Chapter

Structural Health Monitoring of Existing Reinforced Cement Concrete Buildings and Bridge Using Nondestructive Evaluation with Repair Methodology

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Abstract

Sustainable development means the utilization of resources at a rate less than the rate at which they are renewing. In India infrastructure industry is growing rapidly due to globalization and raising awareness. In the present study, challenges faced by countries like India are to sustain the existing expectations with limited resources available. Reinforced Concrete (RC) structure may suffer several types of defects that may jeopardize their service life. This chapter deals with condition assessment and repair of RCC (G+3) building situated at Northern part of the country. There are various techniques available for repair and rehabilitation of reinforced concrete structures. From a maintenance point of view, it is essential to take up the strength assessment of an existing structure. So, to find out the reason behind the deterioration of the concrete structures some of the NDT and partially destructive technique are used. The NDT tests conducted during this study are Rebound Hammer, Ultra-sonic Pulse Velocity, Concrete resistivity Meter, Ferro-scanning and Carbonation, etc. This chapter helps to explains, how identified the different parameters of distress building like strength, density, level of corrosion and amount of reinforcement. On basis of these results, apply a repair methodology to revert back the strength parameters of the buildings.

Keywords: visual inspection, nondestructive testing, repair, rehabilitation, bridges

1. Introduction

The major requirements in structures are to resist the deterioration due to aging. The repairing of the structures is very expensive [1]. In order to prevent the structure from deterioration, it is important to do a routine assessment of structures without damaging the internal part of the structure. The most common sort properties of concrete are its compressive strength, homogeneity of concrete along with corrosion probability [2]. This mentoring is only possible with nondestructive methods. The nondestructive test (NDT) methods are very useful in carrying out the in-situ condition of reinforced concrete (RCC) structures along with parameters causing deterioration of RCC structures [3]. In the present study, a case is carried out to access the levels of deterioration in an RCC structure located in northern India. Monitoring was carried out through detailed visual inspection along with NDT techniques to assess the deterioration for further planning of repair and rehabilitation. Many researchers have used nondestructive methods such as Rebound hammer and ultrasonic pulse velocity (UPV) to monitor the extent of deterioration in RCC structures [4]. The present pH value of concrete is determined with the help of phenolphthalein indicator and corrosion analyzed with corrosion analyzer [5]. There is a lot of demand for repair of damaged buildings and rehabilitation of existing concrete structures. The common structural defects are cracks, spalling, corrosion, leakage, chloride and sulfate attack, carbonation, etc. [1]. If such defects are not solved at their initial stages, it will lead to serious damages to the structures [6].

NDT techniques such as Rebound Hammer, UPV, Carbonation Test, Rebar Locator Test, and Impact Echo Test from a practical standpoint with an experienced Structural Engineer along with some partial-destructive testing methods are sufficient to access the quality and strength of in-situ concrete [3]. The NDT methods indirectly estimate the quality and strength of RCC structures, and the estimated results can be compared with destructive test results. The author suggested performing more than one test for better and accurate results [7]. The maintenance and utilization of new techniques/materials for repair/restoration of the buildings/structures are needed, for long-term sustainable development, especially, in developing country such as India. The author has discussed the various causes of deterioration and the methods for the repair, rehabilitation, and retrofitting [8]. The author also explained various materials and techniques for the repair, rehabilitation, and retrofitting and also the methodologies for the same [9]. The existing RCC buildings in Gujarat are located on the boundary of Gujarat–Maharashtra such as Nasik, Dhule, and Nandoorbar. In this study, the author has taken the case of a health building in the heart of the Nasik city. Based on the physical and experimental investigations, it was concluded that the structure either should be demolished or at least should be rehabilitated/retrofitted with appropriate method to enhance the service life of the building [10]. The RCC columns were strengthened by jacketing technique as this technique was more feasible and easy to execute at the site [11, 12]. All the columns on both the floors are now properly strengthened by jacketing, the concrete from the faulty slabs were completely removed, and the corroded reinforcement was changed with new reinforcement bars as per the design. And the slabs were recasted with M25 grade of ready-mix concrete [13]. In addition, selected tests and feasible techniques as per the latest advances in the industry to be used for health assessment, retrofitting, and rehabilitation are presented in depth with example and calculations [14, 15]. The objectives of the study are to suggest a model for a systematic approach for the repair of RCC structures. From the literature review, it is clear that RCC building undergoes deterioration and subsequent failure due to many reasons. It is, therefore, proposed to undertake a study on RCC framed buildings so as to suggest a proper methodology [16]. The building under consideration has been assessed for the causes of deterioration and for the repair, rehabilitation/strengthening work based on an investigation in order to suggest a suitable model for the rehabilitation of RCC buildings [17]. The outline of this chapter includes determination of building parameters such as strength, covercrete, density, level of corrosion, amount of reinforcement, pH value of concrete, and its carbonation depth.

The repair methodology for different structural members, deterioration types of concrete bridges, testing methods are needed.

3D printing concrete and digital fabricated techniques are on the high peak. The structural modeling of the 3D printing concrete is based on number of time-dependent mechanical properties, which include Young's modulus and compressive strength. These properties should be checked using destructive test methods is a time-consuming process. To avoid that, UPV waves were used to identified the density, strength, and Young's modulus of the concrete. Some of the tests in this chapter might be useful for this type of practices in the future [18].

RCC building located at the northern part of the India was selected to carry out the investigation. The building was around 32–35 years old. Detailed visual inspection was carried out to scrutinize the type, extent, and source for damage. An investigation was carried out to check the concrete quality, corrosion in reinforcing bars, carbonation of concrete, and ingress of salts in concrete. The concrete quality was found out by using UPV and hammer rebound method. The detailed investigation plan is shown in **Figure 1**.

2. Visual investigation

a. From the investigation, it was observed that the exterior columns of the building were having vertical cracks and spalling at some of the locations.

b. Dampness and efflorescence on walls were also observed, especially at the lower level of the building.

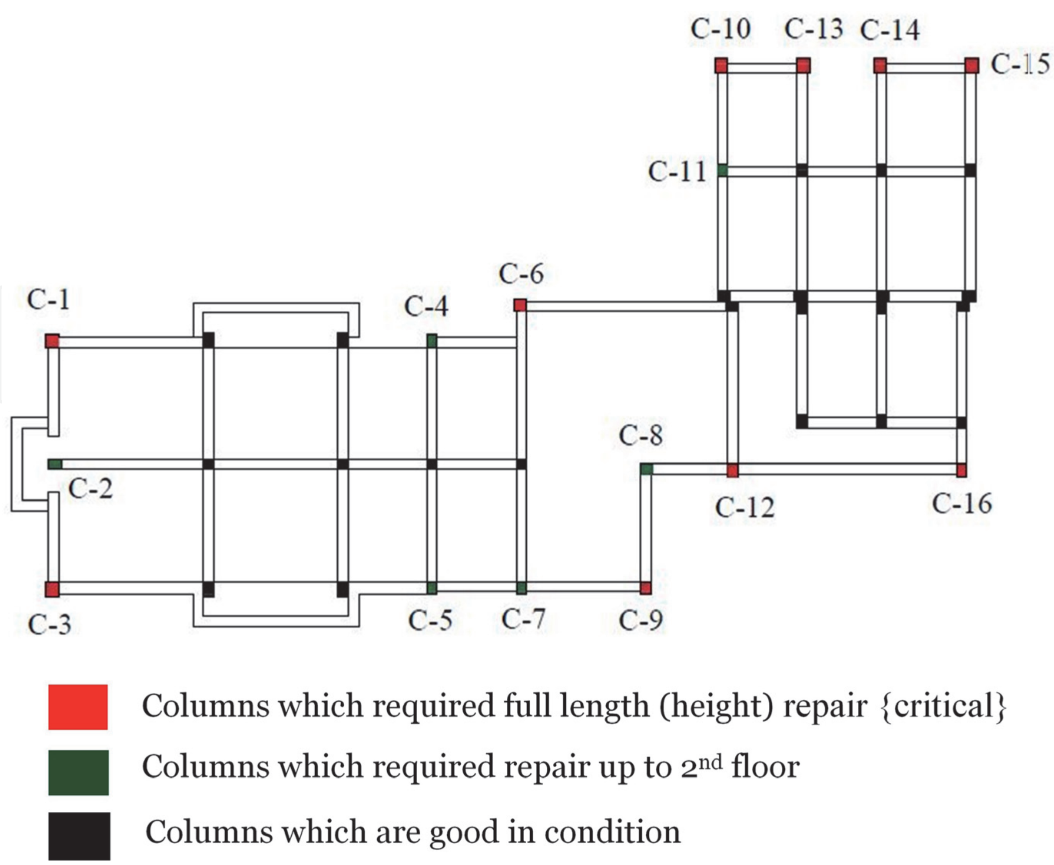


Figure 1.
Plan of the investigated building (not to scale).

c. Some minor cracks along the openings of the windows and doors were present.

d. Damaged staircase of servant quarter entrance from the backyard of the building was present.

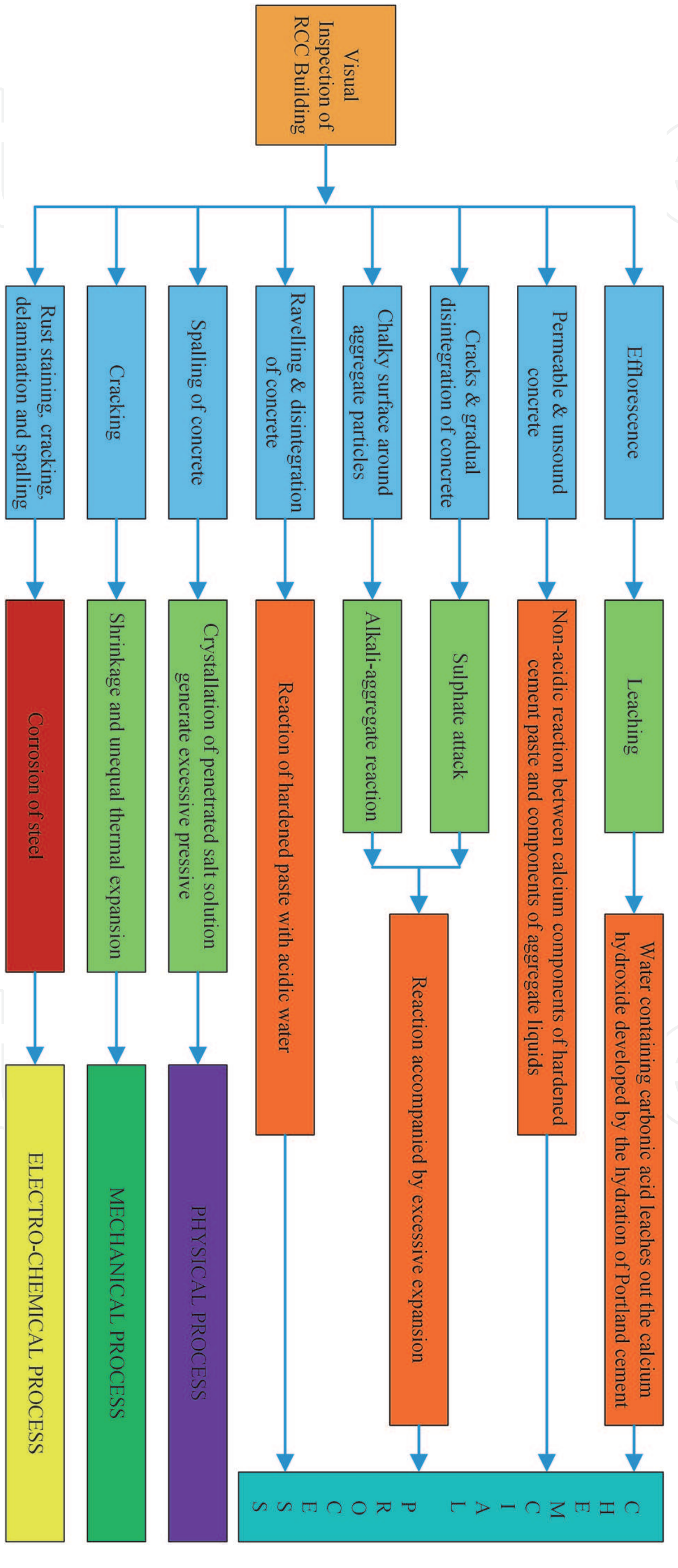


Figure 2.
Flow chart of visual inspection.

(a) (b) (c) (d)

Figure 3.
Damage detection (a) spalling of concrete, (b) vertical crakes on column surface, (c) cracks in the bottom of column, (d) corrosion in steel.

e. Spalling of concrete and exposed corroded reinforcement in exterior columns of both the buildings.

f. Ground floor and the first floor of the building were attacked by termite.

g. Backside staircase along with the servant quarter of the building was completely damaged.

h. Brick tiles on the terrace of the building were damaged due to ingress of moisture through them.

i. Due to growth of plants on the terrace of the building and the rainwater pipes, there were damages.

The visual inspection checks found the presence of efflorescence, permeable, and unsound concrete, cracks, and gradual disintegration of concrete, spalling of concrete and cracking, etc. The flow chart of the visual inspection is shown in **Figure 2** [19–25]. Different types of distresses such as cracks, spalling, and corrosion in the building are shown in **Figure 3**.

3. Nondestructive evaluation

A number of nondestructive and partially destructive techniques for the assessment of the concrete structure are available to predict the cause of deterioration of the existing structure. These NDT techniques can be broadly classified into five groups such as strength tests, durability tests, performance tests, integrity tests, and chemical tests [2]. With the help of these tests, we can find out in-situ strength/quality of the concrete to precisely identify the damage and causes of the deterioration of the structure. Some of the most commonly used NDTs are discussed [21].

3.1 Rebound hammer (Schmidt hammer test)

This is the fastest method to evaluate the quality of concrete based on hardness, which is indicated by rebound number. If the strength of concrete is high, the rebound number is also high. The principle of this test is that when the plunger of the rebound hammer is pressed against the surface of the concrete, the spring controlled the mass rebounds and the extent of such rebound depends upon the surface hardness of the concrete. The surface hardness of the concrete gives the rebound number, which is further related to the compressive strength of the concrete. In latest rebound hammer, there is no need for angle correction. The average

Instrument	Average rebound number	Quality of concrete
Schmidt Hammer N- type	>40	Very good hard layer
	30–40	Good layer
	20–30	Fair
	<20	Poor concrete
	0	Delaminated

Table 1.
Rebound number with respect to quality of concrete.

Figure 4.
Rebound hammer.

value of rebound hammer for a different quality of concrete as per Indian Standard IS: 13311 Part-21992 is given in **Table 1** (**Figure 4**) [26].

3.2 Ultrasonic pulse velocity (UPV)

UPV Test method is generally used for determination of uniformity of concrete, to find crack depth, honeycombing, and to check the condition assessment of deterioration of concrete. The principle of this test is based on the propagation of electroacoustic pulse through the concrete pathway and then calculating the transit time taken, for a known distance. UPV mainly depends on the elastic modulus of the concrete. The general guidelines for quality of concrete as per Indian Standard IS: 13311 Part-11992 are given in **Table 2** (**Figure 5**) [27].

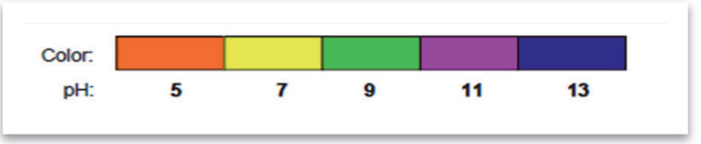
3.3 Concrete carbonation

Concrete has micropores, and these pores are filled with liquid, having pH values up to 12.5. Thus, the concrete is alkaline in nature. Carbonation of the concrete is the reaction of $Ca(OH)_2$ with the atmospheric CO_2 and its conversion into $CaCO_3$. This reaction decreases the pH value of the pore water up to 8.5. As time passes, the outer zone of concrete is affected first, and carbonation proceeds deeper into the mass as CO_2 diffuses inward from the surface. If the carbonation depth reached the depth of steel in concrete, then the steel is prone to corrosion damage. By carbonation test, we can measure the carbonation depth of the concrete. In order to determine the path of the carbonation, drilling a hole is done in stages and the phenolphthalein solution spread over it after every stage. As soon as the color of the concrete becomes pink, we stop the drilling process and the depth of the hole is measured (**Figure 6**) [28].

Sr. No.	Velocity (km/sec)	Concrete quality
1	>4.5	Excellent
2	4.0–4.5	Very good
3	3.5–4.0	Good to very good, slightly porosity may exist
4	3.0–3.5	Satisfactory but loss of integrity is suspected
5	<3.0	Poor and loss of integrity exists

Table 2.
General guidelines for concrete quality based on UPV.

Figure 5.
UPV.



(a)

(b)

Figure 6.
Concrete carbonation: (a) pH scale for concrete carbonation. (b) Rainbow indicator.

3.4 Reinforcement scanning test

Ferro scanner is a device used to locate reinforcing bars and to estimate the diameter and depth of cover. This device is based on interactions between the bars and low-frequency electromagnetic fields. The ferro scanner works on the principle of electromagnetic induction, in which alternating magnetic field induces an electrical potential in an electrical circle intersected by the field. The test for reinforcement scanning is done with the help of HILTI PS 200 Ferro scan [29], a portable system for detecting rebar in concrete structures. The tools help in obtaining a real image of the reinforcement and evaluate the reinforcement mesh. HILTI PS 200 Ferro scan records the depth and positions of rebars over long stretches and obtains average coverage and statistics of the rebar diameter. The tools consist of image scanner that records the data, then the recorded data is transferred to the monitor for further analysis at the site itself. The major analysis is done on the computer by the analysis software to produce reports of the recorded data, and later the data is further submitted to the structural consultant for preparation of structural drawing, thereby ensuring the stability of the structure. The major limitations of this test are that the interferences may occur in images due to scraps of reinforcement in concrete, tie wires near rebars cross, and aggregates with ferromagnetic properties (**Figure 7**).

3.5 Concrete resistivity test

Surface resistivity meter provides very useful information about the surface of the concrete. It does not only provide corrosion information but also provides the corelation between the resistivity and chloride diffusion rate [30].

The operating principle of the Wenner probe, the Resipod, is designed to measure the electrical resistivity of concrete or rock. A current is applied to two outer

Figure 7.
Ferro-scanner.

probes, and the potential difference is measured between the two inner probes. The current is carried by ions in the pore liquid. The resistivity depends upon the spacing of the probes. The resistivity is obtained by the formula given below:

$$\text{Resistivity } \rho = \frac{2\pi a V}{I} \ [\text{k}\Omega\text{cm}] \tag{1}$$

where, a = distance between the probes as shown in **Figure 8** [30], V = potential measured, I = applied current.

The estimation of the likelihood of corrosion is given in **Table 3**.

3.6 Sulfate and chloride ingress test

Quantity of chlorides and sulfate in the concrete is generally determined chemically. Sulfate and chloride contents of concrete samples are collected from various locations. The permissible limit of chloride contents by weight of cement is 0.4%, and 0.15% is enough for the onset of corrosion. Sulfate content is limited to 4.1% by weight of cement [31].

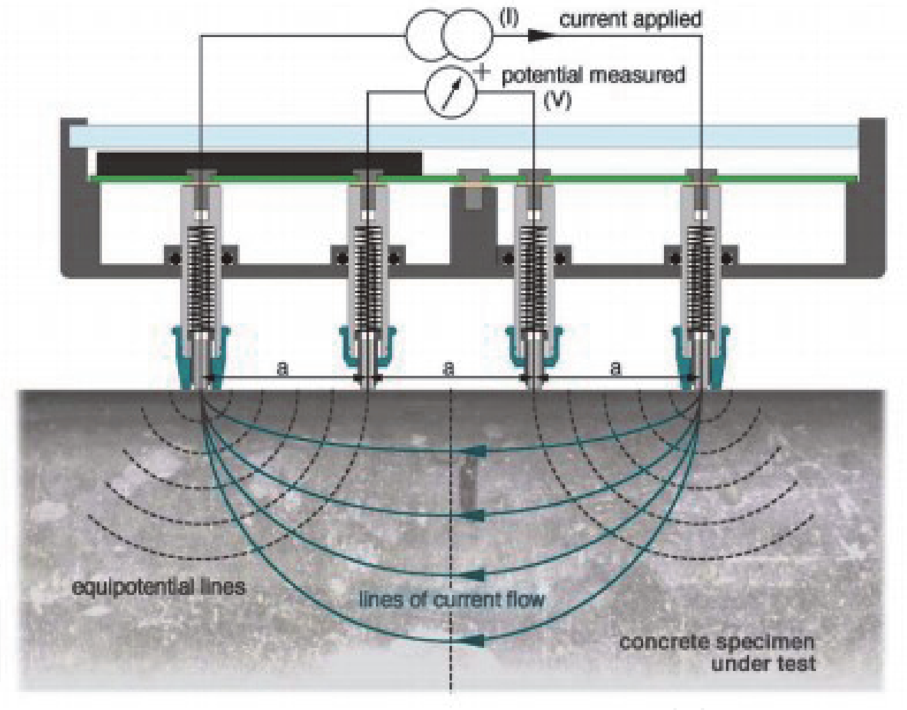


Figure 8.
Concrete resistivity meter.

Sr. No.	Resistively level (Kilo-ohm cm)	Possible corrosion rate
1	≥ 100	Negligible risk of corrosion
2	50–100	Low risk of corrosion
3	10–50	Moderate risk of corrosion
4	≤ 10	High risk of corrosion

Table 3.
The estimation of the likelihood of corrosion.

4. Test results of rebound hammer, UPV, extent of carbonation in concrete, level of corrosion, and chloride and sulfate content

The test results of rebound hammer with pulse velocity at different locations are tabulated in **Table 4**.

The test results of concrete resistivity to check the level of corrosion are given in **Table 5**.

The test results of chloride and sulfate content in concrete samples are tabulated in **Table 6**.

4.1 Summary of problems and defects

1. Cracks: Major cracks were observed at few locations in outer columns of the buildings. Minor cracks were observed near openings of windows and doors in most of the locations. A few cracks were also observed on the parapet of the terrace.

2. Rusting of bars: The corrosion was observed at few locations due to spalling of concrete or carbonation of concrete.

3. Spalling of concrete: Spalling of concrete is observed in outer columns of the buildings.

4. Dampness and efflorescence: Dampness and efflorescence were present in most of the houses especially at ground level, near sunken area, and near staircase areas.

5. Railing: The present railing is damaged and needs to be replaced.

Sr. No.	Id	RN	UPV	f_{ck}	f'_{ck}	G	pH
1	C-1	45.3	2010	24.5	22.05	25	6–7
2	C-2	43.4	1541	22	19.8	25	8–9
3	C-3	26.3	2073	10	9.00	25	6–7
4	C-4	44.7	1843	23.5	21.15	25	6–7
5	C-5	47	2226	26.5	23.85	25	6–7
6	C-6	41.3	1773	20	14.00	25	6–7
7	C-7	46.6	2833	26	18.20	25	6–7
8	C-8	28	2381	10.5	9.45	25	8–9
9	C-9	46.2	2030	25.5	17.85	25	6–7
10	C-10	44.8	2551	24	21.60	25	6–7
11	C-11	40.2	2212	19	17.10	25	6–7
12	C-12	30.9	1895	12	10.80	25	6–7
13	C-13	31.7	2368	14	12.60	25	6–7
14	C-14	36.2	2128	15.5	13.95	25	6–7
15	C-15	30.8	1531	12	10.80	25	6–7
16	C-16	32	2579	13	11.70	25	6–7

Table 4.
UPV, RH, compressive strength, and carbonation test result before repairs.

Sr. No.	Specimen Id	Concrete resistivity values (kΩcm)	Level of corrosion
1	C-1	42,44,38.2,34,36	38.84
2	C-2	18.1,16.4,15.7,15.9,13	15.82
3	C-3	23,27,20.6,20.4	22.75
4	C-4	42,37,36.2,33.1	37.07
5	C-5	42,44,38.2,34,36	38.84
6	C-6	21,22.4,16.8,17.8	19.5
7	C-7	23,27,20.6,20.4	22.75
8	C-8	22,23.4,25.6,28.5	24.88
9	C-9	18.1,16.4,15.7,15.9,13	15.82
10	C-10	34,42,44.3,41	40.32
11	C-11	18,18.5,22.3,22	20.2
12	C-12	21,22,21.8,23	21.95
13	C-13	24,26,20.4,20.6	22.75
14	C-14	45,43.2,42,32.5	40.67
15	C-15	11.4,16.2,14.3,13.9	13.95
16	C-16	28,36,31.8,34.2	32.5

Table 5.
Test results of concrete resistivity.

Sr. No.	Specimen Id	Chloride	Sulfate
		By weight of cement (%)	By weight of cement (%)
1	C-2	0.41	3.2
2	C-4	4.1	3.2
3	C-7	4.2	3.15
4	C-11	0.39	3.6
5	C-13	0.39	3.3
6	C-14	0.36	2.9

Table 6.
Sulfate and chloride content ingress.

4.2 Results and discussions

- From the UPV results, it was observed that all the structural members have very low UPV value. In total, 18.75% elements have the UPV value in the range of 2.5–3.0 Km/sec, 50% elements have the UPV value in the range of 2.0–2.5 Km/sec, and 31.25% members lie in the range of 1.5–2.0 Km/sec. All the UPV values lie below 3.0 (km/sec), which are doubtful. The UPV results cannot fulfill the codal requirements and are shown in **Figure 9**.

- The rebound hammer test results show that the compressive strength of concrete members with various range of percentages is 25%, 37.5%, 25%, and 25%. The compressive strength of these members lies in the range of 20–25 N/mm^2, 15–20 N/mm^2, 10–15 N/mm^2, and 5–10 N/mm^2 respectively and shown in **Figure 10**.

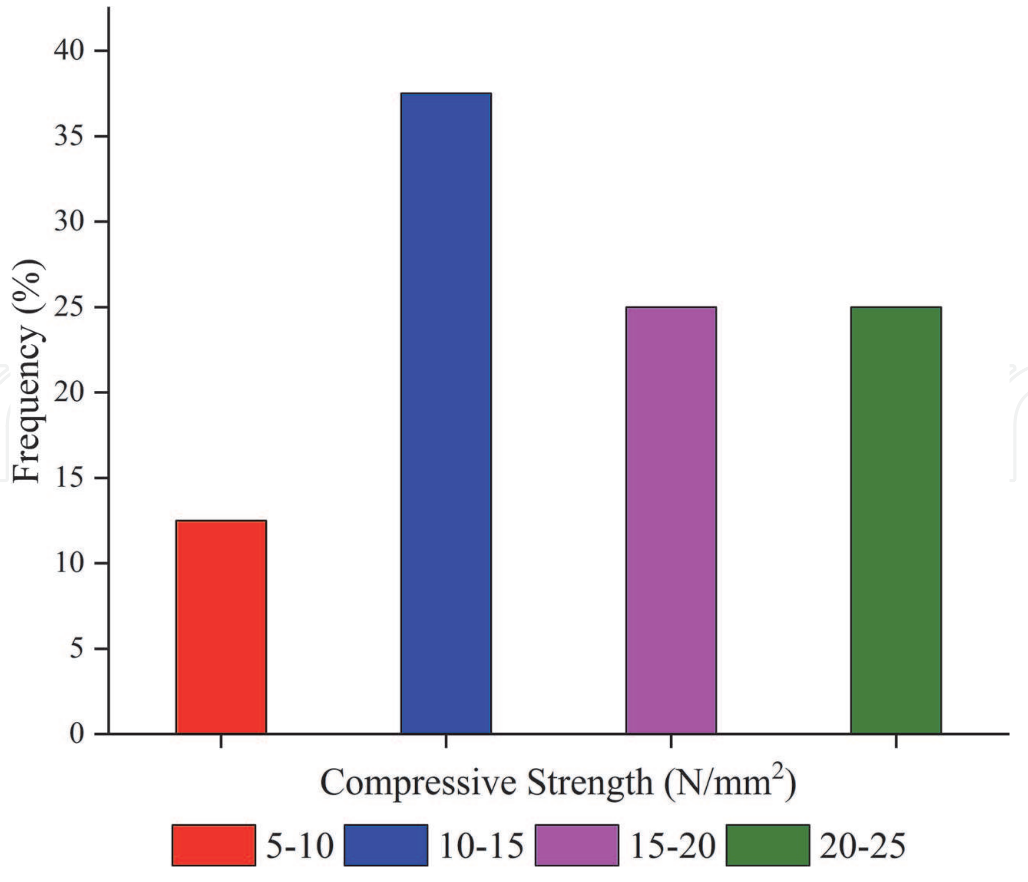


Figure 9.
Ultrasonic pulse velocity (km/sec).

- Adequate concrete cover over the reinforcement is one of the crucial parameters, as far as RCC structures are concerned, but the result of percentage distribution of concrete cover reveals that there is great variation in concrete cover. The specified cover as per drawing detailing is 40 mm. The percentage of less concrete cover is about 54.66% and shown in **Figure 11**. This can be one of the reasons for deterioration in concrete and subsequent corrosion in reinforcing bars.

- The pH value of external RCC members is low in the range of 6–7, and pH of internal members lies in the range of 8–9. From the carbonation depth data, it was observed that the depth of carbonation is more. In 45% of total members, the carbonation has reached up to the rebar level and is shown in **Figure 11**. This has been attributed to porous concrete and unprotected external surfaces from weathering actions.

- Concrete resistivity result showed that the members have a moderate risk of corrosion and is shown in **Figure 12**.

Observing the damaged condition of the outer columns, 10 columns marked in red color in the plan (**Figure 1**) require full height repair, and six columns marked in green color in the plan require repair/jacketing up to the second floor. Exposed concrete was found to be carbonated. The carbonated concrete should be provided with anti-carbonation coating if the spalling of cover concrete has not started. Due to the effect of corrosion, the spalling was observed in these columns, so, it is necessary to repair the structure so that it will be enabled to withstand against the combination of loads for which it is designed. The spalling concrete from columns should be repaired with micro-concrete. All the repair work should be carried out as

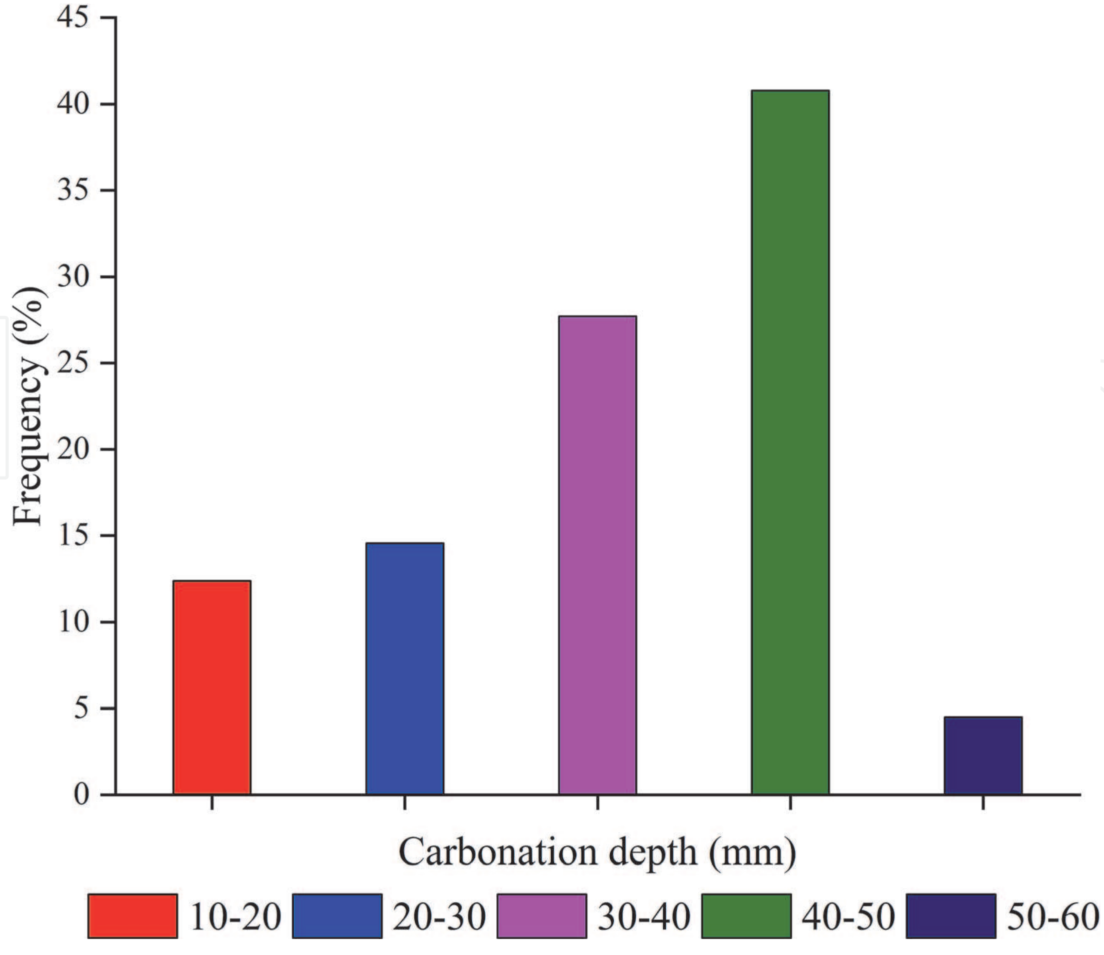


Figure 10.
Compressive strength of concrete members (N/mm²).

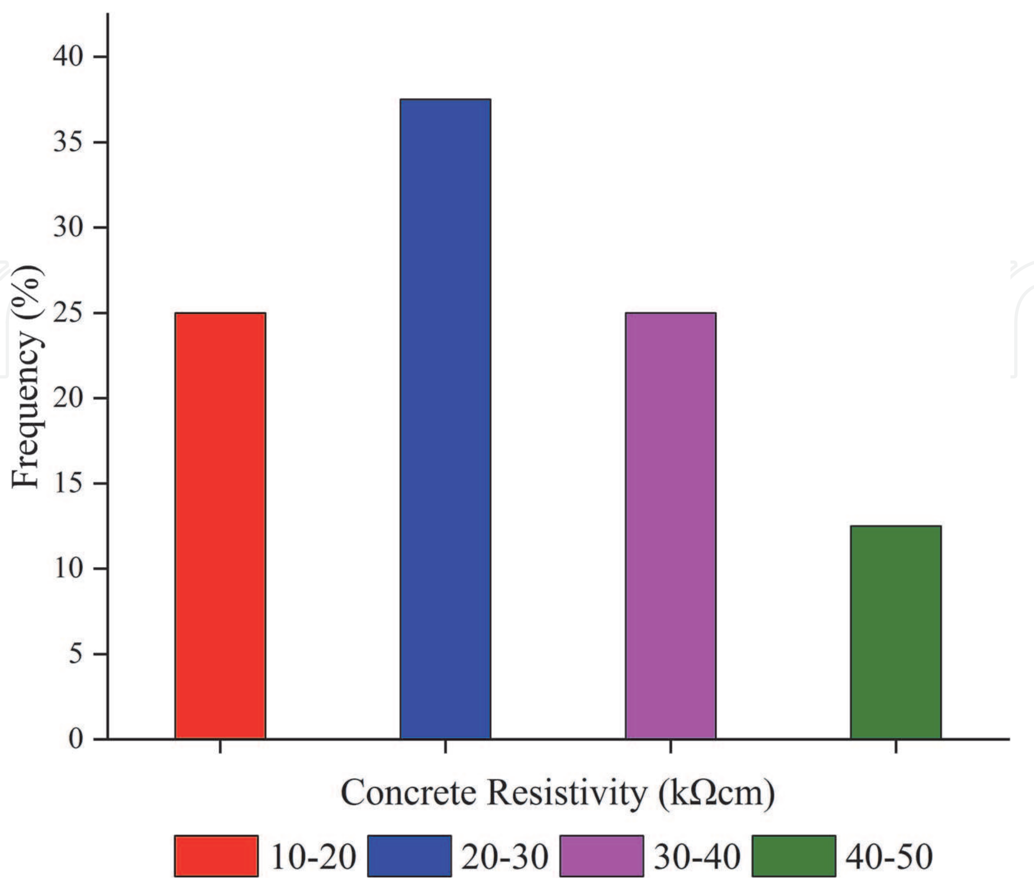


Figure 11.
Carbonation depth (mm).

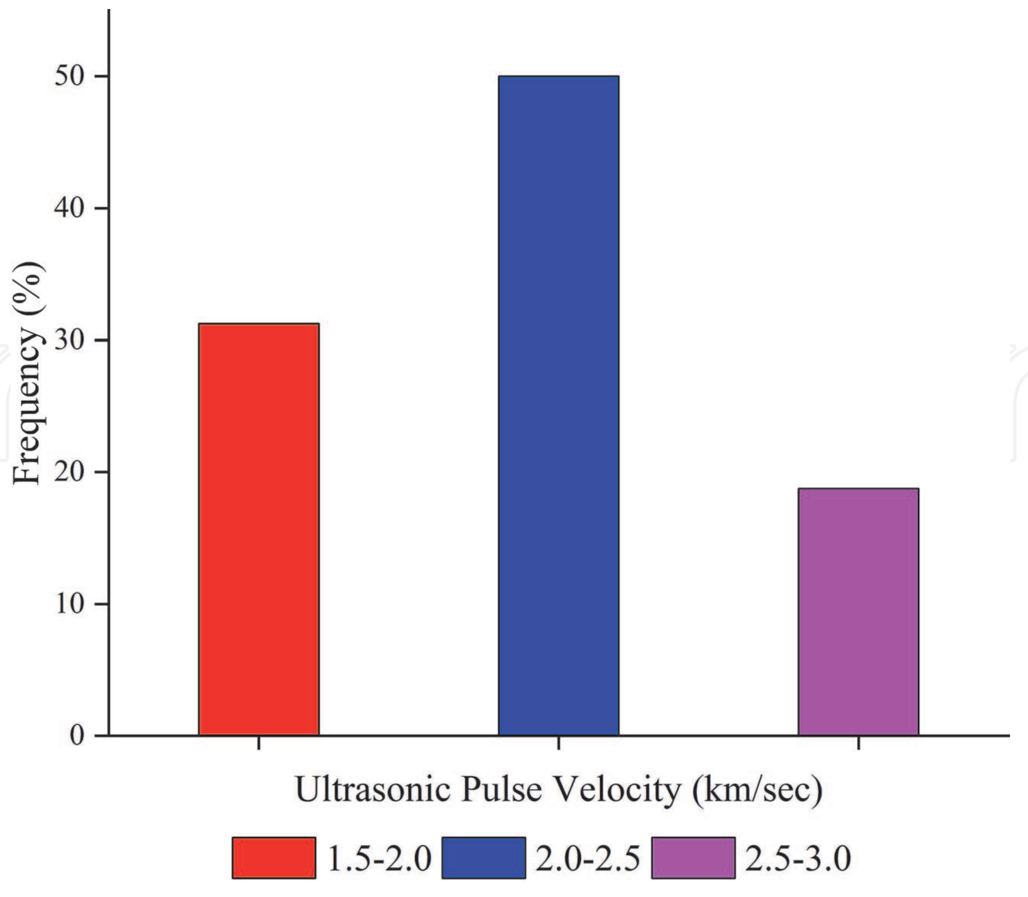


Figure 12.
Concrete resistivity (kΩcm).

per the methodology sequence provided above. The rebound hammer, UPV, and carbonation test results of concrete members before repairs are shown in **Table 4**. Concrete resistivity and chemical analysis results are in **Tables 5** and **6**, respectively.

4.3 Repair methodology

- The strengthening of outer columns of the building needs to be done with jacketing with micro-concrete, and reinforcement is to be provided where steel has rusted more than 20%.
- All the traps and manholes should be repaired to prevent the seepage into the foundations from such locations.
- Water tanks on the roof are causing dampness due to the overflow of water or due to leakage, all the tanks should be repaired, and overflow should be stopped by providing a suitable float valve.
- Exposed concrete was found to be carbonated and hence should be provided with anti-carbonation coating if the spalling of cover concrete has not started.
- If the spalling of cover concrete is taking place, the same should be repaired by treating the affected reinforcement and repairing the cover with micro-concrete.

The suggested model for carrying out repairs of structures and their strengthening for different types of problems is shown in **Figures 13–16**.

4.4 Test results of concrete columns after repair and strengthening

The NDT carried out after repair showed that the concrete strength was in the range of M25–M30 grade of concrete. The UPV also showed the quality of concrete improved from poor to good. **Figures 17** and **18** show that after repairs, the strength

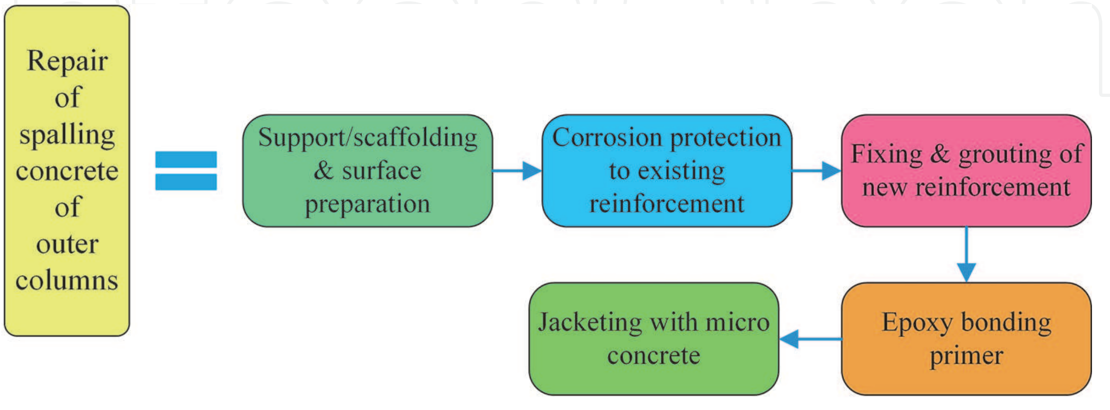


Figure 13.
Repair of spalling concrete of outer columns.

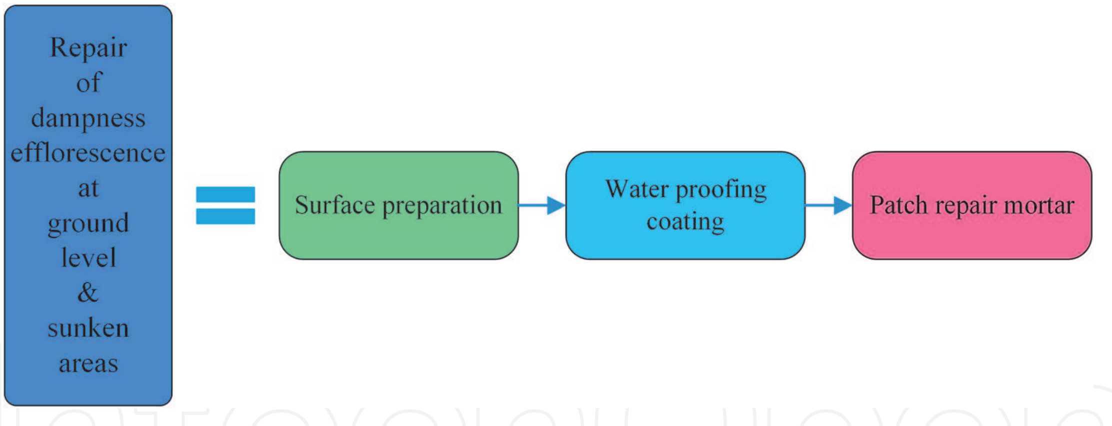


Figure 14.
Repair of dampness efflorescence at ground level and sunken areas.

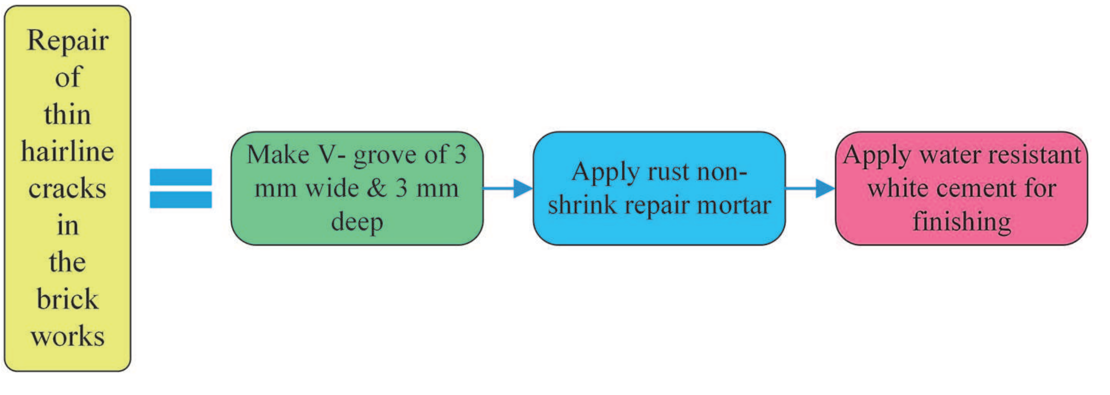


Figure 15.
Repair of thin hairline cracks in the brick works.

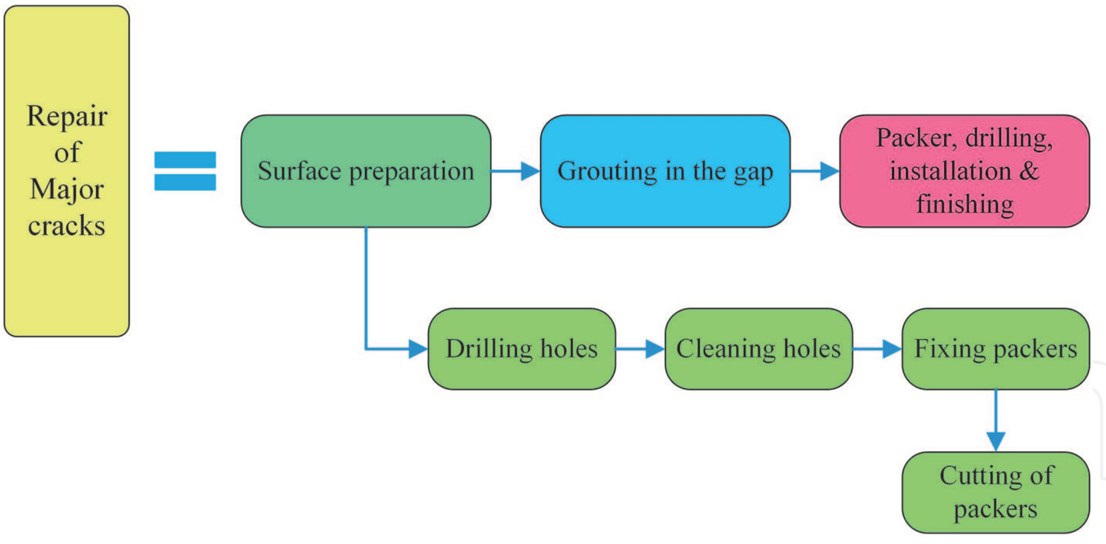


Figure 16.
Repair of major cracks.

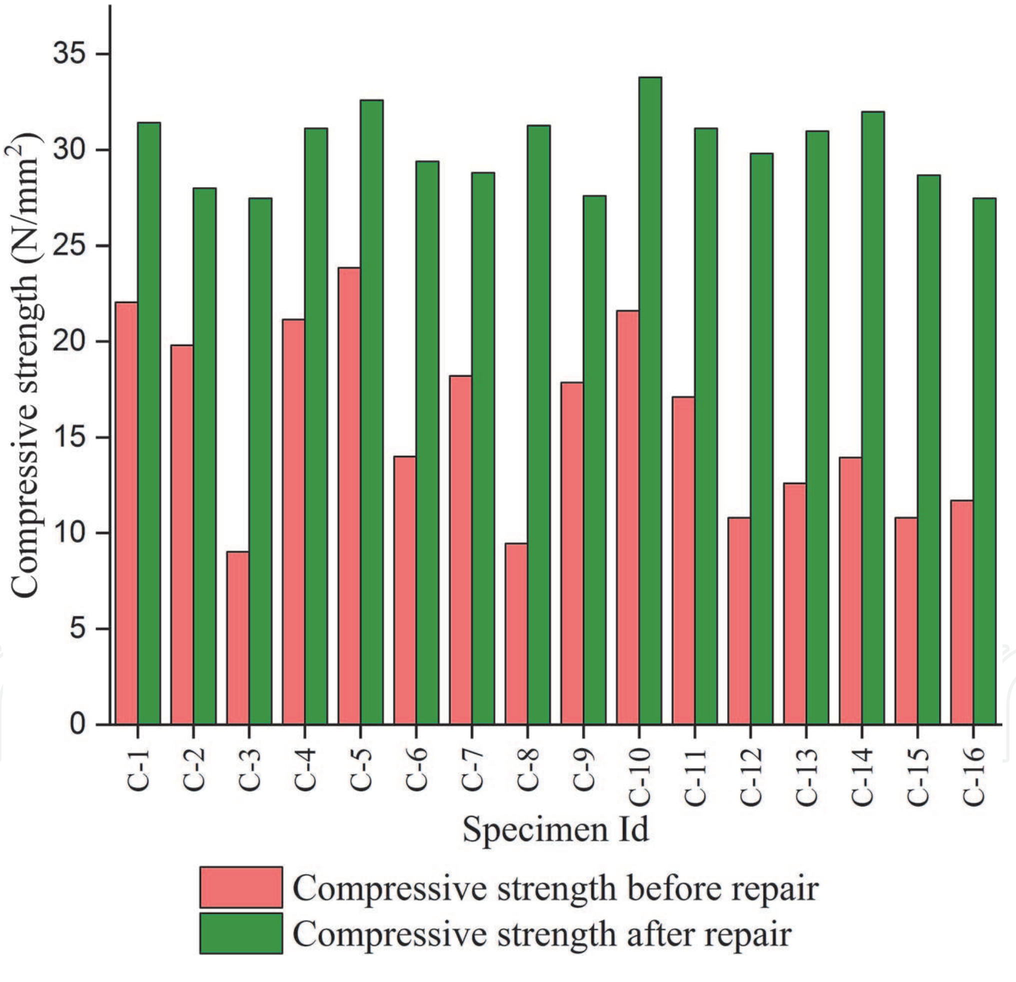


Figure 17.
Comparison of compressive strength before and after repair.

and quality were enhanced, which will also result in improvement of durability of structures in the long run.

Table 7 explains the test results of NDT data of repaired columns. All the enlisted columns are repaired with micro-concreting and in some locations, extra steel is also provided with anti-corrosion paint. This micro-concreting protects the

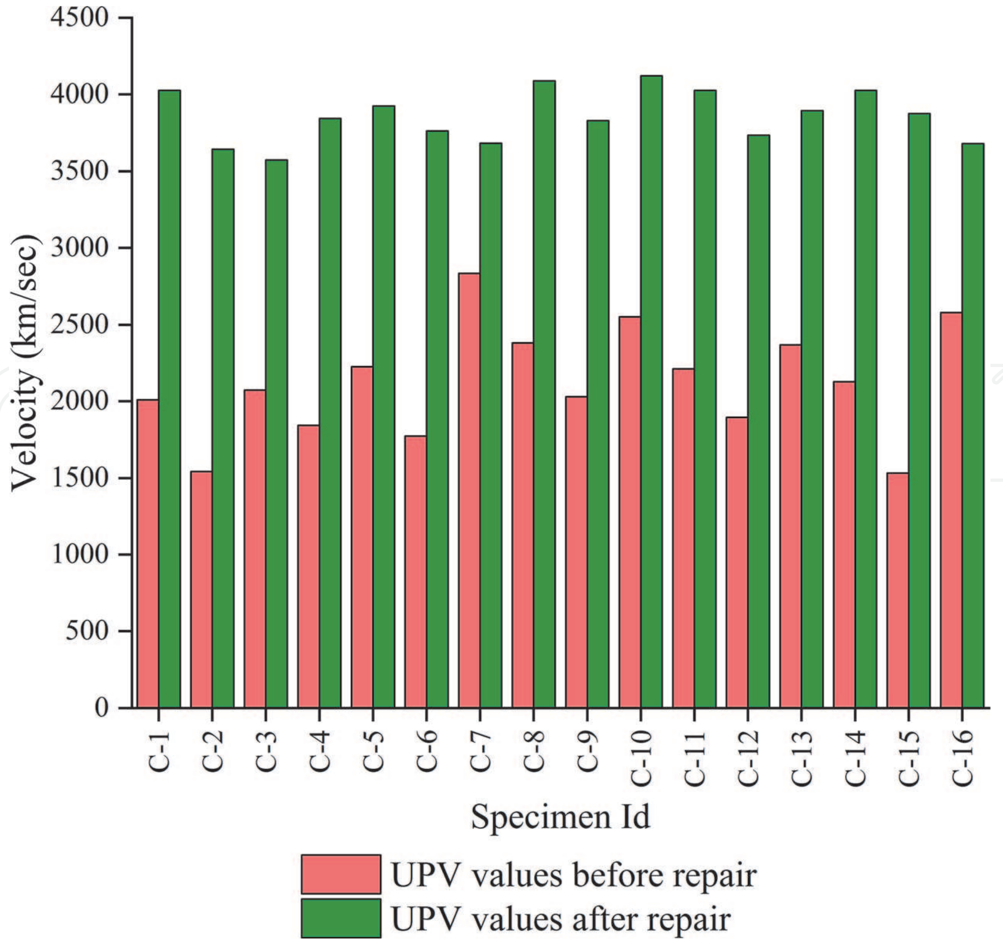


Figure 18.
Comparison of UPV values before and after repair.

Sr. No.	Id	RN	UPV	f_{ck}
1	C-1	50.6	4025	31.42
2	C-2	48.2	3643	28.00
3	C-3	47.8	3573	27.47
4	C-4	50.4	3844	31.13
5	C-5	51.4	3926	32.60
6	C-6	49.2	3763	29.40
7	C-7	48.8	3683	28.80
8	C-8	50.5	4088	31.27
9	C-9	47.9	3830	27.60
10	C-12	52.1	4121	33.78
11	C-11	50.45	4025	31.13
12	C-12	49.5	3735	29.81
13	C-13	50.3	3895	30.98
14	C-14	51	4025	32.00
15	C-15	48.7	3876	28.68
16	C-16	47.8	3680	27.47

Table 7.
Pulse velocity and compressive strength results after repair.

steel from corrosion because the density of this concrete is quite good. The anti-corrosion paint is helpful to protect the new attached steel as well as corroded steel from further corrosion.

5. Health monitoring of concrete bridges

The collection of NDT data in bridge structures is also similar as in the case of buildings. The condition assessment data of bridge deck slab is tabulated in **Table 8** and **Table 9**.

Activity of degradation mechanism dominantly depends on the type of material used for bridge constructions. Comparison of the importance of the basic chemical, physical, and biological mechanisms to deterioration of various materials of bridge structures is shown in **Table 8**.

Information on applicability of selected nondestructive load-independent techniques for detection and identification of defects during field testing of bridges is presented in **Table 9**.

Degradation mechanism		**Material of structures**					
		RC	**P_sC**	**St**	**M**	**T**	**S**
Physical	Accumulation of inorganic dirtiness	֍	֍	֍	֍	֍	֍
	Cyclic freeze–thaw action	֍	֍	֍	■	֍	
	Erosion	֍	֍	֍	■	֍	■
	Crystallization	֍	֍	֍		■	
	Extreme temperature/fire	■	■	■	֍	■	֍
	Creep	■	■	■		■	
	Relaxation	■	■	֍	■		
	Shrinkage	֍	֍	֍		■	
	Overloading	֍	֍	֍	֍	֍	
	Fatigue	■	■	■	֍	■	■
	Geotechnical condition changes	֍	֍	֍	֍	֍	
Chemical	Carbonation	֍	֍	֍		■	
	Corrosion	֍	֍	֍	֍		
	Aggressive compound action	֍	֍	֍	֍	֍	֍
	Chemical dissolving/leaching	֍	֍	■		֍	
	Reactions between material components	֍	֍	֍	֍	■	
Biological	Accumulation of organic dirtiness	֍	֍	֍	֍	֍	֍
	Activity of microbes	֍	֍	֍	֍	■	֍
	Activity of plants	■	■	■	■	֍	֍
	Activity of animals	■	■	■	֍	■	֍

Legend: ֍ - Basic Mechanism and ■ – Additional Mechanism.

Table 8.
Degradation mechanisms versus structural materials.

Technology	NDT technique	Class of defects					
		Df	DM	LM	Di	Co	Dt
Acoustic	Chain drag technique		■	■	■	■	
	Electromagnetic acoustic transducer		֍		■	■	
	Hammer sounding		■	■	֍		
	Impact eco		■	֍	֍		
	Impulse response		■	֍	֍		
	Parallel seismic				֍		
	Phased array ultrasonic		֍		֍		
	Time-of-flight diffraction		■	■	֍		
	Ultrasonic surface waves		֍	֍	֍		
	Ultrasonic tomography		■	֍	֍		
	Ultrasonic velocity		■	֍	֍		
Electrical and electrochemical	Electrical potential		■		֍		
	Electrical resistivity		■		֍		
	Microelectromechanical system	֍			֍		
Electromagnetic and magnetic	Alternating current field		֍		■		
	Eddy-current testing		■	■	֍		
	Electromagnetic conductivity		֍		֍		
	Magnetic flux leakage		■	֍	֍		
	Magnetic particle testing			֍	֍		
	Radar techniques	■	֍		֍		֍
Optic	Closed-circuit television	■				֍	■
	Geodesy/GPS surveying	֍	֍				֍
	Infrared thermograph testing		■	■	֍		
	Laser techniques	֍		■			֍
	Microscopy/endoscopy		֍	֍	֍	֍	
	Visual Inspection	֍	֍	֍	֍	֍	֍
Mechanical	Hardness testing		֍				
	Liquid penetrant				֍		
	Pressure techniques		֍				
	Sclerometric techniques		֍				
Radiological	Computer tomography	֍		֍	֍		
	Gamma or X-ray radiography		֍	֍	֍		
	X-ray fluorescence		֍			֍	
	Transmission radiometry		֍				

Legend: ֍ - Basic Technique and ■ – Additional Technique.

Table 9.
Defects detected by NDT techniques in filed testing of bridges.

Sr. No	Id	RN	UPV	f_{ck}	f'_{ck}	G	pH	R
1	S-1	46.00	3217	35.95	35.95	35	11–12	151.7
2	DS-2	46.17	3281	36.2	36.2	35	11–12	127.2
3	DS-3	45.75	3112	35.40	35.40	35	11–12	128.8
4	DS-4	46.25	3419	36.55	36.55	35	11–12	155.5
5	DS-5	46.08	3321	36.15	36.15	35	11–12	164.4
6	DS-6	46.08	3323	36.16	36.16	35	11–12	166.2
7	DS-7	46.91	2285	38.04	38.04	35	11–12	144.6
8	DS-8	46.75	3024	37.75	37.75	35	11–12	158.7
9	DS-9	46.00	2963	35.98	35.98	35	11–12	172.0
10	DS-10	46.75	3568	37.75	37.75	35	11–12	142.3
11	DS-11	45.83	3245	35.54	35.54	35	11–12	151.0
12	DS-12	46.25	3292	36.56	36.56	35	11–12	122.0
13	DS-13	46.33	3072	36.75	36.75	35	11–12	139.3
14	DS-14	46.25	3463	36.56	36.56	35	11–12	136.1
15	DS-15	46.17	3417	36.70	36.70	35	11–12	145.9
16	DS-16	45.83	3173	35.59	35.59	35	11–12	151.3
17	DS-17	45.66	3174	35.20	35.20	35	11–12	142.3
18	DS-18	45.92	3455	37.79	35.79	35	11–12	178.4
19	DS-19	47.5	3234	36.61	39.61	35	11–12	129.4
20	DS-20	46.167	3139	36.36	36.36	35	11–12	167.7
21	DS-21	46.67	3555	38.10	38.10	35	11–12	129.1
22	DS-22	45.58	3745	35.03	35.05	35	11–12	175.8
23	DS-23	46.08	3577	36.16	36.16	35	11–12	176.3
24	DS-24	45.92	3612	35.78	35.78	35	11–12	146.3
25	DS-25	45.6	3502	35.02	35.02	35	11–12	177.1
26	DS-26	46.1	3789	36.16	39.16	35	11–12	148.3

Table 10.
Test results of bridge deck slab.

The NDT parameters of bridge deck slab such as compressive strength, density, which is obtained from the UPV, pH of concrete, and level of corrosion are shown in **Table 10**.

There is no carbonation present in the concrete, so that the compressive strength and corrected compressive strength after carbonation are the same. The UPV values lie in the range of medium to good. Steel is free from the corrosion as the data given by concrete resistivity meter. The compressive strength of the deck slab varies in the range of 35–39 N/mm^2. The pH value of concrete is also in the normal range. **Figures 19–22** show the UPV values of deck slab (km/sec), compressive strength of deck slab (N/mm^2), cover depth (mm), and concrete resistivity (kΩcm), respectively.

6. Conclusion

In this chapter, the studied tests are rebound hammer, UPV, carbonation of concrete, concrete resistivity, covercrete, and ferrro scan. The repair methodologies

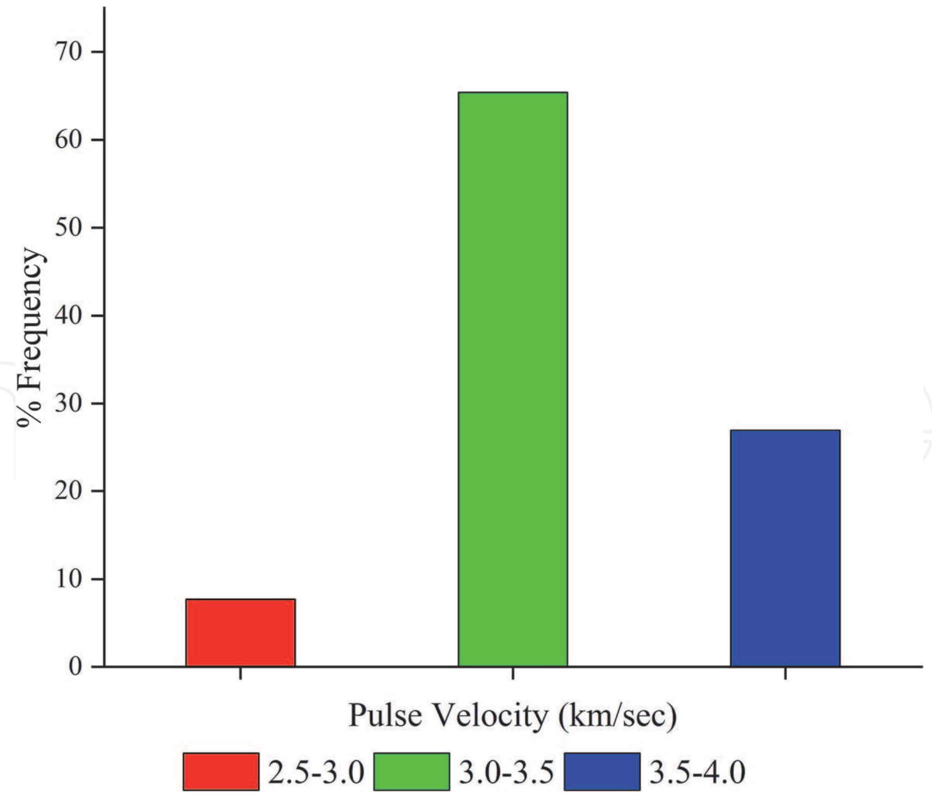


Figure 19.
Pulse velocity (km/sec).

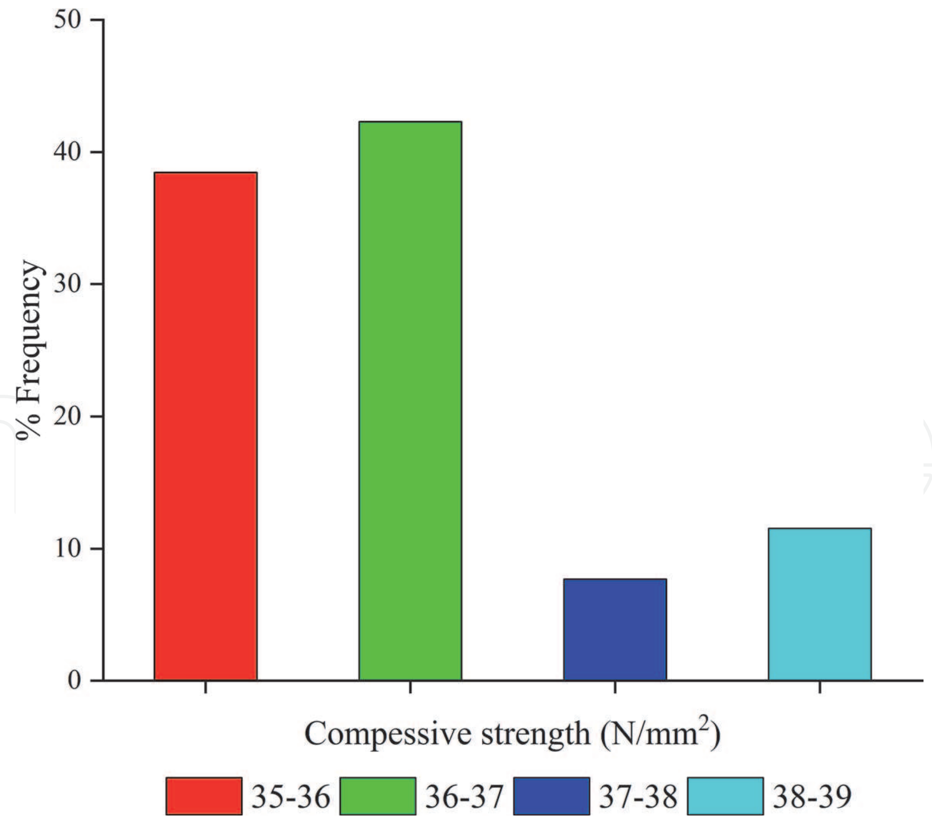


Figure 20.
Compressive strength (N/mm^2).

are helpful to gain the mechanical properties such as strength and density of the concrete members more than original state of the structure. Based on the investigation, the following conclusions are drawn:

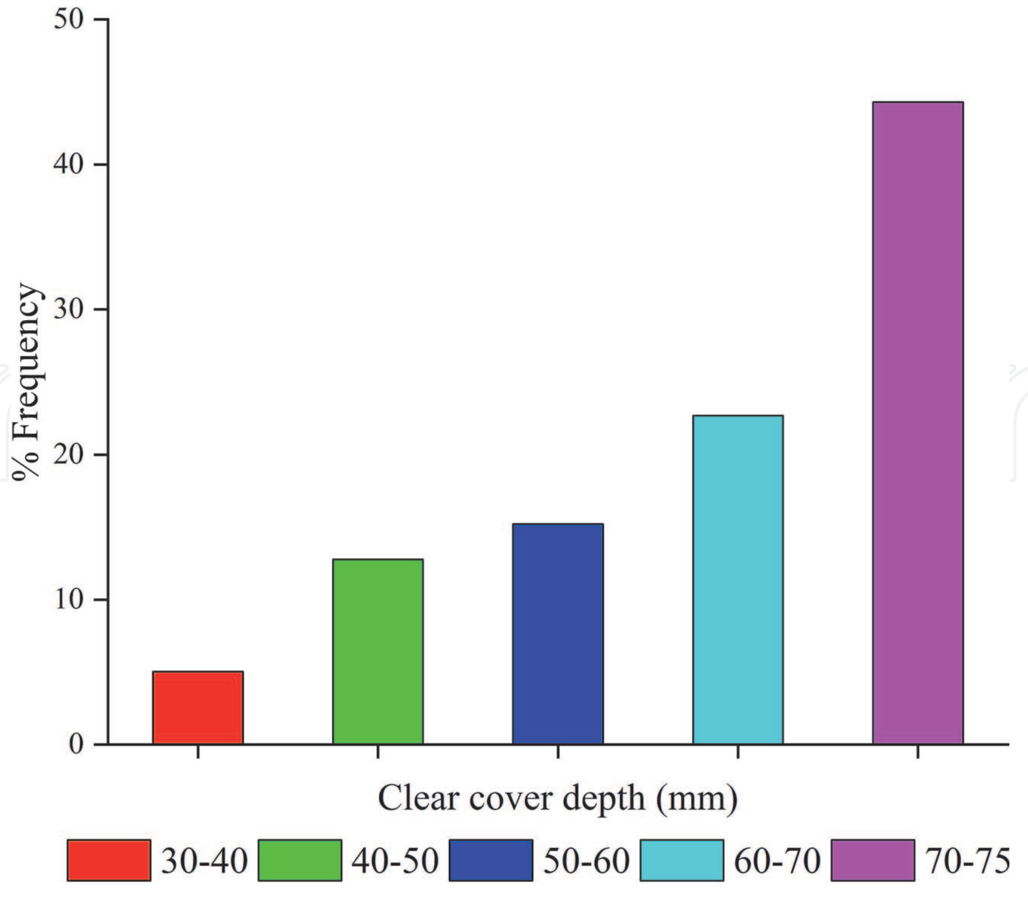


Figure 21.
Cover depth (mm).

- Rebound hammer and UPV test give physical properties of the in-situ RCC members.

- Deterioration of external exposed concrete members due to carbonation is high as compared with internal members.

- Adequate concrete cover to reinforcement is one of the important parameters for RCC structures. A major reason for spalling and corrosion in reinforcing bars is due to inadequate concrete cover. The porosity of concrete and unprotected external surfaces results in a high rate of carbonation.

- A systematic approach to repair and rehabilitation is to be adopted after carrying out the proper monitoring with the help of nondestructive testing techniques.

- The compressive strength of unstrengthened specimens with a frequency of testing specimens is as follows; 12.5% specimens are in the range of 5–10 N/mm^2, 37.5% specimens are in the range of 10–15 N/mm^2, 25% specimens are in the range of 15–20 N/mm^2; and only 25% of the specimens achieved designed grade of concrete, which is 25 N/mm^2. After strengthening all the specimens gained the strength more than 25 N/mm^2, data obtained from rebound hammer. The maximum obtained compressive strength was 33.78 N/mm^2 for specimen having Id C-12.

- The UPV of the test results shows poor quality of concrete, but after strengthening all the values lie in the very good to excellent zone.

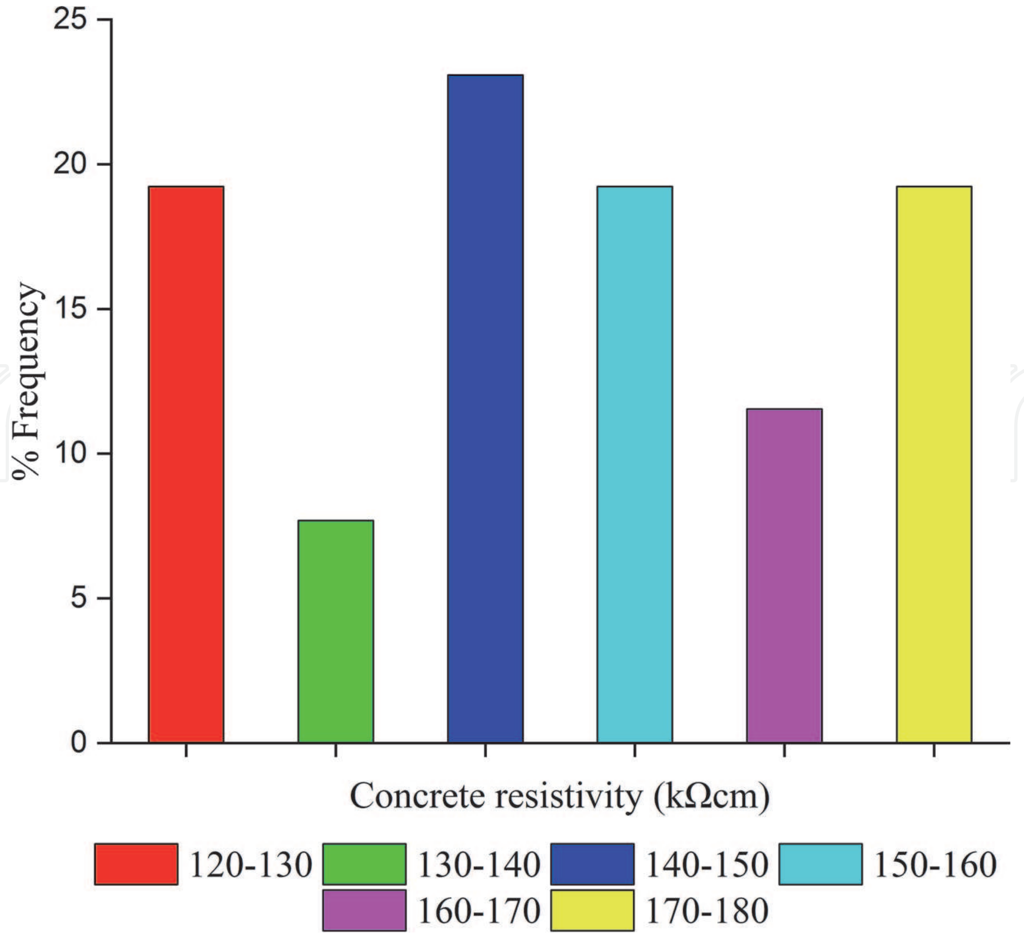


Figure 22.
Concrete resistivity (kΩcm).

- The monitoring to check the effectiveness of strengthening structures can be checked by NDT technique.
- The quality of concrete and steel in the brick deck slab is good and as per the designed detailing.
- There is further need to predict the nondestructive testing data using artificial intelligence.

Conflict of interest

The authors declare no conflict of interest.

Appendices and nomenclature

Co	contamination
Df	deformation
Di	discontinuity
DM	destruction of material
Dt	displacement
DS	deck Slab
f_{ck}	compressive strength (N/mm^2)

f'_{ck}	corrected compressive strength after carbonation (N/mm^2)
Id	specimen Id
LM	loss of material
M	masonry
G	grade of concrete
RC	reinforced concrete
RN	average rebound number
PC	plain concrete
P_sC	prestressed concrete
pH	carbonation range
UPV	avg. UPV (m/s)
St	steel
S	soil
T	timber

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