Corrosion Distress Mapping of Real Life RCC Building Structure Adopting Extensive Non-Destructive Test Data and Their Correlation

By

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This is to certify that the thesis entitled **"Corrosion Distress Mapping of Real Life RCC Building Structure Adopting Extensive Non-Destructive Test Data and Their Correlation"** has been prepared by **SAYANTAN BOSU CHOUDHURY (**Examination Roll Number **-M6CNE19016**, Registration Number. **- 137347 of 2016 - 2017**) for partial fulfillment of the requirement for the degree of Master of Construction Engineering with specialization on Structural Repair and Retrofit Engineering, is a record of research work carried out under my guidance and supervision. I hereby approve this thesis for submission and presentation.

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I hereby declare that this thesis contains a literature survey and original research work by the undersigned candidate, as part of his **Master of Engineering** in **CONSTRUCTION ENGINEERING** (Specialization in Structural Repair and Retrofit Engineering) of Jadavpur University.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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ABSTRACT

Corrosion distress is a major threat for RCC building structure. The use of high energy material, economical and risk based design, inadequate quality control during construction and environmental pollution, adequately increased the corrosion risk in urban building structure. Thus Corrosion becomes the alarming cause for deterioration of reinforced concrete structures. The idea of everlasting concrete has been faded away in many cases mostly due to corrosion, which may even lead to structural failure. Corrosion may be treated as concrete cancer which spreads rapidly and has a great impact on the durability of reinforced concrete structure. Thus the detection of corrosion risk is significantly important. Half-Cell Potentiometer (HCP) test data provides an idea about the susceptibility to corrosion but there are several uncertainties associated with those readings. The present study deals with the mapping of corrosion distress of real-life multi-storied RCC building structure based on various Non-Destructive Test and chemical analysis of concrete. Corrosion distress of different buildings at same location, design and construction has been studied and compared based on HCP readings. Subsequently comparison of corrosion risk for different floors is also made at those highly distressed buildings. The susceptibility of corrosion is initially identified according to ASTM criterion. Then the variation of pH and chloride content based chemical analysis of concrete is studied and compared. Finally the Ultrasonic Pulse Velocity (UPV) based variation at those areas is also studied. A strong correlation between those values is observed in general. Attempt has also been made to develop a multi-parameter based correlation for confirmation of corrosion with greater confidence. The reading of HCP is correlated both with UPV and pH subsequently. A strong indication of corrosion susceptibility is confirmed when the assumed degradation due to UPV as well as that of pH are reaching a threshold value. The identification of corrosion distress in RCC through the proposed three parameter approach seems to be a better proposition with greater confidence.

Keyword: Corrosion Mapping, Half-Cell Potentiometer, pH, Ultrasonic Pulse Velocity

LIST OF PUBLICATION

1. "***Structural Health Monitoring of Corrosion Distressed High Rise RCC Buildings By Correlating Various NDT Results***" **–** published in XI Structural Engineering Convention 2018 (SEC 2018), ISBN 978-93-83660-46-9

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INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete is a versatile, economical and successful construction material for multi-storied building. Concrete is usually durable and strong, performing well throughout its services life. But early deterioration of reinforced concrete structure is quite common in today's world. Old reinforced concrete building and even few new reinforced concrete structures suffered mostly corrosion distress due to aggressive environment and poor quality for construction. There are several factors responsible for concrete corrosion includes absence of good quality ingredients &production process of concrete, aggressive environment, improper design & construction, poor workmanship, inadequate quality control so on. Even concrete with good in terms of strength, the corrosion of steel in reinforced concrete may occur and abetted by due to ingress of chlorides, carbon dioxide and moisture movement along with inadequate cover. This may result in greater concern for structural reliability, which may even lead to structural failure. Typical corrosion distress in reinforced concrete structure is shown in Fig-1.1.

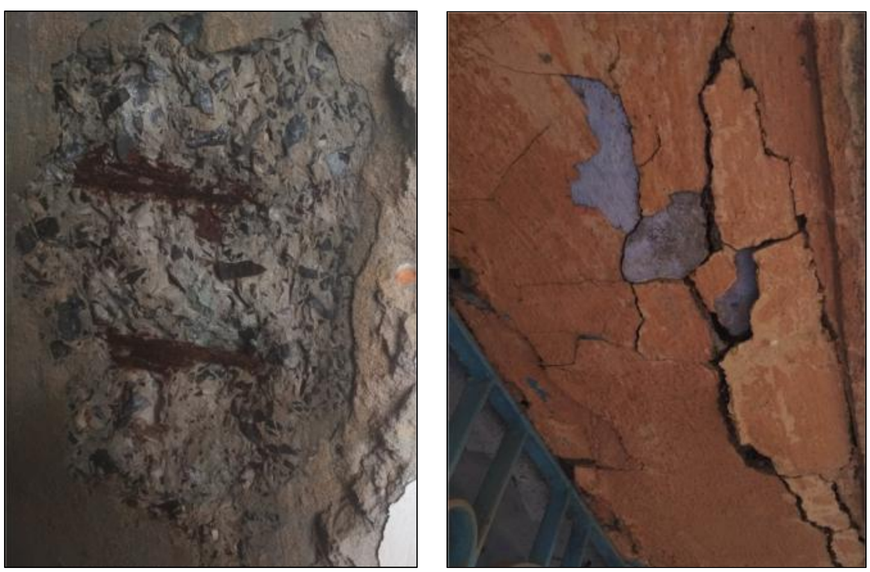


Fig-1.1: Effects of Corrosion Distress in a Real Life Reinforced Concrete Structure

Corrosion distress is a major threat for reinforced concrete, steel and pre-stressed concrete structures. Corrosion is one of the common and frequent causes responsible for the deterioration of Reinforced Concrete structures. The idea of everlasting concrete has been faded away in many cases mostly due to corrosion, which may even lead to structural failure. Cracking and spalling of concrete, reduction in cross-sectional area of reinforcement bars, change in elastic modulus of reinforcement as well as concrete and loss of bond between concrete & corroded reinforcement are the major outcome of distresses in concrete structure due to corrosion. The corrosion i.e. oxides of iron occupies much greater volume than the parent metal, which exerts a bursting pressure on the concrete cover and resulting in cracks and subsequent spalling of concrete. Spalling of concrete, a major cause of corrosion is shown in Fig-1.2 below.

Fig-1.2: Severe Corrosion leads to Spall of Cover Concrete

Corrosion may be treated as concrete cancer which spreads rapidly, can't be detected at its early stage & mostly incurable completely and has a great impact on the durability of Reinforced Concrete structure. The adoption of effective rehabilitation scheme to enhance the structural durability mostly depends on the correct understanding of failure mechanism and subsequent assessment of the distress.

Corrosion reduces the cross-sectional area of the steel reinforcement which affects the reduction of stiffness, results in change of deformation, frequency and mode shape of the structure. Significant corrosion of multi-storied RCC building complex has observed. However, the nature of this distress and its distribution seems to be random in nature. Thus a comprehensive study of corrosion mapping incorporating different Non-Destructive test is employed. Different Non-Destructive Test based on different principles and chemical analysis of concrete is conducted in real life multi-storied building structures. However, the limitation of location dependency of these test, accessibility, sample size in practical situation etc. pose problem in real life cases. Corrosion mapping is attempted initially based on Half-Cell Potentiometer (HCP) test. The integration of all these available test data in a judicial manner may address the corrosion distress mapping with greater confidence. However, the uncertainties associated with the model, instrument, environment may lead to unreliable influence in few cases. Thus other techniques along with HCP are also employed to understand and map the corrosion risk in a better manner. Thus a comprehensive corrosion distress mapping seems to be an effective tool of Structural Health Monitoring and subsequent adoption for its rehabilitation.

1.2 OBJECTIVE

The objective of the present study is to address the corrosion distress of a real life multi-storied Reinforced Concrete structure through mapping of various Non-Destructive Test data(Half-Cell Potentiometer & Ultrasonic Pulse Velocity) and chemical analysis(pH & Chloride content) of concrete. It also includes to develop a multi-parameter (half-cell potentiometer, ultrasonic pulse velocity and pH test data) based correlation for confirmation of corrosion with greater confidence.

1.3 SCOPE OF WORK

In the present study the followings are carried out-

i. Collection of Non-Destructive field test data with respect to Half-Cell Potential, pH &chloride content and Ultrasonic Pulse Velocity of concrete.
ii. Corrosion distress mapping of different tower buildings and subsequent different floors of the towers having greater distressed zones.
iii. Mapping of HCP and UPV of column according to variation of concrete grade at different floors of different tower buildings.
iv. Calculation of Dynamic Elastic Modulus and subsequently Static Elastic Modulus of concrete for different Ultrasonic Pulse Velocity values.
v. Comparison of Modulus of Elasticity obtained design grade of concrete and UPV values of concrete.
vi. Comparative study of the Half-Cell Potentiometer, pH, chloride content and Ultrasonic Pulse Velocity readings for concrete columns of the maximum distressed floors.
vii. Development of correlation between degradation estimated by Half-Cell potentiometer test result with degradation estimated by Ultrasonic Pulse Velocity values.
viii. Development of correlation between degradation estimated by Half-Cell potentiometer test result with degradation estimated by pH values.

CHAPTER-2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

A brief literature review has been exploded prior to commencement of the actual research work of the topic. Different researchers have studied on various aspect of the corrosion in reinforced concrete structure. Few of which are given below.

Bruno Huet & et. al. [2003] reviewed the corrosion mechanism of the reinforced concrete degradation from different literature. Author in his study sub-divide the concrete structure in two categories depends on the stage of corrosion. At initial stage corrosion rate is low termed as passive corrosion. During this stage ingress of aggressive species from the environment through the concrete cover. Later active corrosion begins, influencing the de-passivation of reinforcement in saturated concrete. Various uncertainties are observed for different electrochemical techniques and experimental condition.

Mohammed M. Salman & et. al. [2006] proposed that the relationship between the static modulus of elasticity and the dynamic modulus of elasticity follows a simple linear relationship. Mechanical properties of concrete depend on the mineralogical behaviour of the course aggregate. Mineralogy of course aggregate influences the compressive strength as well as the elastic properties of the high strength concrete.

Alexandre Lorenzi & et. al. [2007] proposed through his experiment that ultrasonic pulse velocity can be used for deterioration control and to identify the quality of concrete. Performance of concrete may varies due to water/cement ratio, aggregate type & size, humidity and cement type. Concrete being a heterogeneous material, interpretation of strength and quality of concrete is complex.

Mike Otieno & et. al. [2011] reviewed the prediction of Corrosion Rate in RC Structures and concluded that rate of corrosion is one of the important input parameters in corrosion induced damage prediction model and thus require sufficient attention with respect to prediction and assessment. Other factors such as cover cracking, resistivity, concrete quality and cover depth should be incorporated in the modelling of corrosion rate prediction model. The inherent variability of corrosion rate and other influencing factors should be modelled in a probabilistic manner.

R. Capozucca [2011] proposed that the dynamic tests on Pre-stressed Reinforced Concrete and Reinforced Concrete beams which were carried out in an experimental research for investigating the behaviour of beams subjected to environmental cause of damage producing corrosion of reinforcement and increase of load. The damage phenomenon was represented by corrosion and visible cracks which are not present on the surface of the concrete. Dynamic tests were carried out considering the condition of free-free ends for the beams analysed and subjected to vibration for impulsive force applied on a point by impact hammer. Frequency values recorded in dynamic testing of PRC beams, undamaged or subjected to an increasing corrosion process with softening of concrete by micro cracking, were almost constant. Damage due to corrosion and increase of applied loads produced a reduction of frequency values evaluated from experiment. The variations of frequency values in damaged RC beams may reach high values of moment for service conditions of loading. Although the dynamic response of PRC and RC beams are influenced by a number of errors, such as the condition of restrains, the results obtained in the experimental research can lead to consider the technique adequate for assessing the damage to beams with non-homogeneous material.

Tiejun Liu & et. al. [2012] proposed on his experiment that the corrosion of reinforcement have a great influence on the dynamic properties of Reinforced Concrete structures like frequency and damping response of beams and frames. Considering Reinforced Concrete beams with different stages of corroded embedded reinforcement, the damage is significant from the change in damping ratio and loss tangent were detected. The damping ratio and loss tangent are firstly decreased by steel corrosion, and then was increased when further corrosion occurs. In case of Reinforced Concrete frames, corrosion damage showing substantial increases of observed fundamental frequency after the accelerated corrosion process even the maximum longitudinal crack widths recorded were 1.0 mm and 2.0 mm. The corrosion can increase the energy dissipation of the frame and there is a critical corrosion point along which makes structural system has the maximal energy dissipation capacity.

V. Kumar & et. al. [2013] studied on corrosion of reinforcement in concrete and effect of inhibitor on service life of reinforced concrete structure through extensive experiment. Calcium Palmitate reduces the compressive strength of the concrete but enhance the inhibition capacity of reinforced concrete considerably increasing the service life of reinforced concrete structure.

Talakokula Visalakshi [2014] studied on the assessment of corrosion distressed rebars within reinforced concrete structure considering equivalent parameters extracted from piezo-patches technique. Author's approach was monitoring of the carbonation induced corrosion in reinforced concrete structure from initiation to rebar corrosion based on equivalent stiffness parameter (ESP) extracted from the signature of Piezo-electric ceramic (PZT) patches on the surface of rebar. The phenolphthalein test result shows a significant correlation with ESP and the microscopic image analysis in identifying the onset of corrosion.

Jaya Nepal & et. al. [2015] proposed an approach for evaluation of the damages caused by the corroded reinforcement and its effect on structural reliability. From the numerical example, it is evident that a) The proposed approach is capable of evaluation of structural behaviour and defects of corrosion damaged RC structures b) Flexural strength decreases significantly due to mass loss as reduction in bond strength loss c) Corrosion causes reduction in rebar size which widens the crack in concrete cover, and consequently reduces residual strength of bond and flexural strength d) The reliability of the corroded structure decreases with progress of defects in concrete.

Naasson P. de Alcantara Jr. & et. al. [2015] proposed that the corrosion of reinforcement bars within a concrete structure can be ascertained by Eddy Current method. In this paper author develop a comparative study between numerical approaches with experiment. The method cannot be suitably comparable with the well-established electrochemical method but can be used as a primitive method for determination of corrosion within the reinforced concrete structure.

Bayan S. Al-Nu'man & et. al. [2015] proposed through experiment that compressive strength of concrete can be determined by ultrasonic pulse velocity method. Ultrasonic pulse velocity and compressive strength test are performed on different test sample for developing a proper correlation between them. Authors proposed the favorable correlation is depending on the coarse aggregate content of the concrete specimen and thus develop a relationship to find the compressive strength of concrete specimen from the ultrasonic pulse velocity reading considering the coarse aggregate content. In a same manner ***D. Dahiru*** [2016] proposed a correlation between ultrasonic pulse velocity and the compressive strength of concrete.

Néstor F. Ortega & et. al. [2016] proposed that the Residual Life of a reinforced concrete structure affected by corrosion of its reinforcing bars. The proposed technique is based on non-destructive measurements and considering dynamic behaviour of the structure. The implementation is relatively simple and the most remarkable aspect of this technique is the possibility to predict when the deteriorated structure should be repaired and when it should be removed. It is also cited that the quality of the predictions depends on the quality and the number of measurements taken in situ.

V. K. Ortolan & et. al. [2016] evaluated the influence of pH of concrete pore solution on the corrosion resistance of steel reinforcement. pH of the pore solution are reduced by partial replacement of OPC by cementitious material thus influencing the passive film on steel. Authors conclude in his paper that at early stage, when concrete resistivity is low, partial replacement of cement by silica fume led to an improved passivation process and increased corrosion resistance. Due to the reduction in pH values caused by the use of supplementary cementitious materials does not seem to have a negative effect regarding the protection against corrosion, but rather on the contrary when mineral admixtures are used, the corresponding reductions in OH^- concentrations (and ionic strength) lead to an enhanced passivation of the steel reinforcement, and increased resistivity (at later ages) further contributes to an improved corrosion resistance.

Sristi Das Gupta & et. al. [2017] studied on the corrosion of reinforced concrete slab with partial replacement of cement through fly ash using non-destructive test methods. Author monitored the corrosion subject to sodium chloride by half-cell potentiometer. It was observed that concrete with fly ash showed longer period of corrosion initiation and lower corrosion rate than those of normal reinforced concrete. A reduction in corrosion area of rebar in fly ash reinforced concrete was also observed.

Muhammad Umar Khan & et. al. [2017] studied on the corrosion of steel in concrete due to chloride and prediction of corrosion initiation time. In this paper authors reviewed the development of chloride diffusion models by incorporating Fick's second law of diffusion. Author concludes that the chloride diffusion parameters obtained from simple Crank's solution of Fick's second law of diffusion represents average concrete properties regarding transportation by diffusion as the concrete matures the ability of chloride ions to penetrate concrete decreases. Further, they conclude that coefficient of chloride diffusion decreases with time and chloride binding inside concrete. It is also observed that synergic effect of simultaneous exposure from more than one side can lead to a faster rate of deterioration and the critical member shows distress much earlier than predicted.

Xiguang Liu & et. al. [2018] cited in their paper about the in-situ and experimental investigation of pH in the pore solution for the initiation of corrosion of reinforcement embedded in concrete under long term natural carbonation. Authors studied the variation in pH and phase compositions of the concrete along the cover depth. In-situ inspection results shows that the steel embedded in concrete had begun to corrode when the carbonation depth was almost less than one-third of the cover depth. The corrosion of reinforcement embedded in concrete can occur when the pH is between 11.30 and 12.10. The pore solution pH test results and X-ray diffraction (XRD) analysis shows that there is a semi-carbonated zone formed in between the fully carbonated zone and the rebar. The pH of a fully carbonated zone is in a range of 8.00–9.50, and the pH of a semi-carbonated zone is between 9.50 and 12.10. It was further concluded by the authors that the pH values decrease with the increase in concrete compressive strength. Crack widths have little effect on the variations in pH. The carbonation depth increases linearly with increases in crack width.

2.2 Critical Observation from Literature Review

i. Corrosion of the reinforcement is the most common distress of RCC structure which leads to crack of cover concrete and deterioration of the concrete.

ii. Several Non-Destructive evaluation techniques are adopted for detection of corrosion of reinforcement in the concrete structure.

iii. Dynamic responses, Eddy current can be used to measure the degree of corrosion of the embedded reinforcement within a reinforced concrete structure.

iv. Damage due to corrosion of reinforcement and reliability of corroded structure are also studied before for the assessment of remaining life.

v. Relationship between dynamic modulus of elasticity and static modulus of elasticity of concrete is studied by various researchers.

vi. Correlation between Ultrasonic Pulse Velocity Test results with the compressive strength of concrete is studied and formulated by different researchers.

vii. Rate of corrosion can be minimized by partial replacement of cementitious material with fly-ash as suggested by some researchers.

viii. Corrosion distress of reinforcement due to carbonation is validated using Piezo-electric ceramic technique by researcher.

ix. Corrosion of reinforcement within the concrete is due to the change of pH of the pore solution of concrete has observed and established.

x. Corrosion of reinforcement due to ingress of chloride had observed to be increased and subsequently, the remaining life assessment of the structure is studied.

CHAPTER-3

CORROSION IN RCC

CHAPTER 3

CORROSION IN RCC

3.1 General

This chapter is about the general discussion about corrosion, corrosion mechanism,corrosion in reinforced concrete structureand its effect on the structure.

3.2 Corrosion

Corrosion may be defined as a process by which a refined metal reverts back to its natural state by an oxidation reaction with the non-metallic environment like oxygen and water. Thus corrosion is the deterioration of a metal as a result of chemical reactions between it and the surrounding environment. Both the type of metal and the environmental conditions, particularly gasses that are in contact with the metal, determine the form and rate of deterioration.Mild steel and high strength reinforcing steel bars corrode (rust) when air and water are present. Concrete is alkaline in nature & porous and contains moisture. Metals corrode in acids, whereas they are often protected from corrosion by alkalis. Alkalinity of concrete is due its microscopic pores with high concentrations of soluble calcium, sodium and potassium oxides. These oxides form hydroxides, which are very alkaline when water is added. In general, pH of concrete ranges between 12.0-13.0 which acts a protective layer to the reinforcement. The composition of the pore water and the movement of ions and gases through the pores are very important when analysing the susceptibility of reinforced concrete structures to corrosion.

There are many different reasons for metal corrosion. Some can be avoided by adding alloys to a pure metal. Others can be prevented by a careful combination of metals or management of the metal's environment.

3.3 Corrosion Mechanism

The Corrosion is an electrochemical process that occurs at anodic spots on the steel surface within parent concrete. Anode & cathode regions are develop on the surface due to slight composition differences of metal and/or due to variations in the surrounding concrete conditions. The alkaline condition of concrete creates a ‘passive’ layer on the surface of the steel reinforcement which is dense, impermeable and impenetrable film whichprevents corrosion of the steel reinforcement. Once the passive layer breaks down, the area of rust will start appearing on the steel surface. The chemical reaction is same for both chloride attack and carbonation. The following reaction occurs at anode and cathodeas shown in Fig-3.1 below.

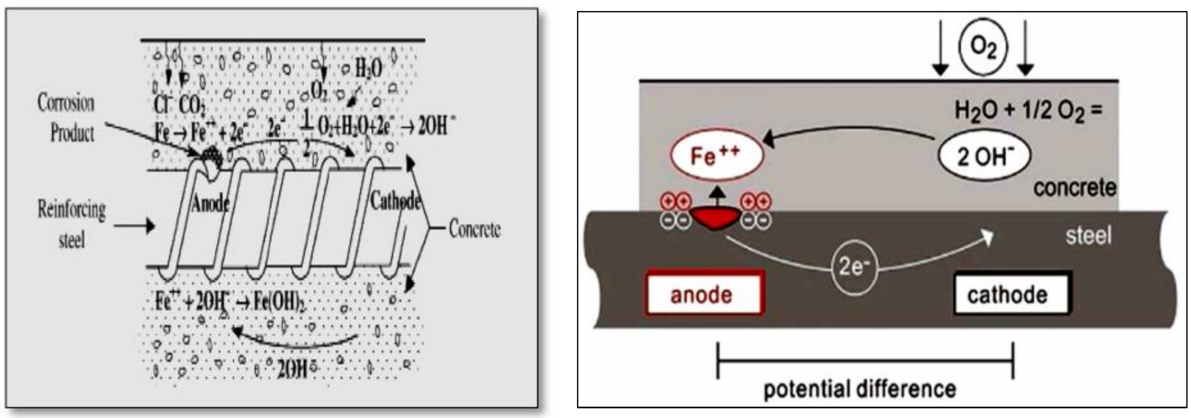


Fig-3.1: Typical Electro-Chemical Corrosion Mechanism Process in Reinforced Concrete

Anode: $Fe \rightarrow Fe^{2+}$ (Metallic iron) + $2e^-$

When steel in concrete corrodes it dissolves in the pore water and release electrons which are consumed elsewhere on the steel surface to maintain electrical neutrality.

Cathode: $\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$

Hydroxyl ions are formed at cathode which increase the local alkalinity and strengthen the passive layer.

There are several parameters essential to initiate the corrosion mechanism. Two important parameters, presence of oxygen and humidity acts as an electrolyte without which corrosion is not possible. The rate of corrosion is slow if the amount of water or oxygen is limited. Presence of humidity, moisture and oxygen acts as catalyst for occurrence of corrosion thus forms more OH^- ions. Even if iron dissolves in pore water we would not observe cracking and spalling of concrete.There are several more stages must occur for ‘rust’ component $Fe(OH)^-$formation.

The reactions represent the formation of rust after the iron dissolution occurs at the anodic sites in the reinforcement.

$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2$ **(Ferrous Hydroxide)**

$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$ **(Ferric Hydroxide)**

$2Fe(OH)_3 \rightarrow 2H_2O + Fe_2O_3 \cdot H_2O$ **(Hydrated Ferric Oxide - Rust)**

Above electro-chemical equation shows the process is a cyclic one which release water molecule after formation of rust on reinforcement which again forms OH^-ions at cathode. Un-hydrated ferric oxide (Fe_2O_3) has a volume greater than the original volume of steelwhich swells even more and becomes porous. This leads to cracking and spalling of concrete.

3.4 Corrosion in RCC & its Effect

Corrosion of the steel reinforcement in concrete is a crucial problem for the construction industry since it poses the most serious risk to the structural integrity of reinforced concrete structures. Inspection and monitoring techniques are needed to assess the corrosion of the reinforcement in order to maintain, protect, and repair of Reinforced Concrete structures so that they remain safe.

Chloride attack and carbonation are the main causes of corrosion of steel in concrete. These two mechanisms are usually not attack the integrity of the concrete unless aggressive chemicals pass through the pores of the concrete and attack the steel.

3.4.1 Chloride Attack

Chlorides can be cast into the concrete or can be diffuse in from outside. The chloride ion attacks the passive layer but no significance drop of overall pH of concrete. Chlorides act as catalyst to the corrosion mechanism where it breaks down the passive layer of oxides on the rebars is shown in Fig-3.2 below.

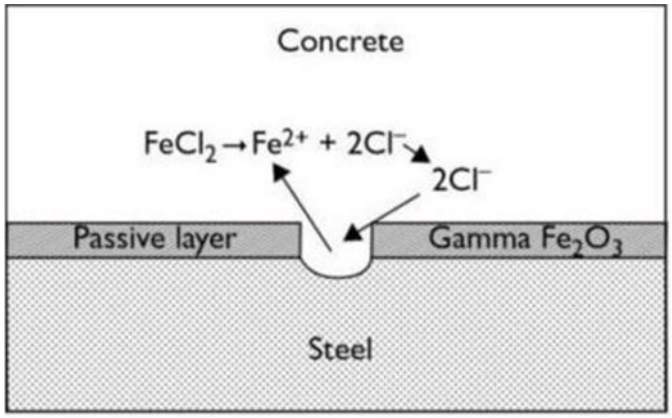


Fig-3.2: The breakdown of the passive layer and 'recycling' chlorides

Sources of chlorides cast into concrete *are stated below-*

i. Addition of chloride set accelerators

ii. Use of saline water in concrete mix

iii. Contaminated aggregates

Similarly, ***sources of chlorides diffuse into concrete*** *are as follows-*

i. Use of saline water for curing

ii. De-icing salts

iii. Use of chemicals

3.4.2 Carbonation

Carbonation occurs due to interaction of carbon di-oxide gas in the atmosphere with the alkaline hydroxides in the concrete. Following Fig-3.3 shows the carbonation reaction within a concrete structure.

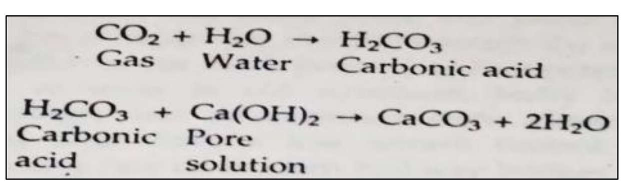


Fig-3.3: Typical Chemical Reaction of Carbonation

From the above figure it is clear that carbon di-oxide dissolves in water to form an acid (Carbonic Acid) which neutralizes the alkalis in the pore water forming calcium carbonate. Calcium hydroxide in the concrete pores dissolves in the pore water to maintain the pH level of around 12.0-13.0. However, the acid within the pores reacts with the cement paste, precipitating calcium carbonate and allows the pH to fall to a level where steel will corrode. Carbonation can occurs rapidly due to inadequate cover to the reinforcement.

*There are several **factors affecting the corrosion** are listed below-*

i. **pH value** of concrete

ii. Severity of **Exposure**

iii. **Quality** of Materials

iv. **Cover**to Reinforcement

v. Initial **curing conditions**

vi. **Ambient temperature**&**humidity**

vii. Free **Moisture**

viii. Oxygen, Carbon Di-oxide

CHAPTER-4

EXPERIMENTAL STUDY

CHAPTER 4

EXPERIMENTAL STUDY

4.1 General

This chapter is includes the general discussion about the non-destructive test adopted and the uncertainties.

4.2 Half-Cell Potentiometer Test

4.2.1 General

The principle of the test is to measure the difference in potential by the Half-Cell potentiometer. The simplest way to assess the susceptibility of corrosion by measuring the potential difference between a standard portable half-cell, normally copper (Cu) / copper sulphate ($CuSO_4$) electrode placed on the surface of concrete with reinforcement underneath. The reference electrode is connected to the positive end of the voltmeter and the reinforcement to the negative end as shown in Fig-4.1 below. The test gives the susceptibility of corrosion activity at the point where the measurement of potential is taken place. An electrical connection is to be developed with the reinforcement and the half-cell is moved across the saturated concrete surface.

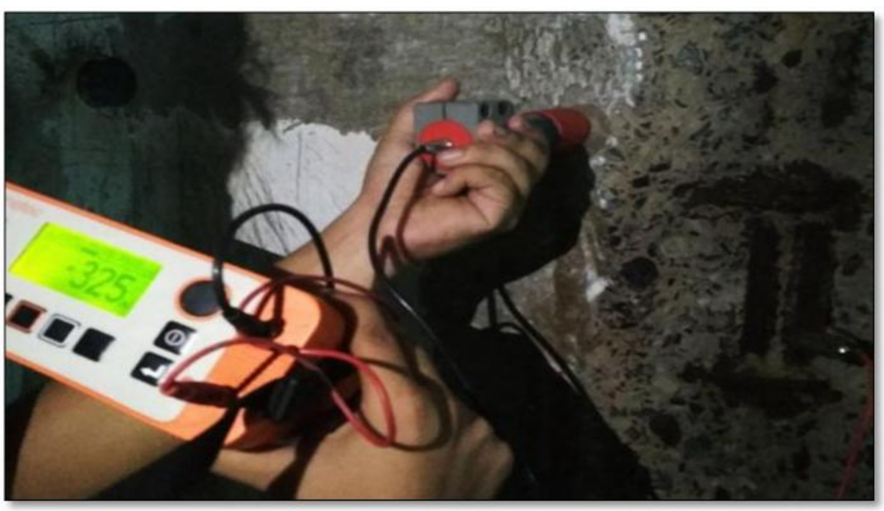


Fig-4.1: Half Cell Potentiometer Test to Assess the Susceptibility of Corrosion

The basic idea of the potential field measurement is to measure the potentials at the concrete surface, in order to get a characteristic picture of the state of corrosion of the steel surface within the concrete. For this purpose a reference electrode is connected via a high impedance volt meter to the steel reinforcement and is moved in a grid over the concrete surface.

The reference electrode of the half-cell potentiometer is a Cu / $CuSO_4$. It consists of a copper rod immersed in a saturated copper sulphate solution, which maintains a constant known potential. The methodology for measurement of corrosion susceptibility is shown in Fig-4.2 below.

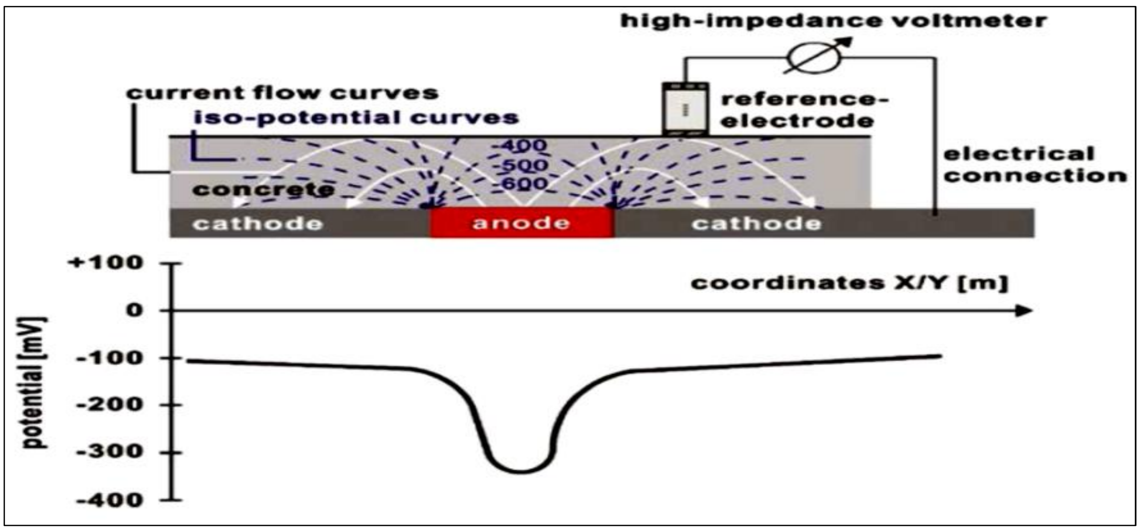


Fig-4.2: Pictorial representation of measurement of susceptibility to corrosion

4.2.2 Details of the Half-Cell Potentiometer test

Half Cell Potentiometer survey was carried out using Elcometer331 of ELCO, USA. The corrosion of steel in concrete is an electrochemical process. It represents a galvanic element, similar to a battery producing an electric current and measurable as an electric field on the surface of the concrete. This potential field can measured with an electrode known as a Half Cell (copper / copper sulphate). By making measurements over the whole surface, a distinction can be made between corroded and non-corroded locations. A high impedance digital voltmeter is used to collect the data. An electrical correction is made to the steel either by exposing it or using already exposed steel. The foam rubber plugs saturated with water are pressed on the concrete surface at the pre-selected grid points. The readings are noted in mili-volt (mV). In accordance to ASTM C876-91, criteria for steel corrosion in concrete for copper sulphate Half Cell are mentioned in Table 4.1 below.

Table 4.1: Half-Cell Potentiometer Range Accordance to ASTM C876-91

HCPT (mV)	Susceptibility to Corrosion
≥ -200	Low to extent of 10%
-200 to -350	Medium in tune of 50%
≤-350	High to extent of 90%
≤-500	Severe Corrosion

4.2.3 Typical Potential Range

Typical orders of magnitude for the half-cell potential of steel in concrete measured against a Cu / $CuSo_4$ reference electrode are in the following range.

- Water saturated concrete without O_2: -1000 to -900 mV
- Moist, chloride contaminated concrete: -600 to -400 mV
- Moist, chloride free concrete: -200 to +100 mV
- Moist, carbonated concrete: -400 to +100 mV
- Dry, carbonated concrete: 0 to +200 mV
- Dry, non-carbonated concrete: 0 to +200 mV

In general, the susceptibility of corrosion increases to the rise of lower (negative) potential.

4.2.4 Factors Affecting the Potential Measurement

i. **Moisture** has a large effect on the measured potential leading to more negative values. Proper saturation of the test location is essential for better prediction of corrosion susceptibility

ii. Potential can be measured at the surface becomes more positive with increasing **concrete cover thickness**. Variations in the concrete cover can lead to more negative potentials which would seem to indicate high levels of corrosion. Thus it better to measure the concrete cover along with the half-cell measurements.

iii. **Low electrical resistivity** of the concrete leads to more negative potentials that can be measured on the surface and the potential gradients become flatter. The measured grid for potential measurements may be coarser, as the risk of undetected anodic areas with flatter gradients becomes lower. Thus resolution between corroding and passive areas is reduced which leads to overestimation of the actively corroding surface area. **High electrical resistivity** leads to more positive potentials that can be measured on the surface and the potential gradients become steeper. The measured grid for potential measurements is finer, however the risk of anode areas having steep gradients.

iv. The main effect of **temperature** on the potential measurements is given by its influence on the electrical resistivity. High temperature will cause higher concrete resistivity and vice versa. Measurement below the freezing point is not recommended and can lead to incorrect readings.

v. With decreasing oxygen concentration and increasing pH value at steel surface, its potential becomes more negative. In certain cases of concrete with high degree of saturation, low porosity, high concrete cover implies low oxygen supply, the potential at the steel surface may be highly negative even through no active corrosion is happen.

4.3 Chloride Content & pH

Chemical test includes the measurement pH of the concrete. Since, concrete is alkaline in nature having pH around 13 at its early stage after construction but with time pH value fall as reaction occurs between carbon dioxide of the atmosphere and alkalis in concrete. However, pH of concrete relates to carbonation, alkali-silica reaction, reinforcement corrosion etc.

The chloride content in concrete is measured in laboratory by Argentometric method using potassium chromate as indicator in a neutral medium or by Volhard's volumetric titration method in acidic medium. In the present investigation, Argentometric method is used to obtain the chloride content of concrete core samples taken from different concrete columns at a random. In a neutral or slightly alkaline solution, potassium chromate can indicate the end point of Silver nitrate titration of chloride. Silver chloride is precipitated quantitatively before red silver chromate is formed. Substances are amounts normally formed in potable waters will not interface. Bromide, Iodide and Cyanide register as equivalent chloride concentrations. Sulfide, Trio-Sulfate and sulfite ions interfere, but can be removed by treatment with hydrogen per-oxide Ortho-phosphate in excess of 0.25 mg/L interferes by precipitating as silver phosphate. Iron in excess of 10mg/L interferes by masking the end point. 50 gm K_2CrO_4 is dissolved in distilled water. Then $AgNO_3$ solution is added until a definite red precipitate is formed. The solution is kept stand for 12 hours, then filtered and diluted to 1 litre with distilled water. This is potassium chromate indicator solution and 2.395 gm $AgNO_3$ is dissolved in distilled water and the same is diluted to 1000 ml. Standardisation is made against NaCl (1.00 ml = 500 μgbCl$^-$). Standard silver nitrate titrant thus formed. Cl is stored in a brown bottle. 824.0 mg NaCl (dried at 140° C) is dissolved in distilled water and diluted to 1000 ml to prepare standard sodium chloride (1.00 ml = 500 μgbCl$^-$). 125 gm aluminum potassium sulfate is dissolved in 1 litre distilled water. It is then heated to 60° C and then 55 ml concentrated ammonium hydroxide is added slowly by stirring. It is then kept for 1 hour, then transferred to a large bottle and precipitate is washed by successive additions, with thorough mixing and decanting with distilled water, until free from chloride, when freshly prepared, the aluminum hydroxide suspension should occupy a volume approximately 1 lit. Other special reagents for removal of interference are

i. Phenolphthalein indicator solution
ii. Sodium hydroxide, NaOH, l N
iii. Sulfuric acid, H_2SO_4, 1 N
iv. Hydrogen peroxide, H_2O_2, 30 %.

100ml sample or a suitable portion is diluted in 100 ml. If the sample is highly colored; 3 ml $Al(OH)_3$ is mixed and allowed to settle and then filtered. If Sulfide, sulfite or thio-sulfate is present, 1 ml H_2O_2 is added & stirred for 1 min. The samples in pH range 7.5 to 10 are titrated directly. H_2SO_4 or NaOH is added to samples to adjust the pH in the range between 7 to 10.1 ml K_2crO_4 indicator solutions is added. Titration is made with standard $AgNO_3$ titrant to a pinkish yellow end point. Adequate care is taken for end point recognition. $AgNO_3$ titrant is standardized and reagent blank value is established by titration method as outlined above. A blank value of 0.2 to 0.3 is usually obtained. The calculation is as follows.

$$mgCl^-/L = (A - B) \times N \times 35450$$

$$mgNaCl/L = (mgCl^-/L) \times 1.65$$

Where, A = mL titration for sample

B = mL titration for blank

N = normality of $AgNO_3$

The maximum water soluble chloride ion (Cl^-) in concrete, percent by weight of cement should not exceed 0.15% for Reinforced concrete structure.

4.4 Ultrasonic Pulse Velocity Test

4.4.1 General

Ultra Sonic Pulse Velocity Test is a non-destructive test method which indicates the quality of concrete in terms of cracks, voids, honeycomb etc. The test doesn't have any direct relation to corrosion but at early stage of corrosion, micro-cracks may be developed within the concrete near to the reinforcement bars. Thus susceptibility to corrosion of reinforcement within the concrete can indirectly identified from the Ultrasonic Pulse Velocity values.

In this test procedure, the ultra-sonic pulse is produced by the transducer which is held in contact with one surface of the concrete and the pulse of vibration is converted into an electrical signal received by the receiver which is held in contact with another surface of the concrete as shown in Fig-4.3. The pulse velocity (V) is given by V=L/T where, L is the path length and T is the time taken by the pulse to travel within the concrete from the transducer to the receiver. The quality of concrete is evaluated by means of velocity obtained.

Fig-4.3: Ultrasonic Pulse Velocity assess the Quality of Concrete

4.4.2 Detail of the Ultrasonic Pulse Velocity test

The pulse velocity test is conducted by the Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) which is internationally reputed highly accurate pulse time recording system. The ultrasonic pulse velocity method consists of measuring the time of travel (in micro seconds) of an ultrasonic pulse passing through the concrete to be tested. Two transducers are used, one to transmit the pulse and the other to receive the pulse. The distance which the pulses travel in the concrete (i.e. the path length) is also measured. The schematic representation of the test circuit is shown in Fig-4.4 below. The pulse velocity is determined from the relation.

$$\text{Pulse velocity} = \frac{\text{Path length}}{\text{Transit time}}$$

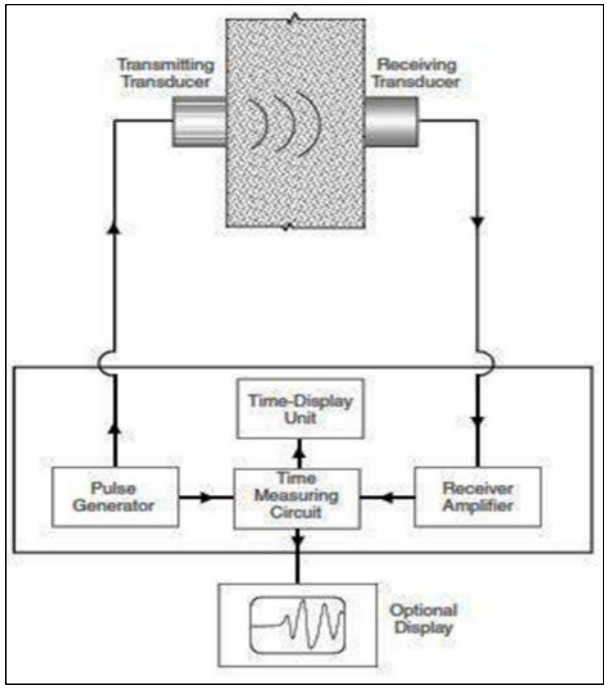
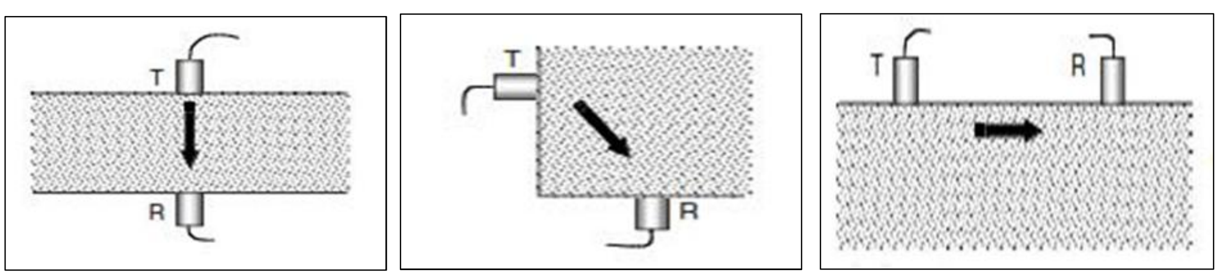


Fig-4.4: Schematic diagram of pulse velocity test circuit

Depending upon the arrangement of transducers, the pulse velocity tests may be Direct, Semi Direct and Indirect. Direct transmission, i.e. placing the transducers on opposite faces is the most accurate method. Semi Direct method is adopted in most of the test location considering the feasibility criterion. Indirect method is adopted when there is only one surface is accessible for test, mostly used to measure the crack depth. Schematic representation of the above test methodology is shown in Fig-4.5 below.



(a) Direct (b) Semi-Direct (c) Indirect

Fig-4.5: Test methodology according to the position of Transducer & Receiver

Three numbers of readings are taken at most of the test locations for a better reliability. Accuracy of transit time measurement is dependent on good acoustic coupling between the transducer face and the prepared concrete surface. The test surface is prepared by rubbing the concrete surfaces with carborundum stone and cleaned subsequently. Light grease is applied as coupling agent.

The Pulse Velocity method of testing may be applied to the testing of plain, reinforced and pre-stressed concrete whether it is pre-cast or cast-in-situ. The measurement of Pulse Velocity may be used to determine the following.

a) The homogeneity of the concrete.
b) The presence of voids, cracks or other imperfections.

In general, the ultrasonic pulse velocity test indicates about the quality of the concrete tested with respect to the ratings, provided in IS 13311 (Part I): 1992. The above may be taken as guidelines for assessing the condition of the structure. Any weakness in the form of cracks, voids, weak concrete will result in lower pulse velocities.The test result may be interpreted in accordance to IS:13311 (Part 1)-1992 as follows referred to Table 4.2.

Table 4.2: Ultrasonic Pulse Velocity Range Accordance to IS:13311 (Part 1)-1992

Pulse velocity (Km/sec)	Quality of concrete
≥ 4.5	Excellent
4.5 to 3.5	Good
3.5 to 3.0	Medium
≤ 3.0	Doubtful

4.4.3 Dynamic Modulus of Concrete from UPV

According to IS 13311 (Part I): 1992, dynamic Young's modulus of concrete (E) can be determined from the pulse velocity and the dynamic Poisson's ratio (μ), using the following relationship:

$$E = \frac{\rho\ (l+\mu)\ (1-2\mu)\ V^2}{(1-\mu)}$$

Where, E = Dynamic Young's Modulus of elasticity in MPa

ρ = density in kg/ms

V = pulse velocity in m/second.

The above relationship may be expressed as: $E = \rho f(\mu) V^2$

$$\text{Where,} \quad f(\mu) = \frac{(l+\mu)(1-2\mu)}{(1-\mu)}$$

The value of the dynamic Poisson's ratio (μ) varies from 0.20 to 0.35, with 0.24 as average.

4.4.4 Factors Affecting the Pulse Velocity

i. The pulse velocity is affected significantly due to **Aggregate size, Grading, Type and content**. In general, the pulse velocity of cement paste is lower than that of aggregate. Same concrete mixture and at the same compressive strength level, concrete with rounded gravel had the lowest pulse velocity, crushed limestone resulted in the highest pulse velocity and crushed granite gave a velocity that was between these two. On the other hand, type of aggregate had no significant effect on the relationship between the pulse velocity and the modulus of rupture. Concrete with same strength level having the higher aggregate content gave a higher pulse velocity.

ii. **Type of cement** did not have a significant effect on the pulse velocity. The rate of hydration, however, is different for different cements and it will influence the pulse velocity. As the degree of hydration increases, the modulus of elasticity will increase and the pulse velocity will also increase. The use of rapid-hardening cements results in higher strength for a given pulse velocity level.

iii. With the increase of **water/cement** ratio, the compressive and flexural strengths and the corresponding pulse velocity decrease assuming no other changes in the composition of the concrete.

iv. Air-entrainment **admixture** does not appear to influence the relationship between the pulse velocity and the compressive strength of concrete. Other **admixtures** will influence the pulse velocity in same manner as they would influence the rate of hydration.

v. The effect of age of concrete on the pulse velocity is similar to the effect on the strength development of concrete. The velocity increases very rapidly initially but soon flattens. This trend is similar to the strength vs. age curve for a particular type of concrete, but pulse velocity reaches a limiting value sooner than strength.

vi. Improper transducer contact also influences pulse velocity reading, sufficient care is not exercised in obtaining a good contact i.e. inconsistent pressure applied to transducers.

vii. Temperature variations between 5 and 30oC have been found to have an insignificant effect on the pulse velocity.

viii. Moisture and curing condition of concrete has a great effect on pulse velocity. The pulse velocity for saturated concrete is higher than for air-dry concrete. Moisture generally has less influence on the velocity in high-strength concrete than on low-strength concrete because of the difference in the porosity. A 4 to 5% increase in pulse velocity can be expected when dry concrete with high w/c ratio is saturated.

ix. The path length travelled by the wave and the frequency of the wave (which is the same as the frequency of the transducer) should not affect the propagation time. Therefore, they should not affect the pulse velocity. However, in practice, smaller path lengths tend to give more variable and slightly higher pulse velocity because of the inhomogeneous nature of concrete.

x. Significant factors that influences the pulse velocity of concrete is the presence of steel reinforcement. The pulse velocity in steel is 1.4 to 1.7 times the pulse velocity in plain concrete. Therefore, pulse velocity readings in the vicinity of reinforcing steel are usually higher than that in plain concrete. Whenever possible, test readings should be taken such that the reinforcement is avoided in the wave path. If reinforcements cross the wave path, correction factors should be used.

xi. The pulse velocity is not dependent on the **size and the shape of a specimen.** Pulse velocity is generally not affected by the **level of stress** in the element under test. However, when the concrete is subjected to a very high level of static or repeated stress, micro-cracks will develop within the concrete, which reduce the pulse velocity.

CHAPTER-5

RESULT & DISCUSSION

CHAPTER 5

RESULT & DISCUSSION

5.1 Problem Considered

Real life multi-storied buildings are considered for the corrosion distress mapping in the present study based on various types of Non Destructive Test. The multi-storied building complex consists of nine towers namely T1to T9 with open ground floor and typical floor plan, having common basement for parking. There are different design grade of concrete were used for columns from M45/M50 at lower stories to M30 at upper stories. However, M25 grade of concrete were used for beams and slabs at all floors of every tower buildings. Fe500 grade of TMT reinforcement were used from different manufactures as per available information, which were also observed in the different reinforcement samples as collected for the laboratory test. Crushed stone chips and river sand were mostly used as coarse & fine aggregates for the concrete. Ground water pumped through few tube wells were mostly used for the concrete produced in the batching plant at site as reported. The buildings are supported on pile foundations.

The following Non Destructive Test has been conducted for assessing the distress including corrosion and subsequently the mapping of corrosion distress was made depending on the degree of susceptibility. Few other types of Non Destructive Test were also conducted as follows for better understanding of the distress and corrosion risk.

1. Schmidts' Hammer Test to ascertain the existing strength of concrete at random.
2. **Ultrasonic Pulse Velocity Test** to ascertain the quality of concrete in terms of cracks, voids, honeycomb, etc.
3. **Half Cell Potentiometer Test** to ascertain the susceptibility of corrosion.
4. Profometer Test to ascertain the cover to concrete
5. Concrete Core Test
6. Carbonation Test to ascertain the depth of carbonation
7. Chemical Test of concrete & reinforcement samples
8. **pH Test of Concrete** to ascertain the existing Alkalinity of concrete

The present study mainly focussed on the **corrosion distress** and therefore, Non-Destructive test results relevant to corrosion distress are duly considered for mapping and subsequent formulation for a correlation between them.

The architectural overview plan of the building complex is given in Fig-5.1 below.

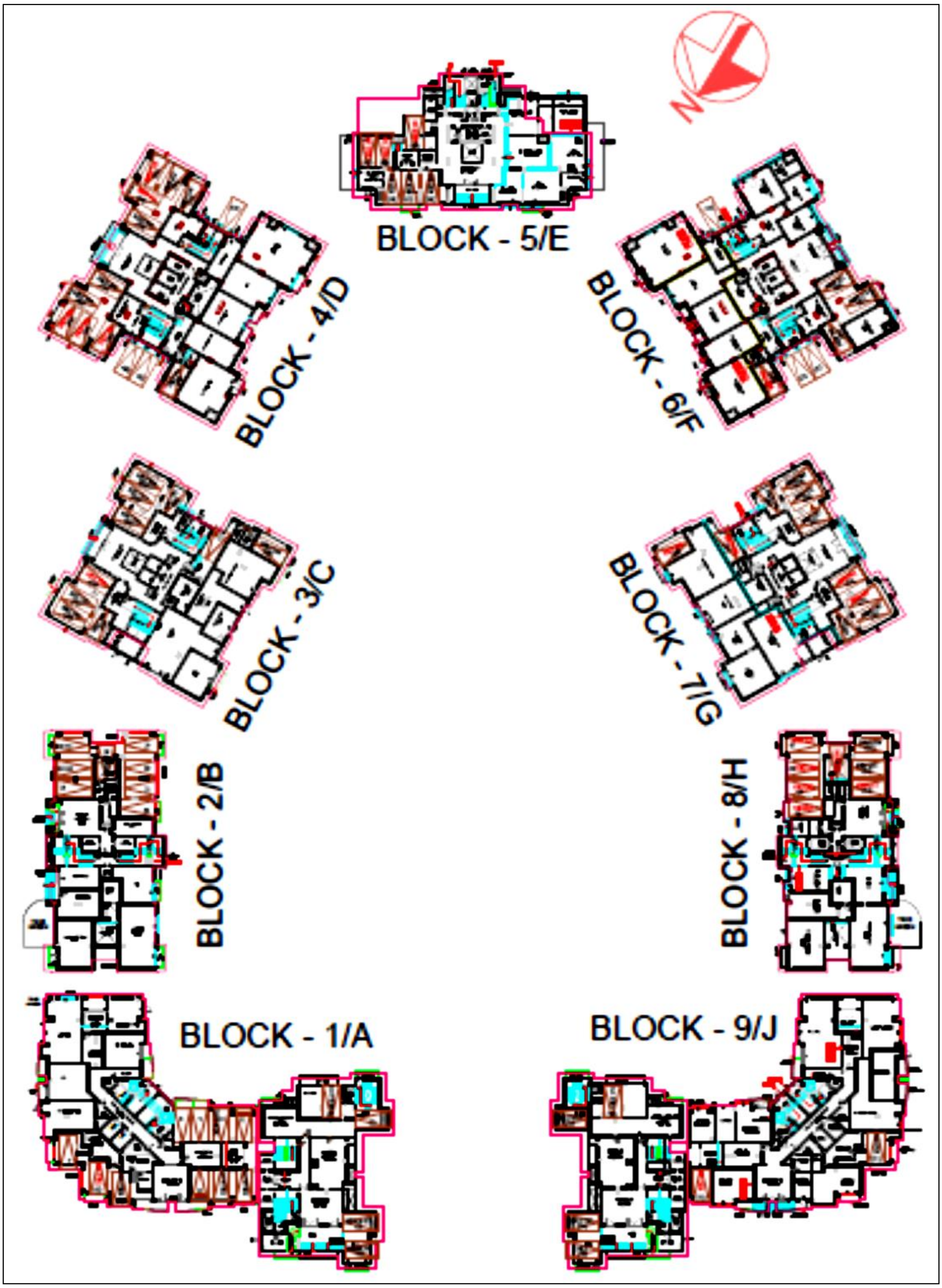


Fig-5.1: Architectural Plan View of the Multi-Storied Building Complex

The building has suffered premature corrosion distress. Extensive field test for corrosion susceptibility were performed on the multi-storied reinforced concrete buildings. Half-Cell Potentiometer Test (HCPT), Ultrasonic Pulse Velocity Test (UPV) and chemical analysis for pH & chloride are duly considered. The tests locations are randomly selected based on accessibility. Columns, which are the most significant structural members of the considered building systems, are mostly considered for the present study.

5.2 Validation of Results

Based on the detail study of Half-Cell Potentiometer (HCP) results, it is noted that the basement columns have suffered greater susceptibility to corrosion at most of the tower buildings as shown below in Fig-5.2.

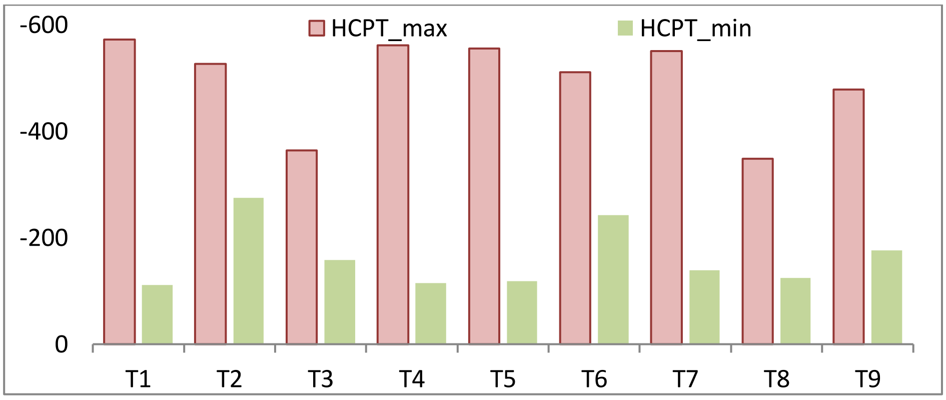


Fig-5.2: Corrosion Mapping of Basement Columns for different Tower Buildings

The maximum HCP value at basement ranges from -348 mV to -572 mV.

Similarly, the study of Half-Cell Potentiometer results of the ground floor columns of all the tower buildings is represented in Fig-5.3 below.

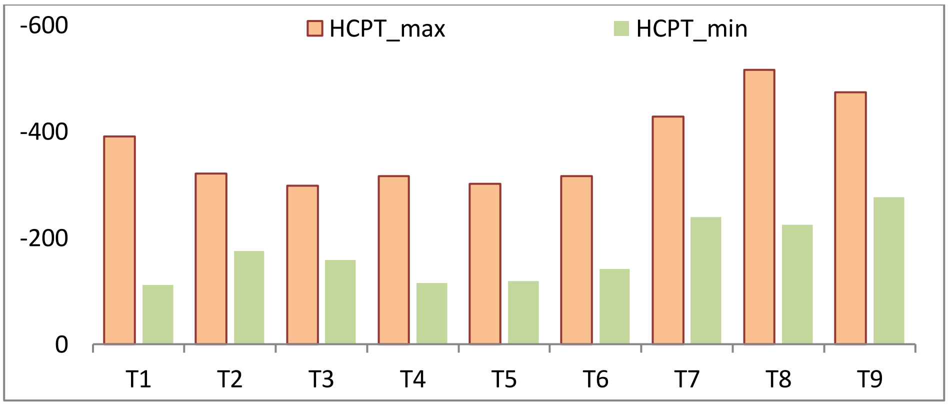


Fig-5.3: Corrosion Mapping of Ground Floor Columns for different Tower Buildings

The maximum Half Cell Potentiometer value at ground floor ranges between -298 mV to -515 mV respectively.

It is also observed that the corrosion susceptibility is more at the basement columns at most of the multi-storied towers buildings, which may be attributed to greater moisture movement. It seems that the corrosion distress not only depends on the exposure condition alone but also on the quality of concrete, cover to reinforcement, temperature stress and composition of reinforcements.

The Corrosion Mapping with respect to degree of susceptibility as obtained by Half Cell Potentiometer at Columns at various floors of all the nine towers are categorized as per ASTM criterion as shown in Fig-5.4 below.

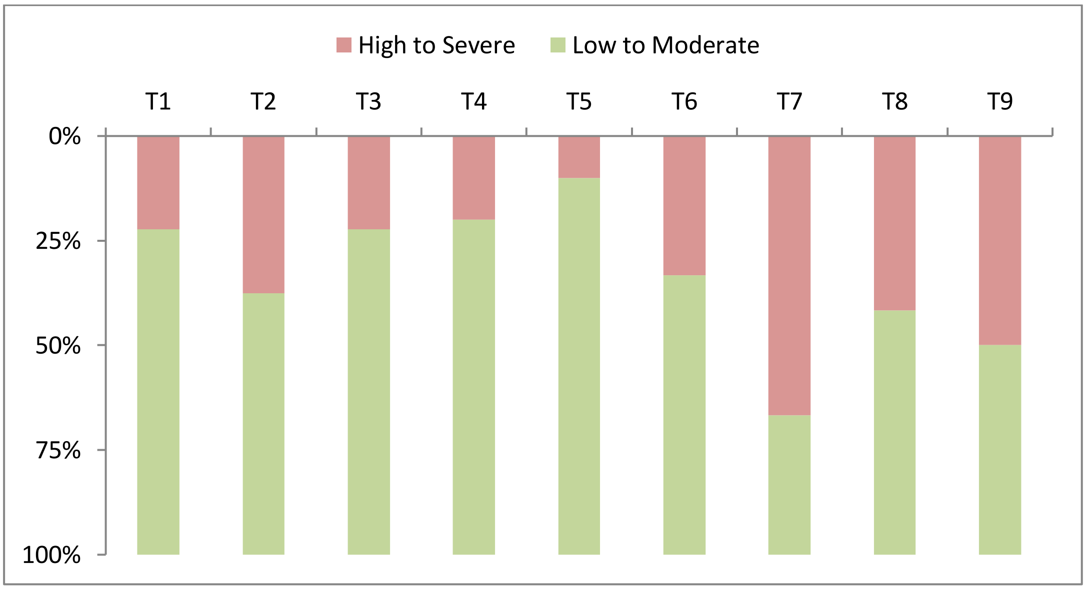


Fig-5.4: Mapping of Corrosion for different Towers with respect to Degree of Corrosion

It is observed that Tower Number T2, T6, T7, T8 and T9 have suffered high to severe degree of corrosion risk for columns to the tune of 38%, 33%, 67%, 42%and 50% of the total tested floors of each tower. These five towers having greater affected zones of corrosion distress are considered for the further detail study. The overall corrosion risk is attempted to be mapped with respect to the design concrete grade of respective floors and for all buildings.

The Half-Cell Potentiometer field Test data conducted at the Basement and Ground Floor structural members of building Towers T2, T6, T7, T8 and T9 are shown below in the following Table 5.1 to Table 5.5 respectively.

Table 5.1: Field Test HCP data for the Basement and Ground Floor of Tower T2

Sl. No.	Location of Test spot	Half-Cell Potentio-Meter										Avarage	Max. HCP	Min. HCP
Basement /Tower2														
1	BB06C	-297	-316	-289	-341	-337	-361	-357	-370	-329	-301	-330	-370	-289
2	BB07C	-288	-280	-296	-290	-276	-320	-420	-310	-297	-356	-313	-420	-276
3	BB10C	-296	-352	-526	-330	-335	-306	-290	-280	-350	-453	-352	-526	-280
4	BB19C	-275	-295	-290	-332	-330	-369	-278	-295	-290	-300	-305	-369	-275
5	BB21C	-295	-275	-333	-338	-352	-330	-342	-354	-350	-332	-330	-354	-275
6	BB22C	-352	-334	-388	-290	-304	-309	-286	-290	-305	-311	-317	-388	-286
Ground Floor /Tower2														
7	GB03C	-321	-239	-264	-209	-250	-175	-265	-236	-190	-262	-241	-321	-175
8	GB04B	-301	-295	-305	-308	-296	-235	-301	-250	-301	-317	-291	-317	-235
9	GB14B	-225	-231	-320	-297	-290	-298	-304	-309	-306	-207	-279	-320	-207
10	GB15S	-273	-235	-225	-243	-236	-250	-310	-305	-290	-304	-267	-310	-225

From the above table it is clear that the Columns at the **basement** of **Tower T2** are susceptible to **moderate to severe** corrosion. However, the Column at ground floor shows low to moderate risk of corrosion. Similarly, the Beams and slabs at the ground floor indicate moderate risk of corrosion.

Table 5.2: Field Test HCP data for the Basement and Ground Floor of Tower T6

Sl. No.	Location of Test spot	Half-Cell Potentio-Meter										Avarage	Max.	Min.
Basement /Tower6														
1	BF01C	-288	-285	-281	-283	-511	-309	-317	-417	-314	-350	-336	-511	-281
2	BF02C	-290	-242	-367	-246	-420	-366	-259	-302	-366	-292	-315	-420	-242
3	BF03B	-205	-175	-170	-183	-154	-181	-190	-173	-332	-317	-208	-332	-154
4	BF04S	-236	-269	-281	-148	-114	-158	-104	-101	-290	-134	-184	-290	-101
Ground Floor/Tower6														
5	GF03C	-185	-142	-228	-177	-236	-197	-192	-165	-144	-170	-184	-236	-142
6	GF05C	-160	-152	-316	-184	-166	-208	-212	-209	-204	-232	-204	-316	-152
7	GF06C	-232	-240	-307	-152	-167	-150	-215	-166	-201	-197	-203	-307	-150
8	GF07B	-130	-267	-161	-290	-128	-180	-175	-265	-199	-201	-200	-290	-128
9	GF08S	-137	-122	-130	-140	-112	-114	-115	-170	-132	-129	-130	-170	-112

In Tower T6, the corrosion susceptibility of columns at the basement is **moderate to severe**. However, beams & slabs at basement and the columns, beams & slabs at ground floor having low to moderate risk of corrosion.

Table 5.3: Field test HCP data for the Basement and Ground Floor of Tower T7

Sl. No.	Location of Test spot	Half-Cell Potentio-Meter										Avarage	Max.	Min.
Basement /Tower7														
1	BG01C	-148	-149	-163	-551	-138	-131	-130	-178	-222	-160	-197	-551	-130
2	BG08C	-360	-335	-331	-365	-385	-442	-448	-481	-425	-544	-412	-544	-331
3	BG12C	-237	-155	-299	-205	-248	-235	-185	-235	-155	-190	-214	-299	-155
4	BG13C	-157	-239	-140	-171	-188	-205	-190	-182	-178	-139	-179	-239	-139
5	BG11S	-180	-159	-160	-195	-175	-169	-159	-193	-116	-143	-165	-195	-116
6	BG14S	-290	-228	-191	-206	-189	-177	-150	-280	-243	-202	-216	-290	-150
Ground Floor /Tower7														
7	GG02C	-326	-254	-347	-341	-333	-428	-245	-240	-316	-239	**-307**	**-428**	**-239**
8	GG03B	-152	-110	-312	-124	-168	-211	-171	-135	-115	-261	**-176**	**-312**	**-110**
9	GG12S	-250	-270	-122	-129	-101	-184	-100	-110	-111	-115	**-149**	**-270**	**-100**

Similarly, the columns at the basement of the tower T7 are susceptible to low to severe corrosion. However, the column at ground floor is **moderate to high** and the beams & slabs at both basement and ground floor indicates low to moderate risk of corrosion.

Table 5.4: Field test HCP data for the Basement and Ground Floor of Tower T8

Sl. No.	Location of Test spot	Half-Cell Potentio-Meter												Avarage	Max.	Min.
Basement /Tower8																
1	BH12C	-231	-220	-215	-195	-166	-229	-233	-195	-220	-218	-348	-125	-216	-348	-125
Ground Floor /Tower8																
2	GH01C	-262	-401	-310	-395	-257	-306	-261	-337	-281	-310	-358	-225	-309	-401	-225
3	GH03C	-318	-246	-295	-237	-284	-245	-312	-291	-252	-292	-307	-315	-283	-318	-237
4	GH06C	-420	-250	-238	-370	-250	-285	-320	-370	-333	-350	-357	-261	-317	-420	-238
5	GH13C	-378	-267	-450	-515	-236	-510	-497	-351	-402	-226	-278	-305	-368	-515	-226

From the above table it is evident that the column at the basement shows low to moderate and **ground floor** have **moderate to severe** risk of corrosion.

Table 5.5: Field test HCP data for the Basement and Ground Floor of Tower T9

Sl. No.	Location of Test spot	Half-Cell Potentio-Meter										Avarage	Max.	Min.
Basement /Tower9														
1	BJ01C	-479	-430	-280	-315	-180	-299	-198	-176	-350	-318	**-303**	**-479**	**-176**
Ground Floor /Tower9														
2	GJ08C	-340	-280	-348	-393	-299	-365	-264	-260	-473	-276	**-330**	**-473**	**-260**

The column of the basement seems to have **low to high** risk of corrosion whereas, the ground floor have a risk of **moderate to high** corrosion.

The field test data of Half-Cell Potentiometer clearly indicate that most of the columns at the basement and ground floor having **moderate to severe** risk of corrosion. Further, the basement columns of Tower T2 & T6 and Ground Floor columns of Tower T7, T8 & T9 seems to be susceptible to greater corrosion and considered for the correlation study with other NDT results.

The overall summary of the maximum corrosion risk for all the tower building columns based on the maximum values of the half-cell potentiometer test data along with grade of column concrete is shown in Table 5.6 below.

Table 5.6: Corrosion Risk at Various Floors of Towers with Design Grade of Concrete

Floors	Towers								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
B	-572	-526	-364	-562	-555	-511	-551	-348	-479
G	-390	-321	-298	-316	-301	-316	-428	-515	-473
1	-201	-	-320	-585	-	-	-	-290	-
2	-	-	-386	-	-	-255	-252	-276	-410
3	-240	-302	-278	-	-	-	-362	-	-
4	-	-	-	-320	-	-398	-	-	-
5	-	-	-	-	-	-367	-	-	-277
6	-	-	-	-	-	-303	-	-	-251
7	-225	-401	-	-	-	-272	-	-363	-310
8	-	-	-	-	-	-	-460	-	-
9	-222	-	-	-	-	-544	-	-	-
10	-	-293	-297	-384	-	-	-	-270	-
11	-	-	-	-285	-267	-473	-	-	-
12	-247	-229	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-
14	-337	-226	-	-	-	-228	-312	-525	-
15	-	-	-	-250	-	-	-391	-305	-
16	-282	-371	-275	-295	-	-244	-	-391	-
17	-	-	-	-267	-285	-	-	-510	-
18	-	-	-	-245	-241	-223	-226	-	-
19	-	-	-	-	-279	-311	-	-	-
20	-	-	-243	-	-	-	-406	-348	-
21	-	-	-	-282	-	-	-	-208	-
22	-	-	-	-230	-	-	-	-	-
23	-	-	-	-245	-	-238	-	-	-
24	-	-	-238	-	-237	-	-	-	-
25	-	-	-	-	-235	-	-	-	-
26	-	-	-	-301	-261	-	-	-	-
27	-	-	-	-	-	-	-	-	-
28	-	-	-	-276	-	-280	-	-	-
29	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-312	-	-	-	-

Design Grade of Concrete	M50	M45	M40	M35	M30
Colour Code					

It is observed that there are mostly **high to severe risk of corrosion at the basement** and **ground floor columns** at most of the tower building even though the **design grade is high** and existing strength also comply with the design grade.

From the study of pH and chloride content of concrete, it is noted that the pH values of column concrete of basement and ground floor have reduced to a greater extent at the tower buildings namely T2, T6, T7, T8, T9 as shown below in Fig-5.5.

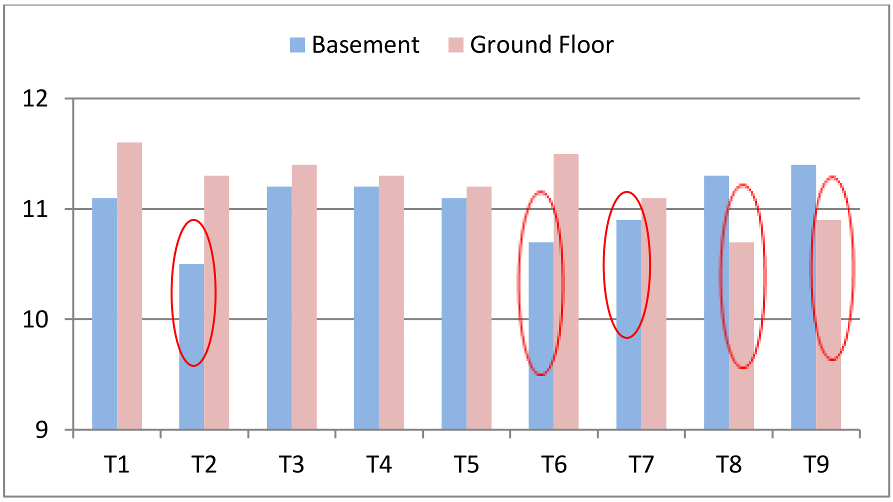


Fig-5.5: Mapping of pH value of Concrete Columns of different Towers

It shows that basement and ground floor columns have suffered greater loss of alkalinity **with pH < 11** at those towers namely T2, T6, T7, T8, T9 indicating higher susceptibility to corrosion, which are in tune with the HCPT results in general.

The chloride content as obtained from the chemical analysis of concrete for all the towers buildings is shown in Fig-5.6 below.

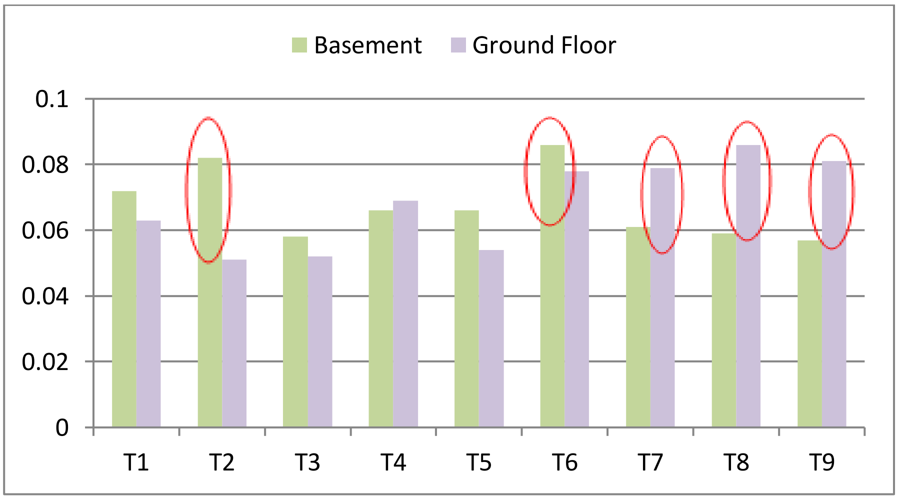


Fig-5.6: Mapping of Chloride Content of Concrete Columns of different Towers

Similarly, from the study of chloride content of concrete, it is noted that the columns of basement and ground floor have greater content of chloride, indicating higher susceptibility to corrosion at those tower buildings namely T2, T6, T7, T8, T9. These results are also in tune with the HCPT results in general.

Ultrasonic readings have been recorded mostly by the direct method, which is the most reliable method of testing. However, semi-direct technique is also employed considering the feasibility criterion. Based on the detail study of Ultrasonic Pulse Velocity results, it is noted that the basement columns of the towers have suffered with respect to the quality of concrete aspect in a greater extent for the respective design grade of concrete as shown below in Fig-5.7.

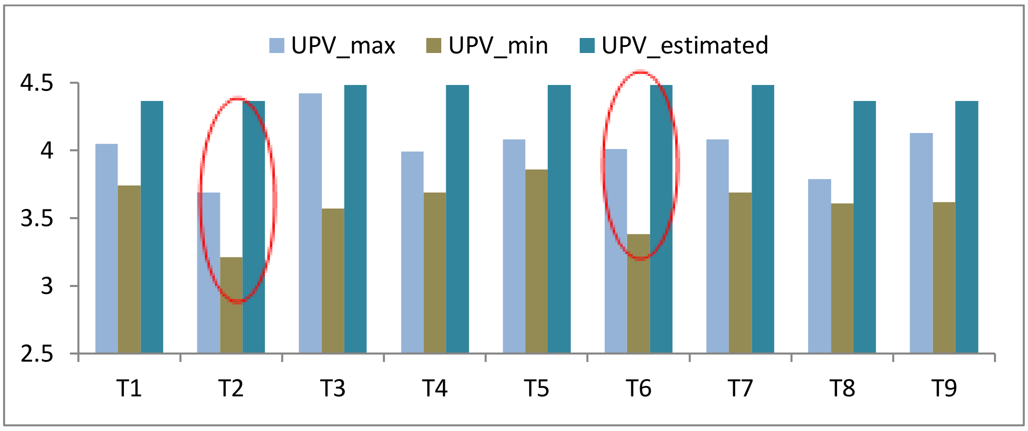


Fig-5.7: UPV Mapping of Basement Columns for different Tower Buildings

It is observed that the minimum Ultrasonic Pulse Velocity (UPV) is much lower than the estimated value UPV value at Tower namely T2 and T6.

Similarly, the column of the ground floor is shown in Fig 5.8 below.

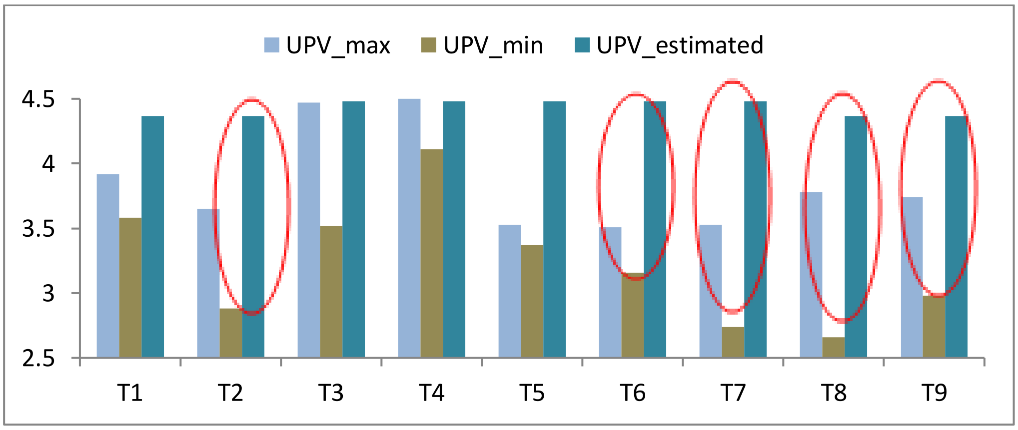


Fig-5.8: UPV Mapping of Ground Floor Columns for different Tower Buildings

It is further observed that the minimum Ultrasonic Pulse Velocity (UPV) is lower than the estimated value in all location which may be due to local poor quality of concrete. However, there is a significant difference between the maximum UPV and the required UPV value at Tower number T2, T6, T7, T8 and T9. It is quite evident that the Ultrasonic Pulse Velocity values are suffered due to degraded quality of concrete which may occurs due to formation of micro-cracks near to the reinforcement bars due to corrosion. Further the overall Ultrasonic Pulse Velocity is mapped with respect to the design grade of concrete of the entire floor and all the buildings.

The test data of the Ultrasonic Pulse Velocity conducted at the Basement Columns of Tower buildings namely T2, T6, T7, T8 and T9 are shown below in the following Table 5.7 to Table 5.11 respectively.

Table 5.7: Ultrasonic Pulse Velocity Test data of Columns of the Basement of Tower T2

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Basement/ Tower2							
1	BB01C	1.7	D	400	100.1	4.00	Avg=
2		1.7	D	400	116.7	3.43	3.68
3		1.4	D	400	119.4	3.35	Sd. Dev.
4		1.1	D	400	117.5	3.40	0.28
5		1.1	D	400	113.2	3.53	
6		0.8	D	400	102.6	3.90	
7		0.5	D	400	104.3	3.84	
8		0.5	D	400	100.4	3.98	
9	BB02C	1.7	D	550	168.5	3.26	Avg=
10		1.7	D	550	166.1	3.31	3.21
11		1.4	D	550	172.4	3.19	Sd. Dev.
12		1.1	D	550	161.5	3.41	0.14
13		1.1	D	550	178.1	3.09	
14		0.8	D	550	183.4	3.00	
15		0.5	D	550	177.7	3.10	
16		0.5	D	550	165.5	3.32	
17	BB04C	1.7	D	400	156.1	2.56	Avg=
18		1.7	D	400	118.3	3.38	3.29
19		1.4	D	400	108.5	3.69	Sd. Dev.
20		1.1	D	400	137.6	2.91	0.40
21		1.1	D	400	114.7	3.49	
22		0.8	D	400	107.5	3.72	
23		0.5	D	400	115.3	3.47	
24		0.5	D	400	128.4	3.12	
25	BB05C	1.7	D	350	103.4	3.38	Avg=
26		1.7	D	350	98.7	3.55	3.39
27		1.4	D	350	100.0	3.50	Sd. Dev.
28		1.1	D	350	101.3	3.46	0.11
29		1.1	D	350	105.6	3.31	
30		0.8	D	350	99.9	3.50	
31		0.5	D	350	103.6	3.38	
32		0.5	D	350	103.1	3.39	
33		0.2	D	350	109.1	3.21	
34		1.4	D	350	107.5	3.26	
35	BB09C	1.2	D	400	105.4	3.80	Avg=
36		1.0	D	400	107.1	3.73	3.61
37		1.5	D	400	123.6	3.24	Sd. Dev.
38		2.0	D	400	137.7	2.90	0.35
39		0.8	D	400	106.9	3.74	
40		0.5	D	400	107.1	3.73	
41		1.0	D	400	102.6	3.90	
42		1.5	D	400	105.1	3.81	
43	BB14C	1.2	D	430	112.5	3.82	Avg=
44		0.9	D	430	116.3	3.70	3.69
45		0.6	D	430	122.5	3.51	Sd. Dev.
46		0.3	D	430	115.6	3.72	0.13
47	BB15C	1.2	D	400	117.5	3.40	Avg=
48		0.9	D	400	114.6	3.49	3.48
49		0.6	D	400	115.5	3.46	Sd. Dev.
50		0.3	D	400	112.5	3.56	0.06
51	BB16C	1.2	D	400	112.4	3.56	Avg=
52		0.9	D	400	116.8	3.42	3.46
53		0.6	D	400	114.7	3.49	Sd. Dev.
54		0.3	D	400	119.3	3.35	0.09
55	BB17C	1.2	D	565	164.5	3.43	Avg=
56		0.9	D	565	152.6	3.70	3.56
57		0.6	D	565	163.5	3.46	Sd. Dev.
58		0.3	D	565	154.2	3.66	0.14
59	BB18C	1.2	D	550	163.5	3.36	Avg=
60		0.9	D	550	154.5	3.56	3.48
61		0.6	D	550	164.0	3.35	Sd. Dev.
62		0.3	D	550	150.5	3.65	0.15

The design grade of concrete for basement columns is **M45** and the quality of concrete obtained from UPV data seems to be **medium** to good which does not in tune with the grade of concrete.

Table 5.8: Ultrasonic Pulse Velocity Test data of Columns of the Basement at tower T6

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Basement/ Tower6							
1	BF01C	1.7	D	450	112.8	3.99	Avg=
2		1.7	D	450	112.1	4.01	4.01
3		1.7	D	450	113.9	3.95	Sd. Dev.
4		1.7	D	450	111.4	4.04	0.03
5		1.7	D	450	111.7	4.03	
6		1.7	D	450	111.8	4.03	
7	BF02C	1.6	D	300	82.1	3.65	Avg. & Sd.Dev
8		1.3	D	300	85.6	3.50	3.38
9		1.0	D	300	100.2	2.99	0.35

It is clear that the basement column of the tower building T6 seems to have **medium** to good in terms of quality of concrete as per design grade of concrete.

Table 5.9: Ultrasonic Pulse Velocity Test data of Columns of the Basement at tower T7

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity Km/Sec	Remarks
Basement / Tower7							
1	BG01C	1.0	D	300	81.3	3.69	Avg=
2		1.2	D	300	81.5	3.68	3.69
3		1.3	D	300	84.6	3.55	Sd. Dev.
4		1.5	D	300	79.5	3.77	0.10
5		0.5	D	300	78.5	3.82	
6		0.8	D	300	82.6	3.63	
7	BG08C	1.2	D	240	58.4	4.11	Avg=
8		0.3	D	240	61	3.93	4.08
9		0.5	D	240	58.6	4.10	Sd. Dev.
10		0.8	D	240	57.3	4.19	0.11
11	BG10C	1.0	D	350	91.8	3.81	Avg=
12		1.2	D	350	83.8	4.18	3.93
13		1.5	D	350	90.1	3.88	Sd. Dev.
14		1.8	D	350	88.4	3.96	0.11
15		2.1	D	350	89.8	3.90	
16		0.5	D	350	89.6	3.91	
17		0.3	D	350	90.0	3.89	
18		0.8	D	350	89.7	3.90	
19	BG12C	1.5	D	360	94.0	3.83	Avg=
20		1.2	D	360	90.3	3.99	3.92
21		1.0	D	360	92.9	3.88	Sd. Dev.
22		0.8	D	360	91.4	3.94	0.07
23		0.5	D	360	90.8	3.96	
24	BG13C	2.1	D	400	99.6	4.02	Avg=
25		1.8	D	400	99.5	4.02	4.05
26		1.5	D	400	99.3	4.03	Sd. Dev.
27		1.2	D	400	99.7	4.01	0.06
28		1.0	D	400	96.6	4.14	
29		0.8	D	400	97.3	4.11	
30	BG15C	0.3	D	400	102.6	3.90	Avg=
31		0.5	D	400	108.0	3.70	3.84
32		0.8	D	400	102.3	3.91	Sd. Dev.
33		1.0	D	400	105.1	3.81	0.09
34		1.2	D	400	105.5	3.79	
35		1.5	D	400	101.5	3.94	

The basement column of the tower building T7 seems to have good quality of concrete. Since the design grade of concrete is high, the ultrasonic pulse velocity value doesn't in tune with such high grade.

Table 5.10: Ultrasonic Pulse Velocity Test data of Columns of the Basement at tower T8

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity Km/Sec	Remarks
Basement/ Tower8							
1	BH01C	1.7	D	400	109.4	3.66	Avg=
2		1.7	D	400	106.8	3.75	3.76
3		1.4	D	400	103.7	3.86	Sd. Dev.
4		1.1	D	400	111.4	3.59	0.12
5		1.1	D	400	107.5	3.72	
6		0.8	D	400	104.3	3.84	
7		0.5	D	400	108.2	3.70	
8		0.5	D	400	107.5	3.72	
9		0.2	D	400	100.1	4.00	
10	BH02C	1.7	D	400	109.9	3.64	Avg=
11		1.7	D	400	112.8	3.55	3.61
12		1.4	D	400	105.8	3.78	Sd. Dev.
13		1.1	D	400	109.5	3.65	0.09
14		1.1	D	400	108.7	3.68	
15		0.8	D	400	113.1	3.54	
16		0.5	D	400	114.2	3.50	
17		0.5	D	400	112.6	3.55	
18		0.2	D	400	109.8	3.64	
19		1.4	D	850	227.0	3.74	
20	BH03C	2.0	D	400	107.7	3.71	Avg=
21		2.0	D	400	107.3	3.73	3.79
22		1.7	D	400	106.5	3.76	Sd. Dev.
23		1.4	D	400	108.4	3.69	0.12
24		1.4	D	400	108.7	3.68	
25		1.1	D	400	105.3	3.80	
26		0.8	D	400	103.4	3.87	
27		0.8	D	400	103.7	3.86	
28		0.5	D	400	98.7	4.05	
29	BH04C	1.9	D	350	94.5	3.70	Avg=
30		1.9	D	350	93.6	3.74	3.76
31		1.6	D	350	92.2	3.80	Sd. Dev.
32		1.6	D	350	96.3	3.63	0.08
33		1.3	D	350	90.2	3.88	
34		1.0	D	350	94.2	3.72	
35		0.7	D	350	91.4	3.83	
36		0.4	D	350	93.1	3.76	

Columns of the basement of tower T8 seems to have good quality of concrete in most of tested columns but doesn't in tune to the design grade.

Table 5.11: Ultrasonic Pulse Velocity Test data of Columns of the Basement at tower T9

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Basement/ Tower9							
1	BJ01C	1.8	D	300	74.5	4.03	Avg=
2		1.8	D	300	74.4	4.03	4.07
3		1.5	D	300	73.3	4.09	Sd. Dev.
4		0.9	D	300	70.6	4.25	0.07
5		0.6	D	300	74.8	4.01	
6		0.6	D	300	74.4	4.03	
7		1.2	D	300	73.6	4.08	
8		1.2	D	300	73.3	4.09	
9		0.3	D	300	74	4.05	
10		1.0	D	850	209.7	4.05	
11	BJ02C	1.9	D	300	73	4.11	Avg=
12		1.9	D	300	70.9	4.23	4.13
13		1.6	D	300	72.8	4.12	Sd. Dev.
14		1.3	D	300	74.1	4.05	0.08
15		1.3	D	300	74.4	4.03	
16		1.0	D	300	71.1	4.22	
17		0.7	D	300	74.6	4.02	
18		0.7	D	300	72.7	4.13	
19		0.4	D	300	71	4.23	
20	BJ03C	1.6	D	350	88.3	3.96	Avg=
21		1.6	D	350	84.4	4.15	4.06
22		1.3	D	350	84.7	4.13	Sd. Dev.
23		1.3	D	350	82.3	4.25	0.13
24		1.0	D	350	84.4	4.15	
25		1.0	D	350	86.6	4.04	
26		0.7	D	350	90.2	3.88	
27		0.7	D	350	89.7	3.90	
28	BJ04C	1.4	D	300	79.6	3.77	Avg=
29		1.1	D	300	76.3	3.93	3.86
30		0.8	D	300	77.8	3.86	Sd. Dev.
31		0.5	D	300	76.9	3.90	0.07
32	BJ06C	2.0	D	300	81.4	3.69	Avg=
33		2.0	D	300	84.3	3.56	3.68
34		1.7	D	300	80.6	3.72	Sd. Dev.
35		1.4	D	300	80.3	3.74	0.07
36		1.1	D	300	81.6	3.68	
37		0.8	D	300	83.3	3.60	
38		0.5	D	300	82.3	3.65	
39		0.5	D	300	79.6	3.77	
40		0.2	D	300	80.5	3.73	
41	BJ07C	1.9	D	350	95.4	3.67	Avg=
42		1.9	D	350	96.5	3.63	3.73
43		1.6	D	350	91.7	3.82	Sd. Dev.
44		1.6	D	350	92.3	3.79	0.14
45		1.3	D	350	97.6	3.59	
46		1.3	D	350	97.2	3.60	
47		1.0	D	350	92.2	3.80	
48		1.0	D	350	87.7	3.99	
49	BJ10C	1.8	D	770	192.6	4.00	Avg=
50		1.5	D	770	188.6	4.08	4.07
51		1.2	D	770	186.8	4.12	Sd. Dev.
52		0.9	D	770	190.2	4.05	0.05
53		0.6	D	770	187.5	4.11	
54		0.3	D	770	188.2	4.09	
55	BJ11C	1.7	D	350	95.6	3.66	Avg=
56		1.7	D	350	98.4	3.56	3.62
57		1.4	D	350	95.4	3.67	Sd. Dev.
58		1.1	D	350	97.0	3.61	0.06
59		1.1	D	350	96.4	3.63	
60		0.8	D	350	97.1	3.60	
61		0.5	D	350	98.2	3.56	
62		0.5	D	350	98.1	3.57	
63		0.3	D	350	93.3	3.75	

Concrete at basement seems to be good of quality of concrete among the tested columns.

The field test data of Ultrasonic Pulse Velocity clearly indicate that most of the columns at the basement having **medium** quality of concrete. Further, the basement columns of Tower building namely T2 & T6 seems to be susceptible to greater corrosion and thus considered for further study.

Similarly, the test data of the Ultrasonic Pulse Velocity conducted at the Ground Floor Columns of Tower buildings namely T2, T6, T7, T8 and T9 are shown below in the following Table 5.12 to Table 5.16 respectively.

Table 5.12: Ultrasonic Pulse Velocity Test data of Columns at Ground Floor of tower T2

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Ground Flooor/ Tower2							
63	GB01C	1.7	D	400	106.8	3.75	Avg=
64		1.7	D	400	108.8	3.68	3.60
65		1.4	D	400	109.2	3.66	Sd. Dev.
66		1.1	D	400	110.9	3.61	0.13
67		1.1	D	400	112.7	3.55	
68		0.8	D	400	118.7	3.37	
69	GB03C	1.7	D	400	110.9	3.61	Avg=
70		1.7	D	400	108.8	3.68	3.65
71		1.4	D	400	115.8	3.45	Sd. Dev.
72		1.1	D	400	107.9	3.71	0.11
73		1.1	D	400	107.1	3.73	
74		0.8	D	400	107.7	3.71	
75	GB05C	1.7	D	400	118.8	3.37	Avg=
76		1.7	D	400	112.3	3.56	3.47
77		1.4	D	400	114.2	3.50	Sd. Dev.
78		1.1	D	400	116.2	3.44	0.07
79		1.1	D	400	115.7	3.46	
80		0.8	D	400	114.9	3.48	
81	GB08C	1.7	D	550	152.4	3.61	Avg=
82		1.4	D	550	157.6	3.49	3.48
83		1.1	D	550	160.8	3.42	Sd. Dev.
84		0.8	D	550	161.3	3.41	0.09
85	GB10C	1.7	D	400	107.6	3.72	Avg=
86		1.7	D	400	108.9	3.67	3.56
87		1.4	D	400	112.3	3.56	Sd. Dev.
88		1.1	D	400	114.5	3.49	0.14
89		1.1	D	400	118.6	3.37	
90	GB11C	1.7	D	400	147.5	2.71	Avg=
91		1.4	D	400	141.5	2.83	2.88
92		1.1	D	400	136.5	2.93	Sd. Dev.
93		0.8	D	400	131.5	3.04	0.14
94	GB16C	1.7	D	550	154.9	3.55	Avg=
95		1.7	D	550	155.1	3.55	3.55
96		1.4	D	550	157.6	3.49	Sd. Dev.
97		1.1	D	550	156.3	3.52	0.04
98		1.1	D	550	152.4	3.61	
99		0.8	D	550	154.3	3.56	
100	GB17C	1.7	D	400	105.9	3.78	Avg=
101		1.7	D	400	106.8	3.75	3.64
102		1.4	D	400	108.8	3.68	Sd. Dev.
103		1.1	D	400	112.3	3.56	0.12
104		1.1	D	400	115.3	3.47	
105		0.8	D	400	110.6	3.62	

The ground floor of tower T2 indicates **doubtful** to good quality of concrete. Such variation in the quality of concrete does not in tune with the high grade of concrete.

Table 5.13: Ultrasonic Pulse Velocity Test data of Columns of Ground Floor at tower T6

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Ground Flooor/ Tower6							
14	GF03C		D	300	99.4	3.17	Avg=
15			D	300	89.5	3.35	3.16
16			D	300	97.3	3.08	Sd. Dev.
17			D	300	98.9	3.03	0.12
18			D	300	94.7	3.17	
19	GF05C		D	300	84.4	3.55	Avg=
20			D	300	81	3.70	3.51
21			D	300	89.3	3.36	Sd. Dev.
22			D	300	90.4	3.32	0.15
23			D	300	85.1	3.53	
24			D	300	83.2	3.61	
25	GF06C		D	450	123.1	3.66	Avg=
26			D	450	121.1	3.72	3.43
27			D	450	150.7	2.99	Sd. Dev.
28			D	450	140.5	3.20	0.31
29			D	450	120.9	3.72	
30			D	450	137.5	3.27	

The concrete columns at the ground floor of tower building namely T6 with M50 grade of concrete indicates **medium** to good in terms of quality of concrete.

Table 5.14: Ultrasonic Pulse Velocity Test data of Columns of Ground Floor at tower T7

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity Km/Sec	Remarks
Ground Flooor/ Tower7							
36	GG01C	1.5	D	300	110.4	2.72	Avg. & Sd.Dev
37		1.0	D	300	108.7	2.76	2.74
38		0.5	D	300	109.8	2.73	0.02
39	GG03C	0.25	D	300	84.5	3.55	Avg. & Sd.Dev
40		0.50	D	300	85.5	3.51	3.53
41		0.75	D	300	84.9	3.53	0.02

Similarly, the tower building T7 at the ground floor column experiences **doubtful** to good quality of concrete for M50 grade of concrete.

Table 5.15: Ultrasonic Pulse Velocity Test data of Columns of Ground Floor at tower T8

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity Km/Sec	Remarks
Ground Flooor/ Tower8							
41	GH01C	1.6	D	550	153.4	3.59	Avg. & Sd.Dev
42		1.3	D	550	142.7	3.85	3.70
43		1.0	D	550	150.3	3.66	0.14
44	GH02C	1.2	D	850	250.3	3.40	Avg. & Sd.Dev
45		1.5	D	850	233.1	3.65	3.31
46		1.8	D	850	295.5	2.88	0.39
47	GH03C	1.7	D	300	80.3	3.74	Avg=
48		1.4	D	300	81.5	3.68	3.72
49		1.1	D	300	80.4	3.73	Sd. Dev.
50		0.8	D	300	80.7	3.72	0.02
51	GH04C	1.9	D	400	124.4	3.22	Avg. & Sd.Dev
52		1.3	D	400	118.5	3.38	3.31
53		0.7	D	400	119.5	3.35	0.09
54	GH06C	1.3	D	850	330.4	2.57	2.66
55		1.0	D	850	325.5	2.74	0.12
56	GH08C	1.6	D	400	111.2	3.78	Avg. & Sd.Dev
57		1.3	D	400	111.7	3.76	3.78
58		0.7	D	400	110.8	3.79	0.02
59	GH09C	1.8	D	550	153.4	3.76	Avg=
60		1.5	D	550	155.7	3.53	3.42
61		1.2	D	550	177.0	3.11	Sd. Dev.
62		0.9	D	550	172.3	3.19	0.27
63		0.6	D	550	157.1	3.50	
64	GH12C	1.6	D	440	130.5	3.37	Avg=
65		1.3	D	440	124.6	3.53	3.50
66		1.0	D	440	130.2	3.38	Sd. Dev.
67		0.7	D	440	118.7	3.71	0.14
68		0.4	D	440	132.0	3.50	

Similarly, the ground floor column seems to have **medium** to good in terms of quality of concrete.

Table 5.16: Ultrasonic Pulse Velocity Test data of Columns of Ground Floor at tower T9

Sl. No.	Location of Test	Y (m)	Direction of Test	Depth (mm)	UPV Time (µSec)	Ultrasonic Pulse Velocity (Km/Sec)	Remarks
Ground Flooor/ Tower9							
64	GJ02C	2.0	D	250	74.5	3.36	Avg=
65		1.7	D	250	73.5	3.40	3.41
66		1.4	D	250	77.1	3.24	Sd. Dev.
67		1.1	D	250	71.5	3.50	0.13
68		0.8	D	250	73.5	3.57	
69	GJ03C	1.7	D	300	84.5	3.55	Avg=
70		1.7	D	300	85.2	3.52	3.49
71		1.4	D	300	83.2	3.61	Sd. Dev.
72		1.4	D	300	88.5	3.39	0.10
73		1.1	D	300	90.2	3.33	
74		1.1	D	300	82.8	3.62	
75		0.8	D	300	86.8	3.46	
76		0.8	D	300	86.4	3.47	
77	GJ04C	1.9	D	250	67.6	3.70	Avg=
78		1.6	D	250	70.3	3.56	3.74
79		1.3	D	250	65.5	3.82	Sd. Dev.
80		1.0	D	250	64.3	3.89	0.15
81	GJ05C	2.0	D	300	100.8	2.98	Avg=
82		1.7	D	300	101.9	2.94	2.98
83		1.4	D	300	99.2	3.02	Sd. Dev.
84		1.1	D	300	101.5	2.96	0.04
85		0.8	D	300	99.5	3.02	

Tested concrete columns at ground floor seems to have **doubtful** to good quality of concrete and doesn’t in tune to the design grade.

From the above field test data of Ultrasonic Pulse Velocity, it clearly indicates that most of the columns at the ground floor seem to have **medium** quality of concrete. Further, the ground floor columns of Tower building namely T7, T8 & T9 seems to be susceptible to greater corrosion and thus further study is essential.

The overall summary of the quality of concrete for all the tower building columns based on the values of the ultrasonic pulse velocity test data along with grade of column concrete is shown Table 5.17 below.

Table 5.17: Mapping of UPV values all Towers with respect to Design Concrete Grade

Floors	**Towers**								
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**
B	3.88	3.61	4.02	3.85	3.94	3.56	3.92	3.74	3.85
G	3.8	3.46	3.83	4.27	3.48	3.4	3.74	3.27	3.49
1	3.84	-	3.08	3.59	-	4.03	-	2.44	-
2	-	-	3.54	3.63	3.84	3.78	3.22	3.21	-
3	3.64	3.43	3.78	3.95	-	-	3.58	-	-
4	-	-	-	-	-	-	3.14	3.16	-
5	-	-	-	-	3.76	3.76	-	-	-
6	-	-	-	-	-	3.61	-	-	-
7	3.41	3.46	-	-	-	3.71	3.7	3.99	3.1
8	-	-	-	-	-	-	3.28	8.65	-
9	3.78	-	-	-	-	4.25	3.36	-	-
10	-	3.79	3.8	3.61	-	-	3.68	3.34	-
11	-	-	-	3.65	3.66	3.07	3.76	3.61	-
12	3.17	3.49	-	3.24	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-
14	3.31	3.53	-	-	-	3.54	3.28	2.8	-
15	-	-	-	3.52	-	-	2.84	3.4	3.19
16	3.54	3.71	3.45	3.53	-	3.46	-	-	3.44
17		-	-	3.41	3.51	3.43	-	-	
18		-	-	3.43	3.47	3.36	3.34	-	
19		-	-	-	3.57	3.37	-	-	
20		-	3.67	-	-	-	3.4	-	
21		-	-	3.57	-	3.49	-	-	
22			-	3.57	-	3.46	3.22		
23			-	-	-	3.4	-		
24			2.91	-	3.69	-	3.01		
25				-	3.32	3.15			
26				3.71	3.43	-			
27				-	-	-			
28				3.38	-	3.46			
29					-				
30					-				

Design Grade of Concrete	M50	M45	M40	M35	M30
Colour Code					

It is observed that there are mostly good in terms of quality of concrete at the basement and ground floor columns at most of the tower building even though the **design grade is high** as used in the basement and the ground floor of the towers, high value of Ultrasonic Pulse Velocity are expected.

The desired elastic modulus of concrete for the different grade of concrete used in the subject buildings as per IS 456:2000 is shown in Fig-5.9 below.

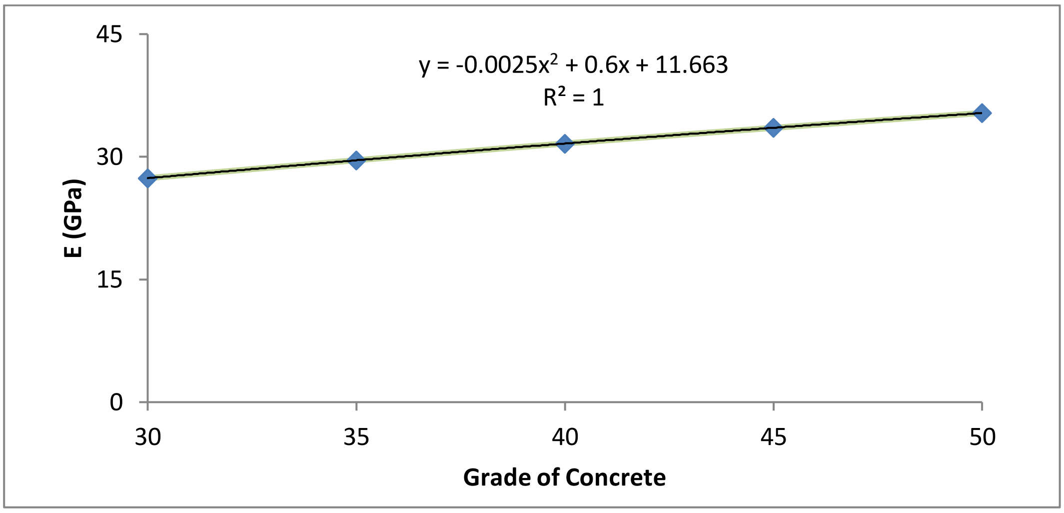


Fig-5.9: Modulus of Elasticity **(**E) for Different Grade of Concrete

It is evident that the modulus of elasticity increases in a parabolic manner with the increase of concrete grade.

Further, the estimated dynamic and static modulus of concrete for different Ultrasonic Pulse Velocity (UPV) values as per IS 13311(Part-I):1992 and relevant research literature [Lydon et. al.] is shown in Fig-5.10 below.

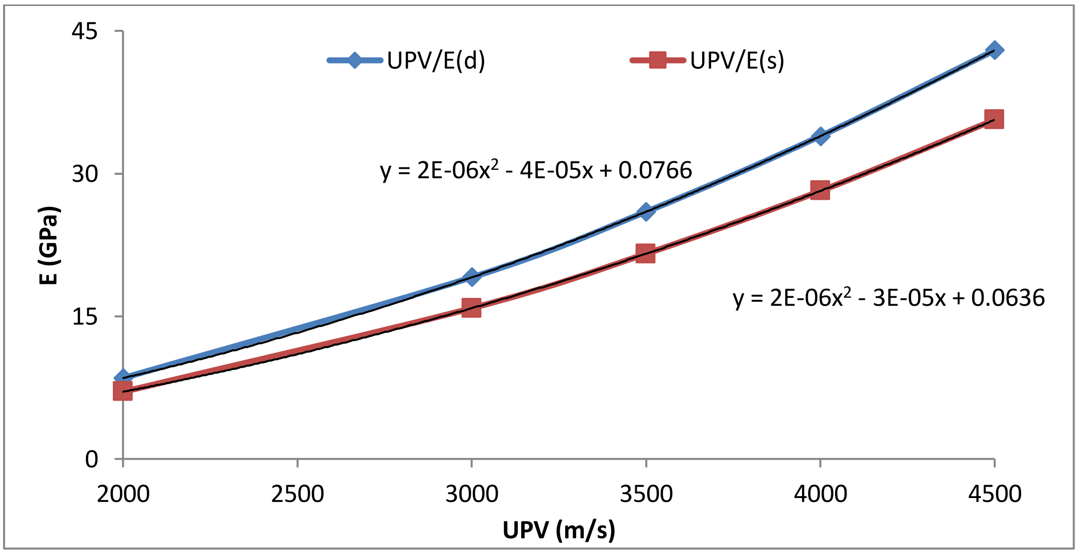


Fig-5.10: Modulus of Elasticity **(**E) for various UPV values

The estimated modulus of elasticity also increases with the increase of Ultrasonic Pulse Velocity values but in a faster ascending order. Thus in case of high grade of concrete as used in the basement and the ground floor of the towers, high value of Ultrasonic Pulse Velocity is expected considering the compatible E values. It is quite evident from the above figures that the higher design grade of concrete should have high values of elastic modulus of concrete and subsequently should exhibit higher values of Ultrasonic Pulse Velocity. Any reduction from its desired value due to loss in the concrete quality in terms of cracks, voids and honeycomb will reduce its actual design strength. The basement and the ground floor columns are mostly distressed and large number of test data are obtained for further study in a detail manner.

The comparison of maximum corrosion risk in terms of Half Cell Potentiometer (HCP) values of different towers for basement is shown below in Fig-5.11.

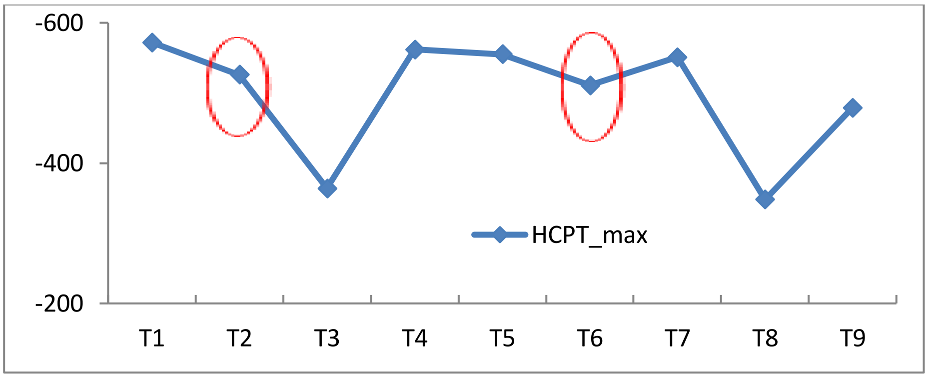


Fig-5.11: HCP values of Concrete Columns of Basement for different Tower Buildings

It is evident from the above figures that tower buildings T-1, **T-2,** T-4, T-5, **T-6,** T-7 & T-9 shows higher values of half-cell potentiometer readings indicating greater susceptibility to corrosion at basement. Similarly, comparison of maximum corrosion risk in terms of HCP values of different towers for ground floor is shown in Fig-5.12.

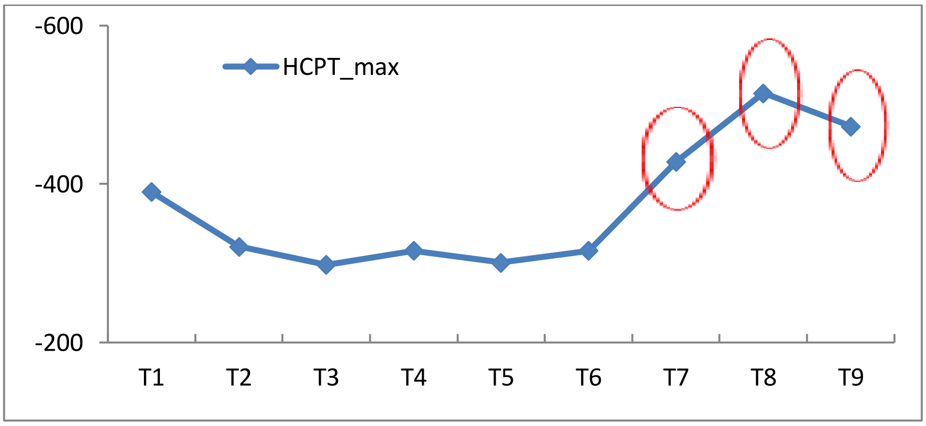


Fig-5.12: HCP values of Ground Floor Concrete Columns for different Tower Buildings

Similarly, tower buildings **T-7, T-8 & T-9** at ground floor exhibit higher corrosion risk.

The comparison of average pH values of concrete column of different towers for basement is shown below in Fig-5.13.

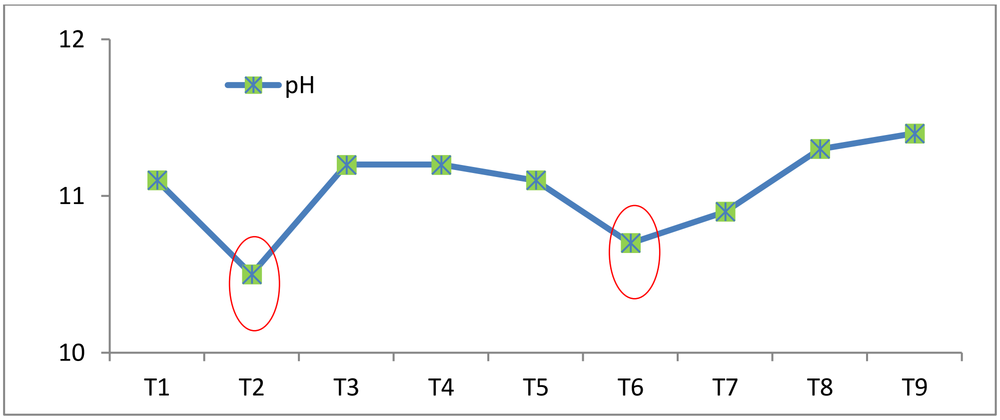


Fig-5.13: pH values of Concrete Columns of basement for different Tower Buildings

The relatively **lower values of pH** indicate reduction of the alkalinity of concrete at those common towers of T-2 & T-6 at basement where greater susceptibility to corrosion have already observed. Similarly, comparison of average pH values of concrete column of different towers for ground floor is shown below in Fig-5.14.

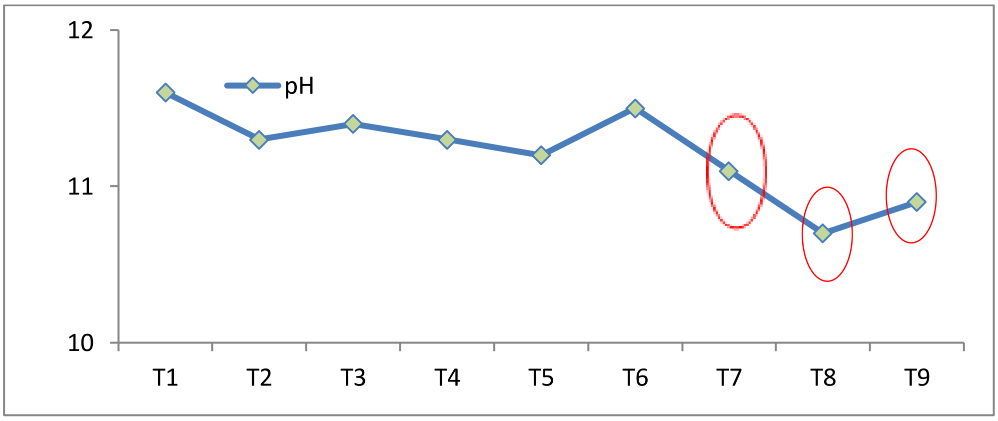


Fig-5.14: pH values of Ground Floor Concrete Columns for different Tower Buildings

Similarly, columns at tower buildings namely T-7, T-8 and T-9 seems to have relatively **lower values of pH** indicating reduction of the alkalinity at the ground floor concrete where greater susceptibility to corrosion already observed.

The comparison of average chloride content values of concrete column of different tower buildings for basement is shown in Fig-5.15 below.

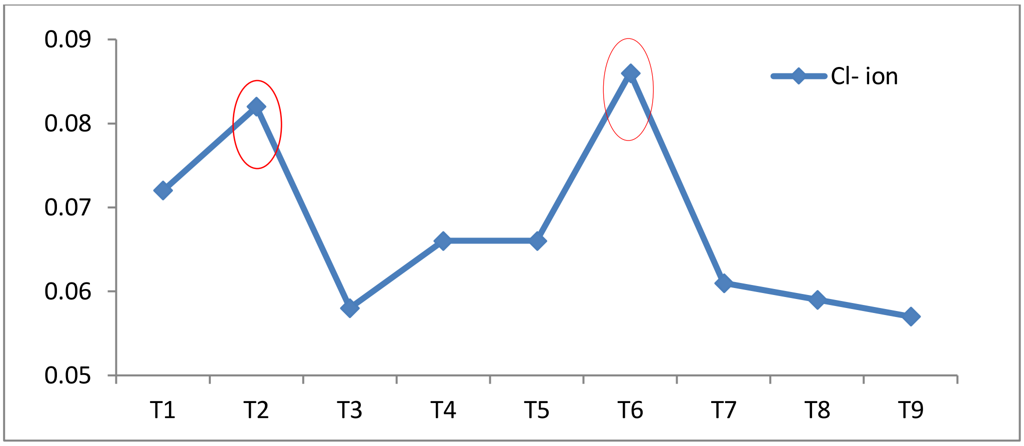


Fig-5.15: Chloride Content (%) for Concrete Columns of Basement for different Towers

Relatively **higher values of chloride content** at those common towers of T-2 & T-6 at basement established the greater susceptibility to corrosion as indicated by the lower pH values and higher Half Cell Potentiometer values already observed. Similarly, comparison of average chloride content values of concrete column of different tower buildings for ground floor is shown below in Fig-5.16.

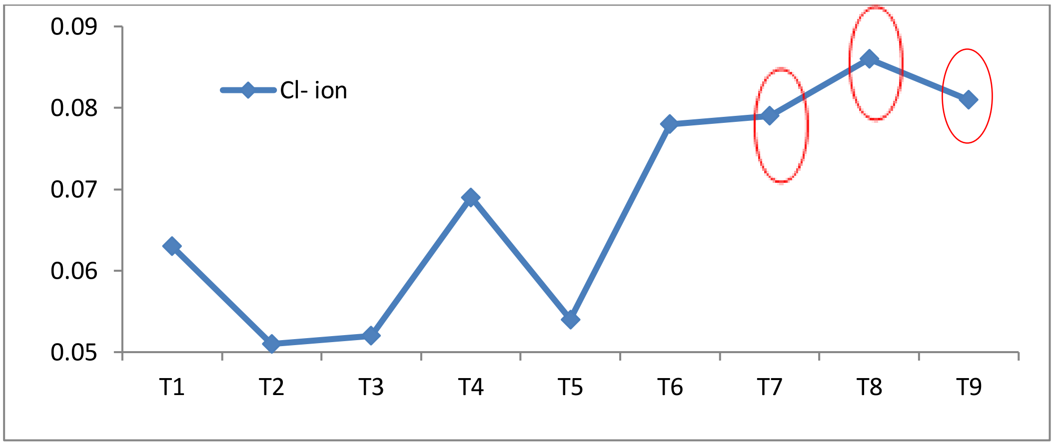


Fig-5.16: Chloride Content (%) for Columns of Ground Floor for different Towers

However, **higher values of chloride content** are observed at those tower buildings namely T-7, T-8 and T-9 having greater susceptibility to corrosion.

The comparison of concrete quality in terms of average Ultrasonic Pulse Velocity values of different tower buildings for basement is shown in Fig-5.17 below.

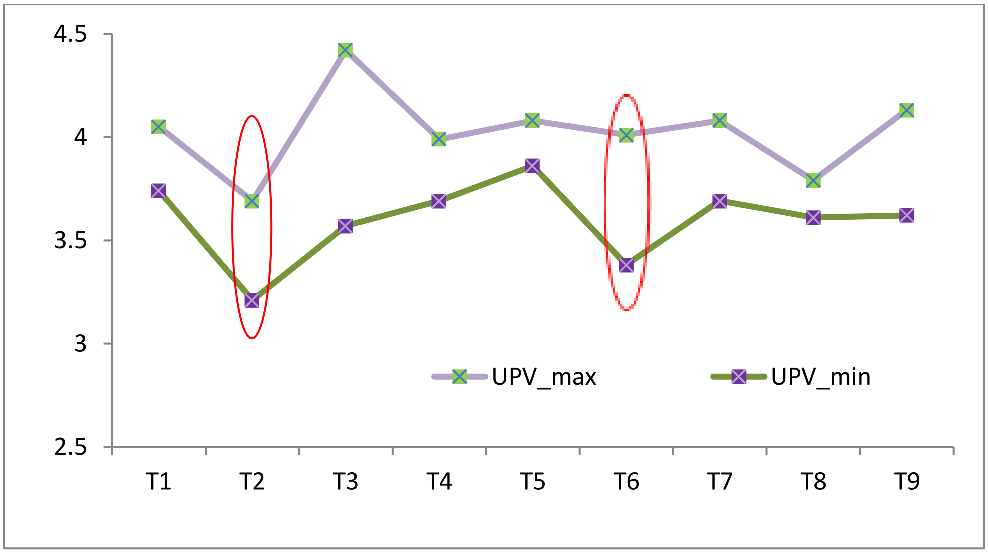


Fig-5.17: UPV values of Concrete Columns at Basement for different Tower Buildings

The tower buildings **T-2 & T-6** shows lower minimum values of Ultrasonic Pulse Velocity readings indicating poor quality of concrete at basement. Similarly, comparison of concrete quality in terms of average Ultrasonic Pulse Velocity values of different tower buildings for ground floor is shown below in Fig-5.18.

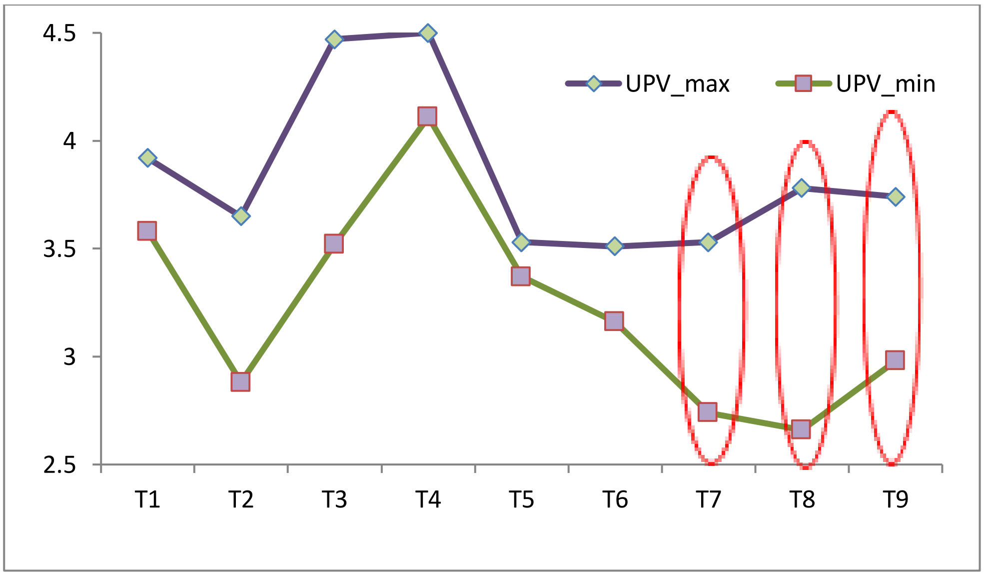


Fig-5.18: UPV values of Columns at Ground Floor for different Tower Buildings

Thus, tower buildings T-2, **T-7, T-8 & T-9** at ground floor exhibit poorer quality of concrete with respect to others. Based on the above study it is clearly noted that higher areas of corrosion risk exhibit possibility of lower Ultrasonic Pulse Velocity values indicating poorer quality of concrete. Thus a correlation between the higher corrosion risks with the reduction of concrete quality is observed. The above observation may be due to the development of micro-cracks adjacent to the corroded reinforcements. Therefore, a correlation between the Half Cell Potentiometer and Ultrasonic Pulse Velocity values for corrosion distressed concrete columns may be established.

Susceptibility to corrosion of reinforced concrete structure can also be affirmed by the ultrasonic reading along with pH and Chloride ion concentration as shown above. The susceptibility of corrosion may be triggered when the pH and chlorine ion concentration reached the threshold value. Subsequently, lower ultrasonic pulse velocity reading may be observe, which are in tune with the above inference. Thus, lower value of Ultrasonic Pulse Velocity with lower pH and higher chloride content of concrete strongly reaffirmed the higher susceptibility of corrosion as indicated by higher Half Cell Potentiometer values.

Every non-destructive test has some limitations and is based on certain basic principle. Thus, there are various uncertainties associated with the respective models in addition to the measurement noise and environmental variations. The greater corrosion risk as indicated by higher half-cell potentiometer value can be judiciously examined by the ultrasonic pulse velocity readings in addition to pH and chloride values to confirm the corrosion risk with greater confidence. Thus a four point confirmation (Half-cell potentiometer reading, ultrasonic pulse velocity reading, pH value and chloride content) of corrosion risk seems to be a better proposition for non-destructive evaluation of corrosion distress in concrete.

Further, we try to develop a relationship between results of HCPT with UPV has been attempted. Few relevant values of above data are selected from the test results where ultrasonic pulse velocity value is low and corresponding half-cell potentiometer values are high to develop a correlation between them. The HCPT & UPV are normalised based on the respective permissible limits. The degree of degradation due to HCPT reading of -600mV is considered as 100% & -200mV reading as 0%. Similarly, the degree of degradation due to UPV reading of 3.0 km/s as 100% & 4.50 km/s as 0% for the considered concrete grade.

Fig-5.19 shows the correlation between these normalised UPV (NU) values with those normalised HCPT (NH) values.

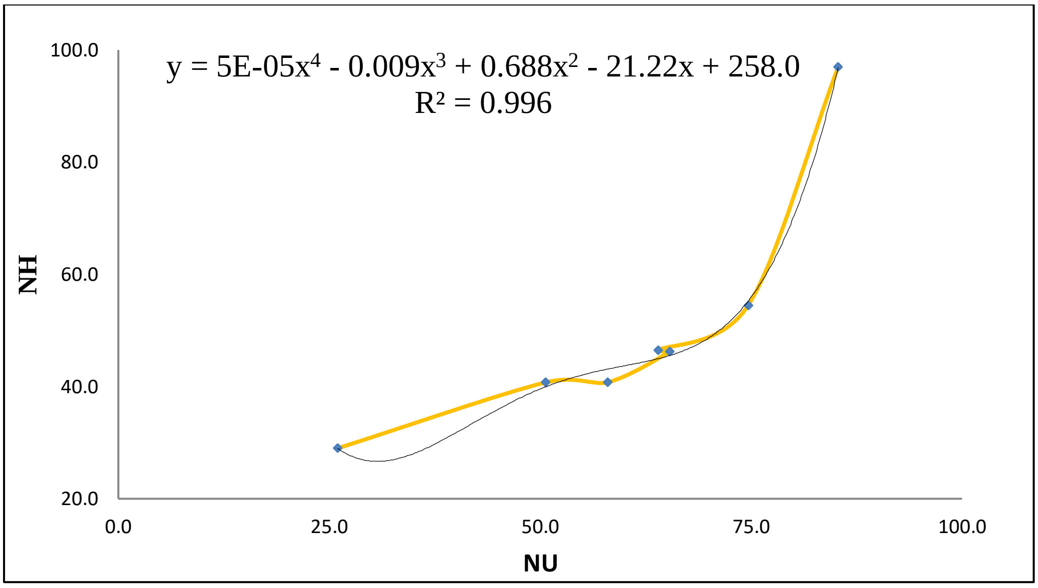


Fig-5.19: Relation between HCPT & UPV

The above curve between NU and NH may be used to reconfirm the corrosion risk in a better way. It is also noted from the above figure that till 50% degradation in ultrasonic pulse velocity value i.e. 3.75 Km/sec, the susceptibility to corrosion is almost 40% i.e.-350 mV, which is low to moderate as per ASTM specification. But when the degradation in UPV is about 66% i.e. less than 3.5 Km/sec for the considered design grade of concrete, the susceptibility to corrosion increases rapidly to the tune of high to severe ranges.

Similarly, a relationship between results of HCPT with pH has also been attempted. Few relevant values of above data are selected from the test results where pH value is low and corresponding half-cell potentiometer values are high to develop a correlation between them. The HCPT & pH are normalised based on the respective permissible limits. The degree of degradation due to HCPT reading of -600 mV is considered as 100% & -200 mV as 0% and the degree of degradation for pH reading of 10.5 is considered as 100% & 12.5 as 0% for the considered grade of concrete.

Fig-5.20 shows the correlation between these normalised pH (NP) values with those normalised HCPT (NH) values.

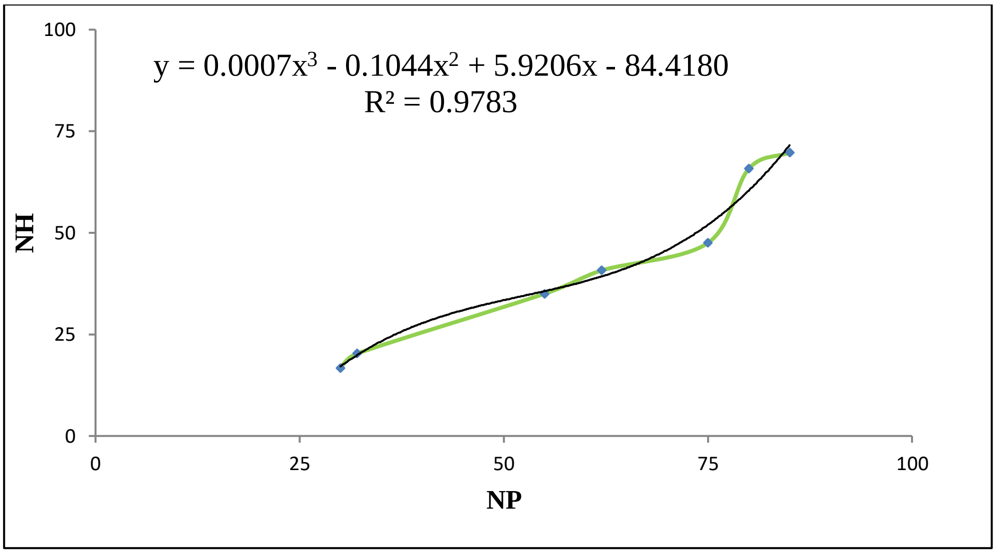


Fig-5.20: Relation between HCPT & pH

The above figure between NP and NH may also be used to reaffirm the susceptibility of corrosion. It is understood from the above figure that till 50% degradation in pH value i.e. 11.5, the susceptibility to corrosion is almost 40% i.e. -350 mV, which is low to moderate as per ASTM specification. But when the degradation in pH is about 75% i.e. less than 11.0, the susceptibility to corrosion is increases rapidly from high to severe.

Based on the above two correlations, the degree of degradation due to corrosion (D_H) can be expressed in a general manner with UPV & pH values are as follows-

$$\mathbf{D_H = aU^4 + bU^3 + cP^3 + dU^2 + eP^2 + fU + gP + h}$$

[a, b, c, d, e, f, g & h are constant]

It is clear from above discussion that for concrete of higher grade having half-cell potentiometer reading more than -350 mV with ultrasonic pulse velocity is less than 3.5 Km/sec and pH value less than 11.0 needs immediate measure from corrosion distress.

CHAPTER-6

CONCLUSION & FUTURE SCOPE

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6.1. Conclusion:

Based on the field study on corrosion susceptibility by Half-Cell Potentiometer Test, pH, Chloride and Ultrasonic Pulse Velocity test and subsequent analysis and corrosion distress mapping the following conclusion may be drawn:

i. The corrosion distress in column concrete seems to be significant for the considered residential complex and distributed randomly among the different tower buildings and at different floors.

ii. The columns of the tower buildings namely T2, T6, T7, T8 and T9 seems to have suffered high to severe degree of corrosion risk among the total towers and thus considered for detail analysis and study for corrosion mapping.

iii. Among these five towers, basement and ground floors seems to have suffered greater susceptibility to corrosion, particularly with respect to the design grade of concrete at those floors.

iv. Further the mapping of pH level for the basement and ground floor of all the towers, it clearly shows that significant loss of pH level i.e. loss of alkalinity of concrete clearly indicates greater corrosion susceptibility and in tune with the high Half-Cell Potentiometer Test readings..

v. Similarly, the mapping of chloride content of concrete at basement and ground floor also indicate higher susceptibility to corrosion at those locations with significant increase in chloride content of concrete.

vi. Relatively lower Ultrasonic Pulse Velocity (UPV) values are also in tune with the greater susceptibility to corrosion, which may be due formation of micro-cracks adjacent to the reinforcement and or poor quality of concrete.

vii. Higher design grade of concrete should have high values of elastic modulus of concrete (E) and subsequently should exhibit higher values of Ultrasonic Pulse Velocity. Reduction of Ultrasonic Pulse Velocity values from its desired value due to poor concrete quality in terms of presence of cracks, voids and honeycomb will indicate loss of its design modulus of elasticity.

viii. A correlation between degradation estimated by Half-Cell Potentiometer test result with the degradation estimated from reduction in Ultrasonic Pulse Velocity values is proposed. Ultrasonic Pulse Velocity values less than 3.5 Km/sec for M45 design grade indicates rapid increase in confirming greater susceptibility to corrosion as per ASTM specification.

ix. Similarly, another correlation between degradation estimated by Half-Cell Potentiometer test result with degradation estimated by pH values is also proposed. pH values less than 11.0 indicates rapid increase in confirming greater susceptibility to corrosion as per ASTM specification.

x. Thus the proposed correlations may address the assessment of corrosion risk of RCC in a much better manner with greater confidence through the three parameter approaches (Half-cell potentiometer reading, ultrasonic pulse velocity reading and pH value).

6.2. Future Scope of Work

- To find out a single reliable correlation between these three non-destructive test result to identify the corrosion risk.
- Development of a Probabilistic model for corrosion risk prediction.
- Monitoring of corrosion risk based on newer technique e.g. incorporating low cost sacrificial anode, used for repair of corroded structure.

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