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Technical Paper

Conservative characteristic strength of concrete from non-destructive and partially destructive testing

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Abstract: In this article, the strategy for evaluation of conservative characteristic strength of concrete from the non-destructive and partially destructive testing on the existing structures is elucidated. Such evaluations becomes essential for health assessment and re-evaluation of the existing structures to fulfill the requirements of periodic assessment, revised loading, changed functionality, regulatory guidelines or post-accident scenario. The non-destructive tests considered were ultrasonic pulse velocity (USPV) and rebound hammer (RH) records. This started with examination of the dataset for outliers, and elimination of the same, if any. Subsequently, the forms of correlation expression best suited for evaluation of compressive strength from USPV and RH were ascertained from the limited number of combined records of USPV, RH and core strength obtained from the structure. Stratified sampling was adopted to divide the data into modeling and testing data for this exercise, the latter being employed for performance evaluation. From the results, it was concluded that for the dataset involved, linear equation would be best suited for evaluation of compressive strength from both USPV as well as RH. The total records of the USPV, RH and core results were thereafter employed to determine the correlation expressions, which were subsequently applied on the USPV and RH records from the entire structure to arrive at the estimates of equivalent cube strength. The conservative characteristic strength of concrete in the structure was suggested from considerations of Indian standard code and may be extended for other codes as well. The conservative characteristic strength of concrete can hereafter be utilized for health assessment and re-evaluation studies for the structure. This case study would be useful as a reference for engineers engaged in condition assessment and re-evaluation exercises of existing concrete structures.

Keywords: Ultrasonic pulse velocity, rebound hammer, non-destructive test, characteristic strength, partially destructive tests, core test, correlation expression, condition assessment.

1. Introduction

Concrete has been a popular building material in last few decades mainly because of the flexibility in the geometry offered by concrete, the resistance to the environment and fire as compared to steel, and the cost effectiveness. However, over the life of the structure the concrete undergoes deterioration depending upon the various factors like the environmental exposure conditions, the loading and stress history, and the accidental impact or fire, among others. Most of the concrete structures survive their design life and still are serviceable. For life extension, health assessment of the structure then becomes essential. In other cases, if the structure displays visible signs of distress during a scheduled / emergency survey, health assessment would be suggested for further analysis of the worthiness of the structure. In certain cases of accidental loading or fire, the evaluation of the structural health becomes mandatory before further use of the facility. For important infrastructure facilities as well as critical structures, health assessment might be a periodic activity as stipulated by the prevailing safety guidelines and standards.

For health assessment of existing concrete structures, the compressive strength of concrete may be estimated directly from partially destructive tests such as concrete cores taken from the structure. However, the number of cores allowed for this

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purpose is limited from the considerations of minimizing additional distress to the structure. Further, there could be practical difficulties in extraction of representative cores from the entire structure in view of installed equipment or continued operation of the facilities. Efficient statistical approach to arrive at the characteristic strength of concrete from limited data has been discussed in literature [1,2]. Nonetheless, the non-destructive testing techniques such as ultrasonic pulse velocity (USPV), rebound hammer (RH), and acoustic emission (AE) have become extremely popular for estimation of the compressive strength of concrete in existing structures due to their obvious advantage of being non-destructive in nature. They are especially useful in cases where the structure is sensitive, or would be distressed by the partially destructive tests such as core tests.

The evaluation of the compressive strength from rebound hammer is based on the principle that the rebound of an elastic mass depends on the hardness of the surface on which it strikes. Thus, a concrete of lower strength and having lower stiffness would yield low rebound number, as it would absorb more energy of the strike. A good quality concrete having higher strength would therefore yield higher rebound number. Thus, an estimate of the compressive strength of concrete can be obtained from the RH value using established correlation curves. The standard curves provided with the instrument might be used, but would have higher errors associated with them. Specific correlation equations developed for a particular structure gives better results in most cases. The various factors affecting the compressive strength estimated from the rebound number are type of cement, type of aggregate, surface condition and moisture content of concrete surface, curing and age of the concrete, and carbonation of concrete surfaces, among others. As the rebound hammer gives an estimate of the strength of the limited depth from the concrete surface, care should be taken to avoid using RH values from areas where surface deterioration or carbonation has occurred.

The estimation of strength of concrete from USPV is generally qualitative in nature. However, there have been studies which worked out quantitative values of compressive strength from USPV readings using correlation equations, and the same has been attempted in this study too. The propagation of the ultrasonic pulses of 50–60 kHz frequency through a concrete medium depends on the soundness of the concrete in terms of homogeneity, uniformity and integrity. A higher strength concrete having a higher elastic modulus would thus, result in higher velocity of the ultrasonic pulses. This relation is captured in the correlation equations developed from the data from the structure.The estimate of concrete strength from USPV would give an idea for the entire concrete member throughout its thickness, in contrast with the surface property given by the RH.

Estimation of concrete strength from such non-destructive tests would be indirect and could be performed by empirical correlation equations describing the relationship between the variable obtained from the non-destructive test, say, USPV or RH and the compressive strength of concrete. The empirical equation may be developed for the particular structure according to the guidelines provided in IS standard [3,4] with the data from the structure.The error margins of the estimated compressive strength from correlation equations and USPV is indicated as ±20% [3] when the equations are developed for the particular structure. Similarly, for estimated compressive strength from RH, the error margins are ±25% [4]. However, the actual estimates of the errors involved in concrete strength estimation derived from the data from the particular structure would be preferable to the generic values of standards [3,4].

In literature there have been reports of correlation expressions for the compressive strength of concrete and USPV or RH using linear regression [5]. In a study where the grade of concrete or its age had been taken as unknown [6], exponential form of equation was advocated for the relationship between USPV and compressive strength. In recent years, linear relationship was favoured between USPV or RH and compressive strength [7]. Samson and Moses [8] developed linear relationship between RH and compressive strength with different grades of concrete and different ages of testing. Kannan [9] explored the relationship between USPV and compressive strength of self-compacting concrete with rice husk and metakaolin with linear equations. Exponential form of the equation was suggested for USPV and compressive strength of roller compacted concrete for different ages and mixes [10] and for USPV and compressive strength of concrete with partial replacement of GGBFS [11]. From the aforementioned discussion, it is observed that linear and exponential forms of equation have been favoured for relationship between the non-destructive tests (USPV or RH) and compressive strength of concrete for different ages and mixes.

In this article, therefore, the limited sets of data pertaining to partially destructive (core) and non-destructive (USPV, RH) tests would be used to identify suitable expression form of the relationships from options such as linear, exponential or any other. From those limited data, the empirical parameters for the suitable relationships (USPV-Compressive Strength; RH-Compressive Strength) would be subsequently estimated. Using the developed empirical correlation expression, the non-destructive test data from the entire structure would be assessed to arrive at the respective compressive strength of concrete and thereafter, conservative characteristic strength of concrete in the existing structure would be suggested. The error in estimate of the compressive strength from USPV or RH would also be evaluated from data obtained from the structure.

2. Data and Methodology

2.1 Data

An important facility was required to be seismically re-qualified due to revision in ground motion parameters and loads. The structure was reinforced cement concrete (RCC) framed type having approximate overall plan dimensions of 120 m × 180 m and consisted of four units separated by expansion joints. The respective units had plan dimensions of 55 m × 100 m (2 storeyed), 65 m × 100 m (5 storeyed), 75 m × 80 m (3 storeyed), 45 m × 80 m (5 storeyed). The typical storey height was around 5 m each, and the structure was founded on raft 7 m below ground level. Few units had thick concrete walls above ground as well as partial basement with thick concrete external walls and internal partitions. The structure had a design concrete strength of 20 MPa, was designed according to then-prevailing IS code of practice [12] and was constructed in late 1980s with the same grade of concrete as was used in design. This was an industrial structure having floor loadings in the order of 10 to 40 kN/m^2 and the design of the concrete mix was according to the then-prevailing codes of practice [13,14]. Being an important facility, strict quality control was implemented during construction. During the service life, continued inspection and periodic maintenance were performed to ensure continued health of the structure.

The various units of the structure were designed together using same material properties and are founded on a common raft. The construction of the facility was executed by the same contractor and the casting of the concrete of the different units was done simultaneously. The raw materials (cement, fine aggregates, coarse aggregates, reinforcement, water, etc.) for concreting came from a common source and the quality control was same for all the units. The inspection and maintenance activities during service life for the units were similar for the entire facility. Presently, for requalification, a common finite element model would be used for analysis of the entire structure and thus, a single material property for concrete (compressive strength) is required. Hence, the results of the non-destructive testing from the four units have been clubbed together to arrive at a single compressive strength of concrete representative of the present day conditions for the entire structure.

A comprehensive non-destructive testing exercise was conducted for estimation of the recent condition of the concrete elements like slabs, beams, columns, beam-column junction, walls, corbels, etc. as regards to strength, carbonation, corrosion, etc. The results of visual inspection indicated that the present concrete quality was apparently good. The structure was exhaustively tested with non-destructive testing methods, such as, USPV and RH. For RH, a mean of nine readings in a grid of 200 mm spacing around the location was recorded as the RH value, according to the stipulations of the IS code [4]. Adopting a similar approach for USPV, which was performed in either direct or semi-direct approach, a mean of nine readings in a grid of 200 mm was recorded as the USPV at a particular location. Limited number of partially destructive tests such as core tests were performed at carefully identified locations over the entire structure.

The objective of this exercise was to develop correlation expressions for determination of the compressive strength of concrete in the existing structure from non-destructive test results. The cores were 69 mm diameter and for testing, length of samples was kept at more than twice the diameter. A total of 65 core test records (with corresponding USPV and RH records) and 558 pairs of USPV and RH records were available for the entire structure. The non-destructive and the partially destructive testing were according to the Indian standards of practice [3,4,12,15]. The rebound hammer machine is shown in Fig. 1a and the execution of the rebound hammer test is presented in Fig. 1b. Similarly, the USPV machine and its execution are depicted in Fig. 2a and Fig. 2b, respectively.

Care was taken to exclude presence of reinforcement in the core samples by employing detailed Profoscope survey. The direction of cores in the columns, and beams was horizontal, which was perpendicular to the direction of placement and compaction. For slabs, the direction of cores were vertical, same as the direction of placement and compaction. Due to the continued operation requirement and functional limitation of the facility, the number of cores was very limited. Thus, the effect due to the core direction or that due to diameter could not be accounted for in the present study. Strength loss due to the variation of the moisture content between the test cores and the in-

Fig. 1 – Rebound hammer: (a) machine, (b) execution

Fig. 2 – Ultrasonic pulse velocity: (a) machine, (b) execution

situ concrete was ignored, as conservative estimate of the strength was intended. The length to diameter ratio for cores tested in the present case was 2.0 and hence no correction was required on this account. The cores were extracted using core cutter as depicted in Fig. 3a and the execution of the core extraction is shown in Fig. 3b. A sample core is shown in Fig. 4a and the testing setup for the compressive strength of the core samples is shown in Fig. 4b. The cores were tested on CTM machine and the compressive strength was estimated by dividing the failure load by the cross sectional area of the core. The correction factor (1.08) for the diameter of core (69 mm < 100 mm) was thereafter applied to arrive at the corrected compressive strength of the cores [15].

For reducing the core test strength to the equivalent concrete strength, various empirical factors reported in literature [16] vary from 0.8 to 0.89. As in this case a conservative concrete strength estimate was desired for the purpose of seismic re-evaluation of the structure for the present day loads, a conservative conversion factor of 0.8 was used to obtain the equivalent cube strength from core results. The equivalent cube strength of concrete obtained from the core test results was available for the study and the same have been referred as the 'core strength' results throughout this article.

For the two sets, first of USPV, RH & core strength, and the second of USPV & RH, were carefully screened for carbonation of concrete and the data sets finally obtained (65 data in first, and 558 data in second) were those where there were no carbonation of concrete.The data consisted of 65 sets of data from non-destructive and partially destructive tests from the structure, namely,USPV, RH, and core strength data, as explained above. These formed the basis of development of correlation expressions. Further, there were 558 sets of data from only non-destructive tests, namely, USPV and RH, from the structure. These were used to estimate the conservative characteristic strength of concrete as present in the structure.

2.2 Methodology

The entire data would be examined for possible existence of outliers on either extremes of the data set and outliers, if any, would be eliminated. Subsequently, the core-USPV-RH data would be explored for determination of the suitable equation form of the correlation expression between the core-USPV and core-RH by splitting them into representative modeling and testing sets. The distri-

Fig. 3 – Extraction of concrete cores: (a) machine, (b) execution

Fig. 4 – Testing of concrete cores: (a) extracted concrete core sample, (b) testing setup for compressive strength of cores

bution of the data into the two sets would be performed by stratified sampling approach [17], in order to ensure the representative samples for the modeling and the testing data sets. The entire data of core-USPV-RH would thereafter be utilized for development of the suitable correlation expressions for estimation of the compressive strength of concrete. Using these correlation expressions arrived at for the structure under study, the estimates of compressive strength would be obtained from the non-destructive tests (USPV and RH) conducted over the entire structure. From the set of estimated compressive strength data, conservative estimate of concrete would be suggested, which could be henceforth used in re-evaluation studies for the structure. The systematic step-by-step approach for the complete methodology for determination of characteristic strength of concrete from the NDT results is depicted in Fig. 5 and explained in the following sub-sections.

2.2.1 Detection of outliers

The detection of the outliers would be performed according to the Indian standard for the same [18] using the Grubs method for the outliers at either extremes of the dataset. The test statistic would be the absolute difference between the maximum (or minimum) value of a variable and its mean, divided by the standard deviation. The limiting values of the test statistic would be taken from Table 1 of IS code [18] for 1% significance level. In this case, limiting value corresponding to sample size of 50 or more would be applicable and this would be '3.336' at 1% significance level.

2.2.2 Forms of equation for correlation of compressive strength of concrete and USPV / RH

The general form of expression normally favored by the industry for correlation between USPV and compressive strength or RH and compressive strength is linear equation (Eq. 1) and such equations have been reported in literature [5,7,8,9]. The IS codes applicable for the USPV and RH testing [3,4] are silent on the forms of correlation expressions with compressive strength of concrete. In literature [6,10,11] there have been reports of a power (exponential) form of equation being suitable for the USPV and compressive strength correlation (Eq. 2). In addition to these two, the reciprocal equation (Eq. 3) is selected for examining its suitability for this study.

$$y = a + bx \quad (1)$$

$$y = a + b \times e^{cx} \quad (2)$$

$$y = \frac{1}{a+bx} \quad (3)$$

where y = compressive strength of concrete; x = USPV or RH; and a, b, c = empirical constants evaluated from the data.

2.2.3 Determination of suitable correlation expression

The regular industrial practice is to determine the empirical constants of the equations and evaluate the performance of the developed expressions from the same dataset. As an improvement over that, in this study, the dataset would be divided into two sets: the modeling set, with which the empirical constants of equations would be determined and the testing set, with which the performance of the equation so derived would be evaluated. The distribution of the data into the two sets would be performed by stratified sampling approach [17], in order to ensure the representative samples for the modeling and the testing data sets. The estimation of the coefficients (a, b, c) of the expressions (Eq. 1 to Eq. 3) was performed using the modeling data based on the least square principle [19]. The evaluation of the different equations for suitability would be performed using the testing set, based on the performance indices such as: root mean squared error (RMSE), mean absolute error (MAE), and maximum absolute error (MaxAE), which are self-explanatory. The best suited expression is selected based on the performance measures taken together to arrive at the correlation equation between the two selected variables. This was performed separately for the USPV and equivalent compressive strength as well as RH and equivalent compressive strength.

2.2.4 Estimation of compressive strength of concrete for the structure from USPV / RH

The estimate of compressive strength of concrete from the correlation expression with RH would reflect the concrete property for a limited depth from the surface. The USPV estimate would yield an estimate that would be reflecting the concrete properties for the entire depth of the member, but would be invariably affected by reinforcements in the path of the USPV measurements.

Hence, it is postulated that a weighted combination of the two to arrive at a robust estimate of the compressive strength of concrete in the structure. Further, the estimates of the compressive strength from the RH would involve an inaccuracy of ±25% according to the IS code [4] for laboratory specimens and similar error margin would be ±20% for the estimate of compressive strength from USPV [3]. However, in this case, as sufficient data was available, the error quantification is performed directly from the analysis of the data from the existing structure, as recommended by the IS code [3,4].

2.2.5 Estimation of conservative characteristic strength of concrete for the structure from USPV / RH

The USPV and RH recording from the entire structure was taken after the outlier elimination (if required), and using the weighted combination of the correlation expressions between the compressive strength and USPV / RH, the estimation of compressive strength was performed. IS code [12] defines the characteristic strength of concrete as the strength below which not more than five percent results are expected to fall, or in other words, the five percentile value. Further, for non-destructive or partially destructive tests on concrete, IS code [12] suggests adoption of the minimum of two values based on the mean and the minimum of the estimates from non-destructive / partially destructive tests. Combining the two stipulations, in this study, the conservative characteristic strength is suggested as the lowest of the following:

i. The mean of estimated equivalent cube strength from USPV / RH is equal to at least 85 percent of the characteristic strength of concrete.

ii. The minimum estimated equivalent cube strength from USPV / RH is at least equal to 75 percent of the characteristic strength of concrete.

iii. Five percentile value of the estimates of compressive strength from USPV / RH.

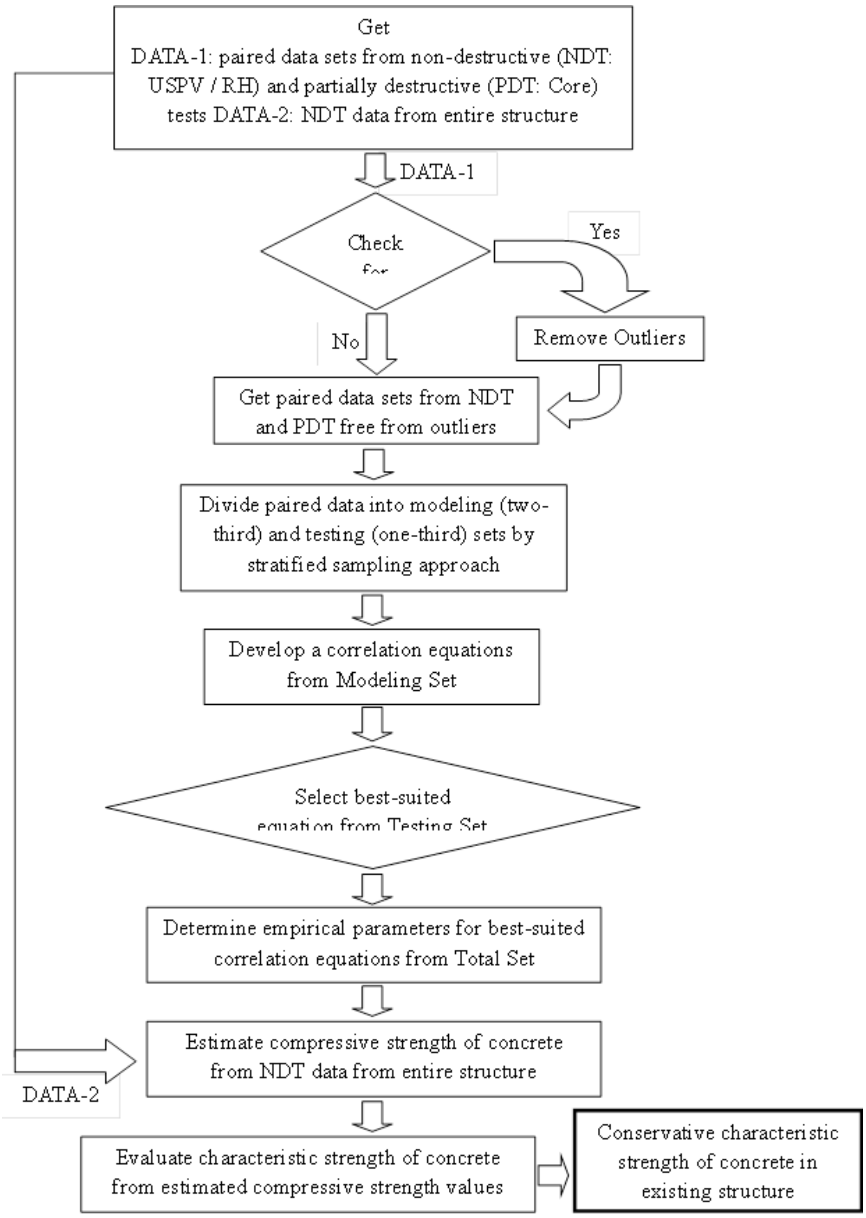


Fig. 5 – Flow-chart for the strategy for determination of conservative characteristic strength of concrete from NDT results

The mean error in the estimate would be as indicated in Section 2.2.4.

3. Results and Discussion

3.1 Data statistics

The descriptive statistics for the basic data (65 sets) from non-destructive and partially destructive tests are presented in Table 1. The mean USPV is 4.31 km/sec representing overall good quality concrete for the structure, though a high coefficient of variation (COV) of 0.33 indicates high variability in the range of 5.28 km/sec to 3.13 km/sec. The high variability could be attributed to the various factors such as occasional presence of reinforcements, internal voids and cracks in concrete in path of USPV.

In case of RH the range of number is quite small from 39 to 54.6 (the decimal value is due to the averaging of the 9 readings) with a mean reading of 47. The COV for RH numbers is 0.11, which depicts a variability lower than USPV. This is expected as the RH represents the properties of concrete up to a limited depth from surface and unaffected by the internal voids or cracks. The core strength results are much less scattered with the COV at 0.07 and high values of both mean (30 MPa) and standard deviation (9.9 MPa). These results indicates that the determination of present characteristic strength of concrete for the structure must be performed with due attention to the outliers, if any. Further, the high degree of variability presented in the results should be considered in arriving at the conservative estimate of the charact-

Table 1 – Descriptive statistics of the non-destructive and partially destructive tests: USPV, RH, and core strength

Statistic	USPV (km/sec)	RH	Core strength (MPa)
Mean	4.31	47.32	29.99
Median	4.36	47.50	28.19
Standard deviation	0.48	3.29	9.90
Maximum	5.28	54.60	61.63
Minimum	3.13	39.00	13.10

Table 2 – Descriptive statistics of the non-destructive tests: USPV, and RH

Statistic	USPV (km/sec)	RH
Mean	3.77	47.63
Median	3.78	47.00
Standard deviation	0.39	3.14
Maximum	5.30	57.00
Minimum	3.00	39.00

eristics strength of concrete. The distribution of RH number as well as USPV appears to be almost symmetric, whereas the core strength is moderately asymmetric towards the left: as indicated by the relative values of mean and median for the variables.

The descriptive statistics for the non-destructive tests (558 sets) on the structure are listed in Table 2. The distribution of the data for both USPV and RH appear to be symmetric, as was observed for the sub-set. The statistics remain almost similar to those for the sub-set, with the standard deviation and COV reducing to lower values – the obvious result of the larger number of data.

3.2 Detection of outliers

The detection of outliers for the data was performed following the procedure outlined in Section 2.2.1 above. The extreme values, that is the maximum and the minimum values for each of the three variables, namely, USPV, RH and core strength were checked for the outliers separately and the results are listed in the Table 3. The check for outliers was negative at the significance level of 1% as can be observed in the Table 3 for each of the extremes. Hence, the entire data could be utilized for the subsequent analysis.

3.3 Division of data (65 nos.) in modeling set and testing set by stratified sampling

As outlined in Section 2.2, the data for USPV-compressive strength from the total set of 65 pairs, stratified sampling was adopted to divide the data into modeling set of 43 numbers (two-third) and testing set of 22 numbers (one-third). The histograms for the total set, the modeling set and the testing set for USPV sets depicted in Fig. 6a, Fig. 6b and Fig. 6c respectively, are very much similar with two peaks at same locations.

Similar histograms developed for the sets of RH-compressive strength pairs are presented in Fig. 7, which shows that the testing set is somewhat differently distributed, when compared to the total set or the modeling set, which are, incidentally, quite similar.

3.4 Determination of equation form for USPV – compressive strength correlation expression

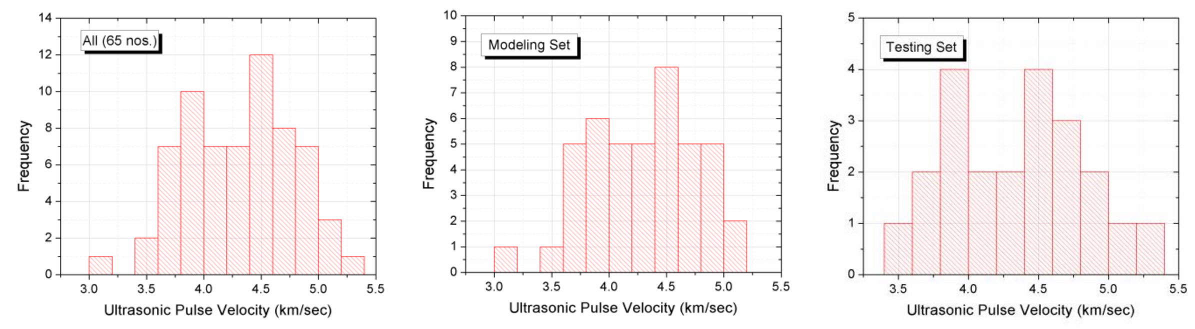
As outlined in Section 2.2.2, three equation forms were explored for suitability and the errors (MAE, RMSE, & Max.AE as explained in Section 2.2.3) obtained from the testing data for the three equation forms are presented in Fig. 8 for the correlation expression between USPV and compressive strength of concrete. It is evident that the three equation forms result in almost comparable values of errors, and therefore, the linear expression is chosen for further analysis owing to its simplicity of appreciation and application.

3.5 Determination of equation form for RH – compressive strength correlation expression

Similar to the USPV, the errors (MAE, RMSE, & Max.AE as explained in Section 2.2.3) obtained from the testing data for the three equation forms (as outlined in Section 2.2.2) are presented in Fig. 9 for the correlation expression between RH and compressive strength of concrete. In case of RH-compressive strength correlation the linear and exponential forms result in almost comparable values of mean errors, whereas the reciprocal form yields higher mean errors. Though the maximum absolute error is less for reciprocal form, the linear expression is chosen for further analysis owing to the lower mean errors as well as its simplicity of appreciation and application.

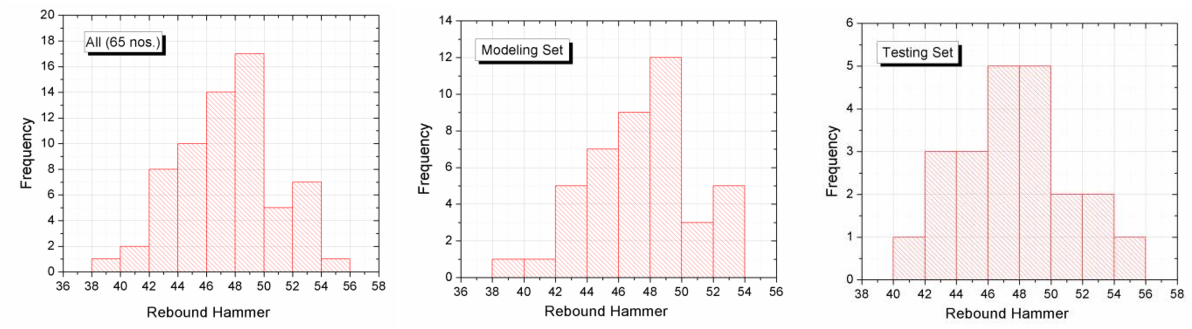
Table 3 – Check for outliers in the non-destructive and partially destructive tests: USPV, RH, and core strength

Number of data	Variable	Test statistic		Limiting value (Significance level: 1%)
		Maximum	Minimum	
65	USPV	2.027	2.491	3.336 (for higher than 50 numbers of data)
	RH	2.211	2.526	
	Core strength	3.197	1.706	
558	USPV	2.99	1.98	3.336 (for higher than 50 numbers of data)
	RH	2.98	2.75	



(a) (b) (c)

Fig. 6 – Histograms for USPV: (a) total (65 nos.), (b) modeling set (43 nos.), (c) testing set (22 nos.)



(a) (b) (c)

Fig. 7 – Histograms for RH: (a) total (65 nos.), (b) modeling set (43 nos.), (c) testing set (22 nos.)

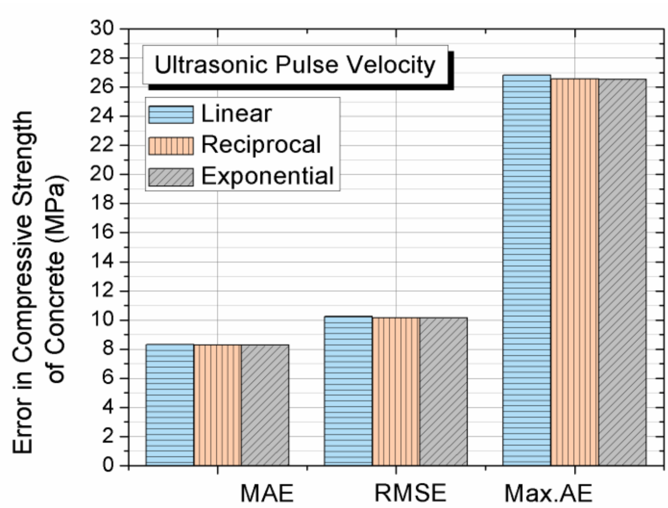


Fig. 8 – Comparison of errors in estimate of compressive strength of concrete with different equation forms for USPV-compressive strength

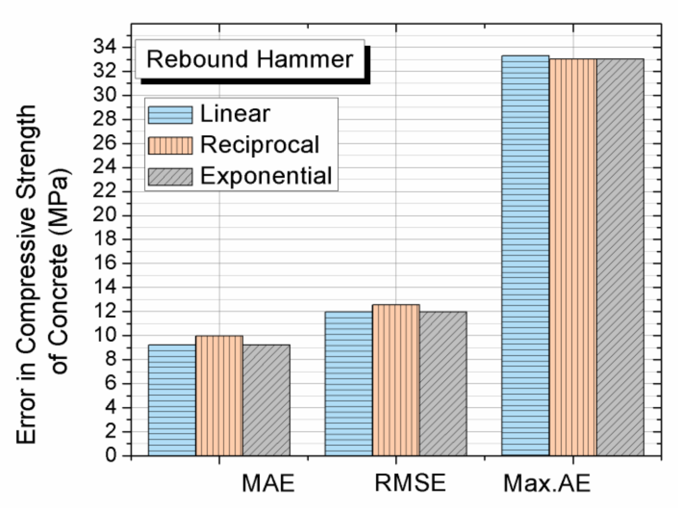


Fig. 9 – Comparison of errors in estimate of compressive strength of concrete with different equation forms for RH-compressive strength

3.6 Determination of correlation expression for the structure: USPV – compressive strength

With the linear equation form (selected in Section 3.4), the total data comprising of 65 sets of paired readings are used to arrive at the empirical coefficients of the equation for correlation between USPV and compressive strength of concrete. The intercept value is 22.97996 and the slope of the line is 1.62501 and the relation is given by Eq. 4.

$$y = 22.97996 + 1.62501x \qquad (4)$$

where y = compressive strength of concrete; and x = USPV.

The errors for the obtained equation from the same set of data are presented in Fig. 10, wherein it is noted that the mean errors have reduced slightly from those of the testing data (Fig. 8), whereas the maximum error has increased considerably more. The reduction of the mean error is due to use of the same data sets for estimation of the empirical constants of equation and the errors. The maximum error increased in this case (compared to the testing data in Section 3.4) due to the inclusion of the set containing the maximum core strength data (this was in the modeling set in Section 3.4). From the foregoing discussion, it is concluded that the error margins of the estimates from this correlation expression would be indicated by the mean errors: of the order of 8 to 10 MPa. This error margin is higher than that of the IS code [3] value, which comes to 6 MPa, and this would be due to the higher dispersion in the data used for developing the correlation expressions.

3.7 Determination of correlation expression for the structure: RH – compressive strength

With the linear equation form (selected in Section 3.5), the total data comprising of 65 sets of paired readings are used to arrive at the empirical coefficients of the equation for correlation between RH and compressive strength of concrete. The intercept value is 18.07067 and the slope of the line is 0.25186 and the relation is given by Eq. 5.

$$y = 18.07067 + 0.25186x \qquad (5)$$

where y = compressive strength of concrete; and x = RH.

The errors for the obtained equation from the same set of data are presented in Fig. 11, wherein it is noted that the mean errors have reduced slightly from those of the testing data (Fig. 9), whereas the maximum error remained similar.

The reduction of the mean error is due to use of the same data sets for estimation of the empirical constants of equation and the errors. The maximum error did not increase in this case (compared to the testing data in Section 3.5) since the maximum core strength data was present in the testing set in Section 3.5. The different data divisions for the USPV (Section 3.4) and RH (Section 3.5) resulted due to the stratified sampling method adopted based on the USPV and RH values. From the foregoing discussion, it is concluded that the error margins of the estimates from this correlation expression would be indicated by the mean errors: of the order of 8 to 10 MPa, similar to that from the USPV. As in USPV- compressive strength correlation, the error margin is higher for RH-compressive strength correlation than that of the IS code [4] value, which comes to 7.5 MPa, and this would be due to the higher variability in the data used for developing the correlation expressions.

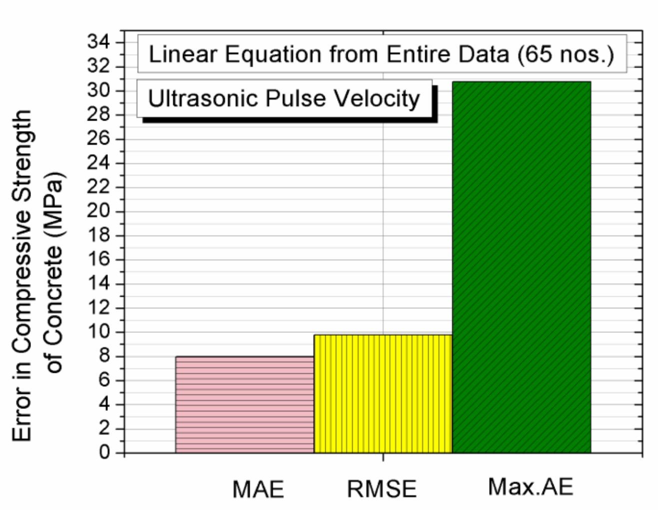


Fig. 10 – Errors in estimate of compressive strength of concrete from USPV

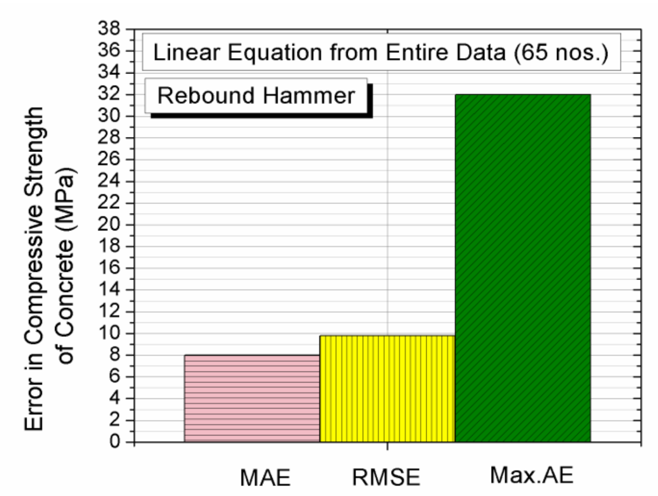


Fig. 11 – Errors in estimate of compressive strength of concrete from RH

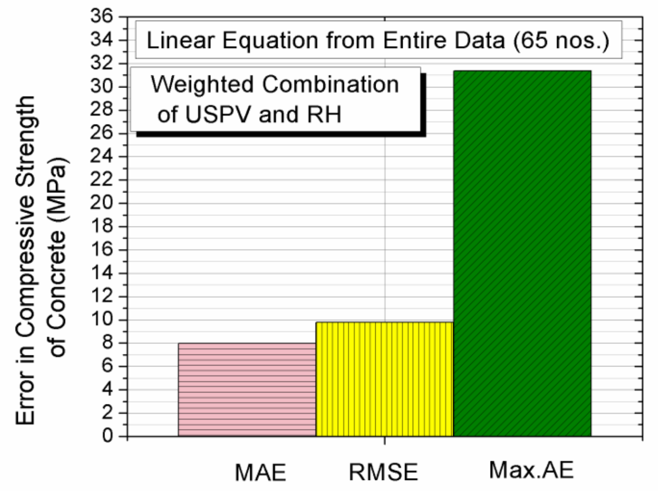
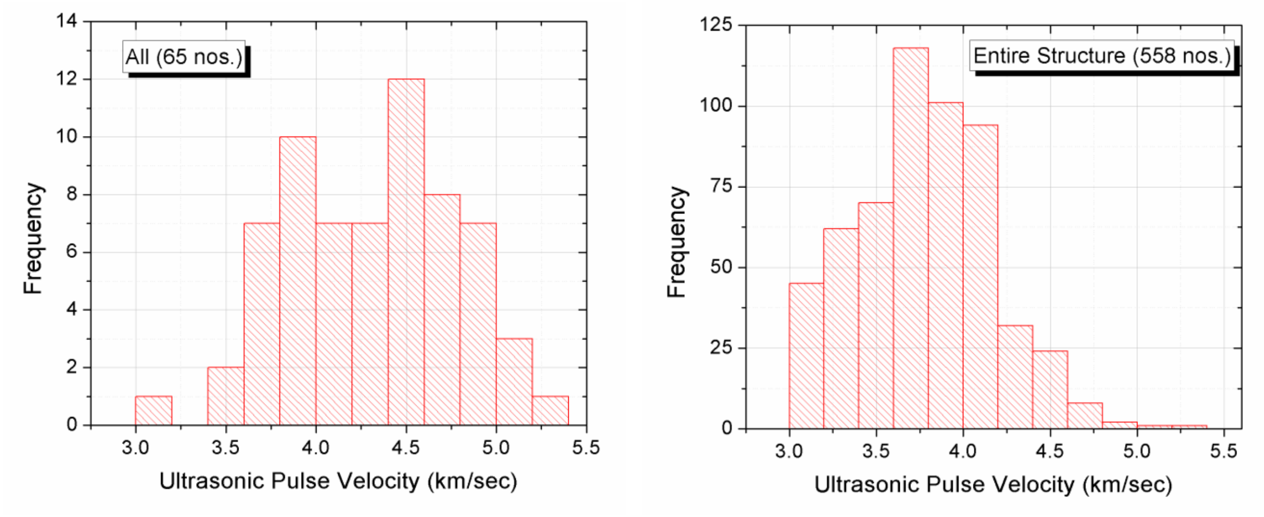
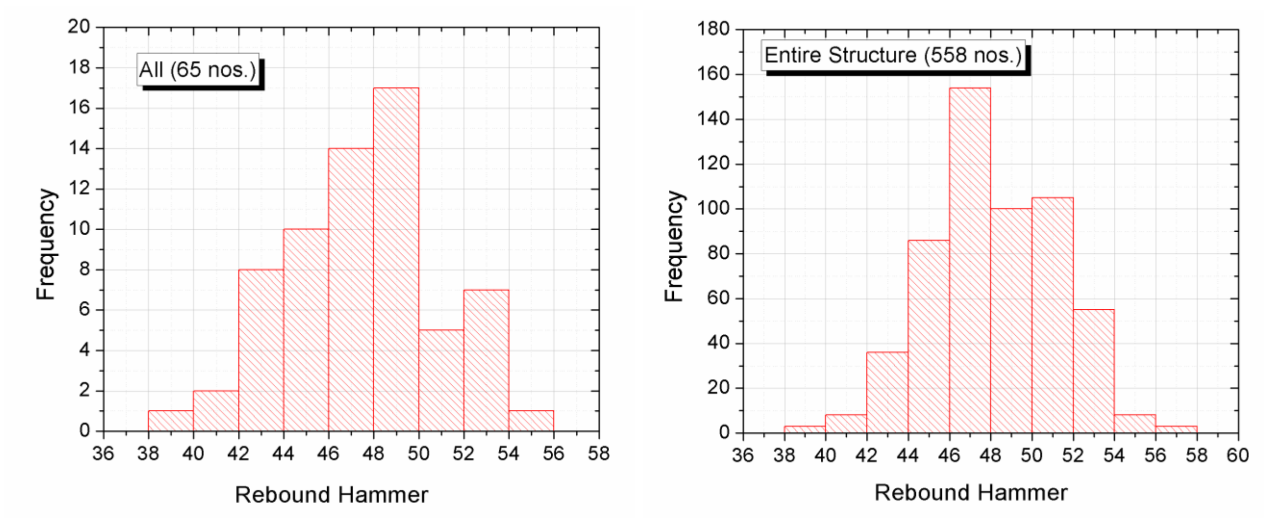


Fig. 12 – Errors in estimate of compressive strength of concrete from weighted combination of USPV and RH



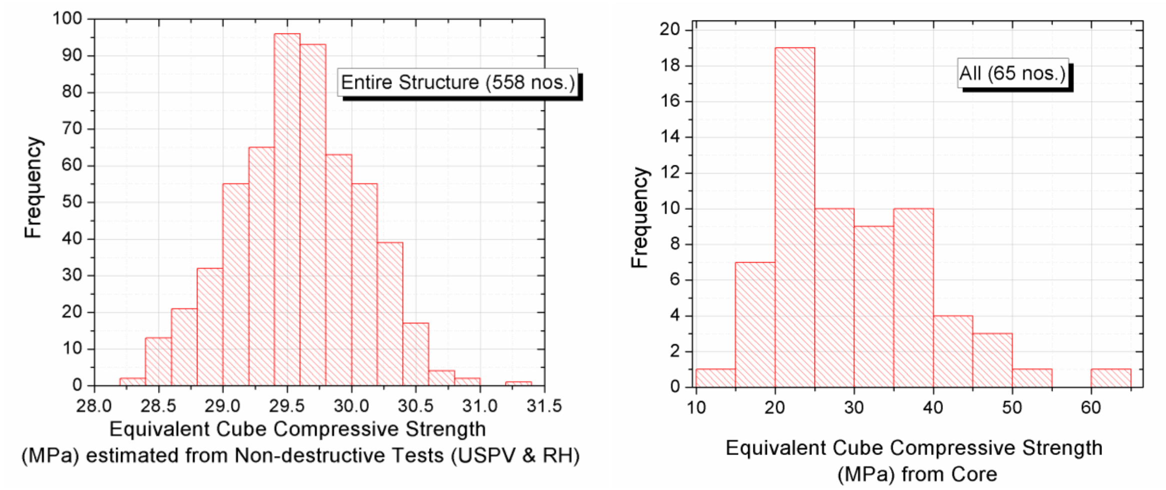
(a) (b)

Fig. 13 – Histogram for USPV: (a) data for development of correlation expression (65 nos.), (b) data from entire structure (558 nos.)



(a) (b)

Fig. 14 – Histogram for RH: (a) data for development of correlation expression (65 nos.), (b) data from entire structure (558 nos.)



(a) (b)

Fig. 15 – Histogram for equivalent cube compressive strength: (a) estimate from non-destructive tests (USPV & RH: 558 nos.), (b) from core test (65 nos.)

3.8 Suggested strategy for evaluation of compressive strength of concrete from USPV and RH

IS code [3,4] suggests use of correlation expression between USPV or RH with compressive strength for estimation of concrete strength from non-destructive strength. However, the rebound hammer estimate is limited to the state of concrete up to a certain depth from the surface. USPV estimate, on the other hand, can account for the internal state of concrete such as voids or cracks, but is affected by the presence of reinforcement in the path of USPV. It is suggested to utilize a weighted summation value for attaining a more robust estimate of compressive strength from the non-destructive tests. For this purpose, different weight pairs were explored and it was concluded that equal weight assigned to the estimates from both USPV and RH would be acceptable for this structure. This is understandable as the mean errors as well as the maximum errors were similar for the estimates from both USPV and RH in this particular case. The resulting expression is presented in Eq. 6.

$$y = 0.5(22.97996 + 1.62501x_1) + 0.5(18.07067 + 0.25186x_2) \quad (6)$$

where y = compressive strength of concrete; x_1 = USPV; and x_2 = RH.

The overall errors involved is presented in Fig. 12 and the error margins of the estimates from this equation would be indicated by the mean errors: of the order of 8 to 10 MPa, similar to those in individual estimates from USPV (Section 3.6) or RH (Section 3.7).

3.9 Estimation of characteristic strength of concrete in the structure from USPV and RH

The compressive strength of concrete in the existing structure is hereby estimated from the non-destructive test results (USPV & RH) employing the correlation expressions obtained in Section 3.6 and Section 3.7, adopting the strategy outlined in Section 3.8.

The histograms for the USPV and RH for the datasets (65 nos.) utilized in development of the correlation expression (Section 3.6 & 3.7 respectively) are presented along with those from the entire structure (558 nos.) in Fig. 13 and Fig. 14 respectively. The concrete quality for the entire structure (Fig. 13b) ranges predominantly from medium to good whereas it ranges from good to excellent in Fig. 13a. It is noteworthy that the cores were taken from locations, which were accessible and did not pose hindrance to the continued operation of the facility. The comparatively better concrete at the core locations relative to the varied concrete quality over the entire structure (due to internal microscopic voids or cracks) as well as the presence of reinforcements in the USPV path (near the core locations) could account for the comparatively poor concrete quality indicated for the entire structure.

In case of the rebound hammer, the histograms for either case appear to be similar, predominantly yielding values between 42 and 54. This indicates that the concrete quality up to a certain depth from surface over the entire structure is similar to those at the core locations.

The histogram of the equivalent cube compressive strength of concrete in the existing structure estimated from the non-destructive tests (USPV & RH) is depicted in Fig. 15 and the histogram for the equivalent cube compressive strength from core tests (65 nos.) is presented alongside for comparison. Due to the high variability of the equivalent cube strength obtained from the core results, the histogram (Fig. 15b) is spread over in the range from 15 MPa to 55 MPa with standard deviation at 9.9 MPa.

However, owing to the fact that the correlation between the USPV and compressive strength as well as that between the RH and compressive strength was poor, the compressive strength estimated from the non-destructive test results fall in a narrow band from 28.5 MPa to 30.5 MPa. It may be appreciated that the apparent difference in the shapes of the histograms arise from the different methods adopted for their estimates, namely direct (core strength) and indirect (USPV and RH). The descriptive statistics for the estimates of compressive strength from the non-destructive test results are presented in Table 4, which clearly signify that the relationship between the compressive strength and the non-destructive test results was very flat allowing marginal improvement of the estimated compressive strength for increase in USPV and RH results.

In order to arrive at the conservative characteristic strength of concrete from the compressive strength estimated from non-destructive tests (USPV & RH), the approach outlined in Section 2.2.5 was adopted and the three resulting values are depicted in Fig. 16, along with the characteristic strength values. The conservative characteristic strength rounded off to lower integer value, comes out to be 28 MPa (or M28), which is lower than the permissible value of characteristic strength (34 MPa) according to IS code (IS 456). Because of the high variability in the initial data used for deriving the correlation expressions for estimation of compressive strength from USPV and RH, the authors advocate adoption of the suggested

Table 4 – Descriptive statistics of the estimates of compressive strength from non-destructive tests (USPV and RH)

Statistic	Compressive Strength (MPa)
Mean	29.59
Median	29.59
Standard Deviation	0.50
Maximum	31.24
Minimum	28.29

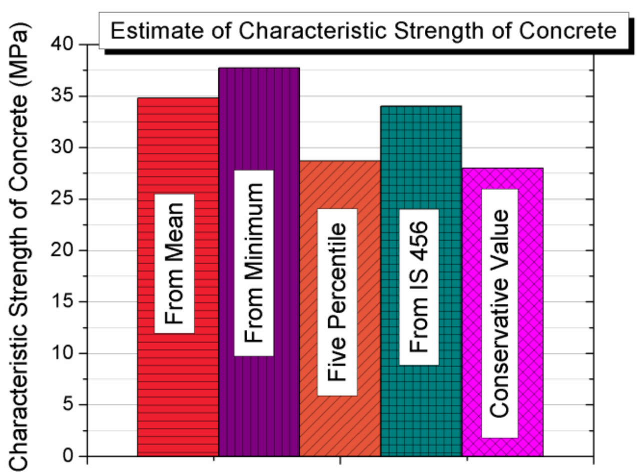


Fig. 16 – Conservative Characteristic Strength of Concrete from NDT

conservative strength for re-evaluation studies for the structure.

4. Summary and Conclusions

In this article, the strategy for evaluation of conservative characteristic strength of concrete from the non-destructive testing (USPV and RH) on the existing structures was elucidated with a case study. Evaluation of different forms of expression (linear, reciprocal, & exponential) for the relationship between compressive strength and USPV and RH resulted in the conclusion that linear expression would be suited for both non-destructive tests.

The total records of the USPV, RH and core results (65 nos.) were thereafter employed to determine the linear correlation expressions, which were subsequently applied on the USPV and RH records from the entire structure (558 nos.) to arrive at the estimates of equivalent cube strength. The mean and median of the estimates were same value of 29.59 MPa with a low standard deviation of 0.5 MPa. All the values were in the narrow range of 28.29 MPa to 31.24 MPa, owing to the low value of the slope of the linear relationship. The low slope parameter resulted due to the high variability of the data (paired sets of USPV-RH-compressive Strength: 65 nos.) used for development of the relationships. The associated errors in the estimate of compressive strength would be limited to around 8–10 MPa, as was ascertained from the data obtained from the structure, as against the IS code [3,4] error estimates of 6–7.5 MPa. The higher variability in the combined data would account for the value of actual error estimate being higher than the IS code.

The characteristic strength of concrete in the structure from considerations of Indian standards was 34 MPa, or in other words, the present grade of concrete in the structure was M34. However, owing to the high variability observed in the dataset (65 nos.) used for development of the correlation equations, it was suggested to limit the characteristic strength of concrete to 28 MPa conservatively. This value was arrived by taking the five percentile value from the compressive strength of concrete estimated from USPV and RH.

It is noteworthy that both the grades thus arrived at, namely M34 or M28, are higher than the grade of concrete used in design of structure, which was M20. Such increase in concrete strength in old structures are admissible provided that quality control in construction was good, efficient and periodic maintenance was performed. Additionally, due to the progressive hydration of cement in concrete structures, certain increase in strength normally occurs. The suggested value of characteristic strength of concrete can hereafter be utilized for health assessment and re-evaluation studies of the structure. The case study presented in this article would be useful as a reference for engineers engaged in condition assessment and re-evaluation exercises of existing concrete structures. The correlation expressions of compressive strength of concrete with USPV or RH developed in this study are best suited for this particular structure. The use of these expressions for other structures of similar or different compressive strength of concrete could be associated with higher errors and uncertainties of estimation.

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