Health Monitoring of Air Force Station using Condition Assessment Rebound Hammer, Ultrasonic Pulse Velocity Tests and Repair Methodology

G. M. Sheikh, N. A. Sheikh and R. Sehgal

***Abstract*: The Blast Pans of AIRFORCE STATION Awantipura is in a distressed condition and as a result the matter was referred to civil engineering department, N.I.T Srinagar. Inspection was done by a team of mechanical and civil engineers of the Institute. The Ultrasonic Pulse velocity test and Rebound Hammer Tests were used to check out the quality of concrete. However, the visual analysis was carried to locate the dampness, cracks and other defects in the buildings. The inspection was arranged and the structure was inspected and tested to find the extent of damage. With the passage of time, the RCC structures are showing signs of deterioration in the form of cracks, spalling and corrosion of rebars. The R.C.C. members have deteriorated which is making building unsafe for its use. If it is allowed to continue further, the structures will be completely deteriorate without serving its desired life period. So it is necessary to study the reasons to deterioration of RCC structures, by considering all the factors, which can cause deterioration. As per the conditions prevailed locally, the probable reasons for deterioration may be carbonation, chlorides, sulphates and corrosion.**

In present work, the strength of RCC components, effects of carbonation, chlorides, sulphates and corrosion levels of building are studied. The specific objectives of the study are to know: the effect of concrete cover, the effect of carbonation, the effect of chlorides and sulphates, corrosion levels in the structures, visual inspection, NDT tests to assess the quality of concrete structures and comparison of condition regarding safety and serviceability of RCC structures.

Index Terms: Health Monitoring, RCC structures, Deterioration and NDT tests.

I. INTRODUCTION

Presently, all constructed modern structures need to be cross-examined for check out their durability and protection during any specific time throughout the year. Since, constructed structures need to be tested initially which are suspected to any kind of failure during the design to maintain their sustainability evaluation. The structural engineers must use these results achieved through proper analysis to specify whether the structure should be reinforced or not. Further, there is a common technique used by many companies to provide information on the quality control and to maintain the design criteria for reinforcing suspicious structure [1, 2]. Especially, great technical and useful importance has been obtained when using the non-destructive testing (NDT) of concrete. The main advantage of using non-destructive test method is to avoid the damage of components of building structure [3]. The examination of empirical research carried out for improving the concrete quality many non-destructive methods have been already used [4, 5]. In this aspect, numerous data and correlation relationships between the pulse velocities of concrete have been arranged and a regression analysis to predict compressive strength of concrete based on sound characteristics like UPV, estimated concrete strength and damping constant [6, 7].

All samples must be at the same age moisture condition and the same carbonation degree and was found that compressive strength of high strength concrete without exposure to temperature (200-400-600-800°C) for one hour [8]. It was also found that for equal compressive strengths concrete made with crushed limestone coarse aggregate show rebound numbers approximately 7 points lower than those for concrete made with gravel coarse aggregate, representing approximately 7MPa difference in compressive strength. Also, the surface and internal moisture effects on rebound hammer and the type of cement significantly affects the rebound number readings [9]. However, research work has been published in which the relation between compressive strength and UPV in columns was studied [10]. Another research work has been published on UPV characteristics [11].

An empirical relationship between concrete compressive strength and UPV has been also derived [12]. The pulse velocity is not affected by the level of stress in the element under test [13]. Further a model was proposed to analyze the compressive strength of concrete in different environments using UPV and probabilistic to predict compressive strength from UPV [14].

Thus, the aim of present research is to study the Health Monitoring of AIR FORCE STATION AWANTIPURA using Condition Assessment Rebound Hammer, Ultrasonic Pulse Velocity Tests and Repair Methodology to evaluate the serviceability and safety of structures. The strength of RCC components, effects of carbonation, chlorides, sulphates and corrosion levels of building are also studied.

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II. METHODOLOGY OF THE RESEARCH WORK

Generally, there is chance of carbonation, ingress of moisture, gases and other deteriorious substances in every concrete building. Chlorides may be present in concrete in the form of accelerators; water used in the mixing and curing and contaminated aggregates. Sulphates may also be present in the water used for concreting. Alternate wet and dry cycles, temperature and relative humidity accelerated the above attack and may finally have led to deterioration. For studying the above factors, the environmental factors are also considered. While studying the above, the structures are assumed that, they all are constructed with same grade concrete, materials, mix etc.

A. Analysis of Structural Integrity

There are some events when a concrete shows signs of failure despite of its high durability when used as construction material. Further, there are numerous causes for the occurrence of damages in structures, like sudden high-loading, foundation settlement or (construction faults) and poor workmanship. However, the corrosion of reinforcement is a common cause of damage which leads to further cracking and spalling of the concrete cover. To determine the percentage of damage and enhance the integrity of modern structures these concretes need to be specifically inspected early, which are in use under severe conditions. In this regard, for assessing the health monitoring of modern structures several important useful techniques are available now.

It is very essential to determine whether the major portion of the structure is of suitable quality and in this regard the first step for successful integrating testing is to carry out a detailed investigation about the structure. In addition, for executing a suitable repair plan the knowledge of intensity and extent of damage is required. Thus, the main goal of the investigation should be; to establish the cause (source) of damage, determine the percent of damage, estimate the material properties, evaluate the safety (serviceability) of the concrete structure, provide recommendations on remedial and obstructive measures, and calculate the cost of repair (replacement).

However, a typical investigation method involves the following processes; inspecting the site (with special attention to potential safety hazards), studying the design criteria, details of construction, loading capacity of the structure, planning and executing the condition survey, laboratory testing of material samples secured from the structure, analyzing and interpreting the acquired data, and load testing of individual members (if necessary).

Further, the different methods used for the inspection of concrete structures can be simply classified as; visual and mechanical inspection, chemical analysis, and electrochemical testing.

Initial Visual Inspection

The starting point of inspection is visual examination in which cracks, rust staining, and spalling are the most common defects which can be identified. Under this stage, until further investigation is undertaken to confirm the root cause the location of these defects can give a good indication of the problems. An in-depth examination should be carried out initially during visual inspection of a structure which will suggest the present problem.

The purpose of the site inspection is to identify the type and age of construction, gravity and lateral load resisting systems, and to make a preliminary assessment of the existing condition of the structure. Visual defects may be related to poor workmanship or material deterioration. These show up as excessive deflection and flexural cracking, while foundation movements may cause diagonal cracks. Material deterioration is normally indicated by cracking and spalling. It is particularly important to differentiate between the various types of cracks found. Examination of crack patterns often suggests the most probable cause of the problem.

Access facilities are usually minimal, so the extent of examination is limited. Hammer- tapping (to locate hollowness or delamination), and the use of the Schmidt Hammer, cover meter, or crack width gauge are often helpful. Potential problems associated with cracking, excessive deflections, water permeability, and evidence of corrosion should be specially noted. By observing the site and examining pertinent drawings and records, the probable causes of damage are deduced, and the areas of serious concern are located. It is often possible to judge whether the damage is corrosion related and this is useful in planning the subsequent detailed survey.

Condition Survey

The purpose of this survey is to accumulate adequate data to find out the root cause and source of the problem and to determine the length of damage, as shown in the Fig.1. Depending on the expected cause of the damage, the site work involves a combination of the following processes:

- Detailed visual inspection
- Analysis of defects like cracks, spalls, steel pitting etc.
- Potential mapping with half-cell potentiometer (or similar instrument) that specifies those areas having high risk of corrosion
- Drilling holes for carbonation test and chloride percent analysis
- Coring of concrete for determination of strength and petrography examination
- Measurement of concrete cover and reinforcing bar spacing with cover meter
- Schmidt hammer test for delamination or compressive strength (comparison only)
- Ultrasonic test for honeycombing depth of cracks, or compressive strength (comparison only)
- Assessment of depth of discoloration (in the damage) with hammer and chisel.

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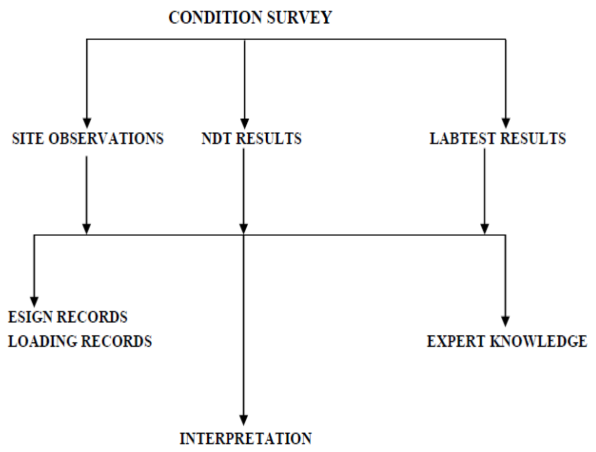

Fig.1. Flow chart describing condition survey monitoring

B. *Physical and Mechanical Inspection*

This comprises of a series of tests conducted physically on the structure to assess its condition. This covers the range of nondestructive tests and semi destructive tests, conducted in-situ. The various tests conducted are as follows:

(a) Simple Hammer

A simple hammer can be effectively utilized to get an idea about the nature and extent of damage in a distressed structure. The sound heard on tapping the surface indicates the qualitative nature. A metallic sound indicates undamaged area while a dull thud indicates delaminated areas. This simple instrument can throw light on the following aspects:

- Delamination of cover concrete
- Presence of honeycombs
- Sulphates attack

(b) Strength tests

The mechanical strength, structural integrity, crack propagation and delamination are estimated by the following tests:

(i)Surface Hardness Tests- Rebound Hammer (IS: 13311- part 2, 1992)

The rebound hammer commercially known, as Schmidt Hammer is a simple hand held device that measures the rebound of a spring loaded mass from a concrete surface, when released with a known energy. There probably exists a relationship between the surface hardness and compressive strength, and thus the device gives an accurate value of strength or variation in strength. All these important mechanical tests can be conducted on a grid pattern marked on the structure. Further, this grid pattern will be beneficial for conducting tests such as Ultrasonic Scanning, Potential Resistivity, and Corrosion Rate measurements. The quality of concrete cover is rated using the Schmidt-Hammer-number as given in Table1.

TABLE 1: Quality of concrete cover (Comparative Hardness of the cover zone)

Instrument	Average Rebound Number	Quality of Concrete
Schmidt Hammer	Greater than 40	Very good hard layer
	30 to 40	Good layer
	20 to 30	Fair

	Less than 20	Poor concrete
	0	Delaminated

(ii) Ultrasonic Pulse Velocity Tests

Assessment on condition of concrete can also be made using Ultrasonic Pulse Velocity test method. Generally, a concrete member will be divided into well-defined grid points of spacing of 250 – 300 mm and pulse velocities can be estimated using standard instruments. A systematic scanning can give useful information on the condition of concrete and this method helps to identify locations, which are corrosion-prone. The pulse velocity method of testing may be used to determine:

- The homogeneity of concrete
- Presence of voids, cracks or other imperfections
- Changes in concrete quality due to internal and external agencies
- Quality of concrete to the specified requirements required for the interpretation of results.

From the pulse velocity measurements the quality of concrete is rated as in Table.2 and locations prone to corrosion damage can be identified by combining UPV and Hammer readings as shown in Table 3.

TABLE 2: General guidelines for concrete quality based on UPV

Velocity	Concrete Quality
Greater than 4.0 km/sec	Very good to excellent
3.5-4.0 km/sec	Good to very good slight porosity may exist
3.5 -3.0 km/sec	Satisfactory but loss of integrity is suspected (Fair)
3.0 km/sec	Poor and loss of integrity exists

TABLE 3: Identification of corrosion prone locations based on UPV and hammer readings (IS: 13311 PART 1: 1992)

S. No	Test Result	Interpretation
1.	High UPV values, high impact hammer number	Not corrosion prone
2.	Medium range UPV values, low impact	Surface delamination, low quality of hammer numbers. Surface concrete corrosion prone
3.	Low UPV high impact hammer numbers	Not corrosion prone, however, to be confirmed by chemical tests, carbonation, pH and Phenolphthalein test values
4.	Low UPV values, low impact hammer numbers	Corrosion prone - requires chemical and electrochemical tests

(iii) Cover Thickness Survey

The surface layer of concrete over the reinforcement is called concrete cover. This cover thickness includes the

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cement skin, mortar and concrete skin.
This concrete cover controls the following:

- Absorption
- Permeability
- Service life of the structure

Cracking, cover and concrete quality is three major interactive and inter related parameters influencing steel corrosion. Cover is an important factor that preserves the electrochemical stability of steel in chloride-contaminated concrete. A cover thickness survey is useful to determine what cover exists in a specific location where a damage has been identified and elsewhere for comparison on the same structure. The cover to reinforcement, or any other embedded steel is required to be known so that the results of other tests, such as carbonation and chloride concentration, can be correctly interpreted with respect to future performance of the concrete structure. The cover thickness can be measured non-destructively using commercially known cover meters. All cover meters work on the electromagnetic interaction between the search-head, which is moved over the surface of the concrete. Care must be taken to check the results of such a survey by physically removing the concrete cover at one or more locations and measuring the depth of the steel. This will ensure that the type of steel or type of aggregate is not influencing the result, and that the cover meter is correctly calibrated. The detailed structural drawing will give an idea in the cover thickness survey. Table 4 shows how the cover meter readings are to be interpreted for corrosion assessment.

TABLE 4: Cover meter readings

S. No	Test Results	Interpretations
1.	Required cover thickness and good quality	Not corrosion prone
2.	Required cover thickness and bad quality cover concrete.	Corrosion prone
3.	Very less cover thickness, yet good quality cover concrete.	Corrosion prone

(iv) Carbonation Test

Concrete is alkaline in nature. The pH value of concrete at the time of construction is around 12.5. During the course of time; carbon-di-oxide from external environment enters inside the concrete. Because of the chemical action of carbon-di-oxide on calcium carbonate, the alkaline environment changes to acidic environment. This is one of the necessary conditions for corrosion. This change can be detected by phenolphthalein test. A solution of phenolphthalein in dilute alcohol is usually used because it has a very strong pink color that is easily visible on any kind of concrete surface, which has retained its alkalinity. But it becomes colorless on the concrete surface which no longer remains alkaline due to the action of carbon-di-oxide, thus paving the way for the corrosion of steel rebars. The change in color of phenolphthalein takes place as pH value changes from 10 to 8.2. Once the pH value reduces below 10, passive layer in the rebar is broken. The freshly broken concrete surface is sprayed with phenolphthalein indicator solution.

The outer most part of the freshly broken concrete surface will be carbonated and will not be stained. The inner part of concrete will not be carbonated. The boundary of pink stain will clearly show how far carbonation has penetrated into the concrete. The position of steel reinforcement at that zone is determined. If carbonation has penetrated up to the steel reinforcement and beyond, the rusting is slow. When concrete is alternatively wet and dry, the steel starts rusting rapidly. In case of salty environment, the change of alkalinity and the presence of chloride fasten the rusting of steel. Measuring the depth of carbonation into the concrete is a test, which can give warning of rusting before serious damage will occur. Thus, the classification of structural damage is mentioned in Table 5.

TABLE 5: Classification of structural damage

S. No.	Intensity	Visual damage	Residual deformation
1.	Light	Final crack (<1mm) light spalling at isolated spots	Not apparent
2.	Moderate	Medium cracks (1-2mm) light spalling door/ windows slightly stuck	Slight
3.	Severe	Wide cracks (< 2 mm) at different locations doors / windows stuck utility pipes and glass broken	Slope of floor not exceeding p/125
4.	Very severe	Wide cracks everywhere doors / window distorted utility pipes and glass broken	Slope of floor exceeding P/125

Planning the condition survey includes selection of the most appropriate tests, the extent or number of test points to reflect the existing conditions of the structural members, and the location of these test points. It is good practice to obtain sufficient test result to make a statistical analysis. However, the number of test points adopted is usually a compromise between reliability, time, cost, and damage. Sometimes the survey is carried out in two stages: first, a preliminary survey with a few test points to establish the necessity for repair; and second, a thorough survey to allow a repair scheme to be designed and cost estimated. While a condition survey may begin with a definite plan, modifications often become necessary as work proceeds and the initial test data becomes available. If the results deviate significantly from expectation, the scope and nature of the survey should be modified accordingly. Assessment of material strengths normally forms part of the condition survey. This part of the work is essential if structural adequately is in doubt. The concrete strength is determined by nondestructive testing on site. It is important to distinguish between the concrete strength in general and the concrete strength of a particular member.

For general assessment, the sampling locations should be randomly chosen, and a sufficient number of samples taken to arrive at a reliable indication of the average strength and the degree of variation. Reinforcement corrosion has been recognized as one of the serious problems in concrete structures as it contributes to substantial damage in a structure exposed to aggressive environments. Corrosion results in the reduction of effective cross sectional area of reinforcing steel and also results in cracking, spalling-delamination of cover concrete finally leading to total failure of the structure.

Factors Influencing Corrosion

The principal factors, which influence corrosion, are:

- **PH value of concrete**: The pH value of the fresh concrete is normally about 12-13 & thus providing an alkaline environment to inhibit corrosion. This alkaline environment is largely due to the generation of $Ca(OH)_{2,}$ which is formed during the hydration of cement. If this pH value reduces, the alkalinity reduces making the steel vulnerable to corrosion.
- **Carbonation:** Carbonation occurs when CO_2 from air finds its way into the body of concrete through its pores in presence of moisture & water forms carbonic acid which neutralizes the $Ca(OH)_2$ formed due to the reaction during setting of concrete thus reducing the alkalinity of concrete. This process continues and destroys the passive layer on steel. Carbonation is dependent on humidity of environment & porosity or permeability of the concrete.
- **Chloride:** The penetration of salt containing chlorides activates corrosion & destroys the passive layer. The sources for chlorides could be water used for concreting & curing or the aggregates which may be contaminated with chlorides. Even chlorine gas from the environment may enter through the pores in concrete. These chloride ions tend to destroy the passive film on steel making the surface activated locally forming a small anode while the rest of passive surface serves as the cathode. Since the latter (cathode) is much larger, the dissolution of iron in the anode is highly localized and a pit is formed. The chloride ions combine with water forming hydrogen chloride & hydroxyl ions. The hydrogen chloride further prolongs the corrosion causing an increase in the pit depth leading to pitting corrosion.
- **Moisture:** Corrosion is essentially an electrochemical reaction setting in galvanic cells & difference in potential. This cell activity is aided by moisture content, which makes the galvanic cell conductive.
- **Oxygen:** Oxygen plays a significant role in accelerating corrosion. The penetration of oxygen in differential concentrations at different places causes formation of differential aeration cells, which in turn produces potential difference, and flow of current. The oxygen ingress depends on permeability, cracks, and cover thickness and water cement ratio.
- **Permeability:** The permeability (K) of concrete is one of the primary factors affecting the rate at which salts, oxygen, moisture, etc. can penetrate into concrete and also influences the behavior of both steel & concrete. The permeability depends on factors like cement content, water cement ratio, degree of compaction, age & curing of concrete.
- **Cover:** The cover thickness is also an important factor affecting corrosion, as the cover thickness is the path through which salts, oxygen, moisture etc. penetrate to reach the steel surface.

Mechanism and Principles of Corrosion

The alkaline environment of concrete protects the embedded reinforcement against corrosion. Good quality concrete with low water cement ratio lowers the permeability minimizing the penetration of chloride ion, carbon dioxide, oxygen and water. Chloride ions in the paste tend to destroy the protective field formed on the steel by the alkaline environment. Higher the chloride ion concentration, lower is the toleration of corrosion. This concept is also used while protecting the concrete from corrosion depending upon the degree of aggressive environment. It is well recognized that the corrosion of base metals in aqueous environs follows an electrochemical mechanism. The corroding metal functions as a mixed electrode on which anodic and cathodic sites are formed and corresponding reactions take place. Corrosion occurs at anodic sites where the metal atoms pass into solution as positively charged hydrated ions (anodic oxidation) and the excess free electrons flow through the metal to cathodic sites where an electron acceptor, such as hydrogen ion or dissolved oxygen is available to consume them (cathodic reduction).

Corrosion process of iron

The essential features of the process are:

1 A reactive metal which will oxide anodic ally to form soluble ions.

2. A reducible substance, which provides the cathodic reactant.

3. An electrolyte, which allows ions to move between anodic and cathodic sites.

Corrosion process of steel in concrete

The electrochemical behavior of corroding metal implies the formation of electrolyte cell and consequent current flow extensive of potential difference between local anodic and cathodic sites. Corrosion is an electrochemical process and most common form of corrosion in concrete is in an aqueous medium. The corrosion process is similar to the action, which takes places in a dry cell battery. In the presence of aqueous medium, which acts as an electrical conductor, anode is formed where the electrochemical oxidation takes place and cathode is formed where electrochemical reduction occurs. Therefore at cathode the reduction takes place lowering the size and therefore the structural ability to carry the stresses. Availability of oxygen, water and chloride ions is the basic requirements for corrosion.

There are five states of corrosion that may occur in steel rebars in concrete, these are:

(a) Passive state
(b) The State of Pitting Corrosion
(c) State of General corrosion
(d) The state of active low potential corrosion
(e) Time dependence of corrosion states

a) Passive state

When cement concrete is dense and not contaminated by carbonation, maintains a high alkaline (pH 13) environment within the pore solutions of the hardened cement matrix. The high alkaline nature is due to the presence of calcium, potassium, and sodium hydroxides occurring in the presence of dissolved oxygen in the pore-water from the reactions of the hydration process.

In reinforced concrete members protection to steel rebar is imparted through quality concrete and adequate cover thickness. However aggressive substances, either mixed in concrete or from environments can penetrate into concrete and alter the pore- water composition thus endangering the passive state of the concrete. The passivity break down occurs due to ingress of chloride- ions (or presence of chloride- ions) and the corrosion mechanism follows an electrochemical process in which the most concrete serves as the electrolyte. It is interesting to note that penetration of chloride to the steel surface does not necessarily destroy passivity. A zone of perfect passivity can exist at high levels of chloride concentration, and it is possible to control the corrosion by maintaining a potential corresponding to this zone. The electrochemical process considers reaction at anodic and cathodic sites of corroding steel and the current flow between these two sites. These reactions can be expressed as given below:

$Fe \rightarrow 2e + Fe^{++} \rightarrow Fe(OH)_2$ (ANODE)

$1/2\ O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$ (CATHODE)

$4\ Fe(OH)_2 + 2\ H_2O + O_2 \rightarrow 4Fe(OH)_3$ (RED RUST)

$3\ Fe + 8\ OH^- \rightarrow Fe_3O_4 + 8e^- + 4\ H_2O$ (BLACK RUST)

(b) The State of Pitting Corrosion

In an alkaline environment the passivity of steel may be decreased due to the presence of chloride ions. However, pitting corrosion is mostly to be observed in reinforced concrete containing sufficient levels of chloride salts, obtained either during the working atmosphere or from the use of polluted mix materials. This type of corrosion is happened by electrochemical action between relatively large areas of passive steel acting as cathode and small anodic pits, where the local environment develops a high chloride concentration and a depressed pH value. For this process to be happened it is necessary that an enough percentage of oxygen should be available to cause polarization of the anodes.

The passivity of steel in non-buffered alkaline electrolytes needs a minimum value of pH that should be maintained further. In concrete building the general loss of passivity can happen when the pH value of pore-water at the depth of the reinforcement becomes substantially less from its high initial condition. This can be happened because of the carbonation, which involves penetration into the material of acidic gases (CO_2 etc.) from the surrounding air and it gives rise to common form of corrosion on the steel.

(c) The state of active low potential corrosion

For fully submerged or buried reinforced concrete structure, where less concentration of oxygen is available, the limiting cathodic current density may ultimately become inadequate to preserve the passive film on steel. The metal looks more active in the highly alkaline atmosphere and undergoing uniform dissolution to form soluble $Fe(OH)_2^{-}$ ions under these conditions. The corrosion potential is extremely low owing to the restricted availability of the cathodic reactant.

(d) Time dependence of corrosion states

The state of corrosion of steel in concrete may be expected to change as a function of time. In attempts to model this time dependent corrosion behavior. The imitation period, during which the metal, having been embedded in concrete remains passive whilst, within the concrete, environmental changes are taking place that, may ultimately terminate passivity. The corrosion period, which begins at the moment of de-passivation and involves the propagation of corrosion at a significant rate until a final state is reached when the structure is no longer considered acceptable on grounds of structural integrity, serviceability, or appearance? Thus, Table 6 shows the classification of corrosion.

TABLE 6: Classification of corrosion

S. No	Intensity	Cracking	Spalling	Carbonation of concrete cover
1.	Light	Hairline cracks (0.1mm) without rust stain	Not apparent	Partial
2.	Moderate	Fine cracks (<0.2mm) with or without rust stain	At isolated spots	Partial
3.	Severe	Extensive with rust stain	Extensive corroded steel visible	Complete
4.	Very severe	Extensive and wide with rust stain	Extensive; substantial steel pitting visible	Complete

C. Half-cell Potential Measurement

This method is developed and widely used with success where reinforcement corrosion is suspected. Galvanic corrosion cells are formed in concrete when corrosion of reinforcement takes place, which can be detected by using half-cell with respect to a reference electrode. The principle involve in this technique is, whenever a metal is exposed to an ion ally conducting electrolyte, like reinforced steel in wet concrete, it attains an electrical potential relative to the ease with which the metal can be dissolved in the surrounding electrolyte. Consequently, equilibrium is set up between the metal ions in solution and solid metal electrode surface.

The potential attains by the metal surface can be measured with respect to a non- polarizable reference electrode. The three-reference

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electrode commonly in use for potential monitoring are:
1. Saturated calomel electrode (SCE),
2. Silver/Silver chloride electrode (SSCE)
3. Copper/Copper Sulphate Electrode (CSE)

ASTM C8 76-77 recommends saturated copper/copper Sulphate ($Cu/CuSo_4$) electrode for monitoring the half-cell potential of the embedded steel in concrete. But this reference electrode is known to give erratic results when used for old reinforced concrete structures. This may be due to the formation of relatively large diffusion potentials at the inter-face between the copper Sulphate solution and the alkaline pore solution in concrete. In this condition saturated calomel electrode (SCE) is used. Using above electrodes, following two methods are employed for monitoring the half-cell potential of embedded steel in concrete.

Single Electrode Method

In this technique, the corrosion potential of the rebar is measured with respect to a standard reference electrode such as saturated calomel electrode, copper/copper-Sulphate electrode, silver/silver chloride electrode etc. In view of its good stability, calomel electrodes are widely used in the condition survey of reinforced concrete structure. The steel bar should be accessible in a few locations for getting electrical connections. In this method, it is necessary to have direct electrical connection to the embedded steel. The measured absolute potential with reference to the reference electrode is considered to be best criterion for assessing the corrosion status of the embedded steel rods. The negative terminal of the voltmeter is connected directly to a protruding end of embedded steel by means of a compression-type ground clamp, or by welding, or brazing. The voltmeter used in this method shall have impedance not less than 10 mega-ohms in the potential measurement range. The digital, hand-held, and battery-operated milli-voltmeters are available and are suitable to measure this potential.

In this method, the necessary commencement potential measurement is taken with the following precautions:

i) The protruding embedded steel bar must be cleaned with an abrasive paper before making electrical connection to ensure low electrical contact resistance.
ii) The concrete surface shall be cleaned thoroughly with a soft-wire brush to remove the adhering calcium carbonate layers, which cause high electrical resistance during the potential measurement
iii) The concrete surface to be subjected to test shall be kept wet uniformly before the commencement of potential measurement. For this purpose, electrical contact solutions are used. One of such contact solution is liquid household detergent, thoroughly mixed in potable water.

After ensuring that all contact points are firm and correct, polarity relation is maintained. The reference electrode shall then be electrically contacted with the concrete surface at all the required locations. There is no pre-defined minimum spacing between measurements on the surface of the concrete member. The grid space may vary from 100 mm for structural elements to about 600 mm for bridges or similar structures and possibly 1000 mm for rapid survey of large areas. Higher grid spacing are maintained to keep the number of measurements to a practical level, but smaller spacing is required to delineate small active areas. From these measurements, numerical values of measured of potentials are noted along with the corresponding X-Y coordinates of the measured locations. Later, these measured potentials are plotted one suitably scaled plan view of the concrete structure.

The ASTM interpretations are shown in following table. These interpretations highlight the significance of numerical potential values measured for embedded steel in concrete. These absolute values cannot indicate the actual state of corrosion due to presence of several chemicals and reactions between them like carbonation, chloride content etc. Table7 shows the interpretation of numerical half-cell potential values for embedded steel in concrete.

Table7: Interpretation of numerical half-cell potential values for embedded steel in concrete

Half-cell potential (Vs. CSE)	Interpretation of results
(i) More negative than –0.35 volts	Greater than 90 percent probability that embedded steel is corroding
(ii) More positive than –0.2 volts	Greater than 90 percent probability that embedded steel is not corroding
(iii) Potentials between –0.2 volts and – 0.35 volts	Corrosion of the embedded steel is uncertain

III. CONCRETE DETERIORATION

Concrete is a strong, versatile building material that has found favor with Architects, Engineers as well as Builders due to the ease of production and capability of being molded into any shape and size. Its quality, performance and behavior however depend on a number of factors. These are mainly related to the constituents and the method of production. In the earlier times the period when most of the old RCC structures were built, the emphasis was on primarily the 28 days strength of concrete. Little was known about the long-term behavior of concrete because IS 456 of 1964 (Code of Practice for Plain & Reinforced Cement Concrete), which was in vogue, then was silent on this aspect. The general belief was that good quality concrete was expected to last for at least a century. Though environmental factors were known to cause damage to concrete but environmental factors were not considered of any major consequence. It was therefore considered that concrete needed no protective coating or covering and so to provide a unique character and also to ensure good quality concrete. The formulators of the specifications at that time decided to provide shutter finished RCC with no coating or plaster to be provided over it for the sake of uniformity. As time passed the concrete technologists realized the importance of durability and the effect of the environmental factors on the performance of concrete. IS 456 of 1978 introduced for the

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first time the aspect of 'Limit State' of Design for Concrete Structures. Among the various Limit States that were set out to be satisfied, one of the important ones was the Limit State of 'Durability'. However even this revision of the Code linked the durability to the 'Condition of Exposure' to which the structure was to be exposed and a minimum content of cement to be used was specified. This leads to over use of cement in many cases with no control on the water cement ratio.

The high cement content leads to high heat of hydration, which results in high initial cracking. This coupled with uncontrolled water cement ratio lead to increased pores in the body of the concrete. The formulators of IS 456 then realized the importance of deterioration of concrete by the process of 'Carbonation' and hence the Fourth Revision issued in the year 2000. This revision has now laid down the limits of minimum cement content as well as the corresponding maximum water cement ratio for different conditions of exposure of concrete. This has been made possible with the advent of the water reducing admixtures for concrete.

A. The Importance of Cover

Concrete is heterogeneous material and, therefore, non-homogenous. Such in homogeneity occurs both at macro and micro levels. The cover has many non-visible micro cracks and these acts as avenues for water and gas penetration. The cover, therefore, should be of proper quality, depth and Bar Spacers could be incorporated to maintain even cover depths. It is observed that when the permeability form work is uncontrolled, the water cement ratio needed is 0.10 more and the cement content gets reduced by about 45 kg/m^3 compared to the original concrete mix and therefore, the cover becomes most vulnerable to attacks.

B. Carbonation of Concrete

Under pure solution of pH values of up to 12.5, the reinforcement in the concrete remains in passive conditions and does not initiate the process of corrosion. Carbonation is the effect of CO_2 from the atmosphere reacting with alkaline component in concrete Ca $(OH)_2$ in the presence of moisture thereby converting the calcium hydroxide to Calcium Carbonate. The pH value of the pore water is reduced to less than 9.5, the reinforcement is no longer in the passive range and corrosion occurs.

IV. RESULTS AND DISCUSSION

A. Visual examination

The results of different experimental investigations carried out under the present study are presented in the form of graphs and tables. The results are analyzed and discussed under the following headings.

- Common observation of structures
- Effect of concrete cover
- Effect of pH – value of concrete
- Relationship between carbonation with age
- Effect of chloride content
- Effect of sulphates content
- Corrosion levels in structures
- Homogeneity of concrete
- The quality of concrete in relation to standard requirements
- The quality of members in relation to others
- The quality of surface hardness of concrete

B. Common Observations and Analysis

On observing the structure, it was found that spalling of concrete and corrosion of reinforcement has caused cracks in the structure. It was also seen that the concrete in some of the structural elements is not found to be of very high quality. On closely observing the cracks and removing the concrete in the cover in cracked slabs, it was found that the reinforcement is completely rusted and worn-out with chipping off iron oxide formed as a result of rusting. Further on observing these cracks, following were the reinforcement elements indicating the rusting of bars and causing the cracking of concrete in the cover.

The concrete in most of the cracked slabs was spalling as a result of increase in volume of steel bars due to rusting. This is the main cause of cracking in both beams and columns. The causes of this cracking are as a result of one or combination of various factors as under:

1. Rusting of bars due to inadequate cover of steel
2. Improper quality of concrete in cover leading to permeability of moisture to steel through the concrete cover.
3. Use of already rusted steel bars during construction.
4. Excessive loading of some of the columns causing distress in the concrete leading to cracks which allows moisture to penetrate the steel bars causing rusting.

V. TEST RESULTS

The whole summary of results obtained after conducting many tests on Blast Pan-1, Blast Pan-2, Blast Pan-3, Blast Pan-4, Blast Pan-5, Blast Pan-6, Blast Pan-7 and Blast Pan-8 are mentioned in Table 8, 9, 10, 11, 12, 13, 14 and 15, respectively.

TABLE 8: Blast Pan-1

BP1					
S. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
1	BP1/1	15,12,20,14,22,8,16,17=15.5	5	1479	poor
2	South BP1/2a	22,15,34,29,34,20,26,35=26.87	10	2122	Poor
3	North BP1/2b	29,23,27,29,31,11,10,25=23.12	8	1986	Poor
4	BP1/3	35,23,26,32,17,34,30,28=28.12	12	909	Poor
5	South BP1/4a	25,22,34,34,31,36,34,32=31	14	2646	poor
6	North BP1/4b	34,24,25,21,30,39,13,32=27.25	11	3135	fair
7	North BP1/5a	17,20,21,25,28,31,20,21=22.87	8	2032	Poor
8	South BP1/5b	29,9,14,23,25,22,22,19=20.37	7	2186	Poor
9	South BP1/6a	28,33,36,29,19,31,36,18=28.75	12	2268	Poor
10	BP1/4 CB	35,38,26,29,19,32,20,28=28.37	12	2343	poor

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TABLE 9: BLAST PAN-2

S. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	BP2/1	38,44,51,54,31,52,55,54=47.37	39	3831	Good to Very-good
2	BP2/2	48,39,32,36,41,36,35,35=37.75	20	3817	Good to Very-good
3	BP2/3	38,30,34,35,28,37,36,33=33.87	15	3390	Fair
4	BP2/4	25,32,40,44,31,34,33,32=33.87	15	3245	Fair
5	BP2/5	33,27,24,33,38,29,30,28=30.25	13		fair
6	BP2/6	25,27,41,37,32,23,29,31=30.62	13		fair
7	* BP2/5	22,21,12,17,30,25,17,25=21.12	7	*1377*	poor
8	* BP2/4	22,12,17,21,22,30,25,26=21.87	7	*1372*	poor
9	* BP2/2	35,28,37,31,24,35,30,14=29.5	12,5	*1989*	poor
Front 10	* BP2/1	17,21,29,21,17,32,25,26=23.5	8.5	2032	poor

TABLE 10: BLAST PAN-3

SR. No	Location	RH No.	Compressive Strength MPa	UPV m/s	Quality
Rear 1	Beam BP3/1	37,27,37,32,22,35,30,14=29.25	12.5	*725*	poor
2	Beam BP3/2	33,30,31,38,28,27,24,25=29.5	12.5	*1958*	poor
3	Beam BP3/3	27,38,35,36,37,33,29,30=33.125	15	*3279*	fair
4	Beam BP3/4	17,21,29,21,17,32,25,26=23.5	8.5	*3093*	fair
5	Beam BP3/5	35,31,17,19,28,28,26,29=26.62	10	*1315*	poor
6	Beam BP3/6	31,28,35,31,26,24,36,34=30.62	13	*3257*	fair
7	Slab BP3/3	15,29,29,21,25,34,33,29=26.87	10	*3145*	fair
8	Slab BP3/2	28,17,28,12,23,35,36,31=26.25	10	*3636*	Good to very good
9	Slab BP3/5	23,16,16,25,13,24,30,33=22.5	8	2123	poor
Front 10	Slab BP3/6	22,16,25,21,23,32,14,27=22.5	8	2023	poor

TABLE 11: BLAST PAN-4

S. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	Beam BP4/1 (t = 280mm)	32,32,26,2,34,29,30,28=2925	12.5	*3955*	good
2	Beam BP4/2	36,36,44,43,36,48,41,29=39.125	22	2674	poor
3	Beam BP4/3	19,19,12,12,24,21,16,21=18	5.5	1789	poor
4	Beam BP4/4	22,34,26,24,28,34,33,33=29.25	12.5	1893	poor
5	Beam BP4/5	9,10,20,12,19,19,12,27=16	5	1506	poor
6	Beam BP4/6	37,31,24,34,32,14,21,23=27	11	2142	poor
7	Slab BP4/1	23,29,32,37,40,42,41,31=34.375	17	3012	Good
8	Slab BP4/3	40,23,34,39,17,38,31,34=32	14.5	2675	Fair
9	Slab BP4/5	40,40,39,36,39,26,30,18=33.5	15	3123	Fair
Front 10	Slab BP4/6	41,46,36,19,34,33,28,28=33.125	15	3235	Fair

TABLE 12: BLAST PAN-5

SR. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	Beam BP5/1	17,28,17,31,32,33,12,32=25.25	9	2134	poor
2	Beam BP5/2	40,45,40,32,32,32,35,32=36	19	1934	poor
3	Beam BP5/3	37,32,25,38,32,45,39,34=35.25	18	2128	poor
4	Beam BP5/4	27,34,28,28,46,35,34,32=33	15	*3337*	fair
5	Beam BP5/5	20,21,30,25,27,17,37,23=25	9.5	2014	poor
6	Slab BP5/2	28,28,40,40,38,34,34,31=34.125	17	3234	fair
7	Slab BP5/3	40,41,36,38,32,32,32,38=36.125	19	3186	fair
8	Slab BP5/4	23,27,28,27,23,34,36,39=29.625	12.5	3015	fair
9	Slab BP5/5	18,22,21,32,20,30,27,30=25	9	1488	poor
Front 10	Slab BP5/6	25,22,16,29,31,23,31,19=24.5	9	1942	poor

TABLE 13: BLAST PAN-6

S. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	Beam BP6/1	26,44,41,34,33,27,25,19=31.125	14	1953	poor
2	Beam BP6/2	29,40,46,37,16,30,37,35=33.75	15	1792	poor
3	Beam BP6/3	46,39,28,37,36,33,33,32=35.5	18	2257	poor
4	Beam BP6/4	36,35,31,27,16,23,38,34=30	13	2134	poor
5	Beam BP6/5	17,48,35,35,32,51,39,15=34	17	1786	poor
6	Beam Top BP6/6	25,39,18,46,29,38,38,38=33.875	15	1739	Poor
7	Slab BP6/5	35,35,39,24,35,40,32,44=35.5	18	1788	poor
8	Slab BP6/6	34,31,39,37,36,33,27,29=33.25	15	2343	poor
9	Slab BP6/3	31,27,29,20,29,33,12,25=25.75	9.5	2101	poor
Front 10	Slab BP6/2	21,35,31,34,33,37,35,43=33.625	15	2332	poor

TABLE 14: BLAST PAN-7

S. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	Beam BP8/1	17,28,32,42,44,45,48,46=37.75	20	2299	poor
2	Beam BP8/2	36,37,31,32,40,36,35,35=35.25	18	2214	poor
3	Beam BP8/3	30,34,41,44,43,46,36,35=38.625	21	2513	poor
4	Beam BP8/4	53,44,34,41,41,45,51,48=44.625	32	1934	poor
5	Beam BP8/5	27,37,28,33,29,31,40,38=32.875	14.5	2778	poor
6	Beam BP4/6	16,24,27,21,22,26,23,15=21.75	7.5	2305	poor
7	Slab BP8/1	13,18,27,30,14,16,17,21=19.5	6	1985	poor
8	Slab BP8/2	30,23,22,10,30,14,20,23=21.5	7.5	1787	poor
9	Slab BP8/3	14,29,35,10,23,20,19,27=22.125	7.5	1978	poor
Front 10	Slab BP8/4	20,24,26,27,34,16,14,17=18.375	5.5	1992	poor

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TABLE 15: BLAST PAN-8

SR. No	Location	RH No.	Compressive Strength (MPa)	UPV (m/s)	Quality
Rear 1	Beam BP9/1	37,31,32,37,20,22,37,35=31.375	14	2321	poor
2	Beam BP9/2	36,35,26,32,28,25,36,35=31.625	14	2222	poor
3	Beam BP9/3	20,26,16,13,20,18,17,16=18.25	5.5	1595	poor
4	Beam BP9/4	36,28,24,22,32,28,34,25=28.625	12	2532	poor
5	Beam BP9/5	35,23,36,33,27,26,23,28=28.875	12	2434	poor
6	Beam BP9/6	30,35,23,26,37,29,28,25=29.125	12.5	2012	poor
7	Slab BP9/1	31,32,36,39,32,26,23,25=30.5	13	2014	poor
8	Slab BP9/2	13,28,24,16,36,24,19,23=22.875	7.5	2145	poor
9	Slab BP9/3	23,27,40,35,43,36,41,38=35.375	18	2734	poor
Front 10	Slab BP9/4	26,27,21,15,23,24,31,30=24.625	9	2456	poor

A. Sulphate/Chlorides Ingress

Sulphate and chloride contents of concrete samples collected from various tanks were found out. The permissible limit of chloride contents by weight of cement is 0.4 percent and 0.15 % is enough for onset of corrosion. Sulphate contents are limited to 4.0% by weight of cement. The results are given below in Table 16.

TABLE 16: Sulphate/Chlorides Ingress Test

S. No.	Location	Chlorides		Sulphates	
		By weight of concrete (%)	By weight of Cement (%)	By weight of concrete (%)	By weight of Cement (%)
1	BP-1	0.043	0.258	0.054	0.324
2	BP-2	0.041	0.246	0.049	0.294
3	BP-3	0.042	0.252	0.045	0.27
4	BP-4	0.038	0.228	0.053	0.31
5	BP-5	0.042	0.252	0.056	0.336
6	BP-6	0.041	0.246	0.056	0.336
7	BP-8	0.039	0.234	0.048	0.228
8	BP-9	0.040	0.24	0.058	0.348

VI. CONCLUSIONS & RECOMMENDATIONS

Based on the investigation & study carried out on various members, the following conclusions are drawn here.

i) Some of members are showing deterioration in the form of cracks, spalling, carbonation, corrosion of rebars.

ii) From concrete cover data taken, few locations satisfy IS 456 minimum cover provision.

iii) The carbonation depth is increasing with the age of the structure. The rate of carbonation is more than for the normal concrete of sound quality. The variation is due to deficiency in field practice. The actual carbonation depth is much higher than normal concrete of sound quality.

iv) The high alkalinity (pH-value) of concrete surrounding the steel protects it from corrosion. From the data available, it was observed that the pH value of concrete is reducing in the structures with age. This reduction in value is due to high chloride level. This reduction in value of pH leads to the corrosion. The pH value of concrete has reduced up to 8.0. The chlorides contents found in concrete samples are not beyond permissible limits as per IS code but enough for onset of corrosion.

v) From the results of above study, it was concluded that the deterioration in structures is due to carbonation/high chloride content and with passage of time.

vi) It was further concluded that, even though deterioration has taken place, the deflection is not observed, if the deterioration is further continued, the structures may not serve for its desired life. Thus, to maintain the life of structure for its desired life, the deterioration should be controlled.

vii) Lack of maintenance and poor construction practices make the external member more prone to cracking and disintegration. In many exposed structural members vertical thin to wide cracks, drying shrinkage cracks and disintegration observed indicate likely corrosion in the members.

viii) UPV investigation results reveal that there is great variation in uniformity and homogeneity in the members of structures, the characteristics velocity is also much less than 3000 m/s. These structures need special attention towards repair.

ix) The quality of external members degraded due to high chloride contents in concrete and thereafter differential volume changes in outer and inner mass of concrete which produces cracks on the surface.

x) Rebound hammer test shows that the condition of various members is poor. The external members require immediate attention.

Thus, it was recommended to the concerned authorities to demolish all the structures without any further delay and construct new structures as the condition of the existing structures was poor.

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