Condition Assessment of In-situ Concrete in Aging Residential Buildings in Mumbai – A Probabilistic Approach

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ABSTRACT: This paper presents condition assessment of in-situ concrete in existing residential buildings which are more than 50 years old since their completion of construction in Anushaktinagar, Mumbai, India. For this purpose, various non-destructive and partially destructive tests were carried out on these buildings; the tests were performed at most of the locations on external structural members of the buildings which are exposed to environment. The paper presents both qualitative and statistical analyses of the test results data. Different probability distribution models have been proposed for these test results, and checks for goodness of fit have been carried out using standard Chi-Square and K-S tests. Finally, best estimated values and 95 % confidence values have been presented for different non-destructive and partially destructive tests using the proposed probabilistic models, which are in excellent agreement with actual experimentally observed values. These findings help in ascertaining the quality of in-situ concrete in existing aged residential buildings in a probabilistic manner.

1. INTRODUCTION

In aged and existing structures, there is a need to assess the actual condition of concrete due to following reasons: (a) the structure displays visible signs of distress during a scheduled and/or emergency survey, (b) for the purpose of life extension and/or maintaining the operating and serviceable requirements, and (c) possible deterioration due to occurrence of earthquake and/or accidental fire etc. Condition assessment of concrete is also necessary before taking up seismic requalification and possible retrofitting of existing structures to meet the current seismic demands. For important infrastructure facilities as well as industrial structures, condition assessment might be a periodic activity as stipulated by the prevailing regulatory standards. Condition assessment of existing structures is achieved by carrying out number of non-destructive tests (NDTs) and partially destructive tests (PDTs) on them.

The paper presents the details of NDTs and PDTs carried out on 29 existing residential buildings in Anushaktinagar, Mumbai, India. These buildings are more than 50 years old since their completion of construction, thus requiring health assessment of such buildings as per Mumbai Municipal Corporation Act (Bombay Act 2016). These residential buildings are mainly reinforced concrete framed structures. The typical plan dimensions of these buildings vary from 34.4 m x 4.85 m to 151.5 m x 7.4 m; the height above ground level varies from 10.55 m to 16.5 m; the number of floors above ground level varies from 3 to 5; the characteristic compressive strength of concrete and characteristic yield strength of reinforcement were 15 MPa and 415 MPa, respectively; clear cover to reinforcement varies from 20 to 40 mm in different structural members.

The paper further presents both qualitative and probabilistic analyses of the test results for holistic assessment of condition of concrete in these residential buildings.

2. TESTS FOR ASSESSMENT OF QUALITY OF IN-SITU CONCRETE AND THEIR RANGE OF RESULTS

First and foremost activity in a condition survey and evaluation of existing concrete structures, is a walkover survey and visual inspection so as to gather information that may lead to positive identification of the cause of observed distress (ACI 1998). Observation of distress and/or design deficiency along with their locations is the main essnce of walkover survey and visual inspection, and which is further supplemented by a series of NDTs and PDTs for assessment of in-situ quality of concrete in existing buildings.

Based on the data collected about damage and/or distress along with their locations in different structural members of all the 29 residential buildings, number of NDTs and PDTs were planned in these buildings for detailed assessment of: (i) quality, carbonation condition, chemical contents and pH of pore solution of in-situ concrete, and (ii) corrosion condition of reinforcing steel. These NDTs and PDTs include Rebound Hammer Test (RHM) (BIS 2020), Ultra Sonic Pulse Velocity Test (USPV) (BIS 2018a), Pull-out Core Test (CE) (BIS 2018b), Half Cell Potential Test (HCP) (BIS 2019), Carbonation Depth Test (DCR) (BIS 2021), Chemical Analysis of Concrete for Chlorides, Sulphates and pH (CHA) (BS 2015; BIS 2001; Kakde 2014).

Table 1 presents type and number of NDTs and PDTs carried out for all the 29 residential buildings of Anushaktinagar, Mumbai. Locations and numbers of these tests were decided based on the data obtained after walkover survey and visual inspection of these buildings. Various RC structural members, such as, beams, slabs, and columns were tested. The tests were performed at majority of locations on the external structural members which are exposed to actual environmental conditions. Tables 2(a) – (b) present range of test results obtained for various NDTs and PDTs; following are inferred from these Tables.

The range of rebound number is obtained as between 15 – 45; the variation may be attributed mainly to type of cement and aggregate, surface condition and moisture content of concrete, age of concrete, and extent of carbonation of concrete. The range of ultrasonic pulse velocity is obtained as between 1.00 – 5.66 km/Sec; the variation may be attributed mainly to surface condition and moisture content of concrete, path length, shape and size of concrete members, temperature of concrete, stress levels in concrete, presence of reinforcing bars, and presence of cracks and voids in concrete. The range of equivalent cube compressive strength is obtained as between 11.78 – 22.37 MPa; the variation may be attributed mainly to place of drilling the cores, micro-cracks present in concrete, curing period and curing temperature, entrapped air in concrete due to poor compaction, and moisture condition of cores. The range of half cell potential is obtained as between -412 to -71 mV; the variation may be attributed mainly to the corrosion condition of the reinforcing steel in concrete. The range of 'R_{DC}' is obtained as between 0.025 – 2.20; the variation may be attributed mainly to amount of carbon dioxide present in air, relative humidity of concrete, concrete permeability, and amount of calcium hydroxide present in concrete. The range of Chloride in concrete is obtained as between 0.19 – 4.56 kg/m^3 of concrete, and the range of Sulphate in concrete is obtained as between 0.36 – 0.81 % mass of cement; the variation is mainly attributed to concrete permeability, relative humidity, and carbonated state of concrete. The range of pH of pore solution of concrete is obtained as between 9.83 – 12.76; the variation is mainly attributed to carbonated state of concrete, and diffusion of Chlorides and Sulphates in concrete.

3. QUALITATIVE ASSESSMENT OF CONCRETE AND REINFORCEMENT

Tables 3 presents quality of in-situ concrete for all the 29 residential buildings put together based on various NDTs and PDTs carried out on them. Following are inferred from Table 3.

RHM shows that the quality of in-situ concrete has been found to be fair to good at more than 95 percent locations of measurement, indicating reasonably good strength of in-situ concrete. USPV shows that the quality of in-situ concrete has been found to be good to excellent at about 10 percent locations of measurement, indicating dense, homogeneous and uniform concrete. CE shows that the in-situ cube compressive strength of concrete in existing structures is more than 75 percent of design characteristic compressive strength of concrete used at the time of their construction, at all the locations of measurement, indicating adequate strength of in-situ concrete. HCP shows that the corrosion condition of reinforcing steel in concrete has been found to be less to uncertain at about 98 percent locations, indicating less diffusivity and permeability, presence of less micro-cracks, and intact concrete in cover regions. DCR shows that 'R_{DC}' values less than 0.75 have been reported at about 35 percent locations, which indicates that carbonation front is yet to penetrate through cover region to reach the reinforcing steel, thus, ruling out the possibility of corrosion initiation of reinforcement. CHA shows that: (a) acid and water soluble Chloride content in concrete is more than the limiting value of 0.6 kg/m^3 at 50 percent locations, thus resulting in uncertain corrosion condition of reinforcing steel as well as localized surface cracks and spalling of cover concrete at some locations in external beams, columns, and chhajjas, and internal slabs, (b) acid and water soluble Sulphate content in in-situ concrete has been found to be less than the limiting value of 4 percent mass of cement in concrete at all the locations, thus, ruling out the possibility of localized expansion and disruption and/or cracking in various structural members of the buildings, and (c) pH value of pore solution of in-situ concrete has been found to be more than limiting value of 9.5 (Ambroziak et al. 2019; Ambroziak et al. 2021) at all the locations, thus, ruling out the possibility of high or severe corrosion condition of reinforcing steel due to carbonation process at majority of the locations of measurement. Similar trends have also been observed for individual residential buildings A01 – A10 as tabulated in Tables 1 – 2.

4. STATISTICAL AND PROBABILISTIC ANALYSES OF NDTS AND PDTS

Tables 4 – 6 present results of statistical and probabilistic analyses of RHM, USPV, CE, HCP, DCR and CHA test results data for all the 29 residential buildings put together.

Table 4 presents statistical descriptors, such as mean, coefficient of variation (*c.o.v.*), coefficient of skewness (C_S), and coefficient of kurtosis (C_K) (Ranganathan 2000).

Table 5 presents fitting of probabilistic models for RHM, USPV, CE, HCP, DCR and CHA test result data; standard Normal and Log-normal probability distributions are presented after assessing their suiability by Chi-square and K-S tests. In Table 5 various notations are defined as follows: χ^2_{cal} stands for calculated value of Chi-square; $\chi^2_{(N,0.95)}$ stands for the value of Chi-square obtained from the standard Chi-square table (Soong 2004) corresponding to N_r degrees of freedom and 5 % level of significance, where, N_r is computed as $N_r = N_I - a - 1$, where N_I = the number of intervals considered for the histograms, a = number of parameters estimated from the data (= 2 in this case); D_{cal} stands for the maximum of absolute values of the n differences between observed CDF and the hypothesized CDF evaluated for the observed samples; $D_{(n,0.95)}$ stands for the value of 'D' obtained from the standard 'D' table (Soong 2004) corresponding to sample size n and 5 % level of significance, where n = number of test results.

Table 6 presents estimation of median value and 95 % confidence value by using fitted probabilistic models, i.e., standard Normal and Log-normal probability distributions for Rebound Number, Ultrasonic Pulse Velocity, Cube Compressive Strength of Concrete, Half Cell Potential, Depth of Carbonation, Chloride and

Sulphate contents, and pH of Pore Solution of Concrete. The 95 % confidence value for Rebound Number, Ultrasonic Pulse Velocity, Cube Compressive Strength of Concrete, and pH of Pore Solution of Concrete is defined as the value below which not more than 5 % of the sample values are expected to fall. The 95 % confidence value for Half Cell Potential, Depth of Carbonation, Chloride and Sulphate content in Concrete is defined as the value which has 95 % probability of not being exceeded. Same Tables also presnt median and 95 % confidence values for the actual measured data.

For Rebound Number following are inferred: (i) the distribution is majorly positively skewed and closer to standard Normal distribution, (ii) follows both standard Normal and Log-normal probability distribution, (iii) excellent agreement has been observed between median values of rebound numbers predicted using probabilistic models and those obtained from actual test result data, and (iv) presdicetd 95 percent confidence values of rebound numbers are found to be about 20 percent lower than corresponding values obtained from actual test result data.

For Ultrasonic Pulse Velocity following are inferred: (i) the distribution is majorly positively skewed and to some extent flatter than standard Normal distribution, (ii) follows standard Log-normal probability distribution, and (iii) excellent agreement has been observed between median and 95 percent confidence values of USPV predicted using Log-normal probability distribution model, and those obtained from actual test result data.

For Cube Compressive Strength of in-situ concrete following are inferred: (i) the distribution is majorly positively skewed and to some extent flatter than standard Normal distribution, (ii) follows both standard Normal and Log-normal probability distribution, and (iii) excellent agreement has been observed between median and 95 percent confidence values of Rf_C predicted using both Normal and Log-normal probability distribution models and those obtained from actual test result data.

For Half Cell Potential following are inferred: (i) the distribution is majorly negatively skewed and closer to standard Normal distribution, (ii) follows standard Normal probability distribution, and (iii) excellent agreement has been observed between median and 95 percent confidence values of HCP predicted using Normal probability distribution model and those obtained from actual test result data.

For Carbonation Depth ‘R_{DC}’, following are inferred: (i) the distribution is majorly positively skewed and closer to standard Normal distribution, (ii) follows standard Normal probability distribution, and (iii) excellent agreement has been observed between median and 95 percent confidence values of R_{DC} predicted using Normal probability distribution model, and those obtained from actual test result data.

For CHA, following are inferred: (i) the distribution for Chloride content is majorly positively skewed and to some extent peaker than standard Normal distribution, (ii) Chloride content follows standard Log-normal distribution, (iii) distribution for Sulphate content is majorly positively skewed and to some extent flatter than standard Normal distribution, (iv) distribution for pH of pore solution is majorly negatively skewed and to some extent flatter than standard Normal distribution, (v) Sulphate content and pH of pore solution follow both standard Normal and Log-normal probability distribution, and (vi) excellent agreement has been observed between median and 95 percent confidence values of Chloride and Sulphate contents, and pH of pore solution predicted using probability distribution models and those obtained from actual test result data.

Similar trends have also been observed for individual residential buildings A01 – A10 as tabulated in Tables 1 – 2.

5. CONCLUSIONS

Following conclusions are drawn based on the present study: (i) qualitative assessment of NDTs and PDTs indicates less diffusivity and permeability, presence of less micro-cracks, and intact concrete in cover regions, less chance of possibility of corrosion initiation of reinforcement, and adequate alkaline environment for in-situ concrete, and thus, resulting in adequate strength of in-situ concrete, (ii) majority of the parameters, such as, rebound number, USPV, cube compressive strength of in-situ concrete, carbonation depth, and chemical analysis results, have been found to be positively skewed and closer to standard normal probability distribution pattern, (iii) Rebound Number, Cube Compressive strength, Sulphate content, and pH of pore solution follow both standard Normal and Log-normal probability distributions. USPV and Chloride content follow Standard Log-normal probability distribution. HCP and Carbonation depth follow standard normal probability distribution, and (iv) excellent agreement has been observed between median and 95 percent confidence values of NDTs and PDTs predicted using probability distribution models and those obtained from actual test result data.

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Table 1: Details of NDTs and PDTs Carried Out on Residential Buildings

Sr. No.	BID (NOB) / YOC	Type and Number of Tests					
		RHM	**USPV**	**HCP**	**DCR**	**CHA**	**CE**
1	A01 (1) / 1969	56	59	26	26	4	4
2	A02 (1) / 1969	74	75	52	52	5	2
3	A03 (4) / 1970	198	203	76	76	4	7
4	A04 (1) / 1970	83	83	41	41	3	3
5	A05 (1) / 1970	36	36	26	26	3	2
6	A06 (1) / 1970	54	56	39	39	3	3
7	A07 (4) / 1970	146	146	36	36	4	7
8	A08 (4) / 1979	140	140	0	0	0	5
9	A09 (4) / 1970	142	142	0	0	0	6
10	A10 (8) / 1970	201	204	55	55	4	15
Total Tests (→)		**1130**	**1144**	**351**	**351**	**30**	**54**

BID: Building Identity; NOB: Number of Buildings; YOC: Year of Completion; RHM: Rebound Hammer Test; USPV: Ultra-sonic Pulse Velocity Test; HCP: Half Cell Potential Test; DCR: Carbonation Depth Test; CHA: Chemical Analysis; CE: Pull-out Core Extraction Test

Table 2(a): Range of Test Results for Buildings – RHM, USPV, DCR and CE

Sr. No.	BID (NOB)	Range of Test Results			
		RHM (N)	**USPV (V: km/sec.)**	**DCR (R_{DC})**	**CE (ECCS: MPa)**
1	A01 (1)	22 – 41	1.41 – 4.04	0.025–2.00	13.05 – 15.65
2	A02 (1)	23 – 40	1.19 – 3.77	0.25 – 1.80	15.16 – 17.95
3	A03 (4)	20 – 45	1.14 – 4.61	0.125– 1.75	11.78 – 19.10
4	A04 (1)	20 – 45	1.34 – 4.28	0.025 – 1.60	13.81 – 17.62
5	A05 (1)	26 – 45	1.00 – 4.37	0.25 – 1.75	13.24 – 17.69
6	A06 (1)	22 – 40	1.35 – 4.44	0.025 – 1.25	11.80 – 14.93
7	A07 (4)	18 – 41	2.05 – 5.61	0.025 –1.80	13.18 – 17.59
8	A08 (4)	20 – 42	1.22 – 5.66	N.A.	13.28 – 22.37
9	A09 (4)	18 – 41	1.71 – 4.76	N.A.	12.19 – 19.35
10	A10 (8)	15 - 38	1.39 – 4.61	0.025 –2.20	12.47 – 19.53

N: Rebound Number; V: Pulse Velocity; N.A.: Not Applicable; R_{DC}: Ratio of carbonation depth in concrete to clear cover to reinforcement in a structural member; ECCS: Equivalent Cube Compressive Strength

Table 2(b): Range of Test Results for Buildings – HCP and CHA

Sr. No.	BID (NOB)	Range of Test Results			
		HCP (HCP: mV)	CHA		
			Chloride (kg/m^3 of Concrete)	Sulphate (% Mass of Cement)	pH Value
1	A01 (1)	-339 to -137	0.48 – 2.88	0.56 – 0.81	11.25 – 11.62
2	A02 (1)	-352 to -160	0.31 – 1.36	0.40 – 0.58	10.90 – 11.78
3	A03 (4)	-362 to -201	1.05 – 3.12	0.51 – 0.73	12.20 – 12.42
4	A04 (1)	-334 to -151	0.38 – 1.44	0.51 – 0.66	10.06 – 12.20
5	A05 (1)	-334 to -173	0.19 – 2.95	0.40 – 0.70	11.54 – 12.76
6	A06 (1)	-412 to -186	1.68 – 2.35	0.36 – 0.56	10.30 – 12.03
7	A07 (4)	-241 to -71	0.40 – 1.24	0.69 – 0.79	11.72 – 12.26
8	A08 (4)	N.A.	N.A.	N.A.	N.A.
9	A09 (4)	N.A.	N.A.	N.A.	N.A.
10	A10 (8)	-305 to -92	0.20 – 4.56	0.36 – 0.81	9.83 – 12.26
HCP: Half Cell Potential; N.A.: Not Applicable					

Table 3: Qualitative Assessment of NDTs and PDTs Results

Sr. No.	Test	(% of Total Test Results)					
1.	RHM (N) (GoI 2007)	< 20 (Weak Surface Concrete)		20 – 30 (Fair Surface Concrete)	30 – 40 (Good Surface Concrete)		> 40 (Hard Surface Concrete)
		1.15		44.96	51.15		2.74
2.	USPV (V: km/Sec.) (BIS 2018a)	< 3 km/sec (Poor Concrete)		3 – 3.75 km/sec (Doubtful Concrete)	3.75 – 4.40 km/sec (Good Concrete)		> 4.40 km/sec (Excellent Concrete)
		65.38		25.00	6.82		2.80
3.	CE (Rf_C)	< 0.75		0.75 – 0.85	0.85 – 1.00		> 1.00
		0.00		18.52	40.74		40.74
4.	HCP (HCP: mV) (BIS 2019)	> -200 mV (Less)		-200 to -350 mV (Uncertain)	< -350 mV (High)		< -500 mV (Severe)
		19.38		79.48	1.14		0.00
5.	DCR (R_{DC})	< 0.5		0.5 – 0.75	0.75 – 1.00		> 1.00
		18.81		19.09	34.48		27.62
6.	CHA	Chloride (kg/m^3 of Concrete) (BIS 2000)		Sulphate (% Mass of Cement) (BIS 2000)		pH value (Ambroziak et al. 2019; Ambroziak et al. 2021)	
		≤ 0.6	> 0.6	≤ 4	> 4	≤ 9.5	> 9.5
		50.00	50.00	100.00	0.00	0.0	100.0
Rf_C: Ratio of in-situ cube compressive strength of concrete obtained from CE test to the design characteristic strength of concrete used at the time of construction of building							

Table 4: Statistical Descriptors for NDTs and PDTs Results

Sr. No.	Test		Statistical Descriptors			
			Mean	c.o.v.	C_S	C_K
1.	RHM (N)		29.96	0.174	0.200	2.92
2.	USPV (V: km/Sec.)		2.83	0.238	0.856	4.34
3.	CE (Rf_C)		1.01	0.170	0.940	3.47
4.	HCP (HCP: mV)		-247.18	0.231	-0.264	3.13
5.	DCR (R_{DC})		0.86	0.557	0.420	2.82
6.	CHA	Chloride	1.31	0.763	0.761	2.19
		Sulphate	0.62	0.218	0.294	3.37
		pH Value	11.64	0.060	-0.890	3.88
Chloride: kg/m^3 of Concrete; Sulphate: (% Mass of Cement)						

Table 5: Probabilistic Models for NDTs and PDTs Results

Sr. No.	Test		Goodness of Fit tests					
			Chi-square test			K-S test		
			χ^2_{cal}		$\chi^2_{(Nr,0.95)}$	D_{cal}		$D_{(n,0.95)}$
			N	LN		N	LN	
1.	RHM (N)		18.280	16.170	15.507	0.022	0.033	0.041
2.	USPV (V: km/Sec.)		239.48	31.83	16.919	0.066	0.032	0.040
3.	CE (Rf_C)		14.97	7.87	9.488	0.166	0.069	0.185
4.	HCP (HCP: mV)		27.670	78.32	12.592	0.050	0.106	0.073
5.	DCR (R_{DC})		14.361	90.785	14.067	0.068	0.146	0.073
6.	CHA	Chloride	35.04	10.90	11.07	0.235	0.061	0.152
		Sulphate	2.34	5.14	11.07	0.020	0.039	0.152
		pH Value	8.30	10.06	11.07	0.060	0.072	0.152
'N' and 'LN' stand for standard Normal and Log-normal probability distributions, respectively.								

Table 6: Estimation of NDTs and PDTs Values Using Probabilistic Models

Sr. No.	Test		Probabilistic Models				Actual Data	
			Normal (N)		Log normal (LN)		P_{50}	P_{95}
			P_{50}	P_{95}	P_{50}	P_{95}		
1.	RHM (N)		29.96	21.42	29.50	22.06	30	27
2.	USPV (V: km/Sec.)		-	-	2.76	1.88	2.78	1.92
3.	CE (Rf_C)		1.01	0.74	1.00	0.77	0.95	0.81
4.	HCP (HCP: mV)		-247.18	-340.94	-	-	-250.0	-337.0
5.	DCR (R_{DC})		0.86	1.65	-	-	0.80	1.75
6.	CHA	Chloride	-	-	0.96	3.75	0.95	3.12
		Sulphate	0.62	0.84	0.61	0.87	0.59	0.81
		pH Value	11.64	10.49	11.61	10.47	11.75	10.06
P_{50}: Median Value; P_{95}: 95 % Confidence Value								