Non Destructive Testing and Condition Evaluation of Structural Components of Concrete Bridges

Submitted in partial fulfillment of the Degree of Bachelor of Technology

By:

Rahul Verma – 081515

Anant Gupta – 081612

Akshay Mihir Das - 081626

विद्या तत्व ज्योतिसमः

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DEPARTMENT OF CIVIL ENGINEERING

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY,

WAKNAGHAT

CERTIFICATE

This is to certify that the work titled **"Non Destructive Testing and Condition Evaluation of Structural Components of Concrete Bridges"** submitted by:

1. **Rahul Verma (081515),**
2. **Anant Gupta (081612), and**
3. **AkshayMihir Das (081626);**

in partial fulfillment for the award of degree of Bachelors of Technology in Civil Engineering from Jaypee University of Information Technology, Waknaghat; has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

(Signature of Supervisor)

DR. AMIT GOEL

ASSITANT PROFESSOR

Date: 28/5/12

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It has been a wonderful and intellectually stimulating experience working on **Non Destructive Testing and Condition Evaluation of Structural Components of Concrete Bridges.** We have taken efforts in this project. However, it would not have been possible without the kind support and help of many individuals and organizations. We would like to extend our sincere thanks to all of them.

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Date:

(Rahul Verma; 081515)

(Anant Gupta, 081612)

(AkshayMihir Das; 081626)

ABSTRACT

Non-destructive testing (NDT) and evaluation technology provides the means to evaluate various structural strength parameters of a structure without affecting its functionality and serviceability. Currently, there are a number of NDT equipment available for the in-situ testing and estimation of various structural strength parameters of a concrete structure like compressive strength, quality of concrete, reinforcement corrosion and cover, etc. Selection of a particular NDT method depends upon proper consideration of a number of related aspects, besides the geometrical and structural properties of the structure that is to be tested.

In this study, various non-destructive testing and evaluation methods are used to estimate each of the various strength parameters of structural components of a concrete bridge. The test data from each of the employed method is analyzed, and a relative comparison of effectiveness of these methods in parameter estimation is made. This relative comparison is based on various related aspects like accuracy and reliability, overall cost of equipment and operation, comprehensiveness of the method to give detailed and varied information, time and resources required, ease of operation of the equipment, and ease of data analysis. Based on this comparison, the study provides suggestions to enable one to take informed decisions regarding the choice of methods for estimation of relevant strength parameters of concrete structural components.

(Signature of Supervisor)

DR. AMIT GOEL

ASSITANT PROFESSOR

Date: 28/5/12

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Chapter 1: INTRODUCTION

Structural condition evaluation for concrete structures may be performed for estimation of remaining service life and decision on the choice of rehabilitation measure. Ideally such testing should be done without damaging the concrete. The tests available for testing concrete range from the completely non-destructive (where there is no damage to the concrete) through those where the concrete surface is slightly damaged, to semi destructive tests (where the surface has to be repaired after the test).The range of properties that can be assessed using non-destructive tests and partially destructive tests includes fundamental parameters such as density, elastic modulus, strength, surface hardness, surface absorption of concrete, location of reinforcement, its size and distance from the surface. It is also possible to check the quality of workmanship and structural integrity by the ability to detect voids, cracking and delamination.

Typical situations where non-destructive testing may be useful are, as follows:

- estimating the in-situ compressive strength
- judging the uniformity, homogeneity and quality of concrete in relation to standard requirement
- identification of reinforcement profile, measurement of cover and/or examining the condition of reinforcement
- detection of presence of cracks, voids and other imperfections

For the purpose of this project the above mentioned parameters have been determined using the following equipment:

- For in-situ compressive strength estimation of concrete
  - Analog Rebound Hammer
  - Digital Rebound Hammer
  - Cut and Pull Out Test
  - Core Cutter
  - Penetration Resistance Test (Windsor Probe)
  - Ultrasonic Pulse Velocity meter
- For quality estimation of concrete
  - Permeability meter
  - Ultrasonic Pulse Velocity (UPV) meter
- For examining the condition of reinforcement
  - Corrosion Analyzer (Half-Cell Potentiometer)

- Resistivity meter
- For identification of reinforcement profile and measurement of cover
  - Profometer
- For crack detection and visual inspection
  - Video Boroscope
  - Crack Detection Microscope

1.1 Objective

Evaluation of concrete structures using various non-destructive test methods and making a relative comparison of results for estimation of concrete structural strength parameters such as compressive strength, quality and reinforcement, etc.

1.2 Organisation of the report

This report is organised into four chapters. This first chapter introduces NDT and discusses its importance for reinforced cement concrete (RCC) structures. The different NDT equipment that were used for conducting field tests as part of this study are also identified.

In Chapter 2 of the report, various equipment used and methods of conducting tests have been described, along with methodology employed and codes of practise used. Chapter 3 provides results of tests conducted and inferences drawn there from. Chapter 4 presents the conclusion drawn from this study along with some suggested guidelines for conducting the tests, and future scope of work **[12]**.

Chapter 2: METHODS AND EQUIPMENT

In this chapter various equipment used by the authors for field work have been described along with their principles and their codes of practice. The methods of conducting various tests and the methodology employed for each of the equipment have also been discussed.

2.1 ESTIMATION OF COMPRESSIVE STRENGTH

Compressive Strength of a material is its ability to sustain axial compressive stress. A variety of NDT equipment can be used to evaluate the compressive strength of a concrete structure. In this section, various NDT methods and related equipment for determining the compressive strength of concrete bridge components are introduced. The underlying principle for each method, working of equipment, etc. are also discussed in details with the help of field pictures taken during actual field testing by the authors.

2.1.1 Rebound Hammer (Schmidt Hammer):

Rebound Hammer is a device which can be used for measuring the compressive strength of a structure rapidly and very conveniently. It consists of a hammer mass controlled by a spring and a plunger. The plunger is pressed against the concrete surface and the rebound of the mass because of the action of the spring is noted (please refer to: **Figure 1** for the schematic diagram of the rebound hammer and **Figure 2: A** for a disassembled Rebound Hammer). This number is called the Rebound Number or Rebound Index. The corresponding compressive strength can then be read from a graph provided on the body of the hammer.

<u>Code</u>:

The rebound hammer testing can be carried out as per **IS: 13311 (Part2) [2]**.

<u>Principle</u>:

The method is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass strikes.

When the plunger of the hammer is pressed against the concrete surface, the extent of rebound of the spring controlled mass depends on the hardness of the concrete surface. The compressive strength is therefore taken to be related to the surface hardness and the rebound number.

<u>Methodology</u>:

The rebound hammer is tested against a test anvil before the start of a test (**Figure 2: B**). The testing anvil is of steel and has a specified Rebound Index to verify the correct functioning of the hammer. For taking the readings, the rebound hammer can be placed vertically upwards, downwards or horizontally but always perpendicular to the surface. Prior to conducting the test, the surface to be tested should be smooth, clean and dry. Wherever necessary (like for loosely adhering or rough surface), surface treatment is done by using grinding stone or sand paper and further cleansing is done with acetone to remove any dust (**Figure 2: C**). After the surface is prepared, a grid of desired dimension is drawn (**Figure2: D**) and it should be ensured that the grid is made at least 100mm far from the edge of the test surface. The rebound hammer is simply pressed at the prepared location on the grid and the rebound index is noted. The compressive strength corresponding to the rebound index is then directly read from a manufacturer provided graph (**Figure 2: E, F and G**) **[1, 10]**.

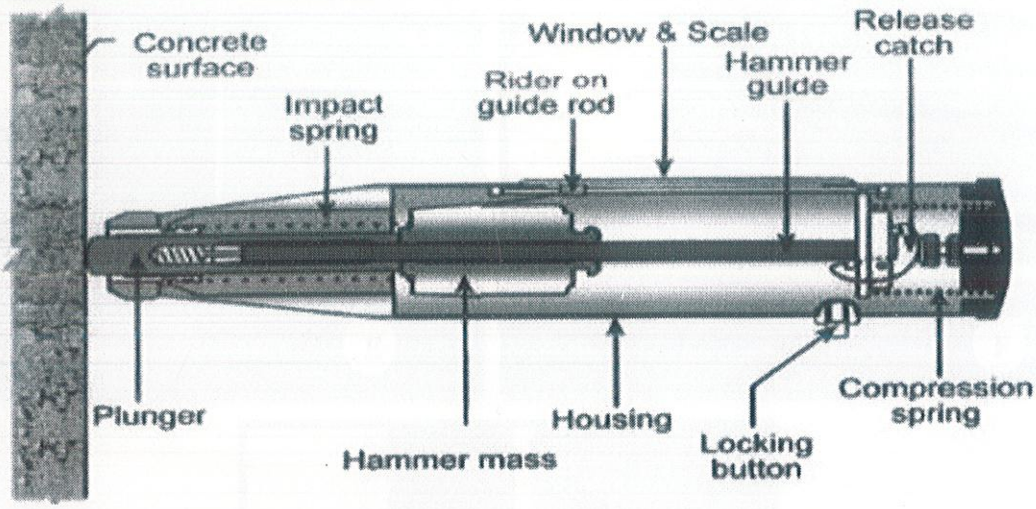

Figure 1: Schematic Diagram of Rebound Hammer [Source: NDT guidelines published by RDSO[1]]

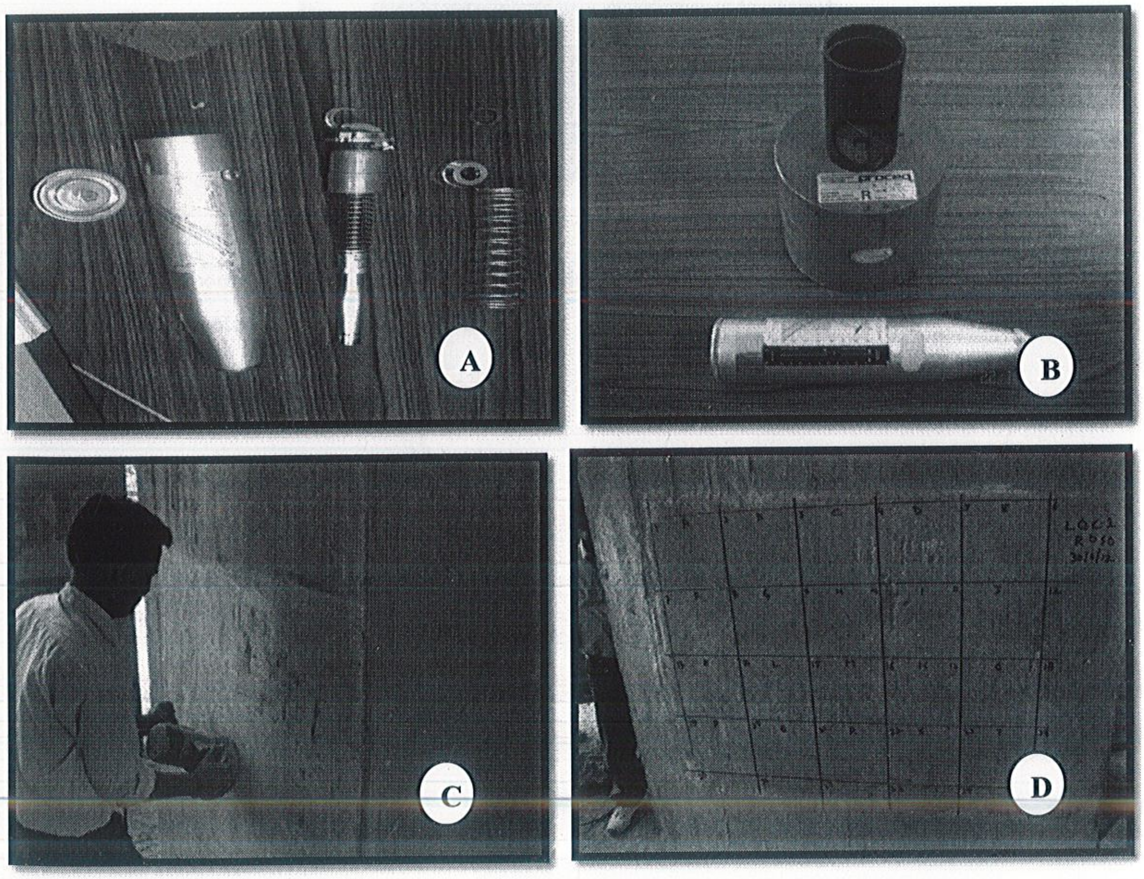

Figure 2: (A) Dismantled Rebound Hammer; (B) Rebound Hammer with Calibration Anvil; (C) Surface Preparation for testing; (D) Grid on the Prepared Surface

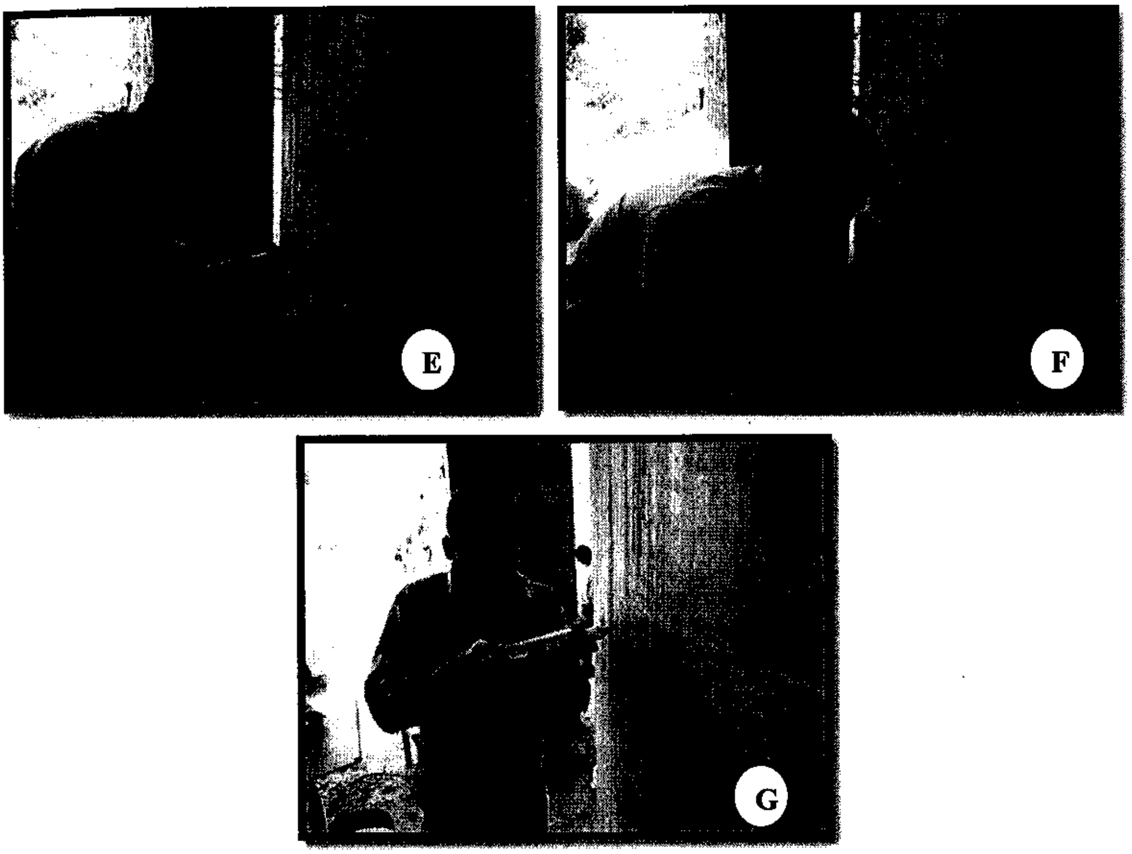

Figure 2: (E) Rebound Hammer placed on the Grid Node; (F) Rebound Hammer Pressed; (G) Rebound Index is noted

2.1.2 Digital Rebound Hammer:

The digital rebound hammer (**Figure 3:** A) is an improvement over the Schmidt Hammer. It is a microprocessor based transducer which converts the rebound of the hammer to electric signals and displays it on the screen in the selected stress units. The device is capable of storing multiple readings and up to 5000 results. It directly displays the mean of the readings and can be directly connected to a computer **[1, 10]**.

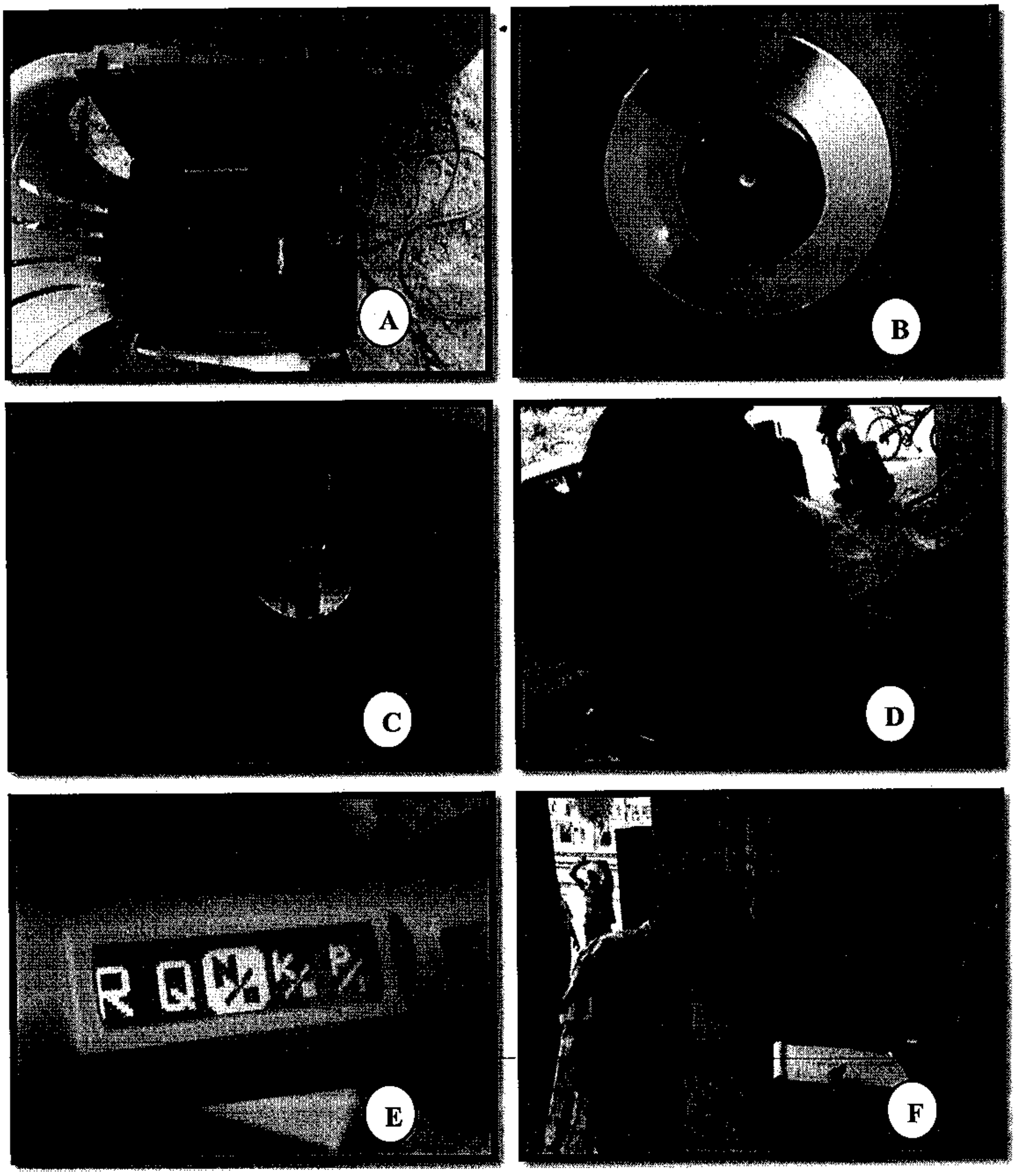

Figure 3:(A) Digital Rebound Hammer; (B) Calibration Anvil for Digital Rebound Hammer; (C) Verifying the functioning of Digital Rebound Hammer; (D) & (E) Inputting required parameters and setting stress units; (F) Conducting the test and taking the reading

2.1.3 Cut and Pull Out Test:

Cut and Pull Out test (CAPO test) is a pull out test used to determine the compressive strength of concrete. A pull out test measures the force or load required to pull out an embedded insert in the concrete mass. The ultimate pull out load is then used to estimate the compressive strength based on previously established relationships. The test is considered superior to the rebound hammer and the penetration resistance test, because large volume and greater depth of concrete are involved in the test.

Code:

The pull out test is conducted as per **ASTM C 900-01[3] & BS-1881 Part 207 [4]**.

Principle:

The CAPO test measures the force required to pull an embedded metal insert with an enlarged head **(Figure 4: J)** from a concrete structure. The pull out strength is proportional to the compressive strength of concrete and is of the same order of magnitude as the direct shear strength of concrete, and is 10 to 30% of the compressive strength. The test subjects concrete to slowly applied load and measures actual strength property of the concrete.

Methodology:

The pullout test can be of two types:

- Pre-planned, where the metal inserts are cast along with concrete
- Insert is fixed by under cutting and subsequent expanding procedure in the hardened concrete of existing structures.

The CAPO test is of the latter type.

While selecting the location for conducting a CAPO test, it should be ensured that reinforcing bars are not within the failure region. The surface at the test location should be flat. An 18 mm hole is cored perpendicular to the surface. A slot is routed in the hole to a diameter of 25 mm and at a depth of 25 mm. A split ring is expanded in the recess and pulled out using a loading ram reacting against a 55 mm diameter counter pressure ring. The concrete in the strut between the expanded ring and the counter pressure ring is in compression. Hence ultimate pullout force is related directly to compressive strength. When the insert is pulled out a conical frustum of concrete comes along with it. The ultimate pullout load measured by the device is converted to an equivalent compressive strength by means of previously established relationships. A large number of correlation studies have reported that compressive strength is linear function of pull out strength **[1, 10]**.

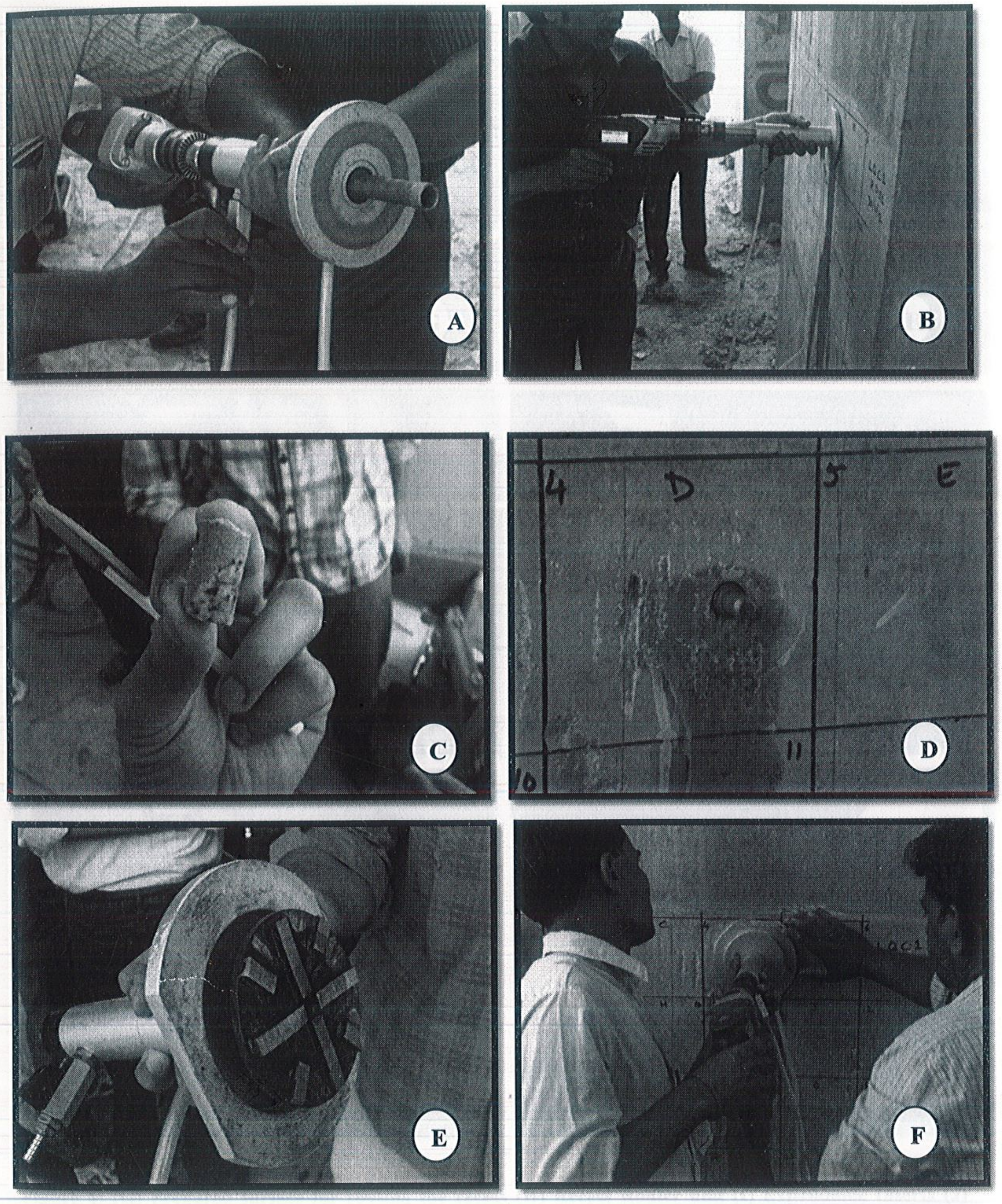

Figure 4: (A) Drill bit for cutting the center hole; (B) Drilling the center hole; (C) Core extracted from the center hole drilled on the test surface; (D) Centering Brass Tap; (E) Diamond Planner (F) Grinding the surface before routing the recess

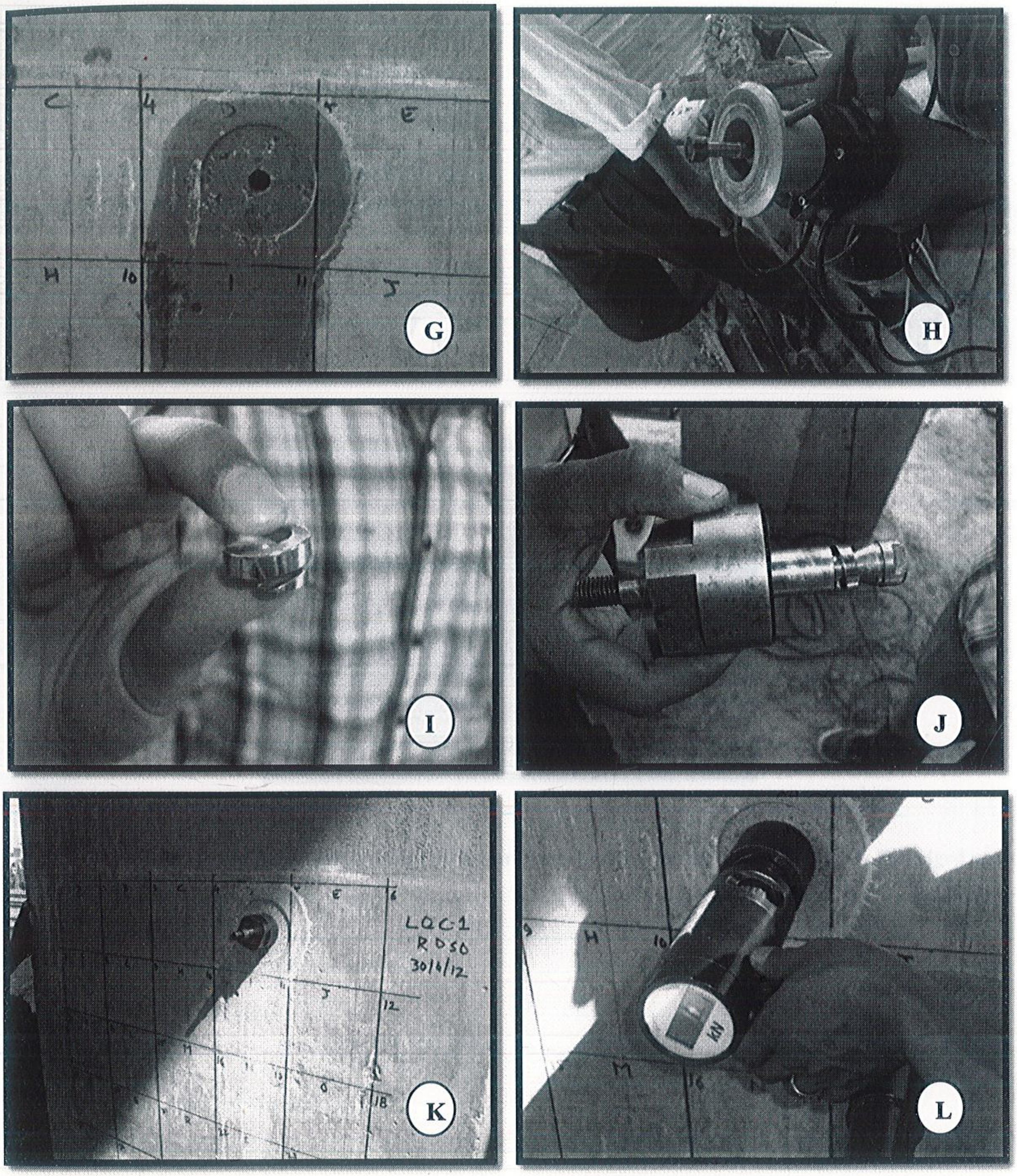

Figure 4: (G) Prepared surface for routing the recess (H) Recess Router unit (I) Expandable Inserts (J) Expansion Unit with Expandable Insert (K) Expansion Unit fixed in the center hole (L) Hydraulic pull machine with electronic gauge

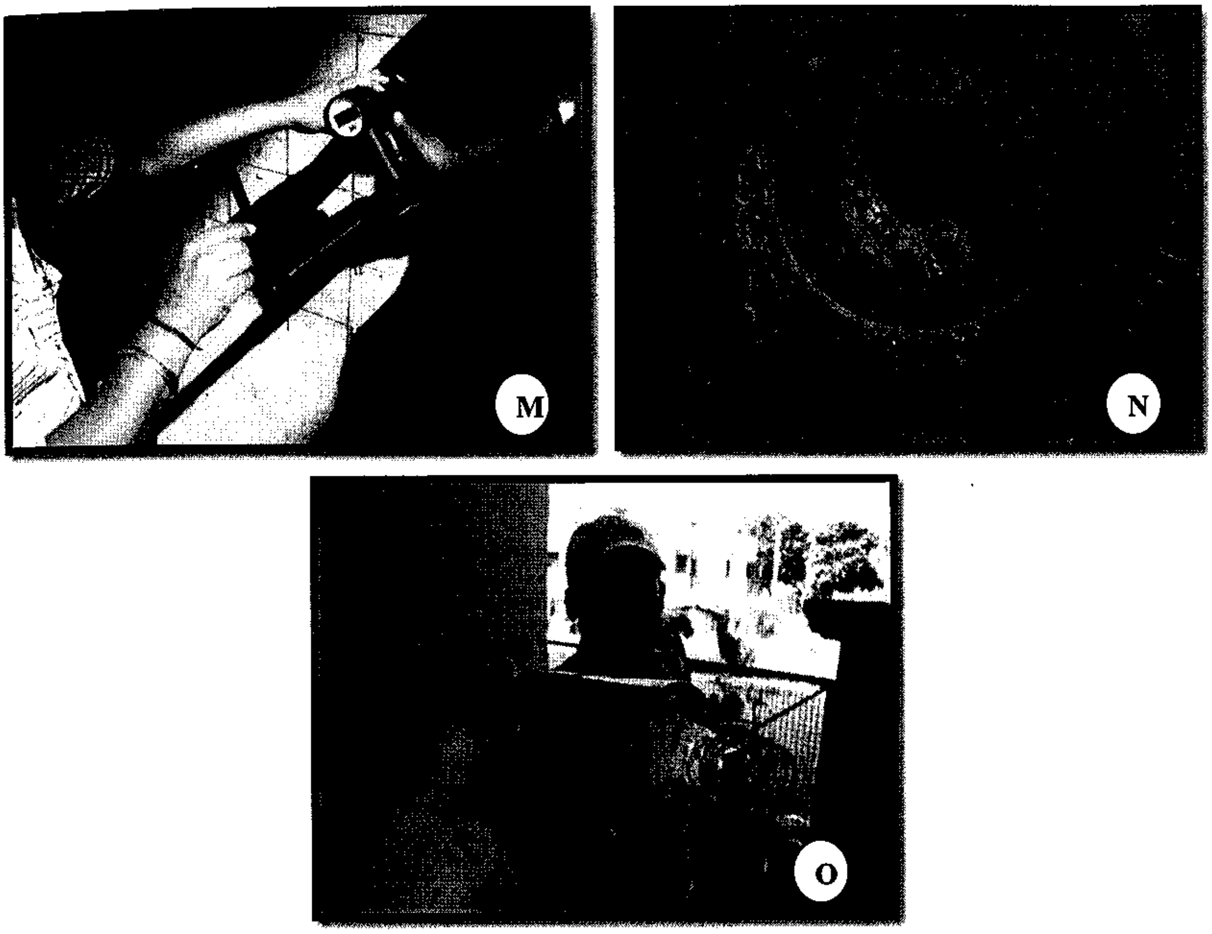

Figure 4: (M) CAPO-Test being performed; (N) Failure rings formed on the test surface; (O) Dislodged conic frustum with the expanded insert

2.1.4 Core Drilling Method:

Core drilling method is a direct way of measuring the actual strength of concrete in the structure. The test location and the number of cores to be taken is of utmost importance. The location should be such that no reinforcement is encountered. If secondary reinforcement or surface reinforcement is unavoidable, strength of core can be taken as 10% less than measured strength.

Code:

- Drilling of cores and compressive strength test are covered in **IS: 1199 [5]**.
- The procedures and influencing factors are to be carefully understood as they affect the measured value and therefore the assessment of the quality of in-place concrete. The provision of **IS 456: 2000 [6]** (vide clause 17.4.3, "Concrete in the member represented by a core test shall be considered acceptable if the average equivalent cube strength of the cores is equal to at least 85% of the cube strength of the grade of concrete specified for the corresponding age and no individual core has strength less than 75 percent").

Methodology:

Cylindrical specimen of 100mm or 150mm diameter are common (**Figure 5: L**); other sizes may also be permitted but the least lateral dimension should not be less than 3 times the maximum size of the aggregates used. The core specimen to be tested should preferably have height of specimen as twice the diameter. If there are difficulties of obtaining samples of such size, the length to diameter ratio is permitted to be lower, but in no case lower than 0.95. The samples are to be stored in water for two days prior to testing and are to be tested in moist condition. The ends of specimens are trimmed, flattened and capped with molten sulphur or high alumina cement or some other permissible capping material to obtain a true flat surface. The specimen is then tested in a compression testing machine **[1, 10]**.

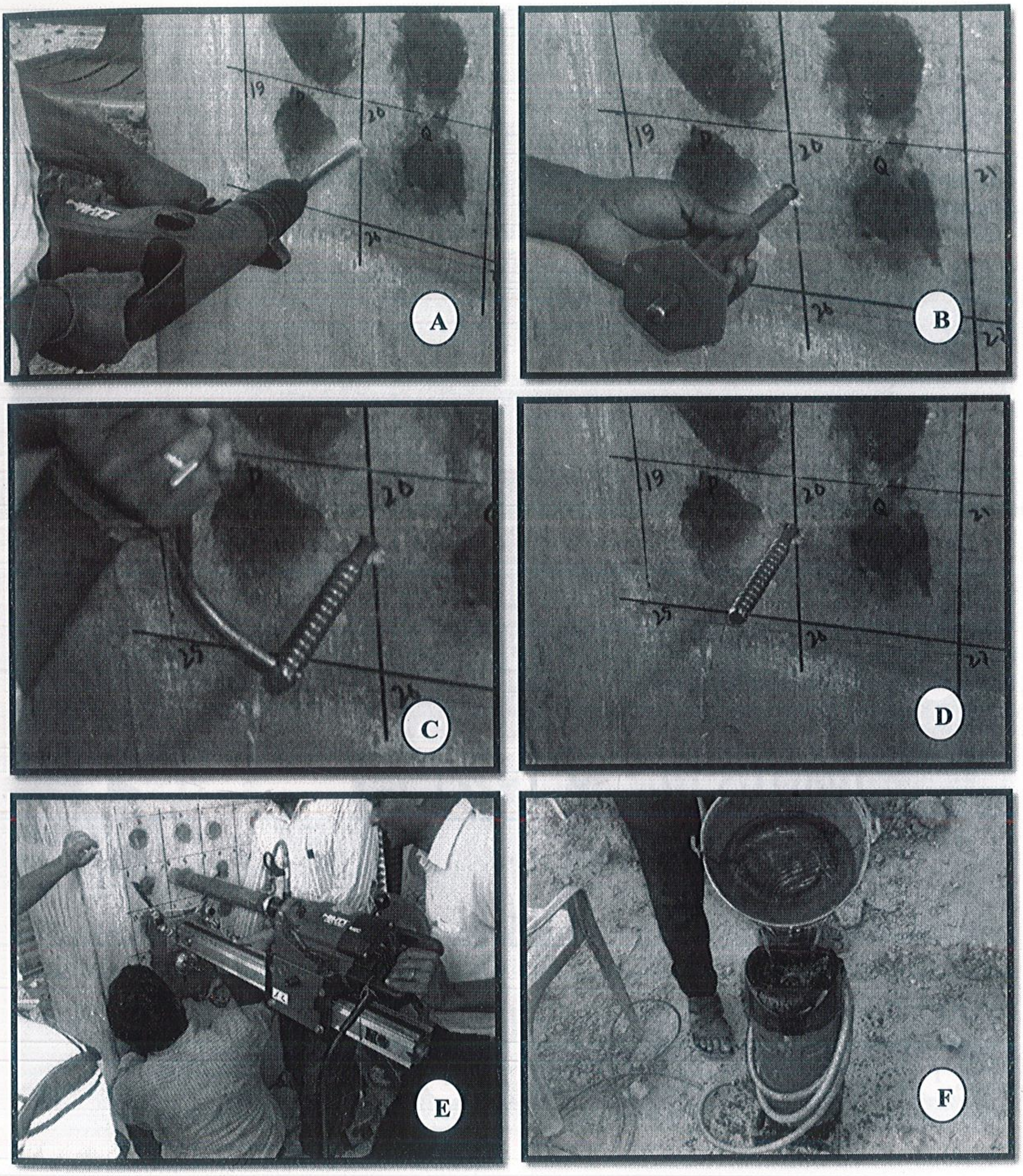

Figure 5: (A) Drilling hole for mounting threaded rod; (B) Flush Anchor; (C) Mounting Threaded Rod; (D) Mounted Threaded Rod; (E) Setting up the drilling assembly; (F) Mechanical Hydraulic Pump

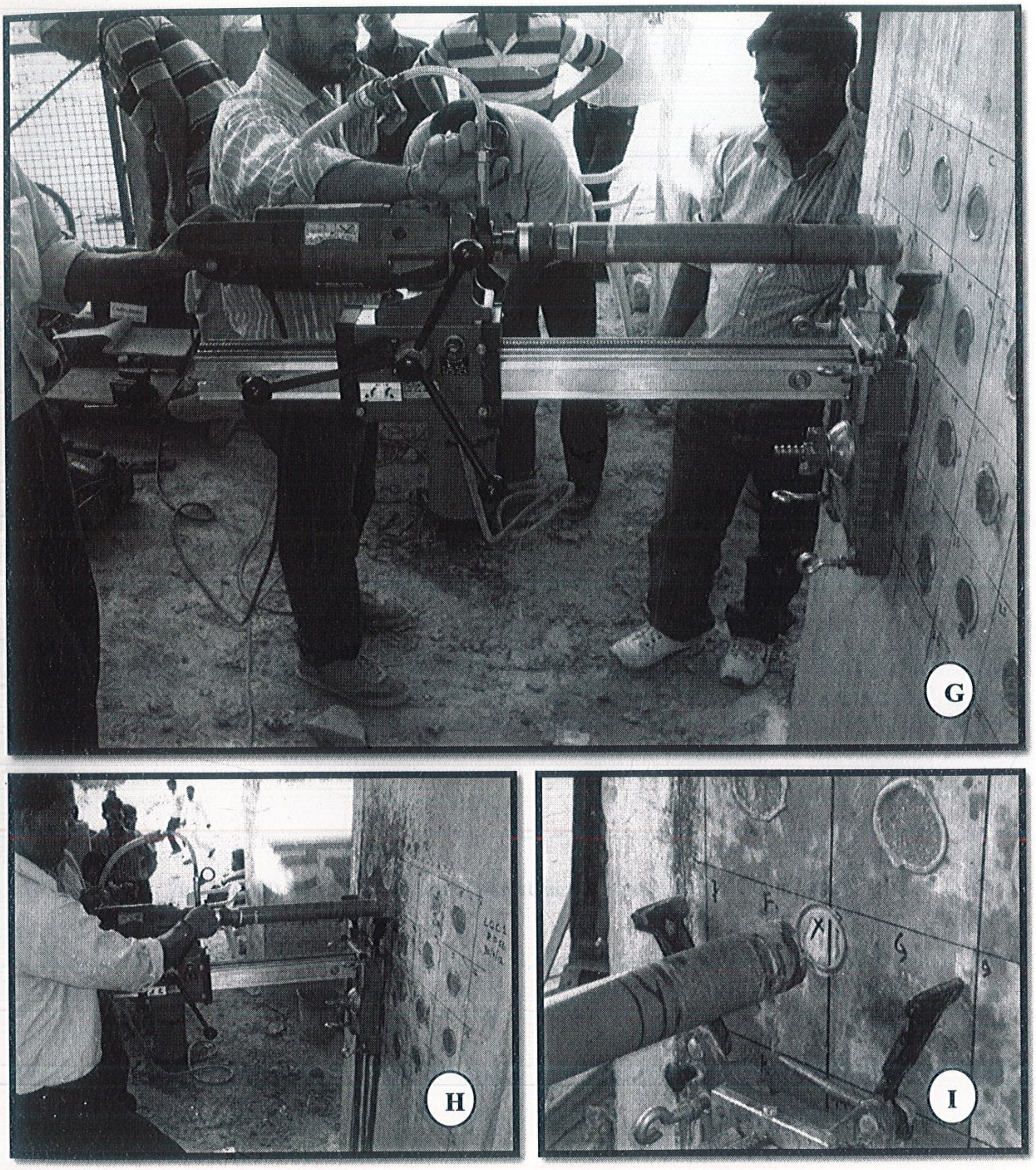

Figure 5: (G) Completely mounted Core-Cutter Assembly; (H) & (I) Extraction of core

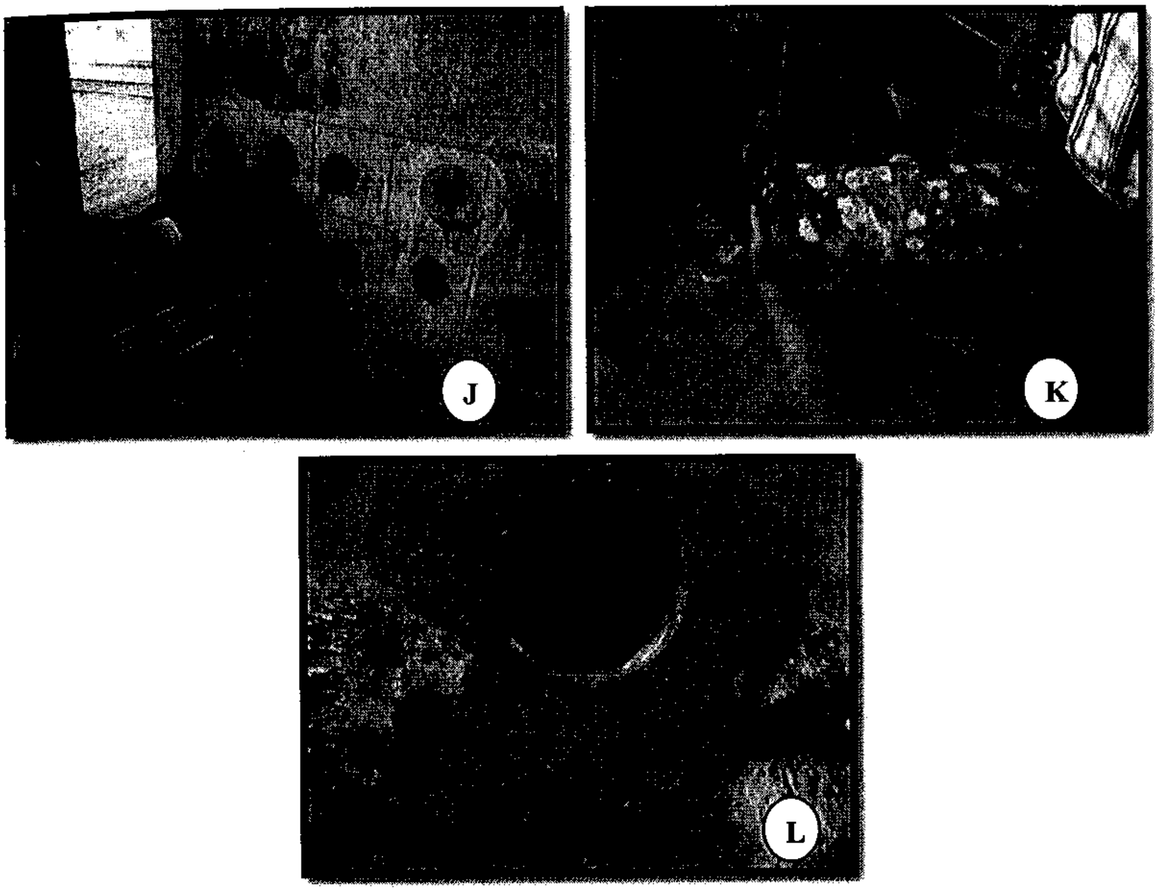

Figure 5: (J) Extraction of core; (K) Extracted core; (L) View of the cavity

2.2 ESTIMATION OF CONCRETE QUALITY

Durability of concrete under aggressive environment, homogeneity of the concrete, presence of cracks, voids and other imperfections; these are some important factors on which bearing capacity of a component in a RCC structure is dependent upon. That's why regular quality assessment of concrete is essential. For this project Permeability Tester and UPV meter were used for the quality assessment of concrete.

2.2.1 Permeability Tester:

Among other factors, bearing capacity of a structural element in a concrete structure is also dependent on its durability under aggressive environmental influences which depends essentially on the quality of the surface layer.

The permeability tester allows a quick and efficient evaluation of the quality of the concrete, with respect to its durability, by measuring the air permeability of cover concrete by a non-destructive method. Its importance has been emphasized as a reliable in-situ measurement of the durability.

Principle:

The rate at which fluid flows through the concrete is a measure of its permeability. The permeability of the concrete at the surface (cover layer) is an excellent indicator of the potential durability and resistance of a particular concrete against the ingress of aggressive media in the gaseous or liquid state.

Description of equipment:

The components of the instrument are given below:

(1) Display Unit (**Figure 6: A**)

(2) Control Unit and vacuum cell

(3) Vacuum pump (**Figure 6: C**)

[NOTE: **Figure 6: D** exhibits complete assembly of Permeability Tester while the test being conducted]

Methodology:

The method involves a two-chamber vacuum cell (**Figure 6: B**) and a pressure regulator (**Figure 6: C**), which ensure that an air flow at right angles to the surface is directed towards the inner chamber. This permits the calculation of the permeability coefficient kT on the basis of a simple theoretical model.

The test requires a dry surface without any cracks and it should be ensured that the inner chamber is not located above any reinforcement bar. Pressure loss is calibrated on a timely basis. After a large change in temperature and/or pressure, 3 to 6 measurements of electrical resistance of the concrete and its mean value is taken for the measurement of coefficient of permeability. The unit measures the pressure increase as a function of time according to a specific sequence. The associated data is automatically collected by the display unit and the permeability coefficient kT and the depth of penetration L of the vacuum are calculated. The measurement takes 2-12 minutes, depending on the permeability of the concrete.

In the case of dry concrete, the quality class of the concrete cover can be read from a table using the kT value. In the case of moist concrete, kT is combined with the electrical concrete resistance ρ (rho) and the quality class is determined from a monogram.

Limitations:

- The determination of kT and p cannot be carried out on wet surfaces as the moisture entering the unit could damage the membrane in the pressure regulator.
- In order to obtain an exact idea of the quality of the cover concrete of a structure or of a finished component, several readings are necessary.
- The quality classification of the cover concrete given in the table and the monogram is related to young concrete i.e. concrete having an age of about 1-3 months. Some experiments conducted have shown that on concrete few years old, the classification in Table and the monogram cannot be directly applied.
- The corrections applied for the effect of moisture content on the permeability, by the measurement of the electrical resistance, generally leads to satisfactory results in the case of young concrete. For old concrete, further investigations are required.
- The test is performed using a vacuum pump with a suction capacity of 1.5 m^3/h and a motor power of 0.13 kW. This pump makes it possible to achieve a vacuum of a few mbar. Pumps of lower power do not reach the same vacuum and it is therefore advisable to use only pumps of similar power.
- The rubber seals can only compensate a certain degree of unevenness present on the surface. If the concrete surface is too uneven, the desired vacuum may not be achieved.
- If the concrete cover is too permeable, the unit may not be able to reach the desired vacuum.

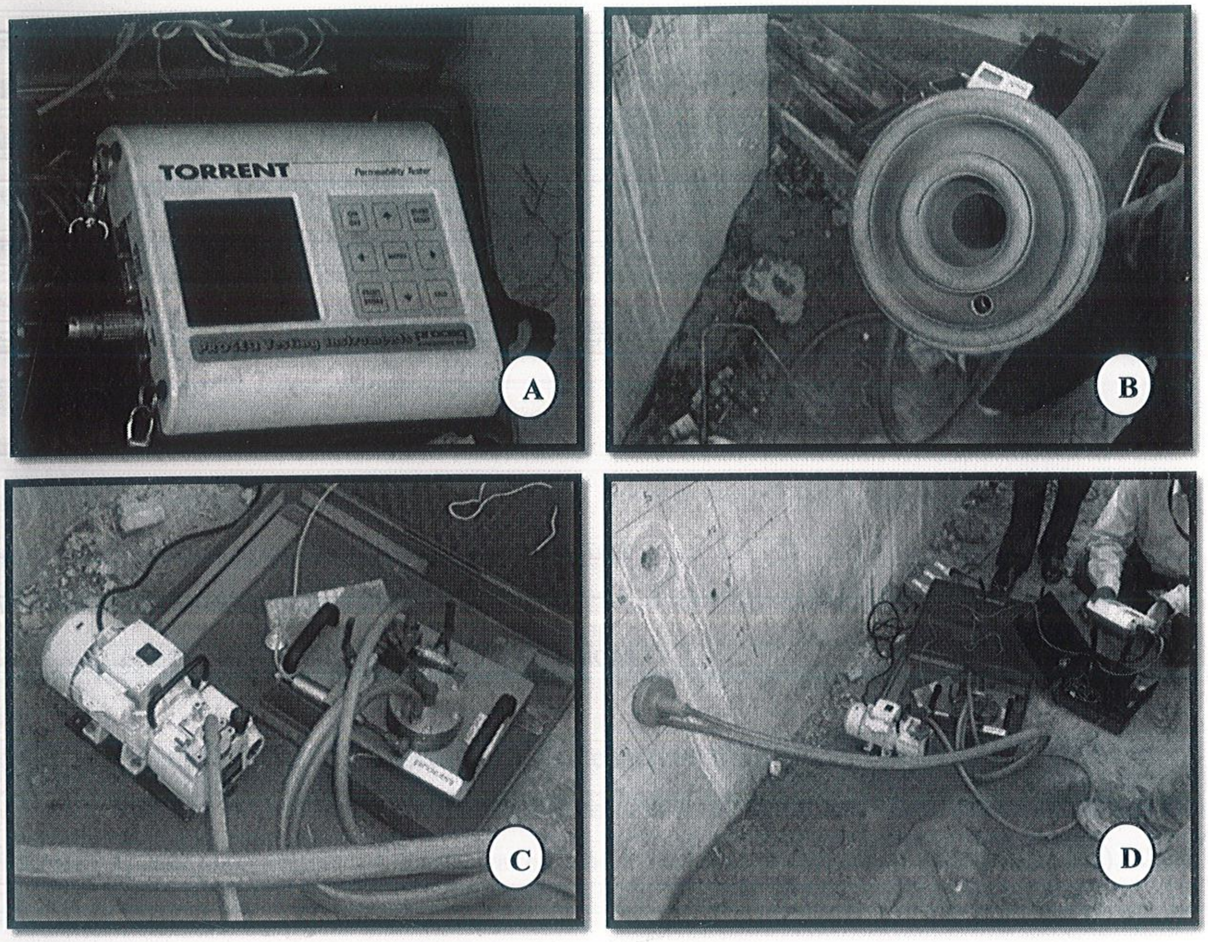

Figure 6:(A) Display Unit; (B) Two-chamber vacuum cell; (C) Pressure Regulator; (D) Complete assembly of Permeability Tester while the test being conducted

2.2.2Ultra Sonic Pulse Velocity Meter (UPV):

UPV uses ultrasonic pulse, generated by an electroacoustic transducer, for testing concrete structures for quality control during new constructions and also for periodic evaluation of a concrete member to measure the changes occurring with time on the properties of the concrete and taking any remedial measure, against deterioration, if necessary.

Code:

The UPV test is conducted as per **IS: 1331-Part 1 [7]**

Object:

The UPV method is used to establish:

- Quality of the concrete used
- Value of dynamic elastic constant of the concrete
- Homogeneity of the concrete
- Presence of cracks, voids and other imperfections

Principle:

When an ultrasonic pulse is induced into the concrete from an electroacoustic transducer, it undergoes multiple reflections at the boundaries of different material phases within the concrete, developing a complex system of stress waves which includes longitudinal (compressional), shear (transverse) and surface (Rayleigh) waves. The receiving transducer detects the onset of the longitudinal waves, which are the fastest.

The velocity of the pulse depends on the elastic properties of the concrete. The inherent principle of assessing the quality of concrete is that comparatively higher velocities are obtained when the quality of concrete in terms of density, homogeneity and uniformity is good. If the quality of the concrete is poor, lower velocities are obtained. Presence of a crack, void or flaw inside the concrete, which comes in the way of transmission of the pulses, attenuates the pulse strength and it passes around the discontinuity, thereby making the path length longer, consequently, lower velocities are obtained **[1, 7, 8]**.

Equipment Used:

(1) Electrical pulse generator (**Figure 8: A**)

(2) Display Unit (**Figure 8: A**)

(3) Transducers (**Figure 8: B**)

(4) Amplifiers

(5) Measuring range

(6) Electronic timing device

Methodology:

The transducers can be mounted on the surface of the concrete member under test, in the following ways (for diagrammatic representations please refer **Figure 7**):

1) Direct Transmission (on opposite faces): This arrangement is the most preferred arrangement in which transducers are kept directly opposite to each other on opposite faces of the concrete. The transfer of energy between transducers is maximized in this arrangement. The accuracy of velocity determination is governed by the accuracy of the path length measurement. A minimum path length of 150 mmis recommended for the direct transmission method involving one unmolded surface. For this project Direct Transmission method was used.
2) Semi-direct Transmission: This arrangement is used when it is not possible to have direct transmission (may be due to limited access). It is less sensitive as compared to direct transmission arrangement and there may be some reduction in the accuracy of path length measurement.
3) Indirect or Surface Transmission: Indirect transmission should be used when only one face of the concrete is accessible (when other two arrangements are not possible). It is the least sensitive out of the three arrangements. For a given path length, the receiving transducer get signal of only about 2% or 3% of amplitude that produced by direct transmission. Furthermore, this arrangement gives pulse velocity measurements which are usually influenced by the surface concrete which is often having different composition from that below surface concrete. Therefore, the test results may not be correct representative of whole mass of concrete. The indirect velocity is invariably lower than the direct velocity on the same concrete element. This difference may vary from 5% to 20% depending on the quality of the concrete. Wherever practicable, site measurements should be made to determine this difference. A minimum of 400 mm for the surface probing method along an unmolded surface **[1, 7, 8, 10, 12, 14]**.

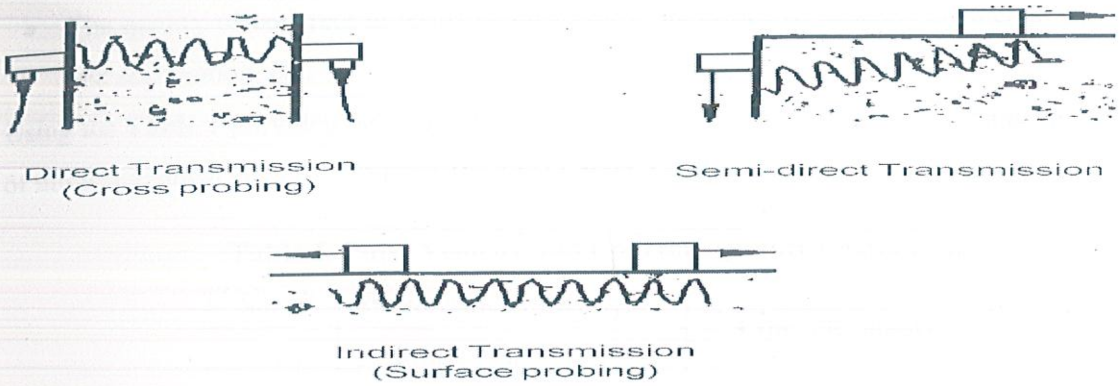

Figure 7: Various Methods of UPV Testing

[Source: Guidelines on Non-Destructive Testing, RDSO [1]]

Test Procedure:

Before the transducers are mounted, the surface of the concrete element is prepared. If there is very rough concrete surface, it is smoothened and area of the surface where the transducer is to be placed is cleaned to remove any kind of deleterious materials. To ensure that the ultrasonic pulses generated at the transmitting transducer pass into the concrete and are then detected by the receiving transducer, adequate acoustical coupling between the concrete and the face of each transducer is used (**Figure 8: C and D**). The couplants typically used are petroleum jelly, grease, liquid soap and kaolin glycerol paste.

The ultrasonic pulse produced by the transmitting transducer after traversing a known path length (L) in the concrete, is converted into an electrical signal by the receiving 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 (**Figure 8: E**). The pulse velocity (V) is given by **Eq. 1**:

$$V = \frac{L}{T} \qquad \text{....(Eq. 1)}$$

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.

Interpretation of Results:

The ultrasonic pulse velocity of concrete is mainly related to:

- Density and modulus of elasticity of the concrete which is in turn dependent upon the materials and mixes proportions used in making concrete as well as the method of placing, compaction and curing of concrete.

- The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks and segregation, etc.

Using the **Table 1** provided below quality of the concrete in structures can be characterized in terms of ultrasonic pulse velocity (**Source: IS: 13311 Part-1, [7]**):

Table 1: Pulse Velocity and Concrete Quality relationship

Serial No.	Pulse velocity (by Cross Probing, in km/sec)	Concrete quality
1	Above 4.5	Excellent
2	3.5 to 4.5	Good
3	3.0 to 3.5	Medium
4	Below 3.0	Doubtful

The dynamic Young's modulus of elasticity (E) of the concrete may be determined from the pulse velocity and the dynamic Poisson's ratio (μ) using the following **Eq. 2 [7]** as mentioned below:

$$E = \frac{\rho(1+\mu)(1-2\mu)V^2}{1-\mu} \quad \text{.... (Eq. 2)}$$

Where:

E =dynamic Young's Modulus of elasticity, in MPa

ρ = density, in kg/m^3, and

V = pulse velocity, in m/second.

The above relationship can also be expressed as:

$$E = \rho f(\mu)V^2 \quad \text{.... (Eq. 3)}$$

Where:

$$f(\mu) = \frac{(1+\mu)(1-2\mu)}{1-\mu}$$

The value of the dynamic Poisson's ratio varies from 0.20 to 0.35, with an average value of 0.24. However, it is desirable to have an independent measure of it for the particular type of concrete under evaluation. The dynamic Poisson's ratio may be obtained from measurements on concrete test-beams of the pulse velocity (V) along with length (l) of the beam and the fundamental resonant frequency (n) of the beam in longitudinal mode of vibration. From these measurements, the factor $f(\mu)$ is calculated by **Eq. 4**:

$$f(\mu) = \frac{(2nl)^2}{V^2} \quad \text{.... (Eq. 4)}$$

Where:

n = fundamental resonant frequency, in cycles per second, and

I = length of specimen in m.

Influence of Test Conditions:

1) Influence of Surface Conditions and Moisture Content of Concrete:

Finish of contact surface under test affects acoustical contact between the transducer and the concrete surface. When the concrete surface is rough and uneven, it is necessary to smooth the surface to make the pulse velocity measurement possible.

In general, pulse velocity through concrete increases with increased moisture content of concrete. This influence is more for low strength concrete than high strength concrete. The pulse velocity of saturated concrete may be up to 2 percent higher than that of similar dry concrete.

2) Influence of Temperature of Concrete:

Variations of the concrete temperature between 5 and 30°C do not significantly affect the pulse velocity measurements in concrete. At temperatures between 30 to 60°C there can be reduction in pulse velocity up to 5 percent. Below freezing temperature, the free water freezes within concrete, resulting in an increase in pulse velocity up to 7.5 percent. **Table 2** demonstrates Effect of temperature on pulse transmission.

Table 2: Effect of temperature on pulse transmission

BS-1881 (Part: 203; 1986) [8]

Temperature °C	**Correction to the measured pulse velocity (%)**	
	Air dried concrete	**Water saturated concrete**
60	+5	+4
40	+2	+1.7
20	0	0
0	-0.5	-1
- 4	-1.5	-7.5

3) Influence of Stress:

Micro-cracks develop in concrete when it is subjected to a stress greater than about 60 percent of the ultimate strength of the concrete. This results in reduction of pulse velocity. When the pulse path is perpendicular to the direction of a uniaxial compressive stress in a member, this influence is likely to be the greatest.

4) Influence of Reinforcing Bars:

The pulse velocity measured in reinforced concrete in the vicinity of reinforcing bars is usually higher than in plain concrete of the same composition. The proximity of the measurements to the reinforcing bar, the diameter and number of the bars and their orientation with respect to the path of propagation affects the apparent increase in pulse velocity.

5) Influence of Path Length, Shape and Size of the Concrete Member:

During the pulse velocity measurements, path lengths should be sufficiently long so as to avoid any error introduced due to the inherent heterogeneity of the concrete. **Table 3** given below can be used to examine effect of specimen dimension on pulse transmission.

Table 3: Effect of specimen dimension on pulse transmission

BS 1881 (Part 203: Year; 1986) [8]

Transducer Frequency in KHz	**Minimum lateral dimension in mm for Pulse specimen velocity in concrete in Km/s**		
	$V_c = 3.5$	$V_c = 4.0$	$V_c = 4.5$
24	146	167	188
54	65	74	83
82	43	49	55
150	23	27	30

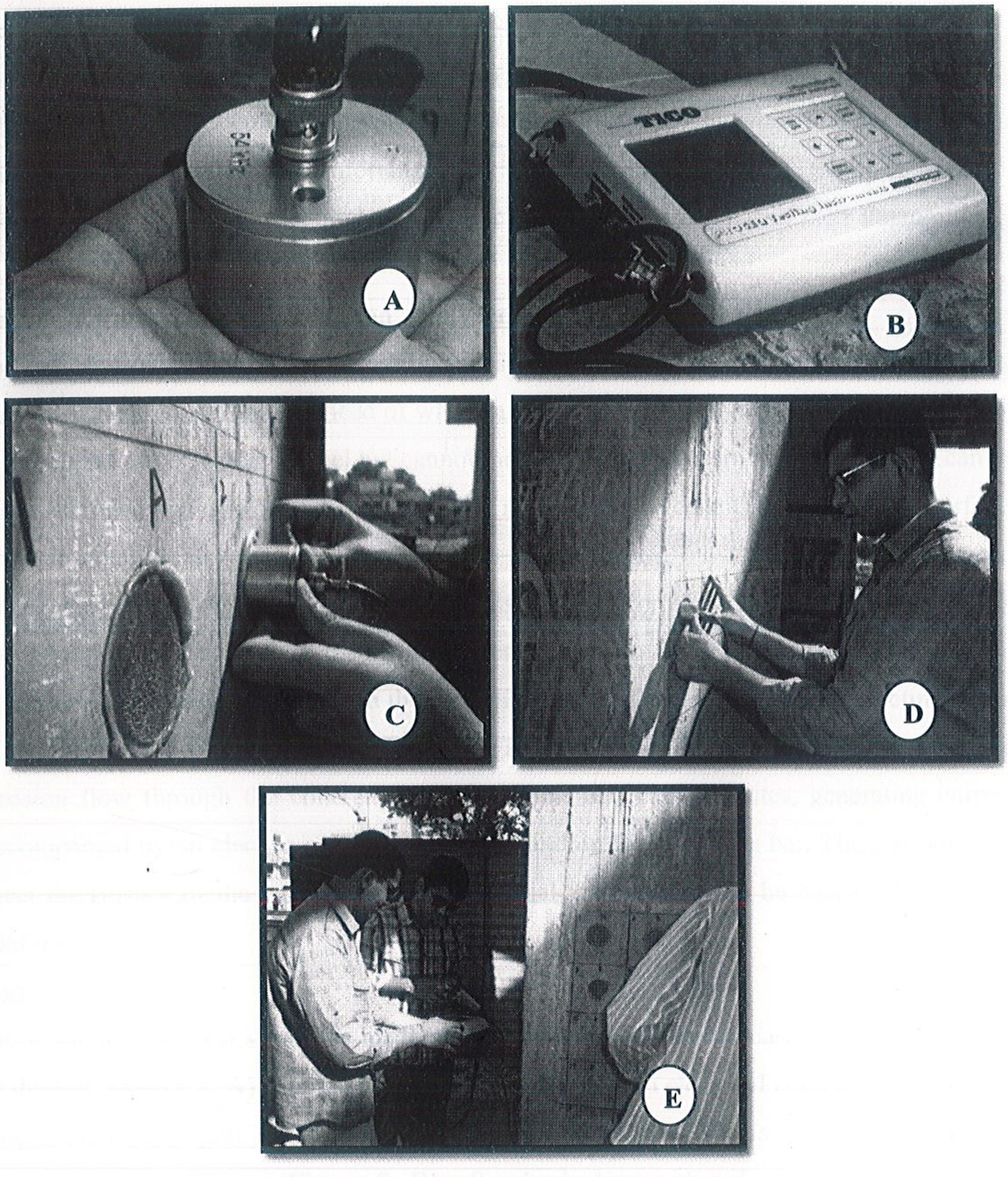

Figure 8: (A) Transducer (54 KHz); (B) U.P.V. Display Unit; (C) & (D) Acoustical coupling between concrete and the face of transducer using grease as couplant; (E) Transit time of the ultrasonic pulse measured by the electronic timing circuit which is further used for the calculation of velocity

2.3 ASSESSMENT OF REINFORCEMENT

For effective inspection and monitoring of concrete bridges, the condition assessment of reinforcement is an important step. Even for deciding appropriate repair strategy for a distressed concrete bridge, the determination of corrosion status of reinforcing bars is a must. Most of NDT methods used for corrosion assessment are based on electrochemical process. For this project Half Cell Potentiometer and Resistivity Meter were employed for condition assessment of reinforcement.

2.3.1 Half Cell Potentiometer Test/Corrosion Analyzer:

Electrochemical Half-cell Potentiometer test provides a quantitative assessment of reinforcement corrosion over a wide area without the need of wholesale removal of the concrete cover. The method detects the likelihood of corrosion of steel but cannot indicate the rate of corrosion. Distinction can be made between corroded and non-corroded locations by making measurements over the whole surface.

Principle:

Corrosion analyzer is based on electro-chemical process to detect corrosion in the reinforcement bars of structure. During active corrosion, the steel-concrete system in the reinforced concrete element represents short-circuited galvanic cell, with the corroding area of the reinforcement bar acting as the anode, the passive surface as the cathode and concrete as electrolyte. The excess electrons generated during corrosion flow through the concrete between anodic and cathodic sites, generating current which is accompanied by an electric potential field surrounding the corroding bar. The equipotential lines intersect the surface of the concrete and the potential at any point can be measured using the half potential method.

Methodology:

Before starting the test, the test surface is made wet (this should be done at least 45 minutes prior to conducting the test, **Figure 9: A**). To measure half-cell potentials, an electrical connection is made to the steel reinforcement in part of the member you wish to assess. This is connected to a high impedance digital millivolt meter (**Figure 9: B**), often backed up with a data logging device. The other connection to the millivolt meter is taken to a copper/copper sulfate or silver/silver chloride half-cell (**Figure 9: C**), which has a porous connection at one end which can be touched to the concrete surface. This will then register the corrosion potential of the steel reinforcement nearest to the point of contact. By measuring results on a regular grid and plotting results as an equipotential contour map, areas of corroding steel may readily be seen **[1,10]**.

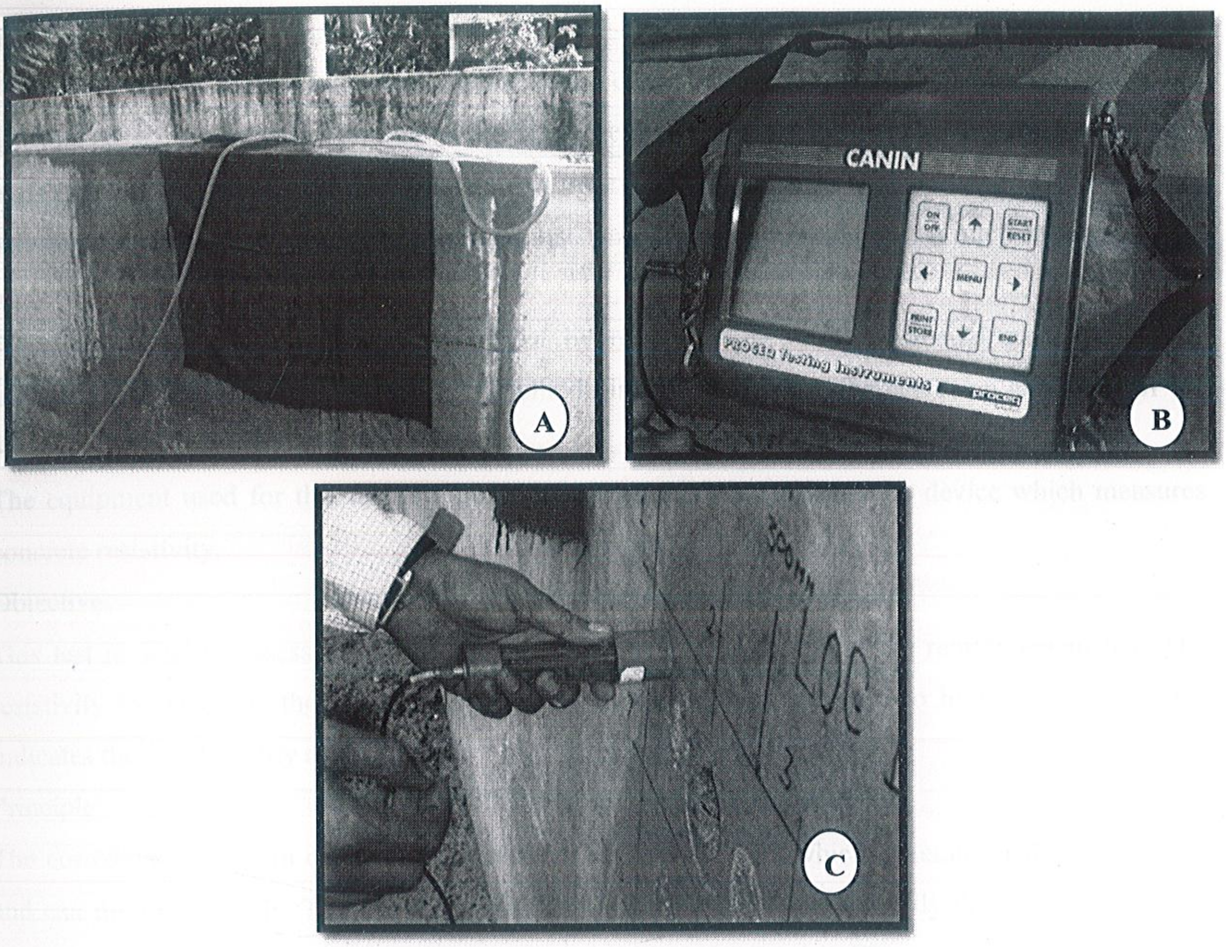

Figure 9: (A) Test surface being made wet; (B) Digital Millivolt Meter; (C) Copper/Copper Sulfate Half-Cell

2.3.2 Resistivity Test:

This test is used to measure the electrical resistance of the cover concrete. Once the reinforcement bar loses its passivity, the corrosion rate depends on the availability of oxygen for the cathodic reaction. It also depends on the concrete, which controls the ease with which ion migrates through the concrete between anodic and cathodic site. Electrical resistance, in turn, depends on the microstructure of the paste and the moisture content of the concrete.

The combination of resistance measurement by resistivity meter and potential measurement by corrosion analyzing instrument give very reliable information about the corrosion condition of the rebar.

The equipment used for this test is a portable, battery operated, four probe device which measures concrete resistivity.

Objective:

This test is used to assess the probability or likelihood of corrosion of the reinforcement bar. The resistivity increases as the capillary pore space in the paste is reduced, so higher resistivity also indicates the good quality of concrete.

Principle:

The corrosion of steel in concrete is an electrochemical process, which generates a flow of current and can dissolve metals. The lower the electrical resistance, the more readily the corrosion current flows through the concrete and greater is the probability of corrosion. The resistivity is numerically equal to the electrical resistance of a unit cube of a material and has units of resistance (in ohms) times length. The resistance (R) of a conductor of area A and length L is related to the resistivity ρ using **Eq. 5** as follows:

$$R = \frac{\rho L}{A} \quad \text{.... (Eq. 5)}$$

The schematic diagram showing the set up for measurement of concrete resistivity is shown below (refer **Figure 10**).

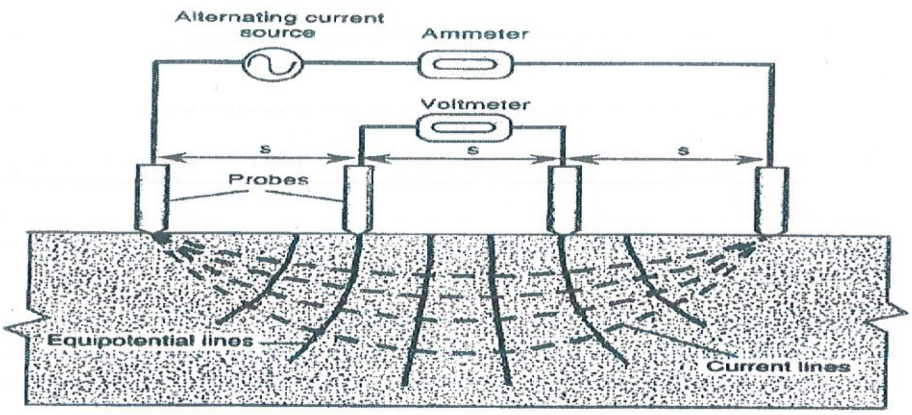

Figure 10: Setup for Measurement of concrete resistivity

[Source: Guidelines on Non Destructive Testing, RDSO [1]]

This is based on the classical four electrode system in which four equally spaced electrodes are electrically connected to the concrete surface. The outer electrodes are connected to a source of alternating current, and the two inner electrodes are connected to voltmeter.

Methodology:

Before starting the test, the test surface is made wet (this should be done at least 45 minutes prior to conducting the test). One of the equipment available for measurement of resistivity is Resistivity Meter. It consists of a set of four probes fitted with super conductive foam tips (**Figure 11: B**) to ensure full contact on irregular surfaces. Once the probes are kept in contact with the concrete surface, the LCD display will indicate the resistivity directly on the screen **[1, 10]**. The limits of possible corrosion are related with resistivity as under:

Table 4: Relationship of Resistivity with Limits of possible corrosion

(Source: Guidelines on Non Destructive Testing, RDSO [1])

S.No.	Resistivity	Limits of Possible Corrosion
1.	With ρ =12 K W cm	Corrosion is improbable
2.	With ρ = 8 to 12 K W cm	Corrosion is Possible
3.	With ρ = 8 K W cm	Corrosion is fairly certain

Here ρ (rho) denotes resistivity.

Limitations:

The method is slow because it covers small area at a time. The system should not be used in isolation because it gives better indication of corrosion in reinforced concrete if used in combination with half - cell potentiometer.

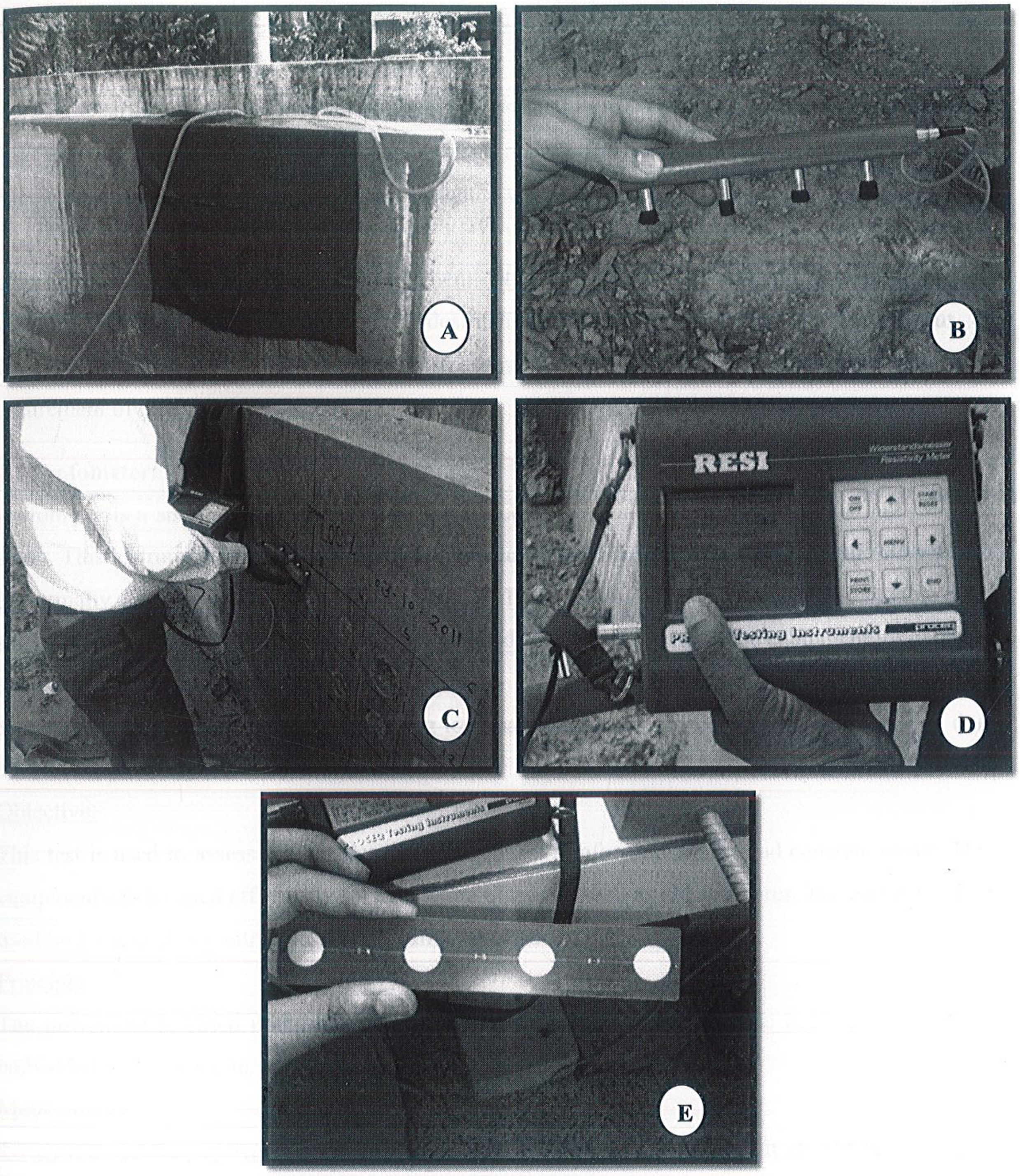

Figure 11:(A)Test surface being made wet, (B) Resistivity Probe; (C) Test being performed; (D) Resistivity Meter Display Unit; (E) Calibration Strip used to ensure proper functioning of the Resistivity Meter

2.4 IDENTIFICATION OF REINFORCEMENT PROFILE AND MEASUREMENT OF COVER

In any RCC structure, adequate cover thickness is essential to prevent corrosion of the reinforcement. In old structures, sometimes the detailed drawings are not traceable due to which it becomes very difficult to calculate the strength of the structure which is essentially required for finalizing the strengthening scheme. Sometimes, the bridges are to be checked from strength point of view to permit higher axle load and in absence of reinforcement details it becomes very difficult to take a decision. Sometimes during conducting some non-destructive tests, like extraction of core, layout of reinforcement grid is needed. For these reasons identification of reinforcement profile and measurement of cover is necessary.

2.4.1 Profometer:

Profometer is a small versatile instrument for detecting location, size of reinforcement and concrete cover. This instrument is also known as **rebar locator**. This is a portable and handy instrument which is normally used to locate the reinforcement on LCD display. This instrument is available with sufficient memory to store measured data. Integrated software is loaded in the equipment for carrying out and printing statistical values.

The equipment is quite handy and weighing less than two kg. It works on normal batteries and thus does not require any electrical connection.

Objective:

This test is used to assess the location and diameter of reinforcement bars and concrete cover. This equipment can be used effectively for evaluation of new as well as old structures. The method can be used both for quality control as well as quality assurance.

Principle:

The instrument is based upon measurement of change of an electromagnetic field caused by steel embedded in the concrete.

Methodology:

To ensure satisfactory working of profometer and to get accurate results, it should be calibrated before starting the operations and at the end of the test. For this purpose, test block provided with the instrument should be used. To check the calibration accuracy, the size and cover of the reinforcement of the test block is measured at different locations on test block and the recorded data should match with the standard values prescribed on the test block.

Path measuring device and **spot probes (Figure 12: A, B, C and D)** are together used for path measurements and scanning of reinforcement bars. These are connected with profometer with cables and are moved on the concrete surface for scanning the reinforcement bars and measuring the spacing. As soon as the bar is located, it is displayed on the screen. Once the bar is located, it is marked on the concrete surface.

Diameter probe is used for measuring the diameter of bars. It is also connected with profometer by one cable. After finding out the location of rebar, the diameter probe is placed on the bar parallel to bar axis. Four readings are displayed and mean value of these readings is taken as diameter of bar.

Depth probe (Figure 12: E) of the profometer is used to measure the cover. It is also connected with profometer by cable and is placed exactly on the bar As soon as, the depth probe is above a rebar or nearest to it, it gives an audio signal through a short beep and visual display. Simultaneously, the measured concrete cover is stored in memory.

For carrying out this test, the proper assess is essential. For this purpose, proper staging, ladder or a suspended platform may be provided. Before actual scanning, marking is done with chalk on the concrete surface by dividing it into panels of equal areas **(Figure 12: F)**.

Advantages and Limitations:

This is a purely non-destructive test for evaluation of concrete structures particularly old structures. The method is very fast and gives quite accurate results if the reinforcement is not heavily congested. The equipment is very light and even one person can perform the test without any assistance.

The equipment is not being manufactured in India and needs to be imported. Some of the Indian Firms are marketing the instrument and this is costly equipment.

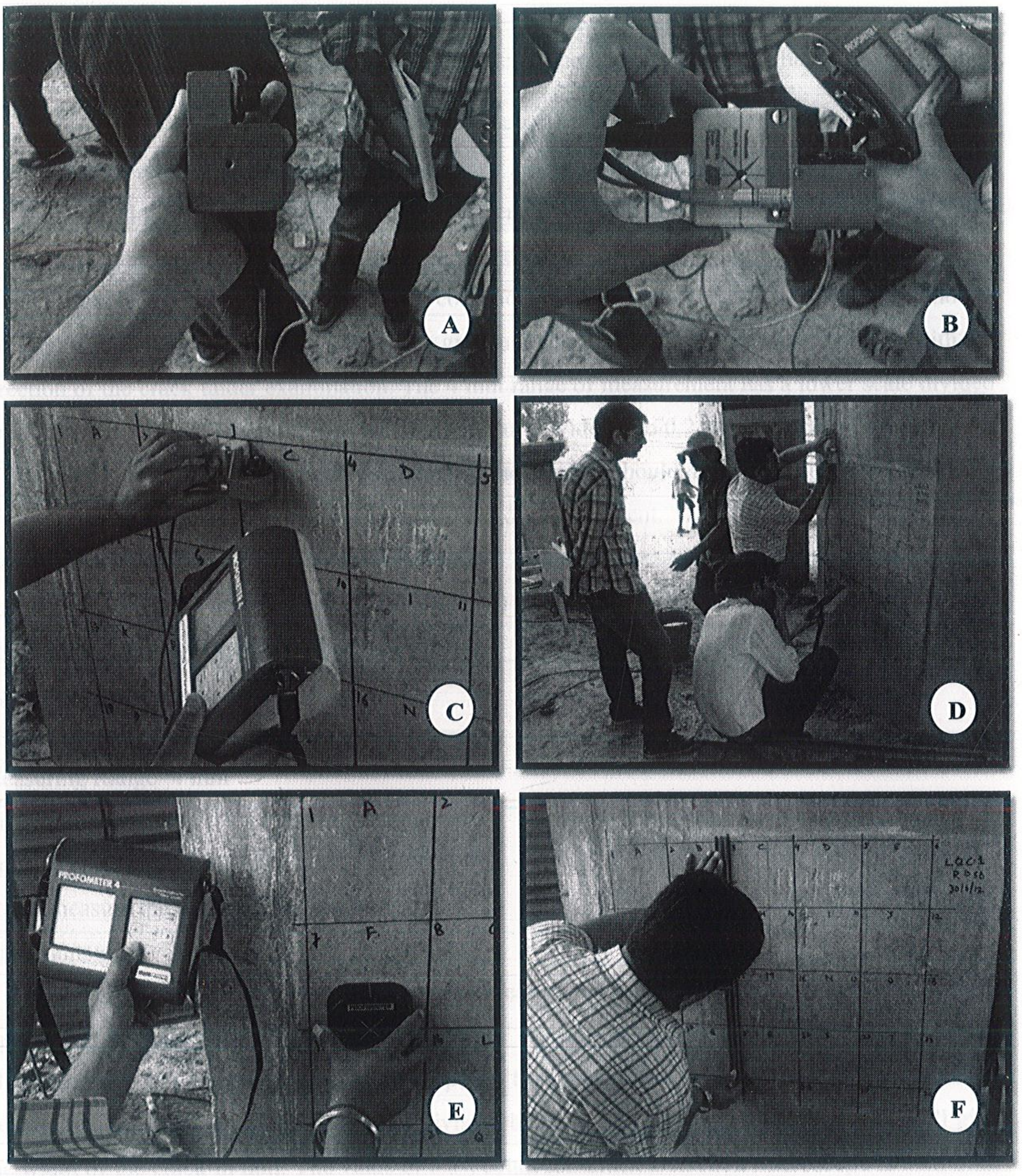

Figure 12: (A) & (B) Spot Probe; (C) & (D) Scanning reinforcement bars using Spot Probe; (E) Cover being measured using Depth Probe; (F)Demarcation of reinforcement bars on surface.

2.5 CRACK DETECTION

In this section NDT methods for crack detection are described. Crack Detection Microscope and Video Boroscope were the equipment used for conducting the field tests.

2.5.1 Crack Detection Microscope:

It is a high quality product designed for measuring crack width, both in concrete and other materials. British made, the high definition microscope is connected to an adjustable light source which provide a well – illuminated image under all working conditions. The image is focused by turning the knob at the side of the microscope and the eye-piece graticule can be rotated through 360^0 to align with the direction of the crack under examination. The 4 mm range of measurement has a lower scale divided into 0.2 mm divisions. These 0.2 mm divisions are sub-divided into 0.2 mm divisions. Current Codes of practice **[1, 10]**, state that calculated maximum crack widths should not exceed certain values:

E.g.: 0.3 mm in **BS 8110: Part 2 [9]** for most types of environment. This value is 15 divisions on the graticule.

The Crack Detection microscope **(Figure 13: A)** is very easy to use and comes with simple instructions in a wooden carrying box.

Specifications

Magnification= 40 times

Measuring Range=4 mm

Divisions=0.02 mm

Advantages

It can measure the width of fine cracks.

Disadvantages

It can measure visible cracks only. Also, it cannot measure the depth of cracks.

Operational Procedure

Place the scale of Crack Detection Microscope on the crack. Read the number of divisions which falls on the crack. Multiply the number of division by least count of the microscope. This will give the width of the crack in mm. The value of least count for Crack Detection Microscope is 0.02 mm. **Figure 13: B** exhibits magnification of a crack through Crack Detection Microscope.

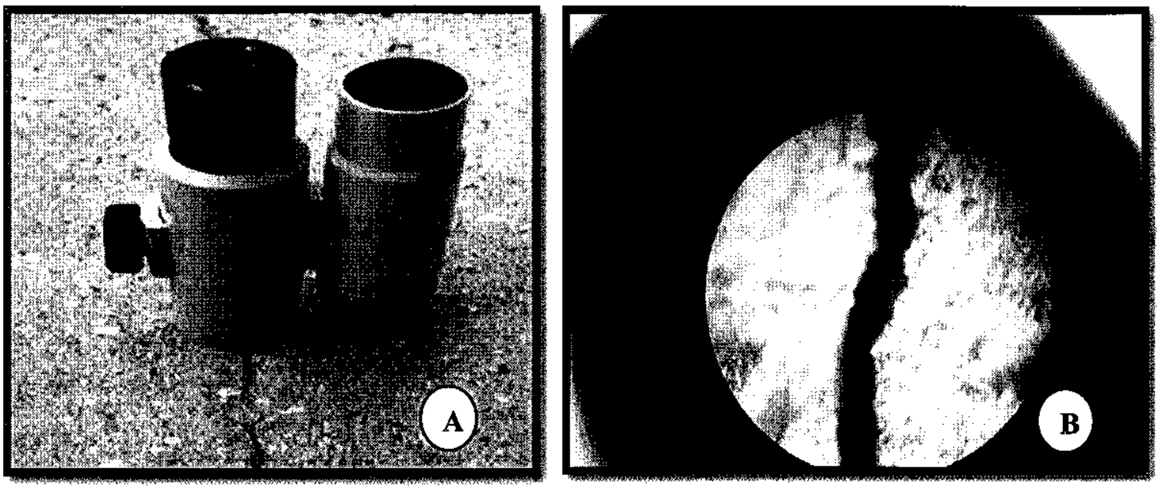

Figure 13: (A) Crack Detection microscope; (B) Magnification of a crack through Crack Detection Microscope

2.5.2 Video Boroscope:

A boroscope is used to look inside inaccessible or small voids. For example, if cable ducts are not injected, it is possible to inspect the strands by means of an endoscope through a contact drilling (here a drilled hole from the surface to the cable duct).

The boroscope equipment includes a lighting source and a fiber optic cable to transfer the light to the boroscope. A system of lenses enables the boroscope to be used as a monocular. A camera or video camera can also be mounted on the boroscope for photo documentation (**Figure 14: A, B and C** shows the assembly of Video Boroscope and the fiber optic cable with the lighting source) **[1, 10]**.

Generally, the method is appropriate and may also be used for visual inspections of structural components such as expansion joints, honeycombs and cracks/slots. **Figure 14: D, E, F and G** demonstrate photo documentation done by the Video Boroscope while examining the interior of a cavity at the test location.

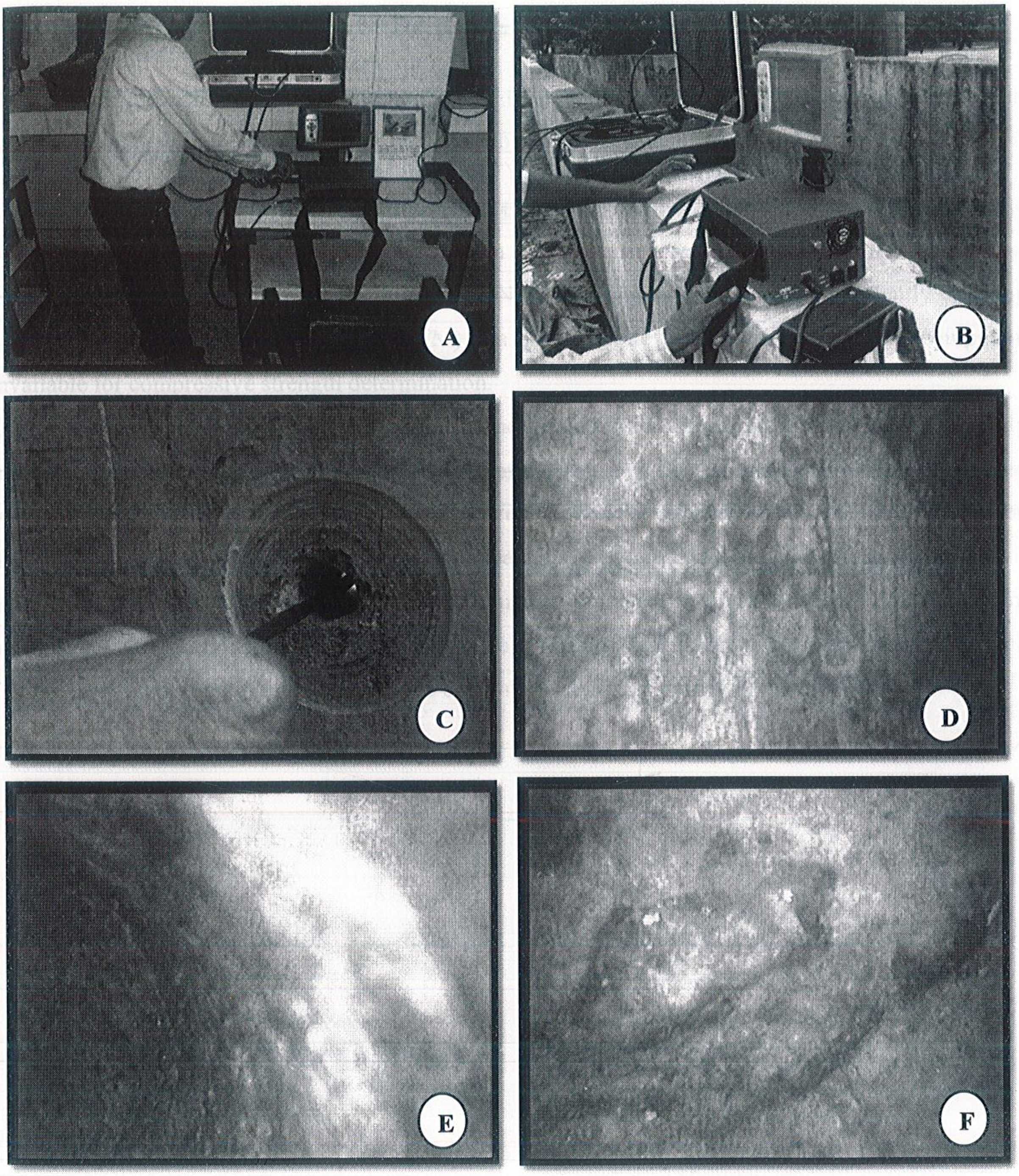

Figure 14:(A) & (B) Assembly of Video Boroscope; (C) Fiber optic cable with the lighting source; (D), (E) & (F) Photo documentation done by the Video Boroscope while examining the interior of a cavity at the test location

Chapter 3: RESULTS AND DISCUSSION

The results of the tests conducted by the authors and the inferences drawn by them on the basis of their experience along with the experience of the RDSO officials have been mentioned in this chapter.

3.1 Estimation of Compressive Strength of concrete bridge components

Generally concrete cubes are cast and crushed in a compression testing machine to determine their average compressive strength. Thus, performing NDT on a concrete cube and subsequently crushing it in a Compression Testing Machine (CTM) is a near accurate way of comparing NDT equipment available for compressive strength determination.

As most of the non-destructive tests cannot be performed on a 150mm x 150mm surface, so only rebound hammer is used for direct comparison (refer **Table 5**) with compressive strength determined using CTM. In Table 1, column three, the average compressive strength of concrete cube by analog rebound hammer is average of the compressive strengths of two rebound hammers (refer **Table 6**).

Results for indicative compressive strength of concrete, obtained by using different NDT equipment at different site locations are mentioned below (refer **Tables 7, 8, 9, 10**). Calibration was performed for the equipment used in this study and the calibration charts are given in **Appendix G**.

Table 5: Direct comparison of compressive strength values from CTM and Rebound Hammer (Analog and Digital); (refer Figure 16)

Cube No.	CTM (N/mm^2)	Analog Rebound Hammer (N/mm^2)	Digital Rebound Hammer (N/mm^2)	Percentage Difference	
				Analog Rebound Hammer	Digital Rebound Hammer
For detailed results refer to Appendix E					
1	44.0	40.58	31.75	-7.77	-27.84
2	38.2	43.21	33.00	13.12	-13.61
3	46.7	48.73	31.00	4.35	-33.62
4	34.2	48.01	38.00	40.38	11.11
5	50.2	47.64	37.5	-5.10	-25.30
6	43.1	40.25	29.75	-6.61	-30.97
7	40.9	40.04	38.25	-2.10	-6.48
8	36.4	40.44	37.00	11.10	1.65
9	40.9	39.85	37.00	-2.57	-9.54
10	39.6	40.74	40.25	2.88	1.64
For detailed results refer to Appendix F					
11	27.1	35.00	25.00	29.15	-7.75
12	21.8	32.50	20.75	49.08	-4.82
13	32.9	36.50	26.25	10.94	-20.21
14	18.2	32.00	17.00	75.82	-6.59
15	21.3	35.50	19.00	66.67	-10.80
16	22.7	32.50	16.50	43.17	-27.31
17	20.0	33.65	17.25	68.25	-13.75
18	24.9	34.88	18.75	40.08	-24.70

19	28.4	40.16	23.75	41.41	-16.37
20	19.6	35.60	22.25	81.63	13.52
Average Percentage Difference (%)				27.69	-12.58

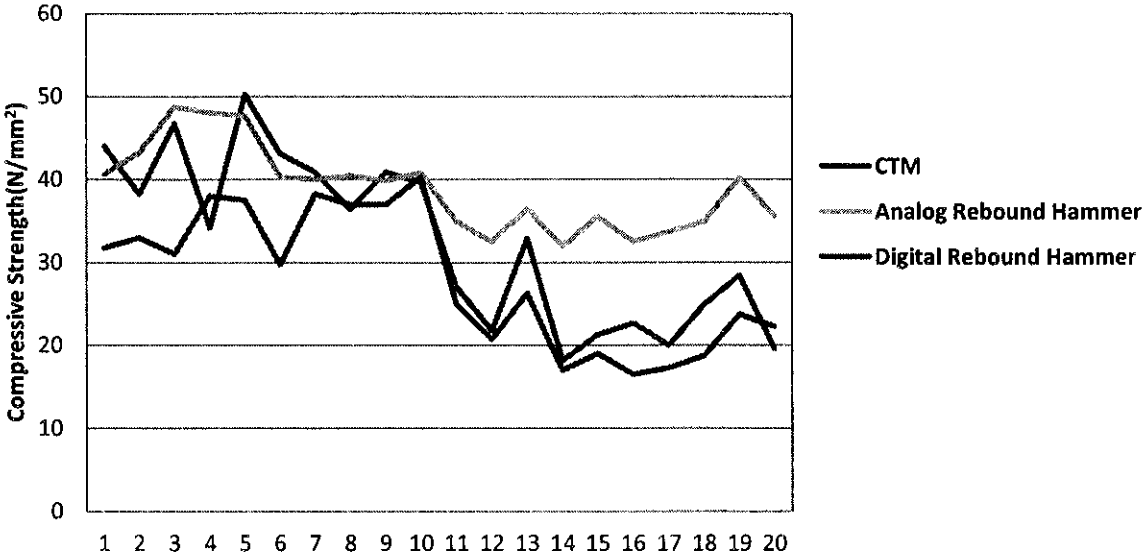

Figure 15: Direct comparison of compressive strength values from CTM and Rebound Hammer (Analog and Digital)

Table 6: Average Compressive Strength of analog rebound hammer (for detailed results refer to Appendix F & G)

Cube No.	Average Compressive Strength (N/mm^2)		
	Analog Rebound Hammer (JUIT)	Analog Rebound Hammer (RDSO)	Analog Rebound Hammer
1	42.96	38.19	40.58
2	47.25	39.16	43.21
3	55.40	42.05	48.73
4	53.55	42.46	48.01
5	53.03	42.25	47.64
6	43.86	36.63	40.25
7	42.4	43.68	40.04
8	37.00	43.88	40.44
9	40.77	38.92	39.85
10	40.74	40.73	40.74
11	37.00	33.00	35.00
12	36.00	29.00	32.50
13	41.00	32.00	36.50
14	37.00	27.00	32.00
15	40.00	31.00	35.50
16	39.00	26.00	32.50
17	38.49	28.81	33.65
18	39.30	30.45	34.88
19	44.91	35.41	40.16
20	41.62	29.58	35.60

Table 7: Indicative Compressive Strength of Concrete using different equipment [Site 4: (ROB, Rectangular bridge Pier), for detailed results refer to Appendix E]

Instrument	Compressive Strength (N/mm^2)	
	Location 1	Location 2
Rebound Hammer (Digital)	53.83	40.5
Analog Rebound Hammer (RDSO)	50.89	49.60
Analog Rebound Hammer (JUIT)	53.62	45.89
CAPO	23.2	-
Core Cutter	12.73	-

Table 8: Indicative Compressive Strength of Concrete using different equipment [Site 1: (RUB, Retaining wall), for detailed results refer to Appendix A]

	Location 1	Location 2
Rebound Hammer (Digital)	33.25	20.25
Rebound Hammer (Simple)	46.87	34.8
CAPO	33.3	23.07
Core Cutter	28	20.36

Table 9: Indicative Compressive Strength of Concrete using different equipment [Site 2: (ROB, Bridge pier), for detailed results refer to Appendix B]

	Rebound Hammer (Digital)	Rebound Hammer (Analog/Simple)
Location 1	46.25	57.07
Location 2	48.75	64.75

Table 10: Indicative Compressive Strength of Concrete using different equipment [Site 3: (ROB, Bridge deck), for detailed results refer to Appendix C & D]

	Rebound Hammer (Digital)	Rebound Hammer (Analog/Simple)	CAPO	Windsor probe	Core Cutter
Location 1	18	23.43	25.4	28.18	25
Location 2	50	53.16	46.2	43.47	-
Location 3	47.75	46.78	62.1	48.34	-
Location 4	42.5	47.42	46.2	41.81	-
Location 5	45.5	46.1	39.5	41.29	36
Location 6	29	37	32.6	29.52	28

3.2 Evaluation of quality of concrete and reinforcement

Quality of concrete and quality of reinforcement need to be assessed for a variety of purposes, for example homogeneity of concrete and its construction quality may be predicted by knowing the quality of concrete. Similarly by judging the quality of reinforcement the corrosion in steel bars may be predicted. For conducting quality evaluation of concrete at different sites, UPV and Permeability Tester were employed (refer **Table 11** for the assessment). **Table 12** illustrates quality evaluation of reinforcement bars at different sites, conducted using Corrosion Analyzer and Resistivity meter.

Due to certain unavoidable conditions at site and limitations of the instruments, tests could not be performed at all the locations. Due to this data available is insufficient for any comprehensive comparison to be made among these instruments. Also during quality assessment of concrete, the tests generate contradictory set of final results and so the comparison is not credible **[7, 12]**.

However the results of the tests conducted have been included in this report for indicative purposes.

Table 11: Quality evaluation of concrete at different locations using UPV and permeability tester (for detailed results refer to Appendix A, B, C & D)

Site & Location(s)	Quality assessment of concrete by	
	UPV	Permeability Tester
Site 1: (RUB, Retaining Wall)	Good	Bad
Site 2 (ROB, Bridge pier)	Excellent	-
Site 3: Location 1	-	Bad
Site 3: Location 2	-	Bad
Site 3: Location 3	Excellent	-
Site 3: Location 4	Excellent	-
Site 3: Location 5	-	Bad
Site 3: Location 6	-	Bad
Site 4: (ROB 2, Rect. Bridge Pier)	Good	Very Bad

Table 12: Quality evaluation of reinforcement at different locations using Corrosion Analyzer and Resistivity Meter (for detailed results refer to Appendix A)

Site & Location(s)	Quality assessment of reinforcement by	
	Corrosion Analyzer	Resistivity Meter
Site 1	Corrosion is unlikely	Corrosion is improbable
Site 2	-	-
Site 3	Corrosion is unlikely	-
Site 4	-	-

3.3 Cost Analysis

NDT offers a relatively inexpensive means for structural evaluation in comparison to destructive testing. However NDT equipment is expensive (one time cost) and since it requires a certain degree of skill to conduct NDT and interpret its results, the operational costs for NDT are also high.

Due to the high operational costs and the expensive NDT equipment (refer **Table 13**), it can be safely said that cost analysis is one of the factors which should be considered while deciding upon the choice of NDT equipment suitable for a particular application.

Table 13: Approximate initial and operational costs of various test equipment

Equipment	Cost of Instrument (Rs.)	Approximate Operational Cost*	Relative Overall Cost
For Compressive Strength			
Rebound Hammer	1,27,000	Rs. 91,000(for 10 locations)	Low
Cut And Pull Out Test	9,71,538	Rs. 1,09,000(for 6 locations)	High
Core Cutter	4,37,620	Rs. 41,000(for 3 cores)	Medium
Compression Testing Machine	1,10,000	Rs. 13,000(for 3 cubes)	Low
For Quality Estimation			
Ultra-Sonic Pulse Velocity Meter	4,07,632	Rs. 1,01,000 (for 10 locations)	Low
Permeability Meter	8,14,694	Rs. 85,000 (for 5 locations)	High
For Reinforcement Profile and Concrete Cover			
Profometer	2,77,131	Rs.72,000 (for 10 locations)	-
For Visual Inspection			
Video Boroscope	14,23,858	Rs.1,06,000 (for 10 locations)	High

*The Approximate Operational Cost mentioned is in accordance with information provided by the RDSO officials. The cost of the equipment cost has been brought down to the same year for the purpose of comparison and approximate operational costs mentioned are the ones being used at present.

3.4 Discussion

For the purpose of comparison, various parameters need to be considered. Since the purpose of conducting the test is to obtain accurate and reliable results, this is the basic and the most important parameter. Cost and versatility are other parameters that need to be accounted for in comparison due to economic considerations. Also the time and resources required for a particular test, the ease with which it can be used and the ease of analysis needs to be considered **[12, 13, 15]**. The comparative assessment of each parameter for equipment used during the field tests can be seen in **Table 14**.

To quantify the above mentioned parameters a weightage is assigned for each parameter and according to the engineering importance of a particular parameter, an importance factor is allotted to it (refer **Table 15**). The weightage and importance factors allotted are based on experience gained by the authors while handling the NDT instruments on the field and their discussion with the supervising RDSO officials.

According to the weightage and importance factor assigned, relative importance of an equipment is calculated using **Eq. 6** (refer **Table 16**) which is further used for the quantitative comparison.

Table 14: Comparative assessment of NDT equipment used

Equipment	Comparative Assessment					
	Accuracy & Reliability	Cost	Versatility	Ease of Operation	Ease of Analysis	Time & Resources required
For Compressive Strength:						
1) Rebound Hammer	Medium	Low	Low	Easy	Easy	Low
2) CAPO	High	High	Low	Difficult	Moderate	High
3) Core-cutter	High	Medium	Medium	Difficult	Moderate	High
4) Windsor Probe	High	High	Low	Difficult	Moderate	High
For Quality Assessment Of concrete:						
1) UPV	High	Low	High	Difficult	Difficult	Low
2) Permeability tester	Medium	High	Low	Difficult	Difficult	Moderate
For Visual Inspection:						
1) Video Boroscope	High	High	Medium	Difficult	Difficult	High
2) Crack Detection microscope	Medium	Low	Low	Easy	Easy	Low

Table 15: Weightage assigned and importance factors for the purpose of comparative assessment

Parameters	Comparative Assessment	Weightage Assigned (W)	Importance Factor(F)
Accuracy &Reliability (A)	High	10	4
	Medium	5	
	Low	1	
Cost (C)	High	1	1.5
	Medium	5	
	Low	10	
Versatility (V)	High	10	2.5
	Medium	5	
	Low	1	
Ease of Operation (O)	Difficult	1	0.5
	Moderate	5	
	Easy	10	
Ease of Analysis (E)	Difficult	1	0.5
	Moderate	5	
	Easy	10	
Time & Resources Required (T)	High	1	1
	Moderate	5	
	Low	10	

For calculating relative importance **Eq. 6** given below is used:

Relative importance $= W_AF_A + W_CF_C + W_VF_V + W_OF_O + W_OF_O + W_EF_E + W_TF_T$ .... **(Eq. 6)**

Here:

W_A = Weightage assigned to Accuracy & Reliability;

W_C = Weightage assigned to Cost;

W_V = Weightage assigned to Versatility;

W_O = Weightage assigned to Ease of Operation;

W_E = Weightage assigned to Ease of Analysis;

W_T = Weightage assigned to Time & Resources required;

F_A = Multiplication Factor assigned to Accuracy & Reliability;

F_C = Multiplication Factor assigned to Cost;

F_V = Multiplication Factor assigned to Versatility;

F_O = Multiplication Factor assigned to Ease of Operation;

F_E = Multiplication Factor assigned to Ease of Analysis;

F_T = Multiplication Factor assigned to Time & Resources required.

Table 16: Relative performance of equipment based on comparative assessment

Equipment	Relative performance
For Compressive Strength:	
1) Rebound Hammer	54.5
2) CAPO	48
3) Core-Cutter	64
4) Windsor Probe	48
For Quality Assessment of Concrete:	
1) UPV	81
2) Permeability Tester	30
For Visual Inspection:	
1) Video Boroscope	56
2) Crack Detection Microscope	57.5

Based on **Table 16**, it has been inferred that the best suitable equipment for compressive strength evaluation is Core-cutter followed by rebound hammer. Similarly for quality assessment of concrete UPV is the better suited equipment than permeability tester. For visual inspection though crack detection microscope scored higher than video boroscope, but based on the field experience of officials regularly performing NDT, it can be safely said that video boroscope is the better equipment for visual inspection.

For compressive strength evaluation, if only an indicative assessment is desired, the appropriate equipment to be used is rebound hammer due to its simplicity in operation and data interpretation. Also the time and resources required for performing rebound hammer are less in comparison to other equipment. However if a greater accuracy is desired and if the site conditions permit, core cutter is the best suited equipment as its results are based on the crushing of cores extracted from the site in Compression Testing Machine.

For quality assessment of concrete Ultrasonic pulse velocity meter is the best suited equipment due its relatively simple operation, low resources required, higher versatility and accuracy.

For visual inspection, based on the field experience of the authors and the RDSO officials regularly performing NDT, the better suited equipment is video boroscope.

Chapter 4: CONCLUSION

In this project various non-destructive condition evaluation methods have been studied and they have been used in field testing of reinforced cement concrete bridge components. Based on the data collected by the authors by performing numerous tests on four different sites, comparisons have been made among various NDT equipment available for determining a particular parameter. Also based on these comparisons, suggestions have been made to help future NDT users in selecting the most appropriate equipment (**refer 3.4**).

Suggested Guidelines

Based on experience of the authors in conducting field tests using various NDT methods, some guidelines are suggested for a more effective testing and to minimize the constraints. The suggested guidelines are:

- At some of the sites, tests like permeability tester and core cutter cannot be performed because of lack of constant supply of electricity, which is one of the principal requirements. So it is suggested that, if such tests are to be performed necessarily, then electric supply (like a portable generator) should be arranged prior to commencement of the tests.
- For condition assessment of reinforcement, authors used corrosion analyzer and resistivity meter during the field tests. For both the tests, it is essential that the surface, on which the tests are being conducted, should be moist to complete the circuit necessary for a valid measurement. This was done by using wet gunny sacks. Due to high test temperature, at some of the sites, the surface was not moist enough. So at those sites, tests were not performed. That is why tests should be performed during morning hours or late evening hours so that the overall rise in the temperature and change in temperature during the period of testing are low.

This suggestion is also valid for the tests whose readings can be affected by temperature, like UPV.

Future Scope

Following areas are identified as scope of work in further development of this study:

- Life cycle cost analysis can be performed for various non-destructive testing and evaluation methods so that more informed decision can be made while selecting a particular method.
- This study can be progressed from conducting non-destructive condition assessment for concrete structures to conducting similar evaluations for steel and masonry structures.

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