Structural Health Monitoring of Concrete Buildings using Non-Destructive Tests and Durability Tests

Basit Mushtaq[1], Deepika Sharma[2]

[1]M.TECH, Dept. of Civil Engineering, Guru Nanak Dev Engineering College, Ludhiana-141006, Punjab, India
[1]M.TECH, Dept. of Civil Engineering, Guru Nanak Dev Engineering College, Ludhiana-141006, Punjab, India

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Abstract-*This study aimed at monitoring the quality of and durability of concrete using* ***non-destructive tes****ts and durability tests like* ***carbonation, chloride penetration test*** *etc. Non-destructive tests performed include* ***Rebound hammer test and ultrasonic pulse velocity test.*** *Tests were carried on old and under construction concrete buildings of* ***SRM University located at Modinagar, Ghaziabad, Delhi NCR.*** *Concrete samples obtained from under construction buildings of said location and were cured in salt and normal water separately. Comparison of compressive strength development was done for both cases at 7, 14 and 28 days. The results of this study showed the importance of structure health monitoring in present times. Quality of concrete in various old portions of buildings was not adequate and proper rehabilitation was required to make it safe from any untoward incident.*

1. INTRODUCTION

The structural safety after construction of structure is very important factor in today's world. Due to increased corrosive and harsh environmental conditions there has been an adverse effect over the quality of concrete structures. Therefore regular assessment of quality of concrete structures is must. Since most of tests performed on concrete are destructive tests that could not be performed over the actual concrete structures. Hence non-destructive tests are used in such cases for structural health monitoring. These tests do not directly gives us the results regarding quality of concrete but their results could be used to establish an idea regarding the quality of concrete. A numerous number of non-destructive test are available for different kind of materials.

1.1 Structural Health Monitoring

Structural health monitoring has been widely used by engineers, inspectors, surveyors etc. for gathering data of structures and structural elements for quality assessment, research work and analysis work. Various techniques are used in structural health monitoring for obtaining required data. It is not possible to perform monitoring of a huge structure with one kind of technique, hence various monitoring techniques are used in combination with each other as per need of the structure.

1.2 Structural Health Monitoring using Non-Destructive Testing

The quality of concrete depends on the type of aggregates, proper proportioning of mix design, type of cement, water cement ratio, type of curing and other environment conditions. But the present system of checking the quality of concrete by performing various tests on cubes are not enough for estimating the actual strength of structure. Therefore testing on concrete used in actual structures is mandatory which could not be by the same tests as in case of concrete cubes. Therefore Non-Destructive testing of structure plays an important role in Structural Health Monitoring of concrete structures. These tests are relatively quick, easy to perform and less time consuming.

2. Experimental investigation

2.1. Materials

2.1.1 Cement
OPC 43 Grade cement confirming as per IS 8112:2013 was used for casting of concrete samples.

Table 1-Properties of cement

S. No	Description	Values Obtained	Codal Provisions
1	Specific Gravity	3.14	3.0-3.5
2	Fineness	2.01	-
3	Consistency	33%	-
4	Initial Setting Time	30 min	30 min
5	Final Setting Time	10 Hours	10 Hours

2.1.2 Fine Aggregates
Fine aggregate used in this research was natural river sand confined to IS: 383-2016. The sand was supplied by a local building material dealer.
The various physical properties of sand are mentioned in Table-2

Table 2-Properties of fine aggregate

S. No	Description	Values Obtained	Codal Provisions
1	Specific Gravity	2.63	2.5-3.0
2	Water absorption	1%	< 3%
3	Sand Zone	IV	I-IV

Table 3-Sieve analysis of fine aggregate

IS Sieve Size	Retained	% Ret	Cum % ret	% Passed
10mm	0 gm	0 %	0 %	100 %
4.75mm	12 gm	1.2 %	1.2 %	98.8 %
2.36mm	8 gm	0.8 %	2 %	98 %
1.18mm	6 gm	0.6 %	2.6 %	97.4 %
600µ	5 gm	0.5 %	3.1 %	96.9 %
300µ	810 gm	81 %	84.1 %	15.9 %
150µ	100 gm	10 %	94.1 %	5.9 %
PAN	59 gm	5.9 %	100 %	0 %
Sum	1000 gm	100 %	187.1	

Based on results obtained from sieve analysis fine aggregate is conforming to Zone IV of IS 383-1970.

2.1.3 Coarse Aggregates

The coarse aggregates used in this work were crushed stones supplied by a local building material dealer. The various properties of coarse aggregate are mentioned in Table-4

Table 4-Properties of coarse aggregate

S. No	Description	Values Obtained	Codal Provisions
1	Specific Gravity	2.84	2.5-3.0
2	Water absorption	0.8%	< 3%
3	Maximum size	20 mm	4.75-20 mm

The sieve analysis date of coarse aggregate in mentioned in Table-4. The coarse aggregate was conforming to 20mm graded as IS 383-2016.

Table 5-Sieve analysis of fine aggregate

Sieve Size	Weight Retained (g)	Cum. Retained (g)	% Retained	% Passing
40 mm	0	0	0	100
20 mm	23	23	2.3	97.7
16 mm	150	173	17.3	82.7
12.5 mm	410	583	58.3	41.7
10 mm	125	708	70.8	29.2
4.75 mm	215	923	92.3	7.7
Pan	77	1000	100	0

2.2. Mix Proportions

Concrete mix proportioning or mix design is a process of determining the ratio in which cement, fine aggregate and coarse aggregate are mixed together along with a definite water cement ratio for obtaining a concrete of desired strength. M20 grade of concrete was designed using (BIS:10262, 2009). Ratio of the concrete mix design are given in Table-6

Table 6- Concrete mix design

Water cement ratio	Cement	Fine Aggregate	Coarse Aggregate
0.45	1	1.3	2.84

For comparison 50% of samples casted were cured in normal water while remaining samples were cured in salt water. Sodium chloride (NaCl) was added to normal water for creating salty curing environment.

2.3. Test Methods

2.3.1 Rebound Hammer Test

In this test a simple equipment called rebound hammer is used to estimate the compressive strength of concrete. It is also called as Schmidt hammer. This devise gives an idea about compressive strength of concrete, uniformity of concrete and hence quality of concrete. The rebound hammer test was performed on columns and beams of different concrete structures as well as concrete cubes of (150*150*150) mm casted at the time of construction and cured under different conditions. Rebound hammer works on the basis of rebound impact energy depending upon the hardness of surface. The output reading obtained is called rebound number that is used to predict the compressive strength of concrete using rebound hammer graph. It is a graph between compressive strength of x-axis vs rebound number on y-axis.

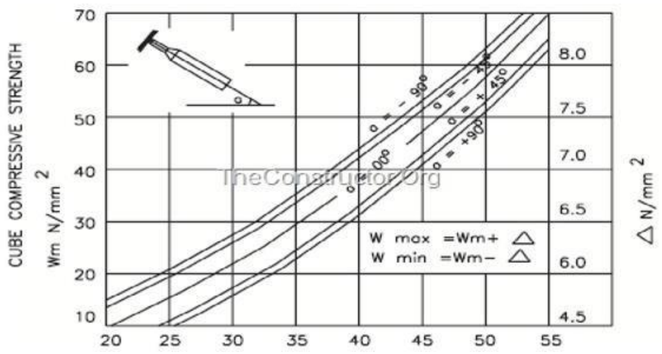

Figure 1- Rebound hammer graph

Picture 1- Rebound Hammer

2.3.2. Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity test is also and indirect method of predicting quality of concrete. Instrument used is a very light and compact device, battery operated and easy to carry. This device consists of electrical pulse generator, Transducer, Amplifier and calibrating rod.

This test is used to predict homogeneity of concrete, presence of cracks, voids, change in density etc. This test was performed on different elements of concrete structures under study and casted concrete samples

Picture 2- Ultrasonic pulse velocity device

of (150*150*150) mm. Samples cured in normal water as well as water mixed sodium chloride were tested.

This test gives the time taken by ultrasonic wave to travel from one surface to opposite surface. Hence velocity of wave could be calculated. The velocity gives an idea regarding the quality of concrete.

Table 7-Relation of Pulse velocity with quality of concrete

PULSE VELOCITY (KM/SEC.)	QUALITY OF CONCRETE
0-2.0	Poor
2.0-2.5	Doubtful
2.5-3.0	Medium
3.0-4.0	Good

2.3.3. Carbonation Test

Durabilty of concrete is very important for quality monitoring of concrete. The durability of concrete is significantly affected by the various environmnetal conditions that are not suitable for concrete. Carbonation of concrete is one such phenomenon in which hydrated products of concrete react with pore water and atmospheric carbon dioxide to reduce the pH value of concrete thus making it acidic which is harmful for concrete as well as reinforcment of concrete.

Concrete samples of size (100*100*100) mm were casted and cured for 28 days. After that samples were air dried and covered with parrifin wax and put inside an accelerated carbonation chamber. The carbonation chamber with a carbon dioxide,concentration at (4.0 ± 0.5),% by volume and temperature should be in range of (30±2)°C and relative humidity,should be (55 ± 5),% as specified in BS-ISO 1920 part 12. After 28 days concrete samples were spilt half into two and carbonation depth on all four sides was measured.

2.3.4. Chloride penetration Test

Concrete structure gets exposed to chloride ions present in the environment. These chloride ions affect the quality of concrete over the course of time. Chloride ion penetration is a slow process hence to test the concrete for chloride ion penetration in short period of time a setup using NT BUILD 492 was prepared in laboratory. Cylindrical Samples of diameter 100 mm and height 50 mm were casted for this test. This tube is placed in the glass container that is filled with the catholyte solution and at the other end of the tube anolyte solution is filled. The catholyte solution is prepared by using 10% Sodium chloride (NaCl) by mass in of water of about 2N. The anolyte solution is prepared by dissolving 0.3N Sodium hydroxide (NaOH) in distilled water. A 30V D.C power was supplied used and anode is placed in anolyte solution and cathode is placed in catholyte solution. Anode is connected to the positive pole and cathode to the negative pole of the power supply. The samples were connected to power supply for duration of 24 hours as given in the NT BUILD 492.

After 24 hours sample was air dried for two hours and then vertically cut into two pieces. The chloride ion penetration was evaluated by using 0.1 N Silver Nitrate solution.

3. RESULTS AND DISCUSSION

3.1. Rebound Hammer Test

Results of the rebound hammer test performed on different floors of the concrete building have been mentioned in tabular form.

Table 8- Rebound hammer test Building-I

C No.	Reading						R No.	Compressive Strength(N/mm²)	Quality
	1	2	3	4	5	6			
C1	20	30	35	34	32	33	30	24	Fair
C2	28	31	27	30	35	28	30	24	Fair
C4	29	31	35	30	28	32	31	25	Good
C5	28	28	36	35	34	30	32	26	Good
C6	25	34	28	31	28	32	31	25	Good
C7	31	29	32	26	33	34	31	25	Good
C12	29	30	35	27	36	32	31	25	Good
C13	20	38	32	28	32	34	30	24	Fair
C14	50	35	20	32	29	27	32	26	Good
C15	38	30	29	30	35	30	32	26	Good
B1	30	39	32	25	25	30	30	24	Fair
B2	35	29	31	32	36	29	32	26	Good

Table 9- Rebound hammer test Building-II

C No.	Reading						R No.	Compressive Strength(N/mm²)	Quality
	1	2	3	4	5	6			
C6	33	31	25	39	35	25	31	25	Good
C7	31	36	25	32	30	26	30	24	Fair
C8	25	32	25	32	33	28	30	24	Fair
C5	33	31	33	27	33	30	32	26	Good
A8	33	31	29	31	33	29	30	24	Fair
A9	30	35	29	36	30	28	31	25	Good

Table 10-Rebound hammer test Building-III

C No.	Reading						R No.	Compressive Strength(N/mm²)	Quality
	1	2	3	4	5	6			
C6	35	33	30	35	32	33	33	28	Good
C7	35	30	38	35	30	35	34	30	Good
C8	30	30	39	30	38	30	32	26	Good
C9	30	30	30	35	38	38	33	28	Good
C5	33	35	32	30	38	32	33	28	Good
C3	31	34	33	35	38	34	34	30	Good
C2	39	32	32	35	31	35	34	30	Good

Results of Rebound hammer test performed on concrete cubes after age of 28 days have been listed below.

Table 11- Rebound hammer test of cubical sample

S No.	Rebound No.
1	30
2	35
3	29
4	36
5	30
6	28
7	31
8	29
Mean	31

Table 12-Comparison between actual and predicted compressive strength

Compressive Strength N/mm² (Predicted)	24
Compressive Strength N/mm² (Actual)	29
Variation	17%

The results obtained from the rebound hammer test of buildings was satisfactory as the concrete was of M25 grade and results from rebound hammer test were matching expected values.

Results of the concrete samples showed there is an average variation of 10%-20% between results of rebound hammer and actual tests done on Compression testing machine.

3.2. Ultrasonic Pulse Velocity Test

Results of the UPV tests have been tabulated below.

Table 13-UPV test building-I

C No.	Distance (meters)	Average Velocity (km/s)	Quality
C4	0.38	2.178	DOUBTFUL
C10	0.38	2.134	DOUBTFUL
C11	0.38	2.146	DOUBTFUL
C12	0.38	2.452	DOUBTFUL
C13	0.38	2.172	DOUBTFUL
C14	0.38	2.105	DOUBTFUL
B1	0.38	2.165	DOUBTFUL
C6	0.17	2.283	DOUBTFUL
C7	0.17	2.440	DOUBTFUL
C5	0.17	2.327	DOUBTFUL

Table 14-UPV test building-II

C No.	Distance (meters)	Average Velocity (km/s)	Quality
C8	0.381	2.135	DOUBTFUL
C7	0.381	2.167	DOUBTFUL
C6	0.381	2.196	DOUBTFUL
C3	0.381	2.212	DOUBTFUL
C5	0.178	2.397	DOUBTFUL
C13	0.178	2.410	DOUBTFUL
C12	0.178	2.373	DOUBTFUL
C11	0.178	2.460	DOUBTFUL
C10	0.178	2.397	DOUBTFUL
C9	0.178	2.362	DOUBTFUL

Table 15-UPV test building-III

C No.	Distance (meters)	Average Velocity (km/s)	Quality
C8	0.38	2.178	DOUBTFUL
C7	0.38	2.247	DOUBTFUL
C6	0.38	2.172	DOUBTFUL
C3	0.38	2.190	DOUBTFUL
C5	0.17	2.476	DOUBTFUL
C9	0.17	2.460	DOUBTFUL
C11	0.17	2.476	DOUBTFUL
C12	0.17	2.426	DOUBTFUL
A8	0.17	2.515	MEDIUM
A9	0.17	2.411	DOUBTFUL

3.3. Carbonation Test

Samples of concrete were taken from the building using core cutter machine. Concrete cubes were also casted using the same materials used in construction of buildings. After proper curing of these samples, they were exposed to carbonation in an accelerated carbonation chamber for 28 days. After completion of 28 days, samples were taken out and broken into two pieces. The cut pieces of these samples were cleaned to make them dust free and to measure the carbonation depth. The phenolphthalein solution (1% phenolphthalein in 70% ethyl alcohol) was sprayed on the cut samples and were left for 1 hour ± 15 minutes. Then two regions were found on the surface of samples, the purple red zone showed the non-carbonated zone and colorless region indicated the carbonated zone. The Vernier caliper was used with accuracy of 0.05 mm to measure the carbonation depth.

Table 16- Carbonation test results

S No.	Sample	Carbonation depth (mm)	Average Carbonation depth (mm)
1	1	14.4	13.86
	2	13.4	
	3	13.8	

The results revealed that carbonation depth of samples was within expected values and hence durability and quality of concrete were predicted as satisfactory based results of carbonation test.

3.4. Chloride Penetration Test Results

As discussed earlier a NT BUILD 492 setup was prepared and samples were kept in the setup for 24 hours after connecting the power supply. After 24 hours samples were taken out and split into two halves vertically. The inner surfaces of the sample were treated with 0.1 N silver nitrate solution. The penetrated free chloride ions bind with the silver and form AgCl, changing the colour of region to white.

The depth of the region showed the depth of chloride ion penetration which was measured with the help of Vernier caliper. The measurement is done at six different points of the region and the average will be reported as the chloride penetration depth in the respective sample. The results obtained from the Chloride penetration test were satisfactory.

Table 17- Chloride ion penetration test results

S No.	Sample	Chloride penetration depth (mm)	Average Carbonation depth (mm)
1	1	5.6	5.86
	2	6.2	
	3	5.8	

3.5. Effect of salt water curing on test results

The surface of the cubes cured in salt water were darker when compared to cubes cured in normal water.

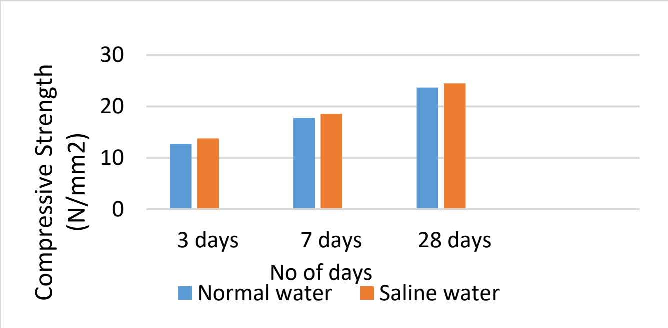

Figure 2-Compressive strength comparison

The results of laboratory tests indicated that NaCl solutions have compressive strength accelerating properties at early stages but that cannot be sustained over a long period of time. Further presence of chloride in Reinforced concrete induced corrosion of concrete which leads to development of cracks and deterioration of concrete. In many parts of world, reinforced concrete structure deteriorates seriously due chloride attack. A primary feature of chloride attack which distinguishes it from other mechanisms of deterioration of reinforced concrete is that the primary action of chlorides is to cause corrosion of steel reinforcement, and as a consequence of this corrosion surrounding concrete is also damaged.

UPV results of cubes cured in saline water are better in initial days as salt occupies the voids of the concrete hence increasing the density of concrete but after passage of time crystallization of salts take place and cracks are developed so the velocity is decreased.

A graph plotted for cubes cured and salt water and normal between compressive strength and pulse velocity gives two distinct curves in which properties of salt water cured cubes in higher than normal ones. But the curve of salt water cured cubes in slightly inclined towards curve of cubes cured with normal water showing the decline in properties of salt water cured cubes with passage of time.

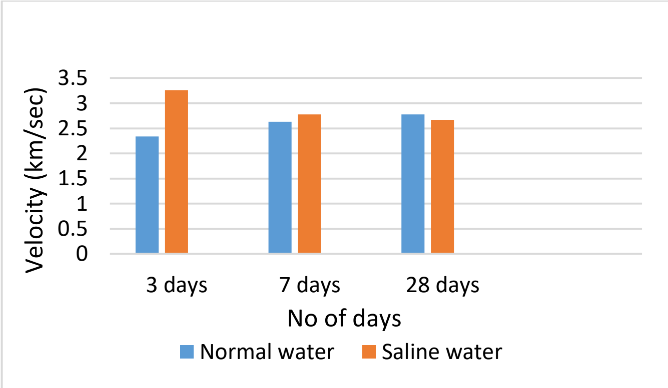

Figure 3-Variation of UPV

Based on this study, it appears that using more than one non-destructive technique provides a better correlation and in this sense contributes to more reliable strength evaluation of concrete. The combined method seems more promising in evaluating the compressive strength and durability of concrete in construction. NDT when used in combination with other durability tests provide a better idea to establish or predict the quality of concrete. In general, the combined method appears more appropriate to conditions on site measurements, very convenient, fast and with a reasonable cost. Once the relations are established between the values obtained from mechanical tests and measurements from non-destructive techniques (the rebound hammer and ultrasonic pulse velocity) the prediction of concrete strength and durability aspects appear more reliable.

The practical use of this technique is gaining pace and popularity on a large scale. It provides authorities with accurate and reliable information for monitoring quality-control of concrete structures.

3. Conclusions

Considerable engineering judgment is needed to properly evaluate the quality of concrete structure. Misinterpretation of results is possible if the data is not studied carefully and a through literature survey has been done prior to testing or carrying other this research work. However using conventional destructive and durability test along with non-destructive testing can help to predict the quality more accurately with ease.
After performing different types of non-destructive and durability tests on concrete buildings and various concrete samples the following conclusion could be observed:

- Rebound hammer alone cannot give us the accurate compressive strength of the concrete as there is a variation of 10 %-20 % in the results of rebound hammer when compared to actual results as shown by calibration tests. Although the compressive strength of the building was found to be satisfactory.

- UPV tests of the buildings showed us the quality of concrete is doubtful in lower floors where concrete was hand mixed and in upper floors quality was slightly better because the concrete was machine mixed and there was less possibility of voids and any other type of non-uniformity.
- Carbonation test showed us that the outer layers of concrete samples were carbonated and there is strong possibility of corrosion if reinforcement was present. Although the values of carbonation depth were within expected limits.
- Chloride ion penetration results showed the importance of cover in case of reinforced structure. Due to penetration of chloride ions into the concrete surface, the under laying reinforcement could be damaged due to corrosion, affect the durability of concrete.
- The compressive strength and UPV test comparison done between samples cured in normal water and saline water showed although the early age compressive strength and UPV results of cubes cured in saline water were more desirable than cubes cured in saline water but over the period of time this trend was revered. Early age properties were enhanced due to salts occupying the voids of concrete and increasing density and conductivity of concrete. But later due to crystallization of salts cracks are developed in the concrete. Also presence of chloride ions in the concrete accelerated corrosion activity decreasing the quality of concrete.

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