Strength Assessment of RCC Beams Subjected To Corrosion

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ABSTRACT
The damage assessment of civil structural members is one of the most important and recently emerging fields in engineering. Deterioration of a structure may occur due to a host of factors such as poor workmanship, improper maintenance, atmospheric effects, accidents, natural calamities. Certain causes like environmental effects, natural calamities can not be controlled. Therefore, durability of concrete structures especially those exposed to aggressive environments is of great concern. In spite of many deterioration causes and factors have been investigated in turn corrosion of steel reinforcement was found to be one of the major deterioration problems. Thus, an Engineer may need to examine the state of reinforcement in structures for a number of reasons including assessment for change of use or exposure, routine maintenance, or investigating signs of distress. In turn, there is a requirement for a method that can determine simply, accurately and non-destructively not only whether corrosion of reinforcement is taking place but also its intensity and the rate of damage. The main aim of this paper is to assess and evaluate the corrosion condition of reinforced concrete beams by using Non-destructive test (NDT) methods such as Half-cell potential test, Rebound hammer test, and Ultrasonic pulse velocity test. Also another thrust of this pilot program is to establish a correlation between Rebound hammer number, and Ultrasonic pulse velocity variation versus concrete strength for different degree of corrosion in turn to interpret the effectiveness of degree of corrosion on NDT values as well as concrete compressive strength. For that a total of six reinforced concrete beams (150x150x1000) mm were considered. An impressed current was applied to beams with different degree of corrosion (5%, &10%) in order to accelerate steel corrosion. Mean while electrochemical measurements were carried out to obtain open circuit potential. Finally the results show that the Linear regression analysis is the best fit for the compressive strength prediction relationship by using Rebound hammer and Ultrasonic pulse velocity test at compression as well as tension side of reinforced concrete beam with different degree of corrosion (5%, &10%).

Keywords
Corrosion, Electrochemical test, Ultrasonic pulse velocity test, Rebound hammer test, , Regression analysis

1. INTRODUCTION
The reinforcing steel may be subjected to corrosion due to many reasons such as exposure to environment, RCC used in marine structures. It is very essential to protect the reinforcing steel from corrosion else the volume of the member may increase due to which the member may tend to fail by increase in stress. There have been many tests reported in literature for the assessment of the corrosion of steel in concrete. Most of the earlier tests, primarily through field exposure could provide only qualitative information, while in the recent year researchers have been utilizing some of the techniques like electrochemical tests as well as non-destructive methods to establish precise and quantitative results.

To estimate the strength in the member non-destructive testing may be carried out it is a method of estimating strength in the member without destructing the member. There are various methods to estimate the strength like pull out pull off test. To estimate strength by this method the fundamental properties like modulus of elasticity, density of the member, percentage absorption like wise other basic properties of the materials should be known by conducting laboratory investigation.

There are many methods of non-destructive testing available out of which rebound hammer, Ultrasonic pulse velocity, and Half-cell electrical potential test are very commonly used. Schmidt/rebound hammer test, used to evaluate the surface hardness of concrete. Although the rebound hammer does provide a quick, inexpensive method of checking the uniformity of concrete, it has some serious limitations.

The results are affected by:

1. Smoothness of the test surface;
2. Size, shape and rigidity of the specimen;
3. Age of the specimen;
4. Surface and internal moisture conditions of concrete;
5. Type of coarse aggregate;
6. Type of cement;

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7. Carbonation of the concrete surface.

Half-cell electrical potential method, used to detect the corrosion potential of reinforcing bars in concrete. Ultrasonic pulse velocity testing, mainly used to measure the sound velocity of the concrete and hence the compressive strength of the concrete.

Also the following factors influences the Ultrasonic pulse velocity such as:

1. Moisture content;

2. Temperature of the concrete;

3. Path length;

4. Shape and size of specimen;

5. Effect of reinforcing bars;

6.Determination of concrete uniformity

In this experimental work for different degree of corrosion, Ultrasonic pulse velocity is used to determine the quality of concrete both at the compression as well as tension side of reinforced concrete beams. A pair of piezoelectric sensors is placed at opposite ends of the reinforced concrete member at an equidistant. Knowing the distance travelled, propagation velocity is calculated and based on the velocity, condition of the concrete is determined. Also Schmidt/rebound hammer test is used to evaluate the surface hardness of concrete both at the compressive as well as tension side of reinforced concrete beams at an equal interval along the longitudinal direction. From the test results, correlation between degree of corrosion/days, Ultrasonic pulse velocity and Rebound hammer number/concrete compressive strength is interpreted by using Regression analysis.

2. RESEARCH SIGNIFICANCE

The impact of reinforcing steel corrosion on performance of reinforced concrete structures is of paramount importance in concrete material and structural design. The objective of this study was to provide a reliable data base for effectiveness of different degree of corrosion on corrosion damage assessment of reinforced concrete beams. This research illustrates the interactions among degree of corrosion rate with age in days, ultrasonic pulse velocity, rebound hammer number, concrete compressive strength of reinforced concrete beams. Thus the results may provide researchers insight into corrosion damage evaluation of reinforced concrete beams by using NDT methods. Also the results may provide correlation between Rebound hammer number/Compressive strength and Ultrasonic pulse velocity/Compressive strength which is interpreted by Regression analysis.

3. EXPERIMENTAL INVESTIGATION

3.1 Basic test on Cement

In the present investigation ordinary Portland cement of grade 53 with a brand name ultra tech is used. Tests are conducted in accordance with the Indian standards confirming to IS-12269:1987. The physical characteristics of tested cement are given in the Table 1

Table 1 Physical characteristics of cement

Sl.No	Physical Properties	Results
1.	Specific Gravity	3.15
2.	Fineness of cement	1.5%
3.	Standard Consistency	30%
4.	Setting time (in minutes) Initial setting time Final setting time	 70min 220min
5.	Compressive Strength (MPa) (70.6X70.6X70.6 mm cubes) 3 Days Strength 7 Days Strength 28 Days Strength	 38 43.8 58.3

3.1.1 Test on Fine aggregate

It is desirable to use a coarse variety of sand having high fineness modulus. Generally, fractions passing through 4.75 mm sieves and entirely retained on 150µ sieve are used. Locally obtained natural river sand are used as the fine aggregate in the concrete mix. The test on fine aggregate was conducted in accordance with IS 650-1966&Is 2386-1968 to determine the specific gravity and the fineness modulus. The sand is confirming to Zone-II as per Indian standards. The results are given in the Table 2 and sieve analysis results are given in table 3

Table 2 Test results on Fine aggregate

Sl.No.	Particulars of the test	Results
1.	Fineness Modulus	2.64
2.	Specific Gravity	2.66
3.	Bulk Density(Kg/m^3) 1.Dense rodded 2. Loose	 1600 1422
4.	Void Ratio	40%
5.	Zone	II

Table 3 Sieve analysis results

Sieve Size	Weight Retained (grams)	Cumulative (%) Retained	Cumulative (%) Passing	Zone I	II	III	IV
4.75 mm	20.00	2.00	98.00	90-100	90-100	90-100	95-100
2.36 mm	39.00	5.90	94.10	60-95	75-100	85-100	95-100
1.18 mm	85.00	14.4	85.60	30-75	55-90	75-100	90-100
600 µ	264.00	40.80	59.20	15-34	35-59	60-79	80-100
300 µ	295.00	70.3	29.70	5-20	8-30	12-40	15-50
150 µ	263.00	96.60	3.40	0-10	0-10	0-10	0-10
Pan	34.00	100.00	0				

The fine Aggregate tested is confirming to Zone-II

3.1.2 Test on Coarse Aggregate

Crushed Granite stone with a Maximum nominal Size 12mm and down was adopted as the coarse aggregate. The tests on coarse aggregate were conducted in accordance with IS 2386-1963 to determine specific gravity and fineness modulus and other tests are carried out as per IS codes and the values are given in the table 4 and table 5

Table 4 test results on coarse aggregate

Sl. No	Particulars of the test	Results
1.	Fineness modulus	6.2
2.	Specific Gravity	2.67
3.	Elongation Index	21%
4.	Flakiness Index	18%
5.	Crushing Strength	26%
6.	Impact Value	16%
7.	Abrasion Value	31%

Table 5 compressive strength of concrete cube

SL No	Weight of cube in Kg	Strength (N/mm^2)
1	8.18	39.6
2	8.2	40.1
3	8.21	39.8

4. EXPERIMENTAL WORK

The dimensions (150 mmx150 mmx1000mm) of the six RC beams with an effective span of 1000 mm were cast using 2-12mm ϕ bars (yield strength of 415 N/mm2) as tension reinforcement, 2-8 mm ϕ bars as compression reinforcement, and 6 numbers of 6 mm ϕ at 150 mm c/c stirrups. The mean strength of concrete used for concrete beam is 35.21N/mm2. The concrete mix used was 1:1.53:3.2 by weight with a water-cement ratio of 0.49. Out of six beams, each two beams were subjected to different degree of corrosion under accelerated corrosion by constant current source (Dc = 5%and 10% of rebar mass loss). The details of reinforcement within the reinforced concrete beam are shown in Fig.1.

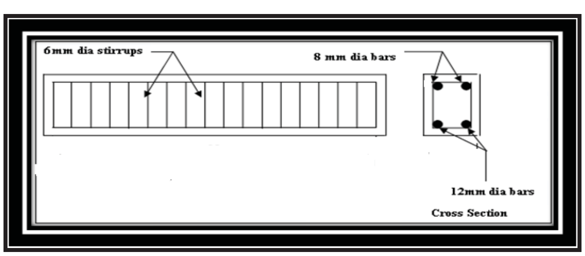

Fig.1 Reinforcement details of beam

4.1 4.1 Accelerated Corrosion process:

The reinforced concrete beams were subjected to an accelerated corrosion process in an electrolytic cell by means of a direct current supply. An electric current was passed through the main longitudinal bottom reinforcing bars of about maximum 5000 mA. The beams were placed on the stainless steel plate SS316 grade acting as a cathode (Non-corrosive plate) and this set up was placed in the 3.5% NaCl solution, which acted as an electrolyte and the solution level in the tank was adjusted to slightly exceed the concrete cover plus rebar diameter in order to ensure adequate submission of longitudinal reinforcement. The layout of corrosion setup and corrosion monitoring are shown in the Fig.2 and Fig.3.

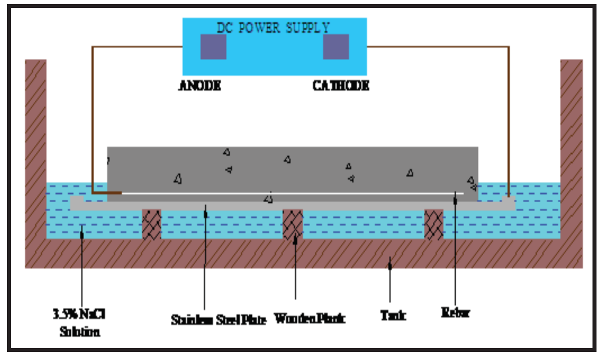

Fig.2 Layout of Experiment

Fig.3 Layout of Experiment

It is possible to convert the current flow in to metal loss by Faraday's law. According to Faraday's law, the time for accelerated corrosion was calculated as 18.30hr,and 45.31 hr for 5%, &10% mass loss (corrosion) of tension steel. The copper-copper sulphate (Cu-CuSO4) half-cell electrode was selected for corrosion measurement in the present research. The testing procedure in this research which was followed the standard test method for half-cell potentials of reinforcing steel in concrete (ASTM C 876) as per code (9). This test can give the probability of corrosion activity that taking place at the point where the measurements of potentials are taken from a half cell, typically a copper-copper sulphate half-cell. An electrical contact is established with the steel and the half-cell is moved across the surface of concrete for measuring the potentials. According to ASTM C 876, if the copper-copper sulphate half-cell potential reading is more positive than -0.20 V CSE (copper-copper sulphate electrode), there is a greater than 90% probability that no reinforcement steel corrosion is occurring in the area at the time of measurement. If the potential reading is in the range of -0.20 to -0.35 V CSE, corrosion activity of the reinforcing steel is assumed to be uncertain. If the potential reading is more negative than -0.35 V CSE, it's assumed that a greater than 90% probability of the reinforcing steel corrosion is occurring. The half-cell potential readings are taken two times per day at eleven different locations that are equally distributed along a beam.

Furthermore, impact hammer or simply Schmidt Rebound hammer test was carried out on compression as well as tension side before and after corrosion damage inducement in RC beams for different degree of corrosion at eleven different locations that are equally distributed along a beam to measure the surface hardness of concrete by releasing a spring loaded plunger which impacts the concrete and measures the rebound distance. It is also well known fact that the test method of rebound hammer for normal concrete has been well documented by ASTM C 805 (10), in turn this code procedure was followed in the present study for the evaluation of the rebound hammer number. The Layout of Rebound hammer with their various components details may be as shown in Fig.4 and general guidelines for assessing the quality of concrete may be interpreted as shown in the Table 6

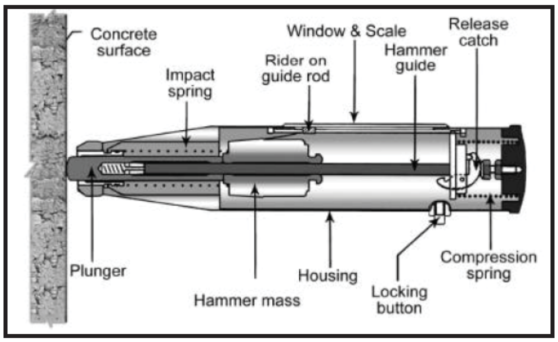

Fig.4 Layout of Rebound hammer

Table 6 Average Rebound number and quality of concrete

Average Rebound Number	Quality of Concrete
>40	Very good hard layer
30 to 40	Good layer
20 to 30	Fair
< 20	Poor concrete
0	Delaminated

Ultrasonic pulse velocity test with opposite faces (direct transmission) was carried out as per IS: 13311-Part1(11) on corrosion damaged RC beams for different degree of corrosion at eleven different locations that are equally distributed along a beam and ultrasonic pulse velocity reading are recorded both at compression as well as tension side. This test is conducted for assessing the quality and integrity of concrete by passing ultrasound waves through the specimen or RCC member under test. The Layout of Rebound hammer with their various components detail may be as shown in Fig.5.

Fig.5 Layout of Ultrasonic pulse velocity

This test can also be used to determine the presence of honeycombs, voids, and cracks. The instrument consists of a transmitter and a receiver (two probes). The time of travel for the wave to pass from the transmitter to the receiver when kept opposite to each other is recorded in the ultrasonic instrument. The distance between the two probes (path length) can be physically measured. Hence the ultrasonic pulse velocity is defined as the ratio between path length and time and general guidelines for assessing the quality of concrete may be interpreted as shown in the Table 7.

Table 7 UPV value and concrete quality

UPV value in km/sec (V)	Concrete quality
V greater than 4.0	Very good
V between 3.5 and 4.0	Good, but may be porous
V between 3.0 and 3.5	Poor
V between 2.5 and 3.0	Very poor
V between 2.0 and 2.5	Very poor and low integrity
V Less than 2.0 and reading fluctuating	No integrity, large voids suspected

5. RESULTS AND DISCUSSION

In fact the corrosion of reinforcing steel can damage or reduce the serviceability of concrete structures in several different ways. First, corrosion produces expansive products that generate tensile stresses in the concrete surrounding the reinforcing steel, which may cause concrete cracking. In turn Cracks can reduce the overall strength and stiffness of the concrete structure and accelerate the ingress of aggressive ions which leading to other types of concrete deterioration and resulting in further cracking. Second, corrosion products are highly porous, weak, and often form around reinforcing steel, thus decreasing the bond strength between the reinforcement and concrete (12). Thus the impact of reinforcing steel corrosion on performance of reinforced concrete structures is of paramount importance in concrete material and structural design. The variations of Half-cell potential versus Distance for different degree of corrosion such as 5% and 10% are plotted as shown in (Fig.4a, Fig.4b, and Fig.4c). As observed from (Fig.4a) that, the half cell potential reading was varied somewhere between -245 to -350 mv which in turn informs statistical risk of corrosion was around 40%-50%. It was also confirmed from (Fig.4b) that, the half cell potential reading was varied somewhere between -210 to -400 mv which in turn indicates statistical risk of corrosion was around 50%-75%. It was concluded from (Fig.4c) that, the half cell potential reading was varied somewhere between -215 to -455 mv which in turn indicates statistical risk of corrosion was around 50%-85%. Actually the Half-cell potentials are measured on the surface of the concrete that is remote from the reinforcing steel, several factors such as concrete cover depth, surface condition, and electrical resistance may influence the potential reading. Thus potential readings only indicate the probability of corrosion activity (13).

The most significant causes that which may lead to variation in corrosion rate of reinforcement steel and corrosion induced damage in turn as a result of cracking and spalling, poor quality of concrete, inadequate cover to reinforcement, chlorides in the concrete. Also if P^h value of the concrete adjacent to reinforcement is above 10, a protective surface oxide layer forms on the metal surface. The rate of corrosion under these circumstances is insignificant. Also the presence of oxygen and sufficient quantity of free chloride ions in the pore water of concrete can increase or decrease the rate of reinforcement corrosion even in highly alkaline conditions. The minimum total chloride content of concrete and threshold level required for corrosion rate enhancement in turn can not be represented by a single factor. It's influenced by several factors such as w/c ratio, cement type, P^h of the pore solution, and exposure conditions. In fact carbon dioxide from various sources diffuses into concrete in moist conditions. This ingresses carbon dioxide reacts with the hydrated cement to form calcium carbonate which lowering the P^h of the cement matrix system. As a result of that over a period of time when the P^h is reduced to a point below 9-10 then the passivity of steel is lost and the steel becomes highly vulnerable to increase or decrease of corrosion rate.

The Schmidt rebound hammer is basically a surface hardness test with little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer. Rebound hammers test the surface hardness of concrete, which cannot be converted directly to compressive strength. There is a considerable amount of scatter in rebound numbers because of the heterogeneous nature of near surface properties (principally due to near-surface aggregate particles). There are several factors other than concrete strength that influence rebound hammer test results, including surface smoothness and finish, moisture content, coarse aggregate type, and the presence of carbonation. In the present study Rebound hammer test was carried out both at compression side as well as tension side of the beam before and after the corrosion damage inducement in the beam with different degree of corrosion. The variations of Rebound hammer number versus Compressive strength for compression side as well as tension side of beam with different degree of corrosion such as 5%, 10%, are plotted as shown in (Fig.5a, Fig.5b,) and (Fig.5c, Fig.5d,).

As observed an experimental calibration equation for the Rebound hammer test that derived from this research at the compression side of the beam was y = 1.629x-23.27, R^2 = 0.85, Dc = 5%; y = 1.184x-0.419, R^2 = 0.83, Dc =10%; and also as observed from (Fig.5c-5d) an experimental calibration equation for the Rebound hammer test that derived from this research at the tension side of the beam was y = 1.716x-24.77, R^2 = 0.87, Dc = 5%; y = 1.432x-17.00, R^2 = 0.857, Dc =10%; and Where as y = rebound hammer number, x = compressive strength (N/mm^2), and R^2 = coefficient of correlation. As observed from (Fig.5a-5c) that, the rebound hammer number was varied on compression side of the beam in the range of 30-55 (Dc = 5%), 25-50 (Dc =10%), which in turn indicates the quality of concrete varied from fair to very good hard layer. As observed from (Fig.5d-5f) that, the rebound hammer number was varied on tension side of the beam in the range of 39-56 (Dc = 5%), 30-53 (Dc =10%), and which in turn indicates the quality of concrete varied from good layer to very good hard layer. There could be more 85% (correlation coefficient) of rebound hammer number and compressive strength data values at compression side of the beam was correlated for in case of (Dc=5%) as when compared to that of correlation coefficient of about 83% (Dc=10%) when they are in the linear regression. The coefficient of correlation was vary extensively both on (compressive and tensile side) of the beam for in case of Dc = 5% as when compared to higher degree of corrosion such as Dc = 10% This coefficient of correlation in turn depends on degree of corrosion as well as test results which are affected by test surface smoothness, size, shape, and rigidity of the specimens, age of specimen, surface and internal moisture conditions of concrete, coarse aggregate type, cement type, and carbonation of concrete surface. Also as observed that, there could be 87% of (correlation coefficient) rebound hammer number and compressive strength data values at tension side of the beam was correlated for in case of (Dc=5%) as when compared to that of 85.7% (Dc=10%) and 80.8% (Finally it was observed that there could be more increased percentage (correlation coefficient) of about 2.3% (Dc=5%), 3.15% (Dc=10%), and 0.87% (Dc=20%) rebound hammer number and compressive strength data values for in case of tension side was correlated as when compared to that of compression side of the beam with different degree of corrosion in turn this may be due to uniform compactness of concrete at tension side.

The Ultrasonic pulse velocity test involves measuring the velocity of sound through concrete for strength determination. Since, concrete is a multi-phase material, speed of sound in concrete depends on the relative concentration of its constituent materials, degree of compacting, moisture content, and the amount of discontinuities present. This technique is applied for measurements of composition (e.g. monitor the mixing materials during construction, to estimate the depth of damage caused by fire), strength estimation, homogeneity, elastic modulus and age, & to check presence of defects, crack depth and thickness measurement. Generally, high pulse velocity readings in concrete are indicative of concrete of good quality. Also in the present study Ultrasonic pulse velocity test was carried out both at compression side as well as tension side of the beam before and after the corrosion damage inducement in the beam with different degree of corrosion (5%, 10%). The variations of Compressive strength versus Ultrasonic pulse velocity for compression side as well as tension side of beam with different degree of corrosion such as 5%, 10%, are plotted as shown in (Fig.6a, Fig.6b,) and(Fig.6c, Fig.6d,).

As observed an experimental calibration equation for the Ultrasonic pulse velocity test that derived from this research at the compression side of the beam was y = 34.38x-118.40, R^2 = 0.821, Dc = 5%; y = 42.74x-152.30, R^2 = 0.717, Dc =15%; and y = 36.99x-129.50, R^2 = 0.671, Dc = 20% and also as observed from (Fig.6d-6f) that, an experimental calibration equation for the Ultrasonic pulse velocity test that derived from this research at the tension side of the beam was y = 43.006x-152.10, R^2 = 0.83, Dc = 5%; y = 33.43x-113.60, R^2 =

0.791, Dc =15%; and y = 19.18x-51.87, R^2 = 0.72, Dc = 20%, where y = compressive strength (N/mm^2), x = ultrasonic pulse velocity (Km/sec), and R^2 = coefficient of correlation. As observed from (Fig.6a-6b) that, the Ultrasonic pulse velocity value was varied on compression side of the beam in the range of 4.1-4.5 (Dc = 5%), 4-4.45 (Dc =15%), and 3.9-4.3 (Dc = 20%) which in turn indicates the quality of concrete varied from good but may be porous to very good. As observed from (Fig.6c-6d) that, the Ultrasonic pulse velocity was varied on tension side of the beam in the range of 4.2-4.6 (Dc = 5%), 4.15-4.55 (Dc =15%), and 4-4.4 (Dc = 20%) which in turn indicates the quality of concrete varied from good but may be porous layer to very good. There could be 82.1% compressive strength and ultrasonic pulse velocity data values at compression side of the beam was correlated for in case of (Dc=5%) as when compared to that of 71.7% (Dc=15%) and 67.1% (Dc=20%). There could be 83% (correlation coefficient) of compressive strength and ultrasonic pulse velocity data values at tension side of the beam was correlated for in case of (Dc=5%) as when compared to that of 79.1% (Dc=15%) and 72% (Dc=20%). Finally it was observed that there could be more increased convergence of correlation coefficient of about 1.08% (Dc=5%), 9.35% (Dc=15%), and 6.8% (Dc=20%) in compressive strength and ultrasonic pulse velocity data values for in case of tension side was correlated as when compared to that of compression side of the beam. This variation in coefficient of correlation (ultrasonic and compressive strength data values) may be due to certain difficulties which are encountered by concrete when some of the established methods used in other areas of material testing are applied to concrete testing and in fact concrete is an in homogenous as well as porous building material.

6. CONCLUSION

Thus the NDT can play an important role in ensuring quality of any structural concrete material, reliably and safely, minimize cost and avoid the loss of human life. From this study it can be concluded that:

- It was confirmed from Half-cell potential test that, the probability of statistical risk of corrosion was around 40-50%, 50-75% for in case of different degree of corrosion (Dc=5%, 10%). Actually Half-cell potential mapping is the simplest technique. Although it's the most widely used, it does not give any indication of the extent or intensity of corrosion in turn it confirms the probability of statistical risk of corrosion for a specified degree of corrosion.

- It was confirmed from the Rebound hammer test that performed at the compression and tension side of the beam depicts 85%, 83%,(coefficient of correlation convergence) rebound hammer number as well as compressive strength data was correlated on compression side as well as 87%, 85.7%, on tension side of the beam for different degree of corrosion (Dc=5%, 10%).

- It was confirmed from the Ultrasonic pulse velocity test that performed at the compression and tension side of the beam depicts 82.10%, 71.70%, (coefficient of correlation convergence) Ultrasonic pulse velocity as well as compressive strength data was correlated on compression side as well as 83%, 79.10% on tension side of the beam for different degree of corrosion (Dc=5%, 10%).

- It was inferred from test result that Rebound hammer number as well as Ultrasonic pulse velocity and compressive strength data values was vary (coefficient of correlation convergence) extensively both in compression and tension side of the beam for in case of lower degree of corrosion (Dc=5%) as when compared to higher degree of corrosion (Dc=10%). This variation (coefficient of correlation convergence) depends on degree of corrosion and test result in turn which are affected by test surface smoothness, size, shape, and rigidity of the specimen, age of specimen, surface and internal moisture conditions of concrete, coarse aggregate type, cement type.

- The Linear regression analysis is the best fit for the compressive strength prediction relationship by using Rebound hammer and Ultrasonic pulse velocity test at compression as well as tension side of reinforced concrete beam with different degree of corrosion (5%, 10%).

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