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NON-DESTRUCTIVE TESTING (NDT)

PART - 1

Dr. Fixit Institute
of Structural Protection & Rehabilitation

A Not-for-Profit Knowledge Centre

Non-destructive Testing (NDT)

Generally, expert opinions are sought to carry out the investigation for condition assessment after any visible sign of deterioration of the structure. Many of us conduct a visual inspection before using any non-destructive evaluation techniques. NDT methods have the capability of diagnosing the internal concrete conditions, enhance the repair design, assure the quality of the repairs and monitor the performance of concrete repairs for a longer period.

Very comprehensive condition assessment is essential for successful concrete repair. With an incomplete condition assessment, a repair programme is unfocussed and possibly misleads, and ultimately costs time and money. Not all NDT methods will bring out all the issues of deterioration. It is essential that the investigator has adequate knowledge of the tools and techniques that are available.

The various types of NDT equipment used are the rebound hammer, the ultrasonic pulse velocity meter (UPV), the cover meter, the corrosion analyser, the thermal imager, etc. Out of these the most widely used are the rebound hammer and the ultrasonic pulse velocity meter. NDT results are further supported by chemical analysis such as chlorides, sulphates, carbonation and petrography analysis.

In this issue, we will discuss about most widely used NDT equipment rebound hammer and ultrasonic pulse velocity meter (UPV), their advantages, correct use, practical limitations, reliability and accuracy for creating some awareness among the users. Rebound hammer is based on the principle of surface hardness having an internal spring and piston that rebound upon its release to impact the concrete surface. The more the rebound number is, the more the compressive strength of the concrete as the rebound number of the same equipment is co-related with the compressive strength which may not be true for all the time.

The ultrasonic pulse velocity method involves transmitting and receiving ultrasonic sound wave energy at a frequency and calculating the pulse velocity as the travel path distance divided by the travel time in microseconds. The velocity depends upon ultrasonic waves passing through the medium of the mass like compact or having voids inside. This velocity is again correlated with quality of the concrete like good or bad concrete.

The factors affecting rebound hammer tests are surface smoothness, moisture content, types of aggregates and presence of carbonation etc. Similarly UPV measurements are influenced by number of factors such as surface and moisture conditions, the path length, the shape and size of concrete member, reinforcement bars and temperature conditions. But the most important factor is the calibration of the equipment which has to be ensured before any NDT testing.

In most of the states in India there is no structural audit norms except few states like Maharashtra where bye-law states that "Structural audits are to be conducted by a structural engineer on the panel of the Municipal Corporation and the frequency of the structural audits should be once in 5 years for buildings between 15 and 30 years old and once in 3 years for the building more than 30 years old". But in this bye-law the methodology to be adopted for structural audit, equipment to be used and calibration required for the equipment are not mentioned. Also NDT can be effectively used in monitoring all the infrastructures in refineries, fertiliser plants, chemical plants, petrochemical plants, ports and marine structures, bridges and culverts, thermal and nuclear power plants, mining and mineral processing industries, and all real estate structures. Also NDT is an effective tool in quality control of new structures which is being used in most of the advanced countries.

But today, there are several agencies claiming their competence to conduct NDT on concrete structures for the assessment of the durability perspective. However, awareness on usage of such equipment and reporting of the condition assessment are based on only a few sample tests and visual inspections or by using one of the NDT methods. Also, it is noticed that some of these agencies are not using the calibrated NDT equipment and testing as per code of practice. For example, the rebound hammer should be calibrated and serviced after every 2000 impacts by an Anvil with known hardness. It has been seen that many agencies do not have an Anvil for the calibration and keep on using the rebound hammer for many years without any records about the usage.

There is a wide range of tolerance given by the code for acceptance of the test results, which is based on several uncertainties and properties of the materials used in concrete structures. Moreover, if the calibration and the correct usage of this NDT equipment is not maintained the results will mislead the whole process of structural assessment by any Structural Consultant/ Engineer. The codes which may be referred are IS 13311 : 1992, Non-destructive testing of concrete - Methods of test (Part 1) Ultrasonic Pulse velocity, (Part 2) Rebound hammer.

We hope our readers will find this issue very useful as it has brought out the details of commonly used NDT methods, which play a major role in deciding the durability of concrete structures. We will also progressively focus on other areas of non-destructive tests in our forth coming issues for the benefit of our readers.

Condition Assessment of the Structures by Non-destructive Evaluation Techniques

[By Editorial Office, Dr. Fixit Institute]

1.0 Introduction

To assess the integrity of old or new concrete and reinforcement, non-destructive testing is one of the most powerful and reliable tool. The need to conduct non-destructive testing for condition assessment of the RCC structures has grown considerably in recent times, due to increase in the number of structures showing signs of distress. Non-destructive Testing (NDT) is fast, easy-to-use on site and relatively less expensive. It can be used for the following:

- To test actual structure instead of representative cube sample
- To test any number of points and any location
- As a quality control tool
- To assess the structure for various distressed conditions
- For damage assessment due to fire, chemical attack, impact, age, etc.
- To detect cracks, voids, fractures, honeycombs and weak locations
- To monitor progressive changes in the properties of concrete, reinforcement, etc.
- To assess overall stability of the structure
- To monitor repair and rehabilitation systems
- To scan for reinforcement location, stress locations.

2.0 Investigation of Reinforced Concrete Deterioration

Experience has shown that a number of testing methods are of proven value in determining the extent of deterioration of a concrete structure and in identifying those areas where remedial measures are necessary. While the list of tests discussed herewith is not exhaustive, it does include most of the common tests as well as some known techniques. A systematic approach has to be adopted for condition evaluation of the structures. A visual inspection should be carried out to understand the basic nature of defects, cracks, etc. followed by some specific non-destructive tests. This helps to find out the exact cause of defects and to provide proper solutions for repair; otherwise repetition takes place to repair the same structure again and again without understanding the nature of defects.

2.1 Approach Methodology

Any investigation can conveniently be split into three stages.

Stage 1 - An initial survey to identify the cause of the problems.

Stage 2 - An extension of the stage 1 survey, perhaps using a limited number of techniques to identify the extent of the defects revealed by stage 1.

Stage 3 - Localized investigation by partial destructive tests to reinforce the test results as carried out in stage 2.

The advantages of such an approach are clear. In the stage 1 survey, work can be carried out on selected areas showing typical defects but choosing these, as far as possible, from areas with simple access i.e. ground level, roof level, from balconies, etc. Occasionally, a light weight scaffold tower or an electrically powered hydraulic lift can be used to advantage. One or more areas, apparently free from defect, will also be examined in this initial survey as it is frequently found that by comparing good areas with bad ones, the reasons for the problem emerge by simple comparison.

In stage 2, once the defects have been identified, it is often necessary to quantify the extent of the problems. This may be as simple as carrying out NDT test such as a cover meter survey over the whole structure, where low cover has been identified as the problem, to the application of one or more of the other techniques described below.

In stage 3, some partial destructive tests may be carried out by taking core samples without cutting the reinforcing bar. The reinforcing bar position can be located by a bar locator/ cover meter. The core samples can be used for compressive strength and chemicals tests such as carbonation, chlorides and sulphates.

2.2 Visual Survey

After collecting as much background data as possible, any testing problem should begin with a thorough visual survey of the structure. This may conveniently be recorded on a developed elevation giving particular attention to the following defects:

- Cracks or crazing
- Spalling
- Corrosion of steel and rust staining
- Hollow surfaces
- Honeycombing due to poor compaction or grout loss
- Varying colour or texture
- Areas in which remedial finishing work had already been carried out
- External contamination or surface deposits
- Wet or damp surfaces

Throughout the course of any investigation colour photographs should be taken of points of particular interest.

In recent years, significant advances have been made in non-destructive testing techniques, equipment and methods which should be carried out after the visual inspection. The various tests and their utility are discussed in the following sections.

The structural diagnostic services are rendered broadly in three stages as shown in Figure 1.

3.0 Selection of Non-destructive Testing Method

Type of tests to be carried out and their purposes such as non destructive testing, extraction of samples and laboratory tests are given in Table 1. Sampling plan indicating the tests and samples quantity, test and sampling locations and rational behind the sampling sizes and locations should be in accordance with the standards. The test and sampling plan would need to address the objectives of the investigation, findings from the visual survey and any limitations and constraints.

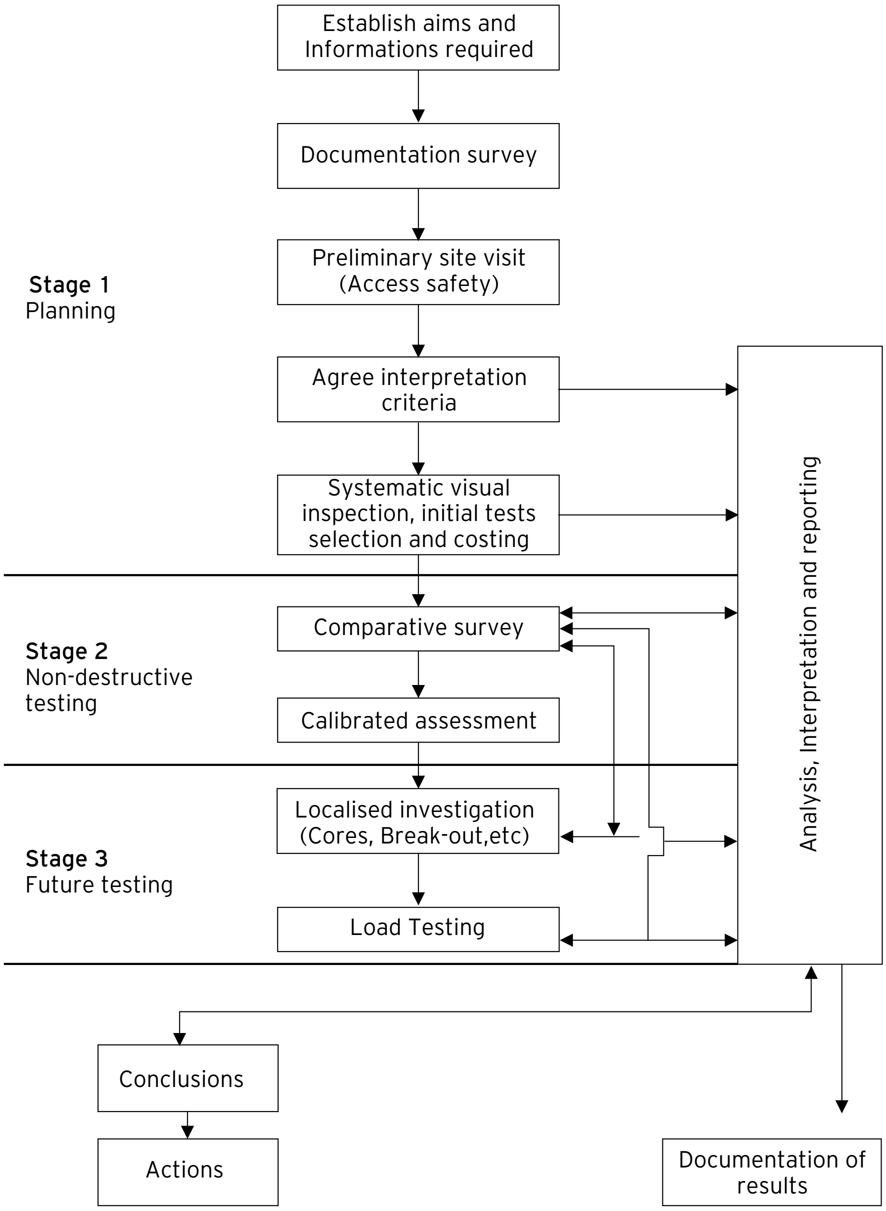

Fig. 1: Three stage approach of condition assessment of the structures

Table 1: Tests and test methods

Parameter	Test / Method
CONCRETE	
Compressive strength	Rebound Hammer Windsor probe Ultrasonic Pulse Velocity Core Capo Pull out Combined methods
Flexural Strength	Break - off
Direct tensile strength	Pull- off
Concrete Quality, Homogeneity Honeycombing, voids,	Ultrasonic Pulse Velocity Pulse echo Endoscopy Gamma Ray Radiography
Damages - Fire/ blast	Rebound Hammer Ultrasonic Pulse Velocity
Cracks - water tanks/ pavements	Ultrasonic Pulse Velocity Acoustic Crack Detector Dye Penetration Test X - ray Radiography Gamma Ray Radiography Thermal imaging Crack scope
STEEL	
Location, cover, size	Re bar locator, Bar-sizer
Corrosion	Half-cell Potential Resistivity Carbonation Chloride Content
Condition	Endoscope/ Borescope
INTEGRITY & PERFORMANCE	Tapping Pulse-echo Acoustic emission Radar Petrography Load Test

4.0 Preparation of Report

The comprehensive report of the condition survey of the building is prepared based on the visual inspection and NDT results as given in Table 2.

The report should include information collected from the occupants, detailed description of the building, condition of various internal and external RCC members with critical photographs, condition of various non-structural elements with critical photographs and NDT and core sample test results and extent of defects/ distress and their causes.

Table 2: A standard dignosis report format

Sl. No	Element	Location/ Identity	Defect Observed	Results from NDT	Remarks
1.					

5.0 Recommendations

Based on the visual inspection and NDT results correlation between different results/ observations should be carried out. The summary of all results including acceptance guides, if available should be provided. It should include variability of results and statistical data. Where appropriate, a separate compilation of results for different structural elements, categories of structures, should be provided along with statistical analysis. The serviceability assessment or remnant life assessment, durability etc should also be calculated. The overall condition assessment of the structures/ buildings should be categorized as follows:

- C1 : The building is structurally unsafe and has been found to be in extremely dangerous condition. This building needs to be vacated immediately and demolished.
- C2 (A) : Only a portion of this building is in extremely dangerous condition (not repairable and worthy of demolition), while other portion can be repaired or strengthened. This building need not be vacated completely. The extremely dangerous portion should be cordoned off.
- C2 (B) : The building has been found to be dangerous (need major repairs/ strengthening urgently, but need not be vacated).
- C3 : The building condition is satisfactory (need minor repairs).

Recommendations should be given for further testing if test results are inconclusive. Finally suitable repair, protection, restoration, strengthening techniques along with their materials and method statements should be recommended. Also future maintenance and inspection schedules should be recommended.

6.0 Conclusion

Non-destructive testing has not yet been adopted as routine testing. Whenever there are some problems with cement/ concrete strength and finish, then NDT is used only as a rescue tool. Now the time has come to use these NDT techniques as routine testing to have more effective quality control. The main advantage of this testing is to assess the in-situ quality of concrete. These techniques help to decide the acceptability of the concrete structure. NDT has become mandatory testing, in addition to cube testing, in some parts of the world. In India some Govt. agencies have included NDT as mandatory testing, in addition to cube testing. All other agencies, RCC consultants, Municipal Corporations, etc. should specify these tests in their tenders as an additional quality control tool. Municipal corporations can make use of these tests to check the stability of old, distressed and unsafe structures.

Proper Use of the Rebound Hammer

[Excerpts from Technical Bulletin 2.0 of CEMEX USA]

1.0 Principle of Working

The Rebound Hammer has been around since the late 1940's and today is a commonly used method to estimate the compressive strength of in-place concrete. Developed in 1948 by a Swiss engineer named Ernst Schmidt, the device measures the hardness of concrete surfaces using the rebound principle. The device is often referred to as a Swiss Hammer.

ASTM C 805, "Standard Test Method for Rebound Number of Hardened Concrete", summarizes the procedure as "A steel hammer impacts, with a predetermined amount of energy, a steel plunger in contact with a concrete surface, and the distance that the hammer rebounds is measured."

The device consists of a plunger rod, an internal spring loaded steel hammer and a latching mechanism. When the extended plunger rod is pushed against a hard surface (Fig. 1), the spring connecting the hammer is stretched and when pushed to an internal limit, the latch is released causing the energy stored in the stretched spring to propel the hammer against the plunger tip. The hammer strikes the shoulder of the plunger rod and rebounds a certain distance. On the outside of the unit is a slide indicator that records the distance travelled during the rebound. This indication is known as the rebound number. By pressing the button on the side of the unit, the plunger is then locked in the retracted position and the rebound number (R-number) can be read from the graduated scale. The higher the R-number, the greater is the hardness of the concrete surface.

Fig. 1: Testing of rebound hammer on concrete surface

The tests can be performed on a horizontal, a vertically upward or a vertically downward or any intermediate angled position in relation to the surface. The devices are furnished with correlation curves by the manufacturer. However, to obtain greater accuracy of test results, it is recommended that the user develop a correlation for the device on each concrete mix design to be tested and at the intended test angled.

2.0 Significance and Uses

ASTM C 805 states that this method is applicable for the following uses:

- To assess the in-place uniformity of concrete
- To delineate regions in a structure of poor quality or deteriorated concrete
- To estimate in-place strength development

The ASTM standard then states that to use the device to estimate in-place strength, a relationship between the strength and rebound number needs to be established for specific concrete mix designs of interest. Different rebound hammers of the same design and manufacture may give rebound numbers differing from 1 to 3 units, therefore the relationship development should use the same device intended for measurements. If multiple devices are going to be used, they should be measured against each other on a range of typical concrete surfaces to determine the extent of differences expected.

3.0 Factors Affecting the Test Results

3.1 Surface Smoothness

The surface texture significantly affects the R-number obtained. Tests performed on a rough-textured finish will typically result in crushing of the surface paste, resulting in a lower number. Alternately, tests performed on the same concrete that has a hard, smooth texture will typically result in a higher R-number. Therefore, it is recommended that test areas with a rough surface be ground to a uniform smoothness. This can be achieved easily with a Carborundum stone or similar abrasive stone. The FHWA (Federal Highway Administration) Guide states that research has shown that trowelled surfaces and surfaces formed by metal forms yield rebound numbers 5%-25% higher than surfaces cast against wooden forms. It also states that trowelled surfaces give a higher scatter of results, which lower confidence in the estimated strengths. ASTM C 805 states that where formed surfaces were ground, increases in rebound number of 2.1 for plywood formed surfaces and 0.4 for high-density plywood formed surfaces have been noted.

3.2 Age of Concrete

The majority of concrete surface hardness is developed in the first 7 days. However, the concrete will typically continue to gain significant strength with cement hydration. Testing of concrete less than 3 days old or concrete with expected strengths less than 7 MPa is not recommended, because the R-numbers will be too low for an accurate reading and will be more destructive to the concrete surface. Concrete that continues to develop strength with age is again a reason for the development of data relating rebound numbers and the compressive strength of the concrete mixture or cores from the structure.

3.3 Moisture Content

This has a profound effect on the test results. Dry concrete surfaces result in higher rebound numbers than wet surfaces. The FHWA Guide references a study where saturated surface-dry (SSD) specimens were left in a room at 21°C and air-dried. The specimens gained 3 units in 3 days and 5 units in 7 days. It is recommended that to achieve the most accurate results where the actual moisture condition is unknown, the surface should be pre-saturated with water several hours prior to testing and the correlation developed for SSD specimens should be used.

3.4 Surface Carbonation

With greater amounts of surface carbonation, higher rebound numbers will be obtained. Rebound numbers on a carbonated surface can be as much as 50 % higher than those on non-carbonated surfaces. Older concrete surfaces may have much deeper amounts of surface carbonation than younger concrete surfaces. ASTM states that the effects of moisture content and carbonation can be reduced by thoroughly wetting the surface for 24 hours before testing, and that where a thick layer of carbonation is present, it may be necessary to use a power grinder to remove the carbonated concrete and obtain more accurate data.

3.5 Aggregate, Air Voids, and Steel Reinforcement

The presence of materials in the immediate area where the plunger comes into contact with the concrete will have an obviously profound effect as well. If the test is performed over a hard aggregate particle or a section of steel reinforcement, the result may be an unusually high rebound number. ASTM C 805 states that tests directly over reinforcing bars with cover less than 18 mm should not be conducted. The use of a bar locator or similar device is recommended to determine the location and cover in structurally reinforced concrete. Likewise, if the test is performed over a very soft aggregate particle or an air void, an unusually low rebound number may result. The FHWA guide reported that for equal compressive strengths, concrete made with crushed limestone resulted in rebound numbers approximately 7 units higher than concrete made with gravel, representing a difference of approximately 7 MPa in compressive strength estimation.

3.6 Temperature

Tests should not be performed on frozen concrete surfaces. Wet concrete at temperatures of 0°C or less may result in higher rebound numbers. Also, the temperature of the Swiss Hammer itself in extreme cold (-18°C) may result in rebound numbers reduced by as much as two or three units.

4.0 Calibration of the Rebound Hammer

Clearly, the influences of the variables described above are so great that it is very unlikely that a general calibration curve relating rebound number to strength, as provided by the equipment manufacturers, will be of any practical value. The same applies to the use of computer data processing to give strength predictions based on results from the electronic rebound hammer unless the conversions are based on case specific data. Strength calibration must be based on the particular mix under investigation, and the mould surface, curing and age of laboratory specimens should correspond as closely as possible to the in-place concrete. It is essential that correct functioning of the rebound hammer is checked regularly using a standard steel anvil of a known mass. This is necessary because wear may change the spring and internal friction characteristics of the equipment. Calibrations prepared for one hammer will also not necessarily apply to another. It is probable that very few rebound hammers used for in-situ testing are in fact regularly checked against a standard anvil, and the reliability of results may suffer as a consequence. Generally rebound hammer should be calibrated and serviced after every 2000 impacts by an Anvil with known hardness.

The device itself should be serviced and verified annually or whenever there is a reason to doubt proper performance. Verification of proper performance of the device includes the use of a test anvil. The required dimensions and steel hardness is listed in ASTM C 805. Impacting the proper test anvil with a properly functioning device will typically result in rebound numbers of 80 ± 2. If the device is believed to not be functioning properly, it is recommended to send it back to the manufacturer or experienced facility for repair and re-verification.

The Federal Highway Administration (FHWA) Publication, No. FHWA-SA-97-105, "Guide to Non-destructive Testing of Concrete", provides a laboratory calibration procedure to be followed:

- Prepare fifteen 150 mm x 300 mm concrete cylinders whose strengths will cover the expected strength range to be encountered on the job site. Use the same cement, aggregates, admixtures and mix designs that are to be used on the job. Cure cylinders under standard moist curing conditions. Test 3 cylinders at each of the following test ages: 1, 3, 7, 14, and 28 days.
- After capping, place the cylinder in a compression-testing machine and apply an initial load of approximately 15 percent of anticipated ultimate load to restrain the specimen. Ensure that all cylinders are tested in a saturated surface-dry condition.
- Take 15 rebound hammer readings, 5 on each of 3 vertical lines 120° apart, against the side surface in the middle two-thirds of each cylinder. Avoid testing the same spot twice.

- Average all the readings, and then use the discard criteria given in ASTM C 805 to determine the rebound number for the cylinder being tested.
- Repeat steps two to four for all cylinders.
- Test each cylinder to failure in compression and plot the average rebound numbers at each age against the compressive strengths on a graph.
- Fit a curve or line to the data using the least squares approximation method.

ASTM C 805 also states that if it is desired to estimate the strength of concrete in an existing structure, the relationship should be established by correlating rebound numbers measured on the structure with the strengths of cores taken from corresponding locations. ACI 228.1 R has also recommended for reference on additional information to develop the relationship and use it to estimate in-place strength. In India IS 13311 (Part 2): 1992 is used to test NDT for rebound hammer.

The importance of specimen mass has been discussed above; it is essential that test specimens are either securely clamped in a heavy testing machine or supported upon an even and solid floor. Cubes or cylinders of at least 150 mm should be used, and a minimum restraining load of 15% of the specimen strength has been suggested for cylinders. BS 1881 (45) recommends not less than 7 N/mm^2 for cubes tested with a type N hammer. Typically the relationship between the rebound number and the restraining load is such that once a sufficient load has been reached the rebound number remains reasonably constant.

It is well established that the crushing strength of a cube tested wet is likely to be about 10% lower than the strength of a corresponding cube tested dry. Since rebound measurements should be taken on a dry surface, it is recommended that wet cured cubes be dried in laboratory atmosphere for 24 hours before test, and it is therefore to be expected that they will yield higher strengths than if tested wet in the standard manner.

5.0 Interpretation of the Test Results

There is an advantage in using the rebound hammer as a means of evaluating concrete to assess the in-place uniformity, delineate regions in a structure of poor quality or deteriorated concrete and estimate in–place strength development. The unit is easy to use and a large number of readings can be obtained in a relatively short amount of time. The method is for the most part non–destructive and typically more economical than other methods. However, with these advantages come some disadvantages related to limitations on accuracy and the need for the specific calibration procedures mentioned previously.

There is a large variance in opinions as to the accuracy of determining an estimation of compressive strength with the use of the rebound hammer. The accuracy of these estimations can be increased significantly by developing the correlation curves with the device to be used on the specific concrete mixture designs or on core specimens. Figure 2 gives such correlation curves as produced by different researchers.

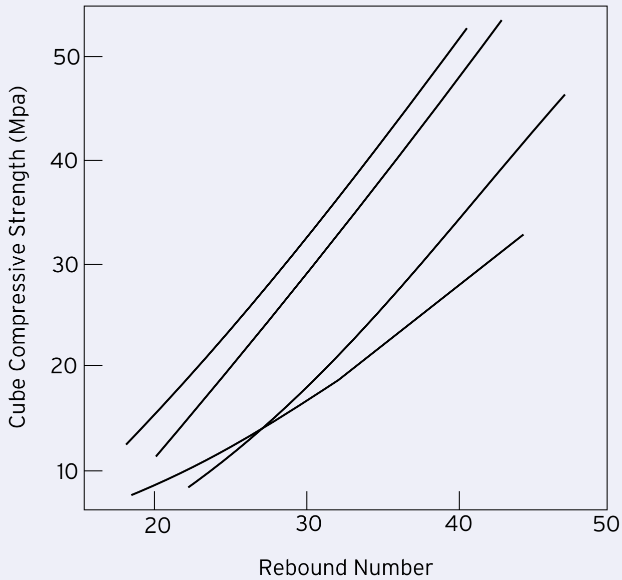

Fig. 2: Correlation curves produced by different researchers. (Greene curve used Type N hammer; others used Type N-2).

6.0 Accuracy

The FHWA Guide states that for a properly calibrated device, the accuracy is ±15 to 20 percent for test specimens cast, cured and tested under laboratory conditions and the accuracy of the rebound hammer to estimate in-place compressive strength in the field is approximately ±30 to 40 percent.

The rebound hammer can be a valuable tool to evaluate the uniformity of concrete in the field provided that the concrete is under the same conditions related to age, moisture content, surface carbonation and temperature. It should not be used as a substitute to perform normal specified quality control procedures.

Standards:

[1] ASTM C 805-02, "Standard Test Method for Rebound Number o Hardened Concrete"; American Society for Testing and Materials, West Conshohocken, PA

[2] FHWA Publication No. FHWA-SA-97-105, "Guide to Nondestructive Testing of Concrete"; U.S. Department of Transportation, Federal Highway Administration, Washington, DC

[3] ACI Committee 228, 'In-Place Methods to Estimate Concrete Strength" (ACI 228.1R-03), American Concrete Institute, Farmington Hills, MI

[4] IS 13311(Part 2):1992 Non-destructive testing of concrete-Methods of test Part 2 Rebound Hammer

Ultrasonic Pulse Velocity its Applications and Limitations

[Excerpts from the report on "Diagnosis, Inspection, Testing and Repair of Reinforced Concrete Structures" by M. G. Grantham & M. J. Gray, M. G. Associates, Clarendon House, Shenley Road, Borehamwood, Herts. WD6 1AG]

1.0 Fundamental Principle

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

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

$v = L / T$ --(Eq. 1)

where, v is the longitudinal pulse velocity,

L is the path length,

T is the time taken by the pulse to traverse that length.

2.0 Equipment for Pulse Velocity Test

The equipment consists essentially of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval between the initiation of a pulse generated at the transmitting transducer and its arrival at the receiving transducer (Fig. 1). Two forms of electronic timing apparatus and display are available, one of which uses a cathode ray tube on which the received pulse is displayed in relation to a suitable time scale, the other uses an interval timer with a direct reading digital display.

Fig. 1: Testing of ultrasonic pulse velocity of a concrete cube

The latest model of Pundit Lab provides exceptional versatility for a pulse velocity test instrument (NDT in concrete structures), offering not only the traditional transit time and pulse velocity measurement, but also path length measurement, perpendicular crack depth measurement and surface velocity measurement. The instrument also includes an integrated wave form display for manual triggering.

The normal model equipment should have the following characteristics. It should be capable of measuring transit time over path lengths ranging from about 100 mm to the maximum thickness to be inspected to an accuracy of ±1%. Generally the transducers used should be in the range of 20 to 150 kHz although frequencies as low as 10 kHz may be used for very long concrete path lengths and as high as 1 MHz for mortars and grouts or for short path lengths. High frequency pulses have a well defined onset but, as they pass through the concrete, become attenuated more rapidly than pulses of lower frequency. It is therefore preferable to use high frequency transducers for short path lengths and low frequency transducers for long path lengths. Transducers with a frequency of 50 kHz to 60 kHz are suitable for most common applications. But the transducer range in Pundit Lab has also been improved and extended to include shear wave transducers for testing poisson's ratio and modulus of elasticity, exponential transducers for rough surfaces and higher frequency transducers up to 500 kHz for rock and ceramics testing.

This feature set has been extended in Pundit Lab+ to include on-site applications requested by customers. The new features provide compressive strength estimation, compressive strength estimation in combination with a rebound hammer value (SONREB method), a real time stamp for all measurements, a review list allowing readings to be checked on site without a computer and an integrated gain stage that makes an external amplifier redundant. Full remote control is possible with the windows based software Pundit Link or via 3rd party software. This provides the user with online data acquisition and data logging functionality.

There are three practical arrangements for measuring pulse velocity, namely direct, diagonal and surface techniques. The direct approach provides the greatest sensitivity and is therefore superior to the other arrangements.

3.0 Accuracy

In most applications, it is necessary to measure the pulse velocity to a high degree of accuracy since relatively small changes in pulse velocity usually reflect relatively large changes in the condition of the concrete. For this reason, it is important that care be taken to obtain the highest possible accuracy of both the transit time and the path length measurements since the pulse velocity measurement depends on both.

It is desirable to measure pulse velocity to within an accuracy of ±2% which allows a tolerance in the separate measurements of path length and transit time of only a little more than ±1%. When such accuracy of path length measurement is difficult or impossible, an estimate of the limits of accuracy of the actual measurements should be recorded with the results so that the reliability of the pulse velocity measurements can be assessed.

4.0 Coupling the Transducers with the Concrete Surface

The accuracy of transit time measurement can only be assured if good acoustic coupling between the transducer face and the concrete surface can be achieved. For a concrete surface formed by casting against steel or smooth timber shuttering, good coupling can readily be obtained if the surface is free from dust and grit and covered with a light or medium grease or other suitable couplant. A wet surface presents no problem. If the surface is moderately rough, a stiffer grease should be used but very rough surfaces require more elaborate preparation. In such cases the surface should be ground flat over an area large enough to accommodate the transducer face or this area may be filled to a level smooth surface with a minimum thickness of a suitable material such as Plaster of Paris, cement mortar or epoxy resin. A suitable time should be allowed to elapse for the filling material to harden.

If the value of the transit time displayed remains constant to within + 1 %, when the transducers are applied and re-applied to the concrete surface, it is a good indication that satisfactory coupling has been achieved.

5.0 Influence of Test Conditions

The pulse velocity in concrete may be influenced by path length, lateral dimensions of the specimen tested, presence of reinforcing steel and moisture content of the concrete.

The influence of path length will be negligible provided it is not less than 100 mm when 20 mm size aggregate is used or not less than 150 mm when 40 mm size aggregate is used.

The pulse velocity will not be influenced by the shape of the specimen, provided its least lateral dimension (i.e. its dimension measured at right angles to the pulse path) is not less than the wavelength of the pulse vibrations. A pulse of 50 Hz frequency corresponds to a least lateral dimension of about 80 mm. Otherwise the pulse velocity may be reduced and the results of pulse velocity measurements should be used with caution. The velocities of pulses in a steel bar are generally higher than they are in concrete. For this reason, pulse velocity measurements, made in the vicinity of reinforcing steel, may be high and not representative of the concrete since the equipment indicates the time for the first pulse to reach the receiving transducer.

The influence of the reinforcement is generally very small if the bars run in a direction at right angles to the pulse path and the quantity of steel is small in relation to the path length. The influence may be allowed for when the bar diameter lies directly along the pulse path. It is, however, preferable to avoid such a path arrangement and to choose a path that is not in a direct line with the bar diameters.

When the steel bars lie in a direction parallel to the pulse path, the influence of the steel may be more difficult to avoid. Again, it is advisable to choose pulse paths that avoid the influence of the steel as far as possible.

The moisture content of concrete can have a small but significant influence on the pulse velocity. In general, the velocity is increased with increased moisture content, the influence being more marked for lower quality concrete. The pulse velocity of saturated concrete may be up to 2% higher than that in dry concrete of the same composition and quality, although this figure is likely to be lower for high strength concrete. When pulse velocity measurements are made on concrete as a quality check, a contractor may be encouraged to keep the concrete wet for as long as possible in order to achieve an enhanced value of pulse velocity. This is generally an advantage since it provides an incentive for good curing practices.

The temperature of the concrete has been found to have no significant effect on pulse velocity over the range from 0° to 30°C so that, except for abnormally extreme temperatures, temperature influence may be disregarded.

6.0 Significance and Uses

The measurement of pulse velocity may be used to determine the homogeneity of the concrete, the presence of voids, cracks or other imperfections, changes in the concrete which may occur with time (i.e. due to the cement hydration) or through the action of fire, frost or chemical attack and the quality of the concrete in relation to specified standard requirements, which generally refer to its strength.

6.1 Homogeneity of the Concrete

The measurement of pulse velocities at points on a regular grid on the surface of a concrete structure provides a reliable method of assessing the homogeneity of the concrete. The size of the grid chosen will depend on the size of the structure and the amount of variability encountered.

It is useful to plot a diagram of pulse velocity contours from the results obtained since this gives a clear picture of the extent of the variations. It should be appreciated that the path length can influence the extent of the variations recorded because the pulse velocity measurements correspond to the average quality of the concrete along the line of the pulse path and the size of concrete sample tested at each measurement is directly related to the path length. The classification of the quality of concrete on the basis of pulse velocity as given in IS 13311 (Part 1) is given in Table 1.

Table 1: Classification of the quality of concrete on the basis of Pulse velocity

Longitudinal Pulse Velocity (km/s)	Quality of concrete
> 4.5 :	Excellent
3.5 - 4.5 :	Good
3.0 - 3.5 :	Doubtful
2.0 - 3.0 :	Poor
< 2.0 :	Very poor

6.2 Detection of Defects

When an ultrasonic pulse, travelling through concrete meets a concrete air interface, there is a negligible transmission of energy across this interface so that any air-filled crack or void lying directly between the transducers will obstruct the direct beam of ultrasound when the void has a projected area larger than the area of the transducer faces. The first pulse to arrive at the receiving transducer will have been diffracted around the periphery of the defect and the transit time will be longer than in similar concrete with no defect. It is sometimes possible to make use of this effect to locate flaws, etc. but it should be appreciated that small defects often have little or no effect on transmission times.

6.3 Detection of Large Voids or Cavities

A large cavity may be detected by measuring the transit times of pulses passing between the transducers when they are placed in suitable positions so that the cavity lies in the direct path between them. The size and position of such cavities may be estimated by assuming that the pulses pass along the shortest path between the transducers and around the cavity. Such estimates are more reliable if the cavity has a well defined boundary surrounded by uniformly dense concrete. If the projected area of the cavity is smaller than the diameter of the transducer, the cavity cannot be detected.

6.4 Estimating the Depth of Surface Cracks

An estimate of the depth of a crack visible at the surface can be obtained by measuring the transit times across the crack for two different arrangements of transducers placed on the surface.

A suitable arrangement is one in which the transmitting and receiving transducers are placed on opposite sides of the crack and at a reasonable distance from it. Two values of x are chosen, one being twice that of the other. The transit times corresponding to these are measured.

An equation may be derived by assuming that the plane of the crack is perpendicular to the concrete surface and that the concrete in the vicinity of the crack is of reasonably uniform quality.

A check may be made to assess whether the crack is lying in a plane perpendicular to the surface by placing both transducers near the crack and moving one of them.

It is important that the distance, x, be measured accurately and that very good coupling is developed between the transducers and the concrete surface. The method is valid provided the crack is not filled with water.

6.5 Monitoring Changes in Concrete with Time

Changes occurring in the structure of concrete, with time caused by either hydration (which increases strength) or by an aggressive environment, such as frost, or sulfates, may be determined by repeated measurements of pulse velocity at different times. Changes in pulse velocity are indicative of changes in strength and their measurement can be made over progressive periods of time on the same test piece or concrete product. This facility is particularly useful to follow the hardening process during the first two days after casting and it is sometimes possible to take measurements through formwork before it is removed at very early ages. This application is useful to determine when formwork can be removed or when pre-stressing operations can proceed.

6.6 Estimation of Strength

Concrete quality is generally assessed by measuring its cube (or cylinder) crushing strength. It has been found that there is no simple correlation between cube strength and pulse velocity but the correlation is affected by the type of aggregate, the aggregate/ cement ratio, the age of concrete size and grading of aggregate and the curing conditions.

In practice, if pulse velocity results are to be expressed as equivalent cube strengths, it is preferable to calibrate the particular concrete used by making a series of test specimens with materials and mix proportions that are the same as the specified concrete, but with a range of strengths. The pulse velocity is measured for each specimen, which is then tested to failure by crushing after which co-relation curve has to be established (Fig. 2). The range of strength may be obtained either by varying the age of the concrete at test or by introducing a range of water-cement ratios. The curve relating cube strength to pulse velocity is not likely to be the same for these two methods of varying strengths but the particular method chosen should be appropriate to the test purpose required. If strength monitoring with time is to be carried out, the calibration curve is best obtained by varying the age but a check on quality at a particular age would require the correlation to be obtained by varying the water-cement ratio (Fig. 3). Although such correlations can be obtained from tests on cubes, it is preferable to use beams such as those

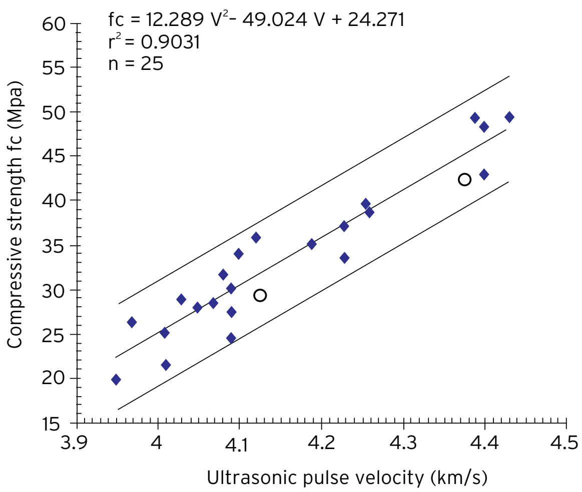

Fig. 2: UPV/ compressive strength calibration curve as given by Brian Hobb and Mohamed Tchoketch Kebir

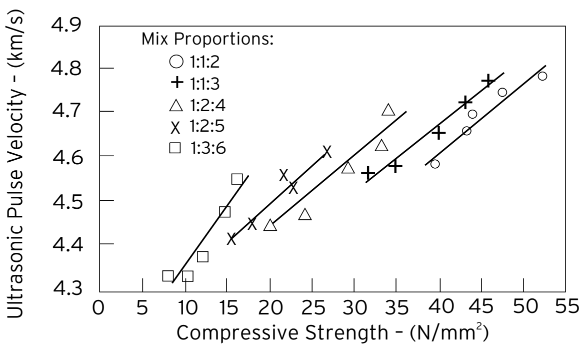

Fig. 3: Relation between ultrasonic pulse velocity and compressive strength for concretes of different mix proportions

used for testing the modulus of rupture of concrete and described in B S 1881 (methods of testing concrete). These beams are 500 mm long and a more accurate value of pulse velocity is obtained by using the long axis as the pulse path. After testing ultrasonically, the beams are tested in flexure to determine the modulus of rupture and the broken halves tested by crushing to measure the equivalent cube strength. All the details of these tests are described in BS 1881. When testing the concrete in a structure, it will be unreasonable to expect the value of the cube strength estimated from pulse velocity measurements to be the same as that specified for the control cubes made on the site, since the design of concrete structures takes into account the fact that cubes are likely to be of higher strength than the concrete in the structure it represents. A suitable tolerance is therefore required to allow for this. Instead of expressing the strength in terms of cube strength, it is preferable to obtain a direct correlation between the strength of a structural member and the pulse velocity whenever this is possible. Such correlation can often be readily applied to pre-cast units and it is possible to obtain a curve relating pulse velocity with an appropriate mechanical test such as bending strength, for the unit. A comparison between UPV and Rebound hammer test methods is given in Table 2.

7.0 Calibration of UPV

The probes are first calibrated using a special steel reference bar, which is used to set the calibration of the instrument and few latest equipment are factory calibrated and simply required zeroing.

Table 2: Comparison between Rebound hammer and Ultrasonic Pulse Velocity NDT methods

Method	Rebound hammer	Ultrasonic pulse velocity
Principle	It consists essentially of a metal plunger, one end of which is held against the concrete surface while the free end is struck by a spring loaded mass which rebounds to a point on a graduated scale. The point is indicated by an index rider. The amount of rebound increases with increase in concrete strength for a particular concrete mix.	Voltage pulses are generated and transformed into wave bursts of mechanical energy by the transmitting transducer (which must be coupled to the specimen surface through a suitable medium). A receiving transducer is coupled to the specimen at a known distance to measure the interval between the transmission and reception of a pulse.
Main applications	It measures the surface hardness of concrete and provides an estimation of surface compressive strength, uniformity and quality of concrete	Determination of the variability and quality of concrete by measuring pulse velocity. Using transmission method, the extent of such defects such as voids, honeycombing, cracks and segregation may be determined. This technique is also useful when examining fire damaged concrete.
User expertise	User expertise is low and can be readily operated by field personnel.	Expertise is needed to interpret the test results.
Advantages	It gives accurate assessment of the strength of the surface layer of material. The entire structure can be tested in its 'as-built' condition	Excellent for determining the quality and uniformity of concrete. It can rapidly survey large areas and thick members. Path lengths of 10m to 15m can be inspected with suitable equipment.
Limitations	The test determines the hardness of the surface only. The impact of hammer is sensitive to the surface layer of about 25 to 30 mm only. The reliability of this test as alone, for compression strength is less, but it can generally indicate uniformity of concrete.	Proper surface preparation is required. The work is very time consuming as it takes only point measurements. Skill is required in the analysis of results as moisture variations and presence of metal reinforcement can affect results. The interpretation of ultrasonic test results based on published graphs and tables can be misleading.

Repair and Rehabilitation of Nehru Memorial College of K.V.G. Group of Institutions at Mangalore – A Case Study

[Extracted from paper published in conference proceedings of CEMCON-2011, organized by Indian Concrete Institute, Pune]

1.0 Introduction

Ageing infrastructures need periodical repair and maintenance to limit the level of deterioration of the structures. Due to poor maintenance the structures are in badly distressed condition. The present case study discusses the repair and rehabilitation of one of such distressed institutional building located in south India.

2.0 Background

The Nehru Memorial College of Sri Kurunji Venkatramana Gowda (KVG) Group of Institutions is located at Sullia near Mangalore, a costal city in the state of Karnataka. It was established in the year 1967. This 44 year old institution consists of framed structures of G+1 and G+2 storyed of different blocks, which has experienced sever water leakage and environmental distress leading to cracking, spalling and deterioration of the structural members. The client was very worried about the safety and stability of the structures. The structural consultant carried out nondestructive testing on the structures and found out that the structure is safe and only needs repair and rehabilitation, and can even carry the load of an additional floor.

3.0 Distress Observed

Since the building was very old and located in a costal area, water leakage and reinforcement corrosion were major issues. There was water leakage on the roof and water seepage through the external walls. The walls were made of laterite stone block masonry. The pointings of the stone masonry disintegrated and water was leaking through these joints. There was spalling of plaster (Fig. 1), cracks in the masonry walls (Fig. 2) and cracks in the ceiling of the RCC roof (Fig. 3). Water seepage and leakage led to the growth of fungus and moss on the walls (Fig. 4) and the ceiling. The corrosion of reinforcement led to spalling of the concrete. There were cracks in the RCC ceiling and corrosion of reinforcement and spalling of concrete in columns (Fig. 5).

Fig. 1: Spalled plaster, fungus growth on walls

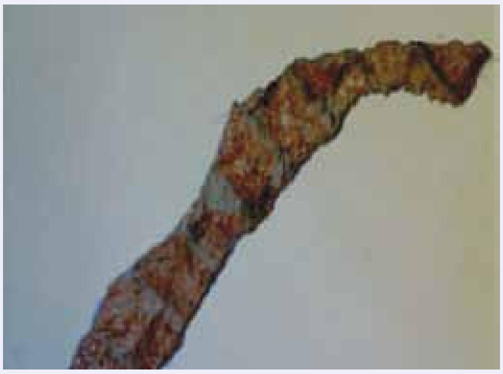

Fig. 2: Cracks in the masonry wall

Fig. 3: Cracks in the ceiling

Fig. 4: Fungal growth on ceiling

Fig. 5: Corrosion of reinforcement and spalling of concrete in columns

4.0 Repair of Cracks in Masonry Walls

There were some cracks in the masonry walls (Fig. 6). At these locations the plasterings were chipped and V-grooves cuts were made along the length of the crack with a chisel. The cleaning was done with a high pressure water jet. A wire mesh was fixed along the cracks after which the cracks were repaired with cement based ready to use fine repair mortar **(PAGEL U – 10)** (Fig. 7).

Fig. 6: Cracks in walls

Fig. 7: Plastering cracks repaired

5.0 Repair and Strengthening of RCC Columns, Beams and Slabs

The reinforcements in most of the columns had corroded. There was complete loss of concrete cover in some columns. The following steps were taken for repair and strengthening:

- Distress and spalled concrete portions were identified and marked for repair and restoration.
- Reinforcements were exposed by proper chiseling with a light weight hammer and chisel.
- The exposed reinforcements were properly cleaned with a wire brush and the entire concrete steel surface was washed with potable water.
- Thereafter the reinforcements were applied with a rust remover **(Dr. Fixit Rust Remover)** and rubbed with gunny sacks, wiped properly and washed with high pressure water jet to remove traces of any residue.
- Then the same reinforcements were applied with anti-corrosive epoxy zinc primer **(Dr. Fixit Epoxy Zinc Primer)** to prevent further corrosion.
- After that the distressed concrete portions were properly applied with epoxy bonding agent **(Dr. Fixit Epoxy Bonding Agent)** which acts as an impervious layer for the restored patches.
- Finally cement based ready to use high early strength structural grade repair mortar of **PAGEL U-40** was applied in mortar consistency to build up the thickness for 10-30 mm cover concrete and **PAGEL U-80** for 40-80 mm cover concrete, as needed at site condition (Fig. 8). The ceiling surfaces of the roof slab and beam were also repaired in a similar manner (Fig. 9).

Fig. 8: Columns repaired with structural grade mortar

Fig. 9: Repairing of ceiling, beam

6.0 Strengthening of Corridor Columns

The columns of the corridor needed to be repaired and strengthened to carry additional load. This was achieved by providing steel jackets to those columns. The steel jackets were made of 4-ISA 75 x 75 x 6 mm and braced with tie rods in a zigzag manner. The concreting was done with cement based structural grade repair mortar **(PAGEL U-80)** (Fig. 10). The properties of cement based repair mortar is given in Table 1.

Fig. 10: Strengthening of columns by steel jacketing

Table 1: Properties of cement based repair mortar used

Sl.	Properties		PAGEL U-10	PAGEL U-40	PAGEL U-80
1	Granulation (mm) 0-1		0-1	0-4	0-8
2	Compressive strength (Mpa)	7 days	50-55	50-55	50-55
		28 days	60-65	60-65	55-60
3	28 days Flexural strength (Mpa)		9	9	9
4	Abrasion resistance (Mpa)		> 2	> 2	> 2

7.0 External Wall Plastering and Protective Coating

- All the external wall plasters were loosened and debonded from the masonry surface for which plastering was chipped of and replastering was done. It was finished with cement mortar mixed with polymer modified mortar, as shown in Figure 11 **(Dr. Fixit Pidicrete URP)**.

Fig. 11: Plaster finishes with polymer modified mortar

- The surface was applied with an acrylic based primer (**Dr. Fixit Prime Seal)** to resist efflorescence and to provide excellent adhesion to the surface.
- The surface was finally protected with an acrylic elastomeric coating **(Dr. Fixit Rain Coat)** (Fig. 12). It is a water based coating with hairline crack bridging ability. Since this coating has higher thickness of 125 micron in two coats, it can provide a relatively longer service life of 6-8 years. The coating is also algae and fungus resistance and having higher dirt pick up resistance. As a result it can maintain a clean surface.

Fig. 12: Surfaces protected with acrylic elastomeric coating

8.0 Conclusion

The building repair and waterproofing were carried out with construction chemical materials in order to increase the service life of the structures. Non-destructive testing helped for proper diagnosis, to assess the existing load carrying capacity of the member of the structure for repair and strengthening and to take a decision for the construction of an additional floor. The photograph before repair of the building is shown in Figure 13 and after repair with the additional floor is shown in Figure 14.

Fig. 13: Before repair in distress conditions

Fig. 14: View of the same building after repair, strengthening and with an additional floor

- Year of repair: 2009-2010
- Structural consultant: Maistry S, Mangalore

Programmes Conducted

• In-house Training Programme

Build Your Structure Waterproof

Date : 12th & 13th May 2011

Participants: Mihir Enterprises, Royal Waterproofing Company, Hallmark Painting, Saifi Waterproofing Co., S. P. Construction, Maruti Leakproof (I) Enterprises, Quality Heightcon Pvt. Ltd., Addi Royal Company

• External Training Programmes

Cracks in Concrete and Crack Repairs

Date : 9th April 2011

Venue : NIRMA University, Ahmedabad

Waterproofing of Roofs and External Walls

Date : 16th April 2011

Venue : The Institution of Engineers, Belapur Local Centre at CBD Belapur, Navi Mumbai

Build Your Structure Waterproof

Date : 24th – 25th June 2011

Venue : NIRMA University, Ahmedabad

Admixtures in Concrete

Date : 28th June 2011

Venue : The Institution of Engineers, Pune Local Centre

Jointly with : Maharashtra Academy of Engineering, Pune and Indian Concrete Institute, Pune

Entrepreneurship in Waterproofing and Repair of Concrete Structures (Two Batches)

Date : 4th - 5th May 2011

Date : 29th - 30th June 2011

Venue : C. B. Kora Training Institute of Khadi & Village Industries Commission (KVIC), Borivali, Mumbai

Participants and Faculties in KVIC training programme

• Special Session

Mr. T. P. Bannerjee conducted special sessions on **"Waterproofing, Joint Treatments and Protective Coatings"** for professional Engineers from various organizations at Engineering Staff College of India (ESCI), Hyderabad on 15th June 2011.

• Paper Presentation

Mr. E. Gopalakrishnan presented a paper on **"Repair Materials and Methodologies for concrete structures along with Advanced Diagnostic Methods"** at India Building Congress, New Delhi held on 29th and 30th April 2011 and another paper on **"Repair and Rehabilitation of Concrete Structures"** at National Conference of "Repair and Rehabilitation of Concrete Structures" organized by Indian Concrete Institute, Ghaziabad at Noida held on 6th and 7th May 2011.

• Seminars and Conferences

An evening technical seminar on **"Roof Treatment for New Construction"** was organized at The Hotel Orchid, Mumbai on 26th May 2011 by Dr. Fixit Instiitute. Invited speakers from National Roofing Contractors' Association (NRCA), USA delivered lectures on the following topics:

- Overview of US Roofing and Waterproofing Market (including emerging technologies) by Mr. Wiiliam Good, Executive Vice Presedent
- Energy Efficiency in Roof Systems by Mr. Paul Apostolos
- Roof Systems used in the US; Application Considerations, Advantages and Disadvantages by Mr. John Schehl

The occassion was graced with senior executives from renowned builders across Mumbai.

Mr. Wiiliam Good presenting his paper in the seminar on "Roof Treatment for New Construction"

Training Programmes and Seminars

Forthcoming Training Programmes

DFI-SPR has scheduled the following training programmes for the upgradation of knowledge base of Practising Engineers, Waterproofing and Repair Contractors, Consultants, Architects, Faculties and Students from Engineering Colleges.

Sr. No.	Date	Venue	Topic	Fees	Details of the topic
1	7th & 8th Oct 2011	Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat	Admixtures for High Performance Concretes	₹ 2000 (Practising Engineers) ₹ 1000 (Faculty Members) ₹ 500 (Students)	• Fundamentals of chemical admixtures and compatibility with concrete • Mineral Admixtures – their characteristic use in concrete • High strength high-performance concrete using admixtures • Role of Admixture in self compacting concrete and in ready mixed concrete • Use of Admixtures for repair and restoration
2	19th & 22nd Oct 2011	Engineering Staff College of India, ESCI Campus, Gachi Bowli, Hyderabad	Sustainable Construction Practices using Construction Chemicals	₹ 16 000 (Residential fees) Fees include twin-sharing/ single AC accommodation as per availability, breakfast, lunch, dinner, tea/ coffee and snacks. ₹ 14,400 (Non-residential)	• Basics of sustainable construction practices • Energy efficiency of buildings and technologies for its improvement • Water conservation in building construction and usage • Role of construction chemicals in modern construction for extending the service life of buildings and green rating of construction chemicals • Safety, health and Environmental issues of construction chemicals
3	11th Nov 2011	DFI - SPR, Andheri (E), Mumbai	Conservation of Heritage Structures, Challenges & Approaches	₹ 1500	• History of the Structure • Analysis of Sructure • Challenges & Approaches • Case Studies
4	5th to 16th Dec 2011	DFI - SPR, Andheri (E), Mumbai	Entrepreneurship in waterproofing, Structural Protection & Repair of Concrete Structures	₹ 5000 Fees include training, course materials, certificate, tea, snacks and working lunch on all the ten days.	• Advanced waterproofing materials, systems and application methodologies • Repair techniques and methodologies • Coatings for structural protection • Maintenance schedules and strategies • Communication skills and art of business conversations • Preparation of business plans and proposals

Corporate Training Programme

In addition to the above scheduled programmes, we do organize separate corporate training programmes on specific topics as per the needs of the customer.

Distance Education Programme for Practising Engineers

One year Graduate Certificate Programme is being offered by DFI-SPR jointly with NICMAR, Pune for practising Engineers on following course:

- **Concrete Technology Waterproofing and Repair Management**

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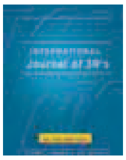

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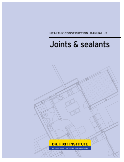

Published Articles

Dr. A. K. Chatterjee has published a paper on **"Smart Concrete"** in Construction Business Today, April 2011, pp-46-48

Mr. Suresh ch. Pattanaik, Mr. E. Gopalkrishnan and Mr. Mohan Kumar have published a paper on **"Repairs and Rehabilitation of Nehru Memorial College of K.V.G.Group - A Case Study"** in the CEMCON 2011 conference organized by Indian Concrete Institute, Pune held on 17 - 18 June 2011.

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