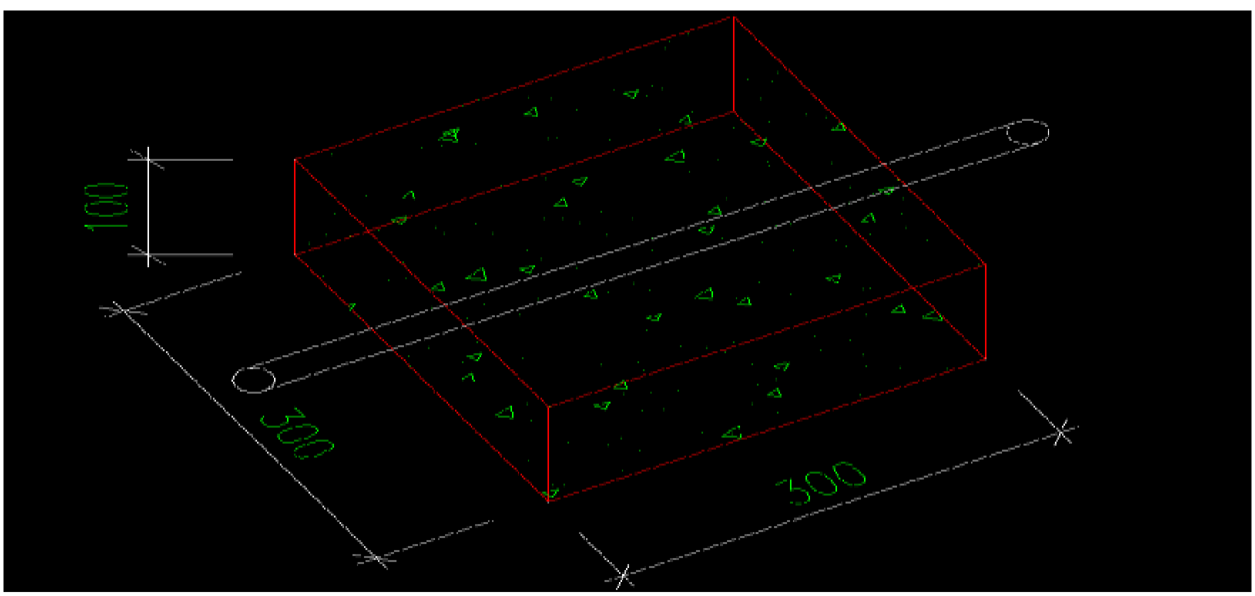


Figure 4.9 Slab specimen for UGW testing

4.6.2 Ultrasonic pulse velocity testing: In all 8 cubes of size 150 mm x 150mm x150mm were cast(two cubes for each mix type).

4.6.2.1 Testing apparatus:

The instrument used to measure the ultrasonic velocity passing through concrete cubes was TICO, model ZI 10006 as shown in Fig 4.10.

Figure 4.10: UPV instrument TICO[www.images.google.com]

4.6.2.2 Testing procedure:

Pulse is generated from one end of the concrete cube through the electro-acoustic transducer. Cellulose gel is applied at the both the ends of the transmitter and the receiver transducer so as to make the surface smooth for contact with the surface of the cube specimen.

Longitudinal pulse velocity is given by:

$V = L/T$

Where, V is the longitudinal pulse velocity

L is the path length

T is the time taken by the pulse to traverse the length L

The experiment was done starting 6 hours after casting till 24 hours after casting.

4.7 Concluding Remarks:

In the experimental tests carried out in this dissertation, all experiments have been conducted with a view on accuracy. It is possible to conclude that the RCA used in this study is of a high quality, uniform and from a common source. In addition to this, there are no significant differences in the mechanical behavior and durability performance in the RCA used in this experiment when compared with NA for the same mix.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.0 General:

This chapter deals with the results obtained after conducting tests on hardened properties and fresh properties of RAC. The results obtained from the samples RAC 30, RAC 60 and RAC 100 will be compared with the results of the standard sample RAC 0. The tests were explained in detail in chapter 4.

5.1 Tests on hardened properties:

5.1.1 Compressive strength values:

As explained in Chapter 4, 36 cubes in total were cast for compressive strength testing. There were 9 cubes to be tested at 3 days, 7 days and 28 days for each of the mixes. The Table 5.1 gives the compressive strength values of each of these cubes.

Table 5.1: Comparison of compressive strength values

Mix	Compressive load P(kN)			Average stress			Average value		
DAYS	3	7	28	3	7	28	3	7	28
RAC 0	305.57	410.11	672.3	13.58	18.22	29.88			
	309.89	439.57	664.3	13.77	19.53	29.52	13.54	19.31	29.34
	298.76	454.1	644.5	13.27	20.18	28.64			
RAC 30	349.2	417	660.2	15.52	18.53	29.34			
	291.4	460.1	644.5	12.95	20.44	28.64	14.71	19.1	29.61
	352.6	412.6	694.2	15.67	18.33	30.85			
RAC 60	318.7	510	668.9	14.16	22.66	29.72			
	312.4	548.24	701.2	13.88	24.36	31.16	14.1	22.94	30.43
	321.2	490.26	684.23	14.27	21.78	30.41			
RAC 100	419.8	699.97	801.23	18.65	31.11	35.61			
	495.6	650.02	774.54	22.02	28.89	34.42	20.73	30.33	34.4
	484.4	697.5	746.7	21.52	31	33.18			

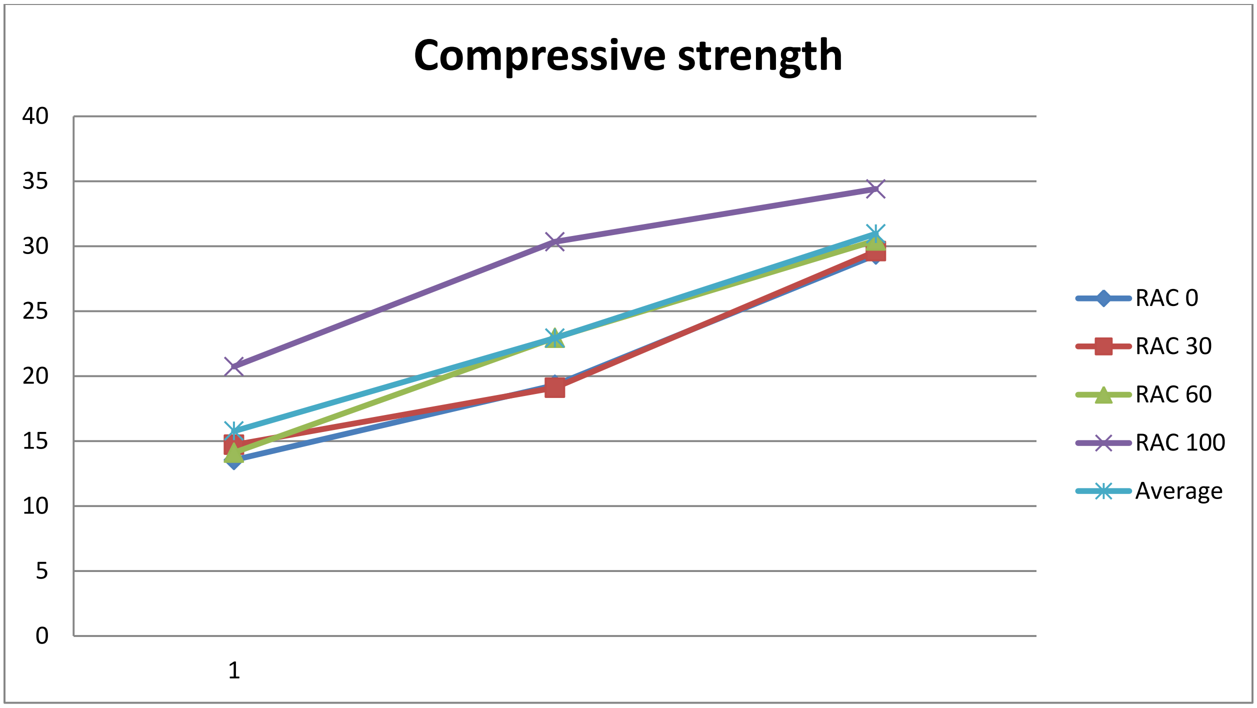


Figure 5.1 Comparison of strength gain of all mixes

Table 5.2 Slump values

Mix	Initial slump(mm)	Final slump(mm)
RAC 0	180	126
RAC 30	165	110
RAC 60	155	0
RAC 100	140	0

From the compressive tests perfomed on all the four mixes, the following observations were gathered.

- Figure 5.1 shows the variation in compressive strength (3,7,28 days) for all mixes prepared by replacing with varying proportions of RCA.
- At 3 days, it can be seen from the results that RAC 60 and RAC 100 show early strength gain. RAC 100 shows significantly higher compressive strength than the other mixes.

- At 7 days, RAC 100 shows much higher value as compared to the other mixes. But RAC 0, RAC 30 and RAC 60 values show marginal difference. Still mixes with proportions of RCA show a higher trend.
- At 28 days, all the four mixes do not differ much in value. The compression test results indicate an increasing trend in the compressive strength for RAC 100. This indicates a 17.24% rise for RAC 100, 3.7% rise for RAC 60 and 0.92% rise for RAC 30 as compared to RAC 0.
- Higher strength was attained at all days for RAC 100. It is believed that quicker hardening and setting of RAC100 caused higher values of strength. Also for RAC 30 the day 3 compressive strength was marginally higher. But at 7days a -1.1% strength reduction was noticed for RAC 30 when compared with RAC 0. This means that RAC 30 shows a higher early strength development but that after 7 days strength development is very low. This has also been noticed in other mixes. It is important to note here that the average compressive strength of RAC100 had the greatest difference with RAC 0 or NAC.
- It is worth mentioning that Figure 5.1 graphically shows the average 28 day strength of all three types of concrete from different steps, indicating no significant influence of RCA replacement. This can be attributed to the higher quality of the aggregate present in the old concrete which acts just like NAC. Alternatively, it is seen that the strength at the plane between the mortar and RCA was no different from the plane between NAC and mortar. This can also be attributed to a strong bond between the old mortar and new mortar or the lack of presence of much mortar adhering to the surface of the RCA.

- Comparison of slump values in Table 5.2 for all mixes shows that water absorption increases with the increasing proportions of RCA in the mix. RCA 60 and RCA 100 showed zero final slump.

5.1.2 Split tensile testing values:

For conducting split tensile tests,36 cylinders were cast of all the four mixes. Mentioned below are the testing results of all these cylinders in tabular format.

Table 5.3 shows the results obtained for all the cylinder specimens.

Sno.	Split Tensile load P(kN)			Average stress			Average value		
	3	7	28	3	7	28	3	7	28
RAC 0	62.17	82.37	106.1	0.87	1.16	1.5			
	67.82	88.85	137.9	0.95	1.25	1.95	0.91	1.25	1.85
	63.72	94.62	148.9	0.9	1.33	2.1			
RAC 30	67.82	98.2	131.9	0.95	1.38	1.86			
	60.05	109.8	104.6	0.84	1.55	1.48	0.92	1.47	1.75
	69.23	104.5	135	0.97	1.47	1.91			
RAC 60	59.34	111.62	135.8	0.83	1.57	1.92			
	66.41	116.57	140.21	0.93	1.64	1.98	0.89	1.57	1.92
	64.99	105.35	131.2	0.91	1.49	1.85			
RAC 100	77.71	110.3	145.3	1.09	1.56	2.05			
	78.3	105.6	140.2	1.1	1.49	1.98	1.12	1.59	2.02
	82.1	122.4	144.2	1.16	1.73	2.04			

Table 5.3 Comparison of split tensile values

The Figure 5.2 gives the graph comparison of all the mixes with respect to their split tensile stress values.

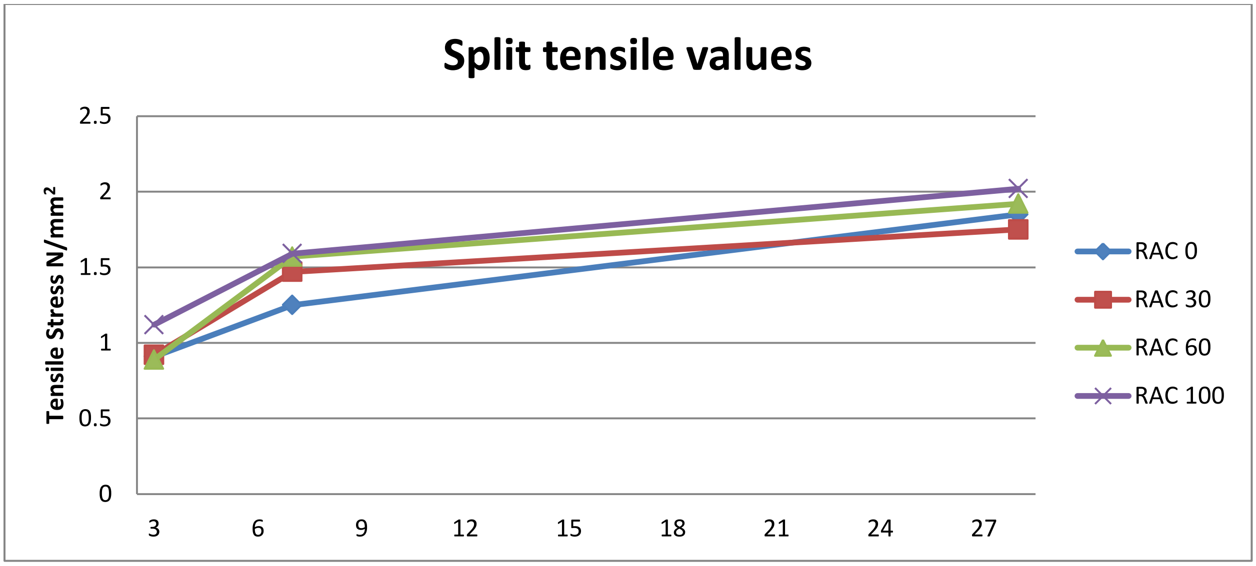


Figure 5.2 Comparison of split tensile values

- At 3 days, from the Table 5.3 it can be seen that split tensile strength for RAC 0, RAC 30 & RAC 60 do not differ much in value. RAC 60 shows marginally lesser value as compared to RAC 0. RAC 100 value is a lot higher than the other mixes.
- At 7 days, RAC 0 shows lower split tensile value as compared to the other mixes. RAC 100 shows the highest value although there is not significant difference between RAC 60 and RAC 100 values. RAC 30 values are lesser than RAC 60 and RAC 100 is generally greater than the values obtained for RAC 0.
- At 28 days, RAC 100 shows the highest split tensile value. Also, there is not much difference in the values obtained for the other mixes. It is important to note that RAC 30 showed lower value than RAC 0.
- Lower the proportion of RCA in the mix, lower tends to be the split tensile strength. It is also evident from these tests that RCA contributes directly to making the split tensile strength more than that of NAC.
- The average characteristic strength (i.e the strength at day 28) for RAC 100 tends to be 8.5% more, for RAC 60 it tends to be 4% and for RAC 30 it tends to -5.4% less than that of RAC 0 at 28 days.

- It is again important to note here that the average split tensile strength of RAC100 had the greatest difference with RAC0 or NAC. It was also observed that the failure plane for RAC 60 and RAC 100 was at the interface between aggregate and mortar. The reason for this can be attributed to the presence of a higher quality aggregate in the old concrete, somewhat lesser mortar adhering to the surface of this aggregate or a stronger bond between the mortar and natural aggregates of old concrete.

- In the beginning of the experiment it was assumed that splitting strength of RAC 0 would be higher than that of RAC 30, RAC 60 and RAC 100. Lower splitting strengths was confirmed for RAC 30 at 28 days. A possible explanation is the existence of micro-cracks in RCA caused by crushing the old concrete from which the RCA is produced. Also, comparing the fracture surfaces of both RAC0 and RAC 30 showed that most of the failure in RAC0 occurred along the interfaces between the mortar and the aggregate particles. However, in RAC the failure plane goes through or around the aggregates. This type of failure may cause a somewhat more abrupt collapse of the concrete due to the brittleness of the aggregate, which may explain why in some cases RAC is more brittle than NAC.

5.2 Ultrasonic guided wave investigation:

The UGW test was carried out on a beam specimen on dimensions 300mm x 300 mm x 150 mm. A 25 mm diameter rod of 600 mm length was embedded in the beam specimen. Readings for this experiment were taken continuously for a period up to 24 hours after casting. Initially a healthy signature i.e. voltage vs time graph is captured (Fig 5.1a and b) and then compared with results signatures taken at different time intervals. Finally pk-pk voltage is measured and results are plotted as V-T (Voltage vs Time) graphs.

Ultrasonic investigations are carried out in both pulse echo mode where a single transducer acting as transmitter and receiver is used. In addition to this, testing is carried out in pulse transmission mode. The following section gives the results obtained in both modes using 0.1 Mhz frequency and L(0,1) mode.

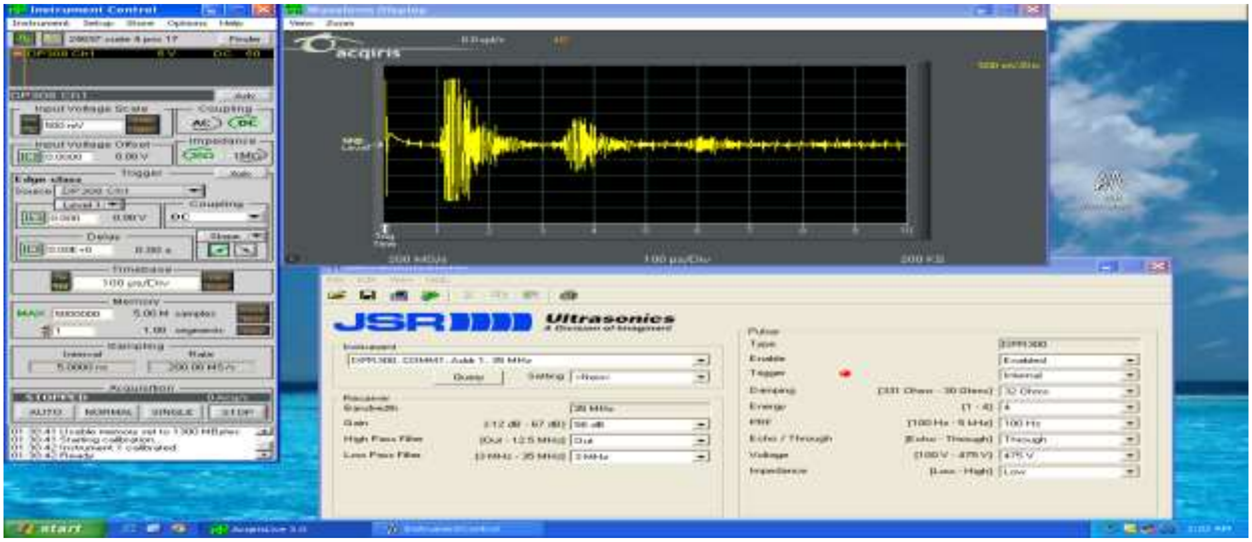


Figure 5.3 Image of waveform

5.2.1 Ultrasonic Pulse Echo (PE) Investigations:

Typical PE signature

Figure 5.3 shows a typical PE signature.

The time of flight (TOF) of the reflected pulse is calculated as:

Length of travel = 1200mm

Group Velocity of L(0,1) mode (Figure ….)= 4600 m/s (5.1)

Time of flight (TOF) = L/V = 0.0025 sec

The reflected peak appears at 0.0025 sec for all mixes as shown in Figure 5.3.

The voltage amplitude of the peak is measured as pk-pk voltage.

The PE signatures are taken at regular intervals after every 24 hours and are shown in **Figures 5.4(a) to (d).**

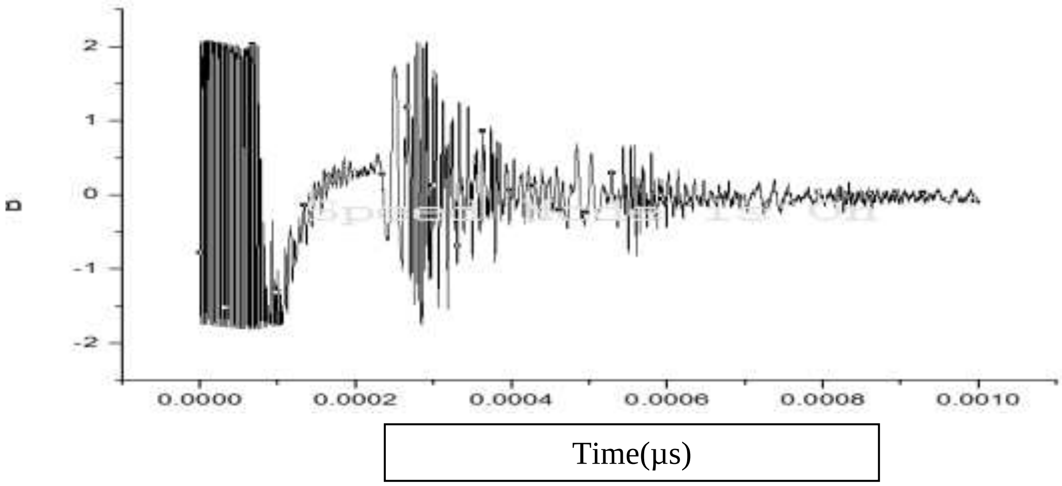
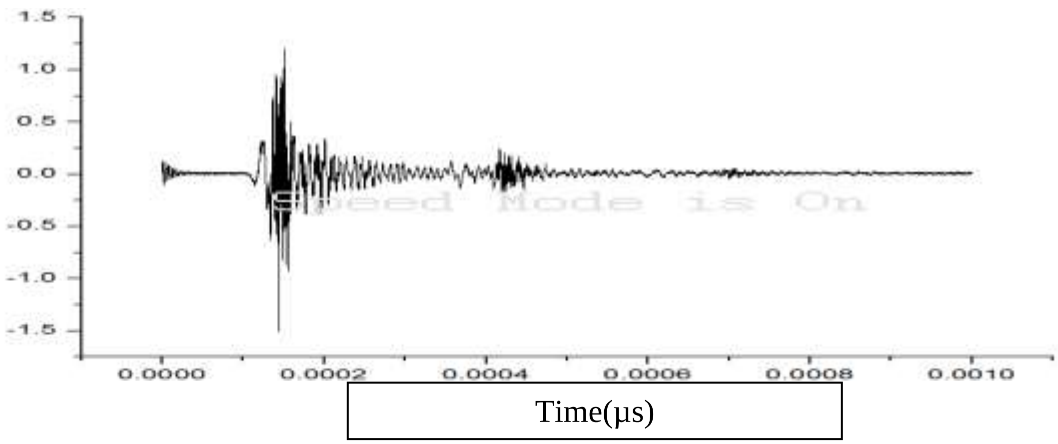
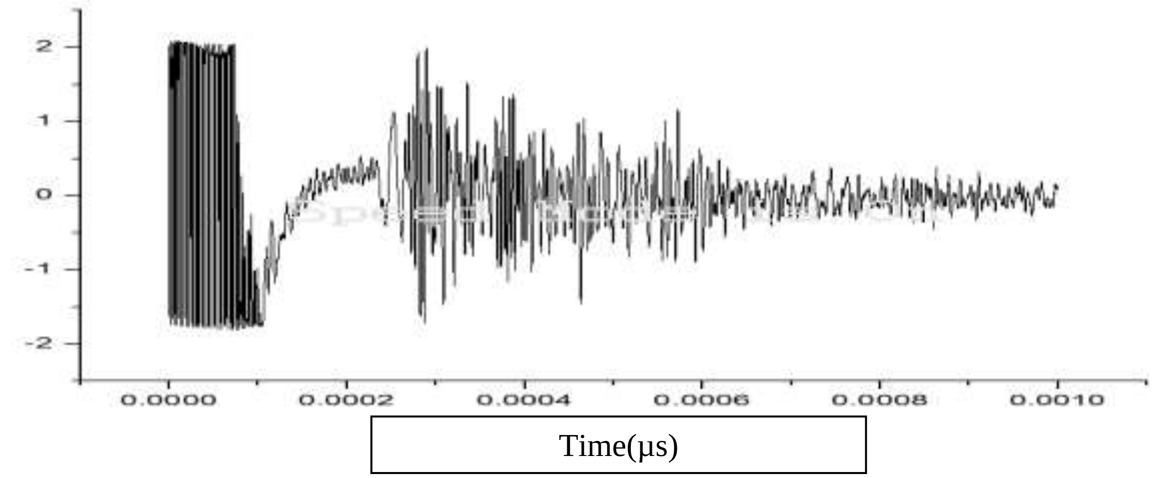


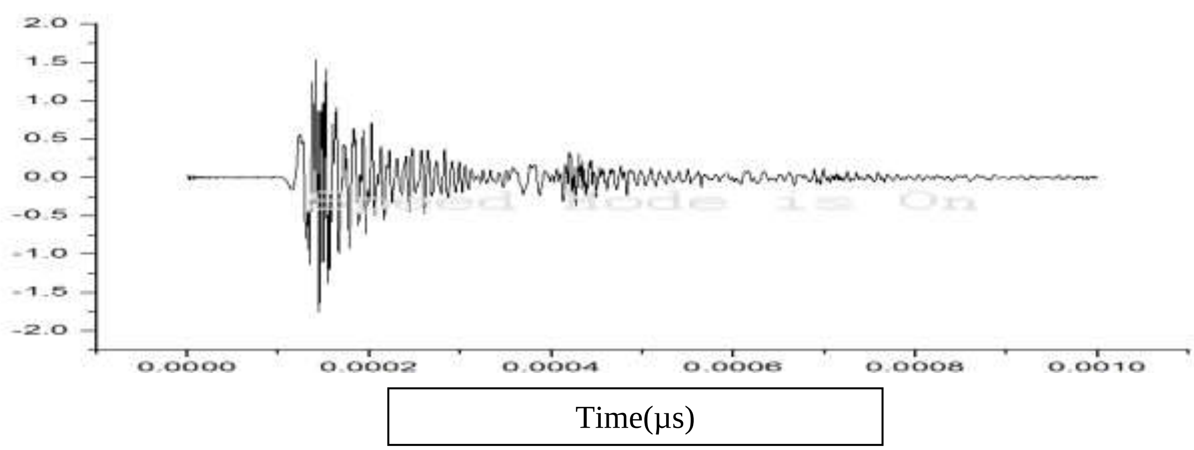
Figure 5.4(a) 2h



b) 6h



c) 12h



d)18h

Fig 5.4: Typical PE signatures at regular intervals

The peak to peak voltage amplitudes of the reflected pulses at different hours of setting of concrete are plotted as shown in Figures 5.5(a) to (d)

a) RAC 0:

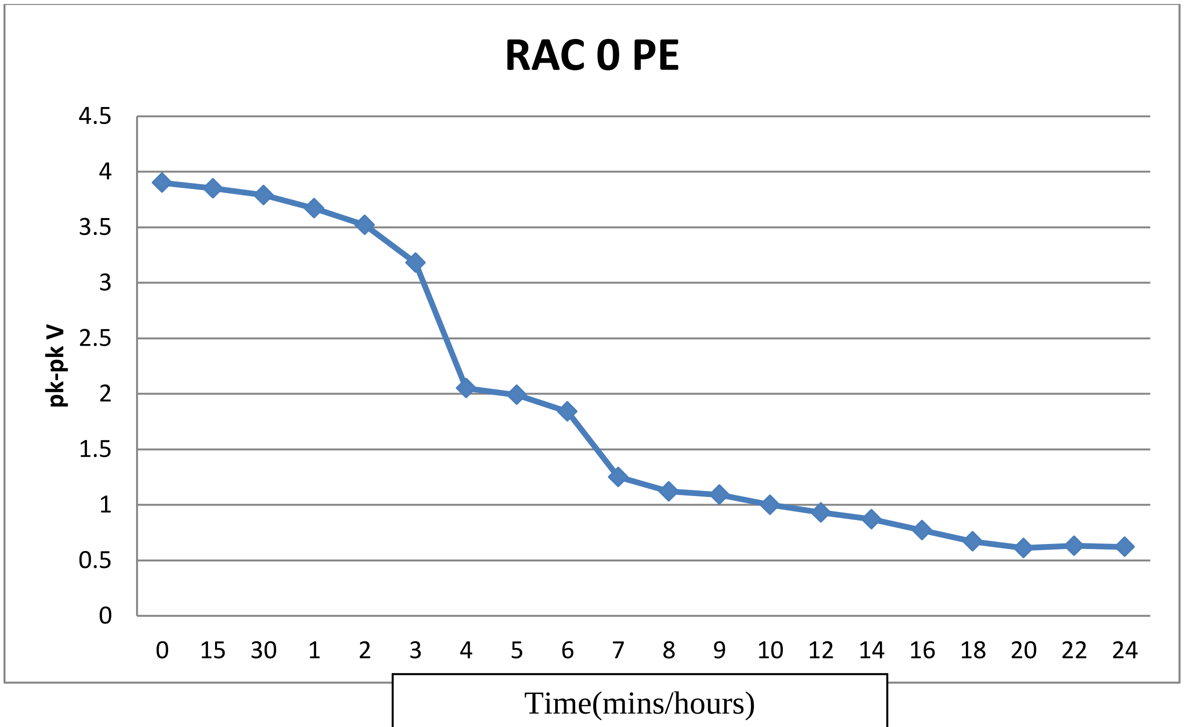


Figure 5.5a) Voltage vs time graph of 0.1 Mhz PE for RAC 0

b) RAC 30:

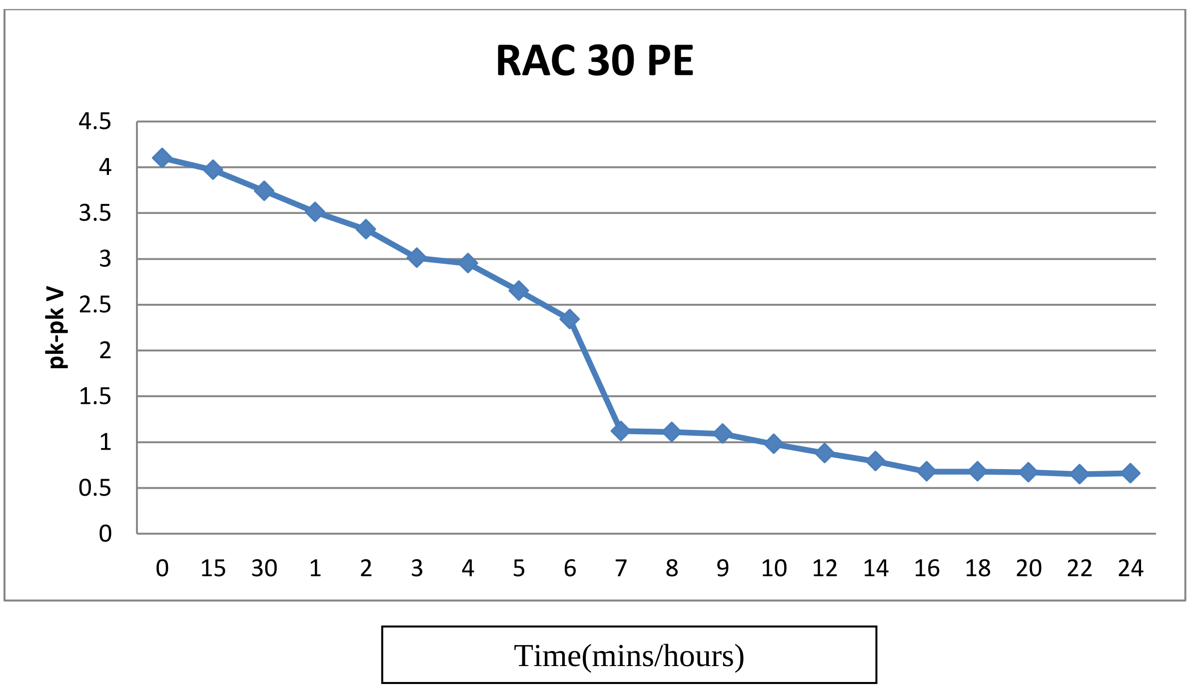


Figure 5.5b) RAC 30

c) RAC 60:

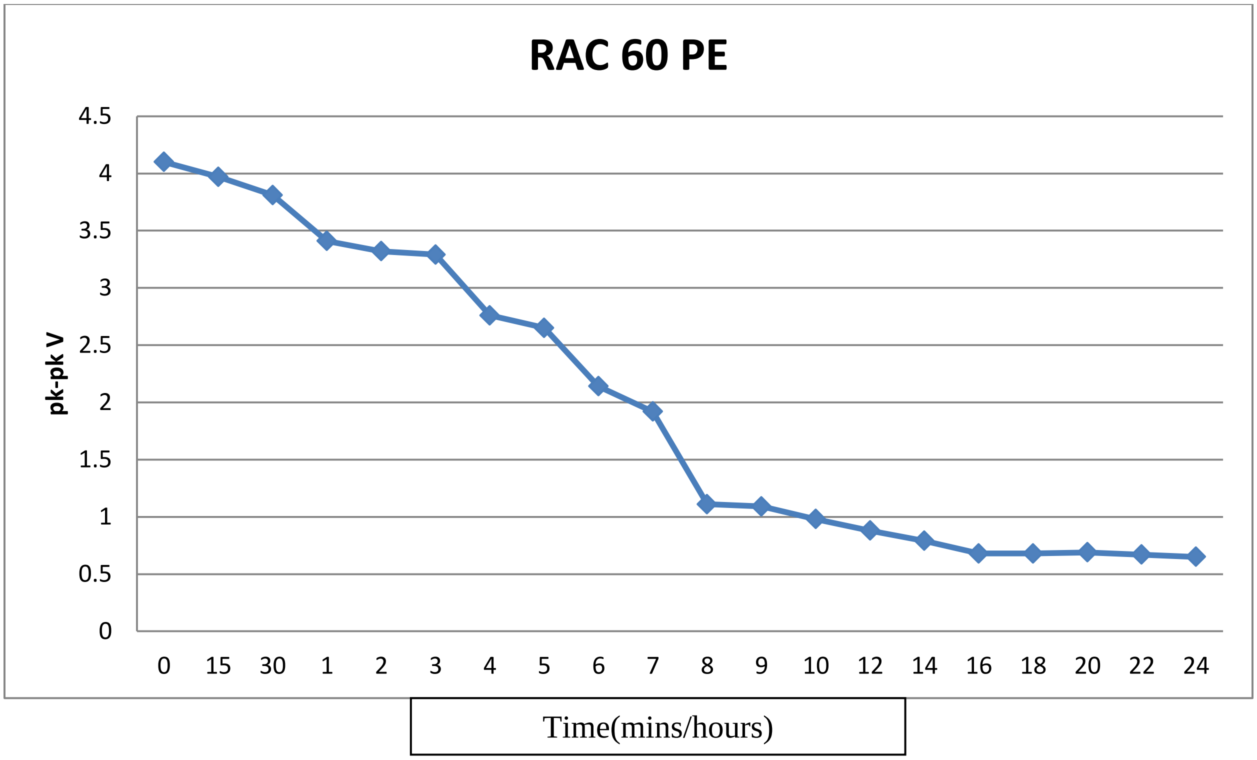


Figure 5.5c) RAC 60

d) RAC 100:

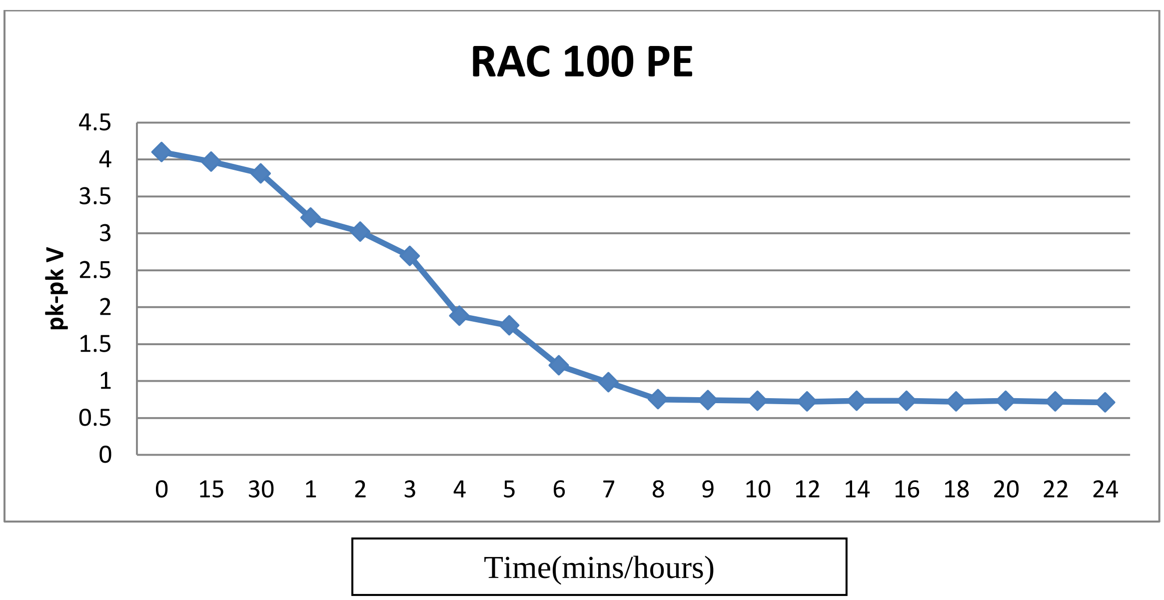


Figure 5.5d) RAC 100

- From the figures it is evident that, RAC 0 shows a uniform setting slope. There is no sharp fall in the voltage amplitude. The semi solid phase starts 3 hours, the transition phase at 6.5 hours and the solid phase at 7 hours.
- RAC 30 shows early fall in signal. There is no clear starting of transition phase but it starts around 30 mins. The solid phase starts at 7 hours.
- RAC 60 also shows sharp fall in signal strength at early stages. The transition phase starts from the beginning and lasts till 8 hours. The solid phase continues from 8 hours.
- RAC 100 shows similar readings as RAC 60. There is no clear beginning of transition phase and it ends at 7.5 hours. The progress of setting is very rapid and amplitude values rapidly come down after 15 mins.
- From these values, it can be concluded that RCA is responsible for quicker setting of RAC mixes. RAC 100 and RAC 60 show rapid fall in amplitudes and also show comparable amplitudes for the duration of 24 hours.

5.2.2 Ultrasnoic Pulse Transmission (PT) investigations

a) RAC 0:

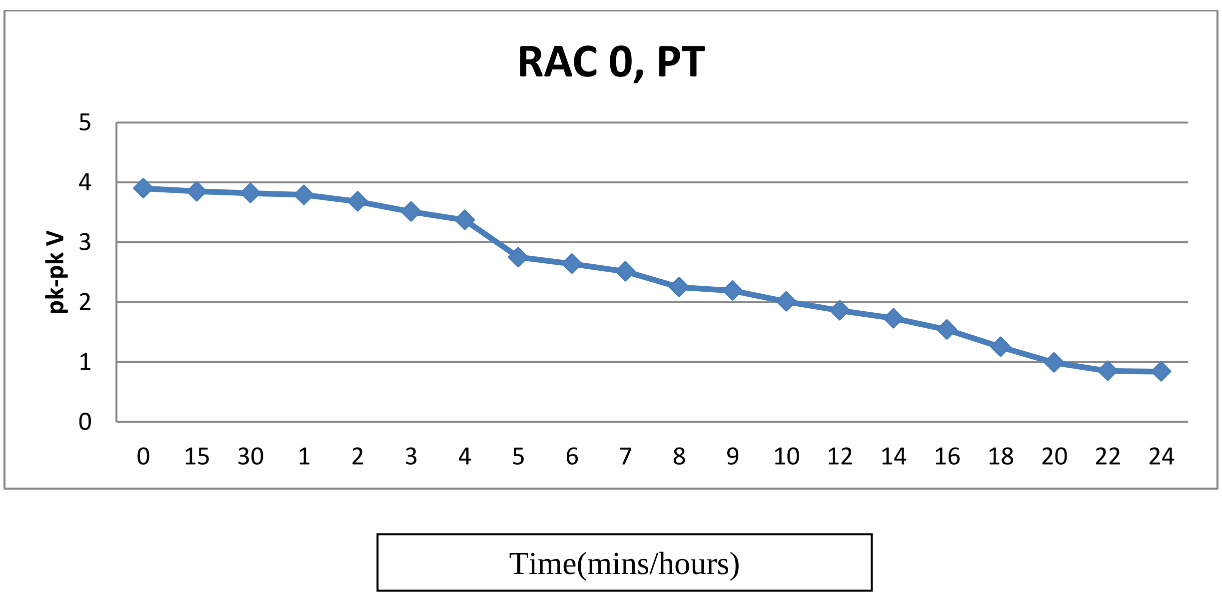


Figure 5.6a) RAC 0

b) RAC 30:

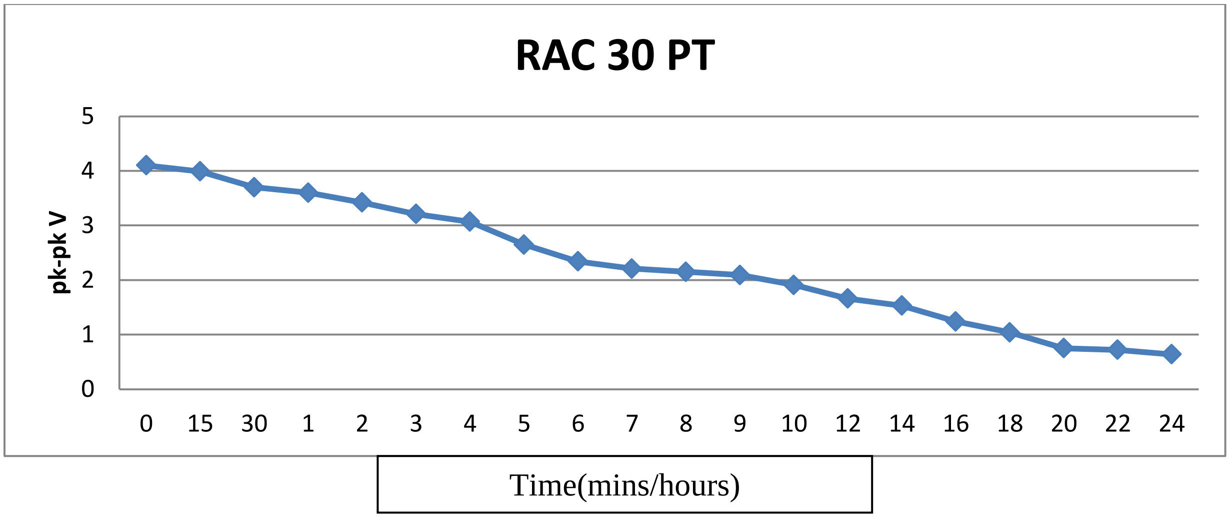


Figure 5.6b) RAC 30

c) RAC 60:

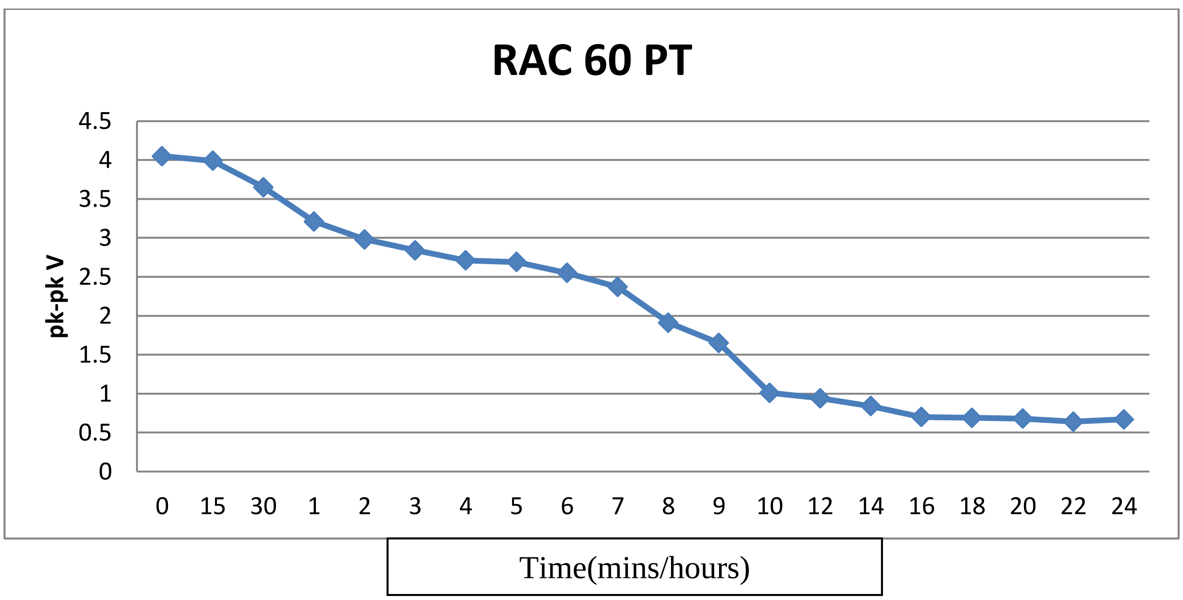


Figure 5.6c) RAC 60

d) RAC 100:

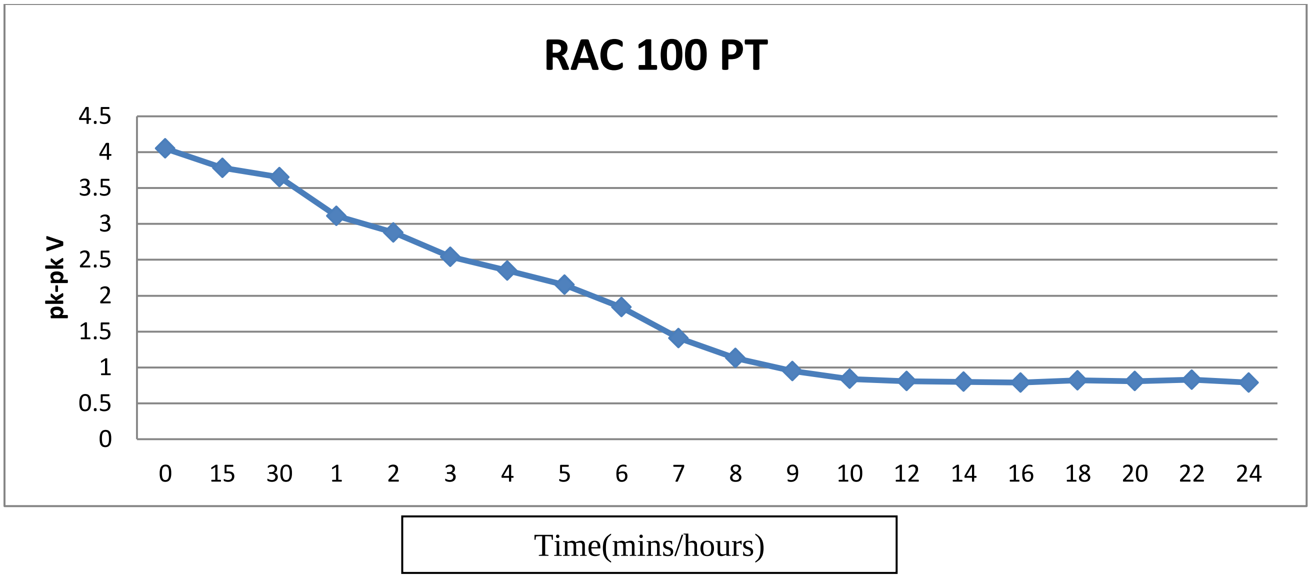


Figure 5.6d) RAC 100

- After casting has been done and as concrete begins to set and harden, the Pk-Pk voltage drops and in turn the signature also drops. This can be attributed to the surface seeking nature of the mode selected.
- This mode picks the bond development between the surrounding concrete in the beam and the embedded 25 mm diameter mild steel rod. The ultrasonic Pulse Transmission (UPT) investigation of all the mixes is conducted for 24 hrs and results obtained are plotted as Voltage vs Time.
- It can be clearly seen that RAC100 and RAC 60 have comparable readings of pk-pk voltage just after casting. However, after that they show sharp fall in signature strength with time. Also the values tend to be very close after 14 hours to 24 hours. This can be attributed to quick setting of these mixes because of high water absorption by mortar adhering to the RCA.
- This is because of mortar adhereing to the surface of the recycled concrete aggregates present in the mix. Also, as the proportion of recycled aggregates in the mix increases, the peak voltage values tend to be towards a constant value in shorter time compared to NAC.

- With passing time after curing, as the concrete hardens the 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. Also during setting bond develops between steel and surrounding concrete indicating more energy leakage into the surrounding concrete thus causing drop in signal strength. Hence the fall in signal strength is a measure of development of bond and hence setting of concrete.
- The UPT result graphs of all mixes indicate that concrete was undergoing two phases i.e. Transition & Solid Phase. For RAC 60 and RAC 100, the semi-solid Phase was for not clear. After that there was quick progression to the transition phase which lasted between 2 hours to 14 hours and lastly it was observed that the solid phase lasted between 14 hours to 24 hours.
- During the semisolid phase for RAC 0it was observed that there was slow but gradual fall in Pk-Pk voltage. Thus indica ting quick setting or bonding between the mild steel bar and the surrounding concrete.
- In the transition phase, the concrete undergoes change from semi-soild to solid phase and starts to set or bond with the embedded mild steel bar. The max fall in Pk-Pk Voltage is observed in this phase.
- Lastly in the solid phase there is marginal fall in Pk-Pk voltage, indicating that the concrete has become almost solid. There is hardly any setting or bonding occurring in this phase which shows that the max setting or bonding occur upto 14 hours after casting for high proportions of RCA in a concrete mix.
- For RAC 0 and RAC 30, the semi solid phase lasted for upto 3.5 hours, after that the transition phase lasted between 3.5 to 18 hours and lastly the solid phase lasted between 18 to 24 hours.
- After comparing the readings of all mixes, it was observed that RAC 100 and RAC 60 have quick transition to the transition phase. The readings are distinctly different in

comparison to readings of NAC and RAC 30 which has a lower proportion of RCA. This phenomenon can be attributed to the quick setting of the concrete because of presence of adhered mortar on the recycled aggregates which has high water absorption.

5.2.3 Comparison between PE and PT

- The PE values show early fall in amplitude as compared to PT values. This can be attributed to the distance covered for each case, which is double for PT.
- Both are fine for monitoring setting of concrete
- PE is better as access is required on only side. Also at the same time, it is more convenient to expose one side of the concrete to rebar.

5.3 UPV investigations

Table 5.10 shows the comparison of UPV results obtained with control and modifies mixes.

Table 5.4 Comparison of UPV values

	RAC 0	RAC 30	RAC 60	RAC 100	Std. Deviation
6h	1365.8	1465.1	1747	1896.8	245.919316
8h	1449.5	1608.5	1998.4	2010.1	281.999709
10h	1798.6	1947.2	2104.9	2312.6	220.15589
12h	2178.5	2458.4	2487.6	2623.9	186.879765
14h	2447.2	2657.2	2657.4	2865.2	170.648987
16h	2647.1	2748.6	2941.8	2947.5	148.411152
18h	2805.4	3006.5	3008.5	3105.5	126.149656
20h	3135.7	3165.3	3125.8	3310.2	85.627118
22h	3257.4	3208.5	3447.5	3365.2	107.470632
24h	3261.4	3374.1	3557.4	3658.2	178.474991

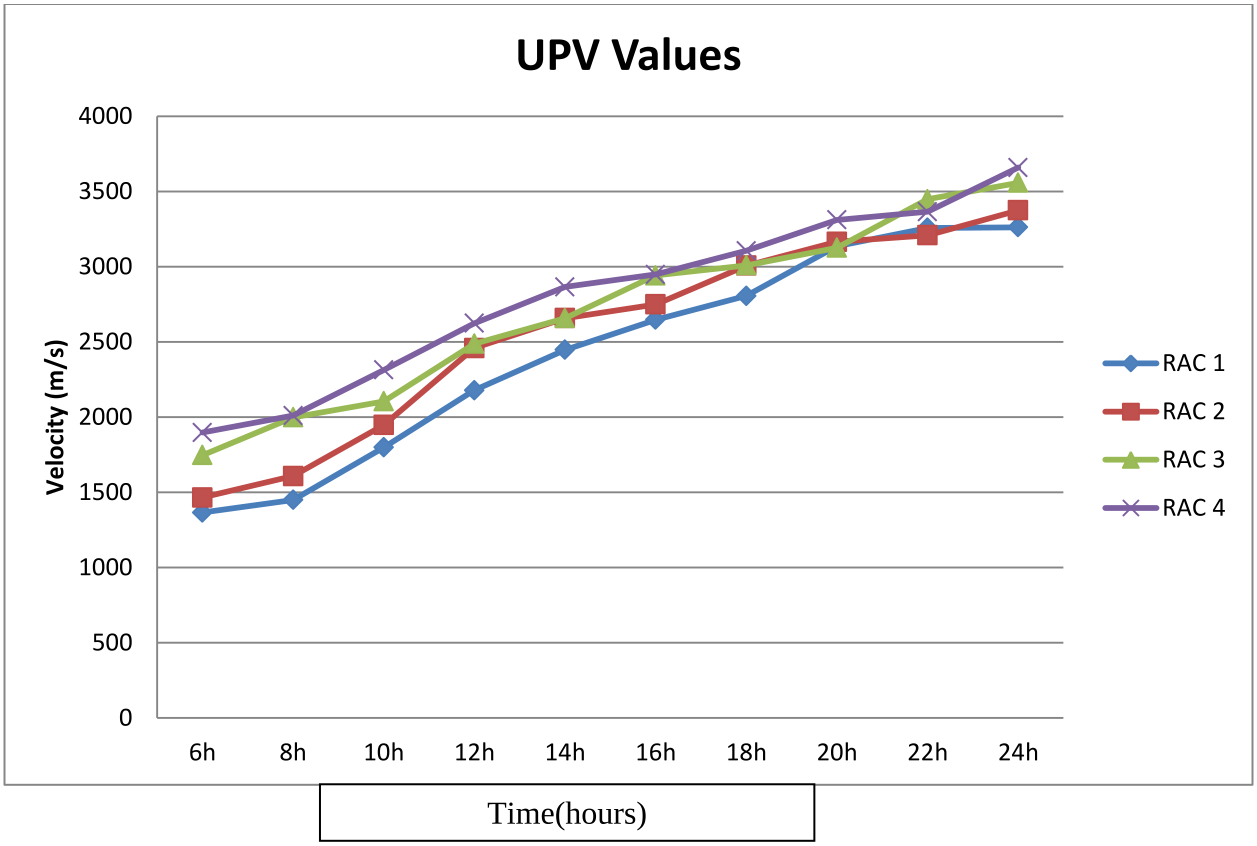


Figure 5.7 Graph showing comparison of UPV values

- It can be clearly seen that RAC have higher readings of ultrasonic velocities as compared to the other mixes.
- This is because of absorption of water by the mortar adhereing to the surface of the recycled concrete aggregates present in the mix.
- Also, as the proportion of recycled aggregates in the mix increases, the ultrasonic pulse velocities show higher readings in the first 24 hours.
- The UPV values show similar trends to the UPT values as well as strength tests on the hardened properties.

5.4 Concluding remarks

Hence UPT monitoring has distinct advantages over the UPV method because it can be tested on concrete right after curing starts. Since the transition phase of mixes containing high proportions of RCA starts very early, it will be difficult to record initial readings using the UPV method. Also UPT uses lower frequency of probing, which shows the results magnified and clear. It becomes easy to quantify the readings of a UPT low frequency test.

CHAPTER 6

CONCLUSIONS AND SCOPE OF FURTHER WORK

6.0 General:

This chapter presents the conclusions derived after obtaining the results for all the mixes undergoing tests for hardened state and fresh state. The conclusions drawn are also in line with the literature work studied for this research.

6.1 Hardened properties:

The conclusions derived after obtaining the results for strength measurements on hardened properties of concrete are as follows:

a) With increase in the proportion of RCA in the mix, the slump value goes down. This means RAC might have problems in transportation, pumpability and/or workability during structural use in construction.

b) There is not a significant difference in the compressive strength values obtained at 28 days for all the mixes. This means RAC can successfully be used as a replacement for NCA in concrete. Also the split tensile values obtained at 28 days for the mixes with replacements were marginally higher.

c) Since water absorption of RAC is high, it necessitates the use of a higher measure of superplasticizers in the mix. Also for the same target mean strength of mix, the water content of a RAC mix would always be higher compared to a NAC mix if SP is not used or is the same.

d) RAC requires higher quality control to ensure that waste concrete is free from impurities as much as possible, the mixing is done properly and ensure sufficient water availability for the hydration of cement.

6.2 Fresh properties:

a) For mixes with higher proportion of RCA(i.e 60% and 30%), the semi solid phase is shorter compared to that of NCA which lasts for upto 3.5 to 4 hours. The maximum bond development occurs during the transition phase.

b) The transition phase stops earlier for RCA and the solid phase sets in early for higher proportions of RCA in the mix.

c) As seen in this experiment, UPV results did not show a significant difference in the readings of all mixes. Also UPV test is incapable of monitoring the fresh properties during the semi solid and early transition stage of RAC as concrete has not set by then and the test is not feasible.

d) After the initial solid phase, there is a sharp drop in pk-pk values of higher proportion of RAC mixes and they tend to be constant around the end of the transition phase.

e) Variation in properties like slump value of concrete affects the test results.

6.3 Scope of future work:

RAC has tremendous potential in developing countries like India. The use of industrial wastes as well construction waste together in a mix and its effects on the strength properties, fresh properties and durability properties proves to be exciting research work in the future. In addition to this, the presence of both kinds of industrial and construction wastes in concrete and their monitoring using the Ultrasonic Guided Wave testing method also contains bright possibilities. The use of both industrial waste like GGBS, etc and RCA has the potential to eliminate the need for mining new aggregates.

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