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Estimation of present-day strength of concrete for a 40-year-old building from non-destructive tests: A case study

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Abstract: Assessment of the present health of existing concrete structures is necessary, particularly for enhancing the life of the infrastructure facilities reaching the end of their design life. The codes stipulate establishment of site-specific correlation expressions to estimate the compressive strength of concrete from indirect non-destructive tests (NDT) such as rebound hammer or ultrasonic pulse velocity tests. However, in certain circumstances, requisite number of partially destructive (core) tests required for establishing the site-specific equations might not be feasible. In such scenario, selection of a suitable correlation expression from literature has to be performed in a rational way, as discussed in this article with a case study of a 40-year-old concrete building. From the study, it has been observed that for the limited number of direct tests, the Indian code stipulation resulted in higher characteristic strength of concrete as compared to the parametric estimation, which can be attributed to the assumption of Normal distribution and code stipulated (conservative) standard deviation value. In case of the indirect estimation cases, the parametric characteristic strength was pretty close to the corresponding non-parametric values indicating that the fitted distributions represented the strength values very well. Recommendations for the suitable correlation expression from literature applicable for estimation of equivalent strength from NDT for the structure, recommendation for characteristic compressive strength of concrete and the suggestions for accounting for the inaccuracies in estimated strength in subsequent structural re-analysis have been provided from the results of the study.

Keywords: Non-destructive test, Ultrasonic pulse velocity, Rebound hammer, Structural health assessment, Correlation, Concrete characteristic strength.

1. Introduction

Assessment of the health of the existing structures becomes necessary in many scenarios, particularly for periodic evaluation or verifying adequacy of the structure after some distress. This distress might arise from some accident such as occurrence of a seismic event (for which the structure was not designed), an explosion or a fire. The perceived damage in the structure might also arise from long term effects such as strength degradation or corrosion related to environmental exposure conditions. In such cases, the tools available to the engineer are conducting non-destructive test (NDT) and / or partially destructive testing (PDT) followed by interpretation of the results of NDT / PDT that would provide the necessary data for further analysis of the structure according to the present-day strength and subsequently, decision about retrofitting and rehabilitation or demolition might be judiciously taken. Among the most popular and widely conducted NDT methods, two are ultrasonic pulse velocity test (USPV) and rebound hammer test (RH), whereas the core test remains the most common PDT which gives the compressive strength of the concrete directly. For aged structures or for heavily damaged structures, PDT is avoided or very much limited in number to limit the distress to the already distressed structure. In that case, the estimate of the strength has to be performed solely from NDT results. As the NDT do not provide the strength parameters directly, the strength

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estimate is based on the correlation equation between the NDT and the compressive strength of concrete.

The Indian national code on NDT [1,2] suggests that building specific expressions be developed for improved accuracy in the strength estimates from NDT. If representative PDT results are available for the structure, the present concrete strength may be evaluated according to the provisions of Indian national code on concrete [3]. However, as discussed earlier, PDT results might not be feasible to execute or sufficient in number for proper representative sample or for development of suitable correlation expressions specific to the structure in certain cases. Therefore, the option available to the practicing engineer is to utilize the expressions from literature in a judicious manner to arrive at the best estimate of the compressive strength of the structure. A plethora of research is available reporting various correlation expressions between NDT and PDT, and a few were selected for this study [4–14].

Factors affecting the core strength and NDT have been discussed by Kabay and Fevziye [15]. NDT has been employed for post fire residual strength assessment of concrete structure as well [16]. Poorarbabi et al. [17] examined the conversion factors between NDT of cube and cylindrical concrete specimens. A concept of condition rating was suggested by Wiyanto et al. [18] based on analysis of the results of NDT. Estimate of conservative strength for existing structure from NDT results was discussed by Dauji et al. [19], but the data used in the study was pair-wise NDT and PDT results, from which site-specific correlation expressions could be developed. The latest technologies available for NDT of concrete along with their relative merits and demerits were dealt in detail by Masri and Rakha [20]. It is highlighted that in most of the research works where relationships were developed for estimation of compressive strength of concrete from NDT, the direct (core) results were available corresponding to the NDT data.

In the problem taken up for the present study, not only were core results available for very few (5 nos.) with concurrent NDT data, but also the design strength of the structure was unknown. Whereas the structure apparently was constructed with same grade of concrete for all members, due to unavailability of the design documents or drawings, the specific grade of concrete or similarity / difference of the grades for the various members could not be ascertained. This imposed limitation in initial shortlisting of correlation expressions from literature, for obtaining present-day strength of the building. Therefore, the crux was to estimate the present strength of concrete using NDT data and correlation expressions from literature, with only five core test data for columns, and no information regarding the original grade/s of concrete. Therefore, the selection of suitable correlation expression could not be performed in a straightforward manner. Use of different formulae could give a wide range of strength estimates in most cases. Therefore, an indirect approach was adopted in order to obtain the present-day compressive strength of concrete from NDT data and this would be discussed in detail in the following sections.

2. Uncertainties and challenges in concrete strength estimation of the building from NDT

In health assessment or re-evaluation purposes, characteristic compressive strength is the key quantitative parameter required to carry out further analysis or to estimate other properties indirectly such as modulus of rupture and modulus of elasticity. Generally, USPV and RH provide qualitative information regarding the health of the structure which is subsequently interpreted quantitatively. USPV values of concrete in existing structure does get affected with surface condition, moisture content of concrete, density, shape and size of member, temperature, path length, stress, presence of reinforcement or micro cracks, method of testing (direct, semi-direct or indirect) and etc. These uncertainties may sometimes give variability in obtained results as high as + 20% [1]. On the other hand, RH values may also involve various uncertainties up to 25% [2], primarily due to type of cement, type of aggregate, surface condition, moisture content, curing, age of concrete and state of carbonation of the concrete surface among others. Although, there are uncertainties involved in both the test methods and interpretation of results, RH is perhaps slightly better representation of present concrete strength as the USPV results are highly influenced by the composition, heterogeneous nature, presence of reinforcements and density variations of concrete. It is needless to mention that both tests involve certain inherent limitations which manifest as various uncertainties in generated correlation expressions. Hence, to a capture the wide spectrum of above-mentioned uncertainties, it is always better to use both methods of the testing to arrive at the conclusion of compressive strength of concrete.

The present study required estimation of present-day strength of a 40-year-old structure from NDT results (USPV and RH) distributed over the entire structure and PDT results (core tests: 6 nos.) in selected locations. Due to advanced age of the structure the number of PDT allowed was restricted to six. The strength estimate could be performed from the PDT results according to the national standard [3], but due to the limited locations at which the PDT could be performed, that particular strength estimate might not properly reflect the present health of concrete over the entire structure. In order to have a better representative concrete strength estimate, the NDT results, which were distributed over the entire structure, would have to be used along with the PDT strength estimate in a judicious manner.

For this purpose, however, the low number of PDT data (six, out of which NDT tests had been carried out at five locations) was deemed insufficient for accurate estimation of the empirical parameters of the correlation equation relating the NDT results to the compressive strength. Therefore, earlier studies from literature [4–7,7,9–14], where such correlation equations had been reported, were examined for suitability and utilized in order to arrive at the equivalent compressive strength from NDT results, namely, USPV and RH.

3. Data and methods

3.1 Data

The particular building considered in this study is an institutional building, having more than 40 years of occupancy and some distress was observed at certain locations in the structure. Therefore, for continued and safe occupancy of the building, it was decided to assess the present-day health of the concrete for subsequent decision making. The building is a single storied building having plan dimension approximately 70 m × 30 m, and height of approximately 5 m situated in Kolkata, West Bengal, India having facilities such as laboratories, lecture halls, office spaces, and other functional areas such as kitchen and toilets. The building is having approximately90 number of columns and 125 beams at plinth & roof levels. Due to unavailability of structural drawing and embedded columns in walls at site, estimation of beam and column numbers could not be done with 100% accuracy. Further details about the facility cannot be disclosed due to confidentiality issues. The design documents or drawings for the building were not available for reference. For the purposes of NDT campaign, a layout drawing was regenerated from measurements and the test locations (core test: 1; RH & USPV: 2) were marked on the same (Fig. 1). As the building had passed 80% (40 years) of the design service life of 50 years, the core tests were limited to only six carefully selected locations (marked with '1' in Fig. 1). Additionally, due to functional limitations, accessibility issues and further, to avoid any local damage to the structure, locations of the limited number of core test were selected from non-critical locations. All these samples for core test (out of which NDT was carried out only at five locations) were taken only from column locations. Among these test locations five samples were from ground floor (marked with '-G' in Fig. 1) and one sample was taken below plinth (marked with '-P' in Fig. 1). Location-wise, four samples were on external columns (marked with 'E-' in Fig. 1) and two were for internal columns (marked with 'I-' in Fig. 1). The diameter of the cores was 68 mm for all cases, but the lengths were different resulting in length-to-diameter ratios between 1.68 to 2.01, for which the appropriate correction factor was applied to arrive at the equivalent compressive strength according to the BIS code [21].

Otherwise, the NDT tests, namely, RH and USPV were distributed evenly over the entire building on beams (65 locations), columns (41 locations) and slabs (34 locations) to ensure representative sample space for the complete structure. Readers may note that among the locations marked for NDT (with '2') in Fig. 1, NDT was conducted at different levels for some locations marked in plan, and therefore, the number of locations marked in plan ('2' in Fig. 1) would be less than the total number of NDT datasets reported. As recommended in the applicable national standards [1,2], the RH or USPV value reported for each testing point is the mean value of nine readings obtained in a grid pattern around the designated testing point. The details of the procedure adopted for tests (RH and USPV) may be referred in literature [1,2]. NDT results would be used to estimate the present strength of concrete in different elements separately, and subsequently the compressive strength for the entire structure can be selected in conservative manner. The salient statistics have been presented in the form of box-and-whisker plots in Fig. 2 and Fig. 3 for RH and USPV respectively. Complete data (after removal of outliers) have been provided in Appendix.

Whereas the mean of the RH is highest for column and lowest for the beams, the USPV is lowest for the slabs while it is highest for column. The spread of data is the maximum for columns, followed by beams, and the spread is the minimum for slab – for both RH and USPV. Such differences in values for different members could be explained by the fact that the RH mainly reflects the surface strength and is affected by surface cracking etc. whereas the USPV represents the internal strength of concrete member and gets affected by proximity of reinforcement to the test location.

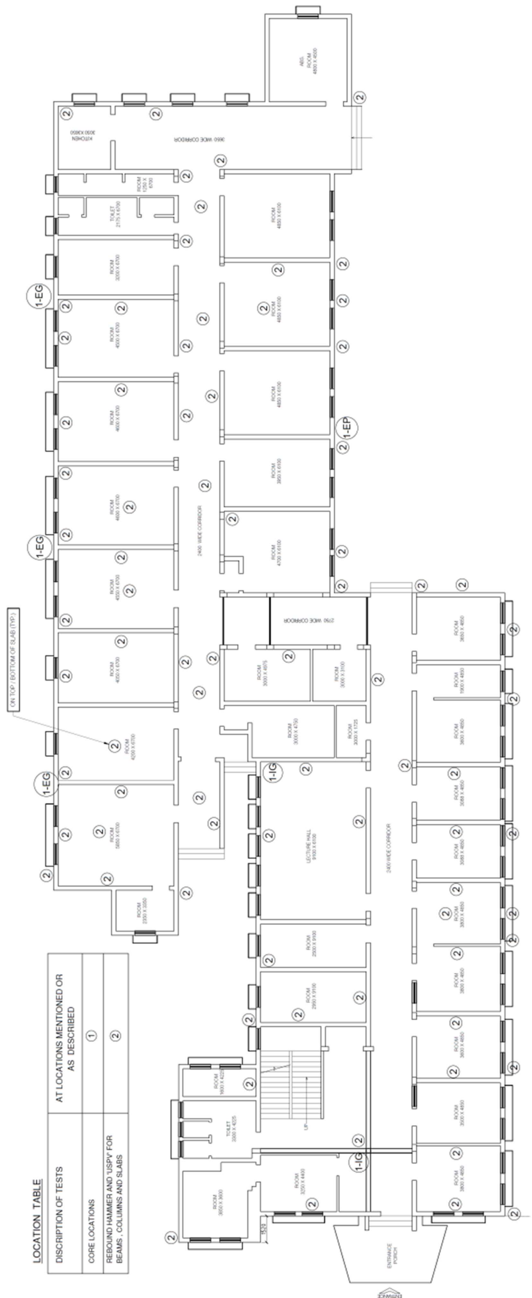

Fig. 1 – Building plan showing test locations (IG-internal Ground floor, EP-External below Plinth, EG-External Ground floor)

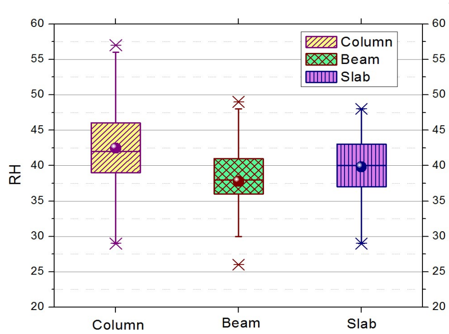

Fig.2 – Box-and-whisker plot for rebound hammer results

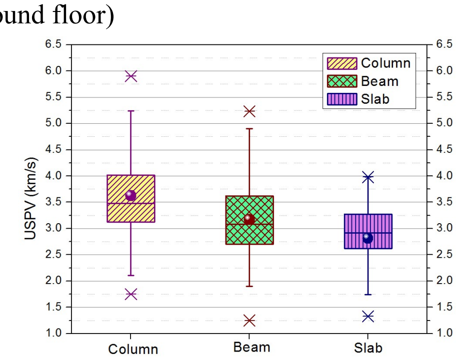

Fig.3 – Box-and-whisker plot for ultrasonic pulse velocity results

Whereas the mean of the RH is highest for column and lowest for the beams, the USPV is lowest for the slabs while it is highest for column. The spread of data is the maximum for columns, followed by beams, and the spread is the minimum for slab – for both RH and USPV. Such differences in values for different members could be explained by the fact that the RH mainly reflects the surface strength and is affected by surface cracking etc. whereas the USPV represents the internal strength of concrete member and gets affected by proximity of reinforcement to the test location.

3.2 Correlation expressions from literature

As development of site-specific equation was not possible, correlation expressions relating the compressive strength (f) of concrete to RH (R) and USPV (V) were obtained from literature. Most of the equations from literature used linear or exponential relationships for estimation of compressive strength from RH or USPV, and four equations were selected for this study. The selected equations are summarized for both RH (R) and USPV (V: km/s) in Table 1 for estimation of cube or equivalent cube (150 mm × 150 mm × 150 mm) compressive strength (f: MPa).

Table 1 – Correlation expressions from literature

Reference	Equation
RH	
Shariati et al. [9]	$f = 1.7206\ R - 26.595$
Patil and Shivakumar [10]	$f = 0.1918\ R + 17.128$
N-curve from Silver Schmidt manual [11]	$f = 1.8943\ e^{0.064\ R}$
Qasrawi [14]	$f = 1.353\ R - 17.393$
USPV	
Raouf and Ali [12]	$f = 2.016\ e^{0.61V}$
Gehlot et al. [7]	$f = 9V - 0.850$
Turgut [13]	$f = 1.146\ e^{0.77V}$
Shariati et al. [8]	$f = 15.533V – 34.358$

3.3 Methodology

To begin with, the NDT data was checked for outliers according to the Indian national standard [22]. The policy adopted was to check for one outlier on either end first, followed by re-check for another at that end again. Though such successive checks would help eliminate outliers from data, the significance level could get affected in case of repeated application [22] and therefore, if more than one outlier would be obtained, then for the chosen significance level, the check for 'more than one' outlier was applied on the data, once for each end. For outlier checks on the data, significance level of 0.05 was selected.

Subsequently, NDT (RH and USPV) test data, free from outliers, was converted to equivalent cube compressive strength using correlations from literatures and histograms are plotted. The grouping of data set has been done using Eq. 1 [23].

$$a = 1 + 3.3 \times log_{10}\ (n) \qquad (1)$$

where, a= number of intervals; n = number of samples.

Concrete strength has been traditionally known to follow the Normal or Log-normal distributions, corresponding to good and not-so-good quality control during construction. Accordingly, goodness-of-fit was checked for both Normal and/or Log-normal distribution using Chi-squared(χ^2) and K-S test. For details about the statistical distributions, parameter estimation methods, goodness-of-fit tests, or other details of statistics, readers may refer textbooks [23–25]. The outcome after this step was a best suited probability distribution function for each of the six data sets and the associated parameters of distribution.

There are limitations associated with the hypothesis testing for similarities of mean of sample and that of the fitted probability density function [26,27]. Literature emphasizes that consideration of the various aspects of a physical process, mechanism, study design and limitations, and data quality and uncertainties could be much more important than the associated p-value of confidence intervals [26]. It has been advocated to report the p-value and discuss the reasons rather than assigning the categorization 'statistically significant' or otherwise [26], because in reality non-significant results basically means they are less compatible with the hypothesis. Wasserstein et al. [27] warns against use of 'statistical significance' or 'p-value' for (dis)proving any hypothesis. Specifically for p-value, the authors [27] opined that it would not indicate that only chance produced the observed association or effect or that the probability of the test hypothesis being true. Readers are directed to the original articles and references therein, for more comprehensive treatment on this subject.

However, for completeness, the checks for similarity of sample mean and the ensemble mean have been worked out for each of the member types (column, beam, slab) for both tests (RH, USPV values) and p-value of for datasets have been listed in the respective tables. The statistic for checking the similarity of means with unknown population variance would be the t-statistic, which would follow the student-t distribution and this would be for two-tailed test. The formulation for the t-statistic would be according to the Eq. 2 given below [24]:

$$t = \frac{\bar{X} - \mu}{S / \sqrt{n}} \quad (2)$$

where, $\bar{X}$ is the sample mean, μ is the population mean (calculated from the complete set of strength estimates corresponding to that from which the sample is taken), S is the sample standard deviation and n is the number of data in each sample space. From the estimated *t*-statistic, *p*-value has been calculated from the Student-*t* distribution, corresponding to the number of samples for that particular case and this has been reported in all the tables in the results. The calculated *p*-value would indicate the similarity (or difference) between the sample mean and the population mean (the data estimated using all four equations are treated as population for want of any better estimate) – higher value would mean the similarity is more. Moreover, the main objective of the present work is to arrive at some logical inference, addressing the huge variation in estimated strength obtained from available correlations. Therefore, the authors would refrain from categorizing the finding as 'acceptance' or 'rejection' owing to the various limitations of using *p*-value for inferences, as discussed earlier.

Next, the compressive strength of concrete corresponding to 95% confidence value has been estimated using parametric method (using selected distribution and its' parameters) and that has been compared with non-parametric estimation of 95% confidence value from the data set of equivalent compressive strength. This exercise has been repeated for all the three members (column, slab, and beam) and for the two tests, USPV and RH, thus making a total of six cases in all. The indirect strength estimates from the two different NDT-s, for the three member types would be compared.

In order to corroborate the direct strength test results (core strength) of the columns with the estimated strength from NDT, the strength was estimated using the same equations, for the RH and USPV values paired with the core test data. Comparison of the strength estimated from NDT and measured in PDT for these five cases would help to finally identify the equations that would be best suitable for estimation of concrete strength from RH and USPV for the structure. Readers may note that comparison of strength estimates from NDT and PDT would be possible only for column members due to the limitations discussed earlier.

4. Results and discussion

4.1 Outlier analysis

The outlier check was applied according to the Indian standard [22]. First, check was performed for single outlier at each end. Of the six sets of data, only one outlier was detected for the high end of USPV results for beams. Presently, the outlying value (6.79 km/s) was removed from the USPV results for beams and the test for a single outlier was performed again, wherein it was concluded that there was no outlier left. Hence, use of the check for one outlier at each end was justified and further checks were not deemed necessary. On removal of the single outlier from the USPV of beams, the data length became 64 numbers for NDT of beams. Otherwise, the columns had 41 sets and slab had 34 observations. This was applicable for both the NDT performed on the structure, RH and USPV.

4.2 Compressive strength using correlations with rebound hammer data

The compressive strength of concrete was obtained from the RH results for the three members, namely, column, beam and slab separately. Brief data statistics and salient details of the best suited probability distribution function (PDF) for beams, columns and slabs obtained from RH data are listed in Table 2, Table 3, and Table 4 respectively, along with the corresponding *p*-value.

Table 2 – Strength from RH: Beams (64 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [9]	38.38	8.58	Normal	0.000
Ref. [10]	24.37	0.96	Normal	0.000
Ref. [11]	22.30	7.02	Log-normal	0.000
Ref. [14]	33.70	6.74	Normal	0.000

Table 3 – Strength from RH: Columns (41 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [9]	46.47	10.04	Normal	0.000
Ref. [10]	25.27	1.12	Normal	0.000
Ref. [11]	30.75	12.34	Log-normal	0.002
Ref. [14]	40.06	7.90	Normal	0.000

Table 4 – Strength from RH: Slabs (34 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [9]	41.87	8.34	Normal	0.000
Ref. [10]	24.76	0.93	Normal	0.000
Ref. [11]	25.29	7.50	Normal	0.000
Ref. [14]	36.45	6.56	Normal	0.000

In general, it was noted that all the datasets could belong to both Normal and/or Log-normal distributions, as verified with Chi-squared and K-S tests and there were few rejections as well. The selection of the better suited distribution was based on lower value of the goodness-of-fit statistics along with the plot of resulting probability density function on the histogram. Though in few cases the two distributions were indistinguishable (column from Patil and Shivakumar [10]: Fig. 4; Chi-square: 3.69 for Normal & 3.74 for Log-normal; K-S: 0.08 for Normal & 0.09 for Log-normal), in others the Normal or Log-normal distribution could be identified as the better suited one: Normal (slab from Qasrawi [14], Fig. 5; Chi-square: 5.78 for Normal & 7.88 for Log-normal; K-S: 0.08 for Normal & 0.11 for Log-normal) or Log-normal (beam from N-curve [11], Fig. 6; Chi-square: 9.43 for Normal & 5.67 for Log-normal; K-S: 0.12 for Normal & 0.13 for Log-normal).

The very low *p*-value obtained for each of the 12 RH estimates (Tables 2 to 4) suggested very strong presumption against null hypothesis (the mean values are similar) and depicts that the difference between sample mean and population (ensemble) mean would be statistically significant at the 0.05 level of significance for all the RH cases. However, as mentioned earlier, there are limitations associated with use of *p*-value as well [26–28] and therefore, the analysis is presented only for completeness and no inferences such as 'acceptable' or 'rejected' would be drawn from the results of this analysis. This also indirectly reflects in the huge variation as obtained compressive strength value estimated from different correlation expressions. This finding highlights the limitations in adopting a correlation expression from literature for estimation of compressive strength of concrete from NDT result directly. However, readers may note that the selection of the better suited PDF to represent the estimated concrete strength from RH is performed in this study using Chi-square and K-S statistic and *p*-value is not considered due to aforementioned reasons.

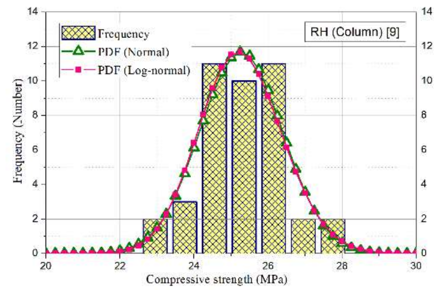

Fig.4 – Compressive strength from RH for column [10]

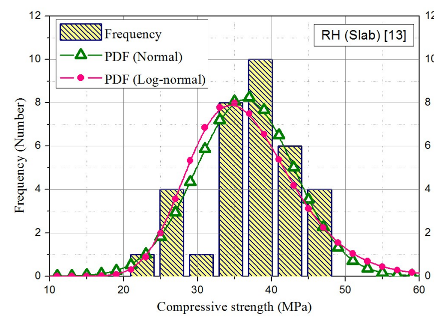

Fig.5 – Compressive strength from RH for slab [14]

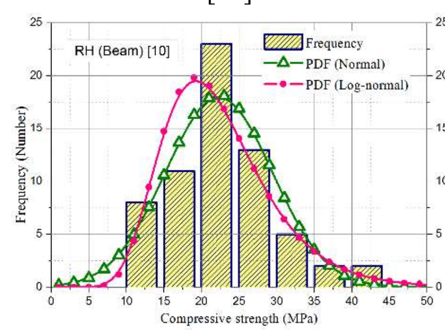

Fig.6 – Compressive strength from RH for beam [11]

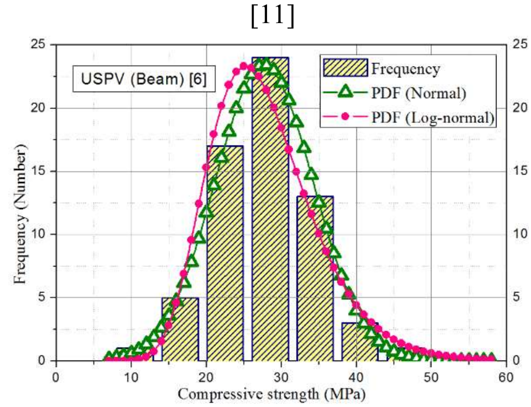

Fig.7 – Compressive strength from USPV for beam [7]

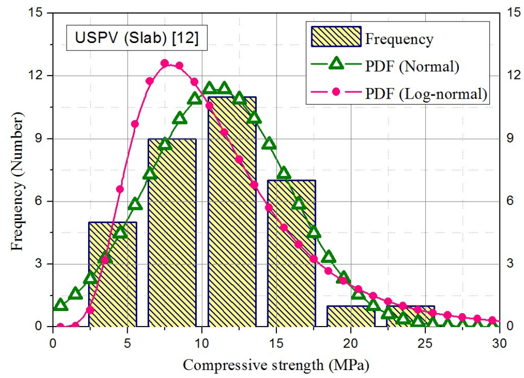

Fig.8 – Compressive strength from USPV for slab [13]

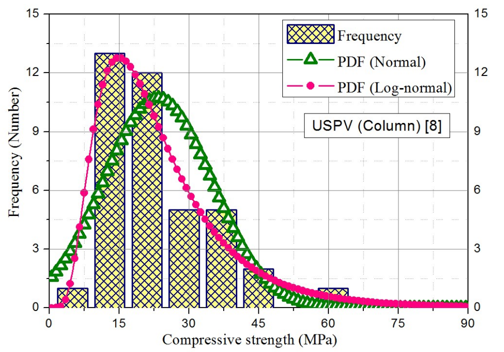

Fig.9 – Compressive strength from USPV for column [9]

The detailed results and other plots are not included for brevity. Particularly it was noted that the strength obtained from the N-curve [11] was adjudged better or equally good fit to Log-normal distribution, when compared to Normal distribution.

These results from RH sample sets have shown a high mean value of compressive strength of concrete using formulation from Shariati et al. [9] and Qasarwi [14], which could be due to the higher grade of concrete considered for those studies. For example, the calibration curve obtained by Shariati et al. [9] had used concrete strength in a range of 30 – 60MPa with a coefficient of determination (R^2) value 0.9364, whereas in case of Patil and Shivakumar [10] the range was 21.6 – 22.3MPa with a coefficient of determination (R^2) value 0.8658. Taking a much broader range, the formulation of N-curve [11] was based on concrete having cube strength ranging from 10 – 100 MPa with a (R^2) value 0.9771. Moreover, all except the second formulation [10] ended up with a much higher standard deviation, which was around five to ten times for different cases.

4.3 Compressive strength using correlations with Ultra-Sonic Pulse Velocity data

The compressive strength of concrete was obtained from the USPV results for the three members, namely, column, beam and slab separately. Brief data statistics and salient details of the best suited statistical distribution for beams, columns and slabs obtained from USPV data are listed in Table 5, Table 6, and Table 7 respectively.

It must be noted that when equations (particularly from [9]) yielded negative values of compressive strength, those were discarded, and the analysis was performed with the remaining data. In such cases, the number of data actually taken for analysis has been mentioned in footnotes. This scenario arises possibly due to the present concrete strength falling beyond the range considered for the equation, or other reasons such as difference in the aggregate quality, mix proportions, etc.

Table 5 – Strength from USPV: Beams (64 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [7]	27.68	6.54	Normal	0.000
Ref. [13]	15.35	10.14	Log-normal	0.007
Ref. [12]	15.32	7.62	Normal	0.000
Ref. [9]#	16.91	9.72	Normal	0.132

58 Nos. of samples.

Table 6 – Strength from USPV: Columns (41 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [7]	31.78	7.44	Normal	0.000
Ref. [13]	23.03	18.69	Log-normal	0.599
Ref. [12]	18.85	8.48	Log-normal	0.000
Ref. [9]#	23.31	11.61	Log-normal	0.534

39 Nos. of samples

For twelve sets of RH estimates, out of the total 48 (four equations for each set), around ten cases (21%) were obtained for which some test (chi-square or K-S) rejected some distribution (Normal or Log-normal), and the corresponding number was five out of 48 (10%) for USPV estimates. For majority of cases of rejection, it was observed that either the particular distribution was rejected by both tests, or only

Chi-squared test. For example, when using USPV in case of columns, both Normal and/or Log-normal distributions were rejected by Chi-square test for Turgut [13] but both were accepted by K-S test, whereas for beams, Normal distribution was rejected by Chi-square for Turgut [13] and accepted by K-S test. The authors would offer the following explanation for this observation. The Chi-square test evaluates the overall goodness-of-fit, whereas the K-S test focuses on the maximum deviation observed. As the data contained high values of standard deviation, the overall data might be well scattered and thus produces high Chi-square value. In such case, distribution rejected by Chi-square test could get accepted by the K-S test. In case of column USPV estimate using Gehlot et al. [7] formulation, the K-S test rejects Normal distribution whereas the Chi-squared test does not. Such scenario could have arisen due to one or two large deviations contributing to the high standard deviation of the data, leading to the large values of maximum deviation (tested by K-S test) even when the overall fit was acceptable (tested by Chi-square test). These results indicate that the mean value obtained from the correlation-based strength could be a good indicator of the concrete strength of the structure, though the standard deviation could be suspect.

Table 7 – Strength from USPV: Slabs (34 Nos.)

Literature	Mean (MPa)	Standard deviation (MPa)	Suitable PDF	*p*-value
Ref. [7]	24.47	5.69	Normal	0.000
Ref. [13]	11.01	4.75	Normal	0.000
Ref. [12]	11.92	4.14	Normal	0.000
Ref. [9][#]	12.96	6.10	Normal	0.009

[#] 28 Nos. of samples

The PDFs were superimposed on the histograms and these were considered along with the test statistics (Chi-square / K-S) for selection of the suitable distribution. As was observed for strength from RH correlations, in few cases the two distributions were pretty close (beam from Gehlot et al. [7]: Fig. 7), in others the Normal or Log-normal distribution could be identified as the better suited one (Normal: slab from Turgut [13], Fig. 8; Log-normal: column for Shariati et al. [9], Fig. 9). The other plots are not included for brevity.

The examination of the *p*-value for the USPV estimates of strength present a different picture when compared to the RH estimates. The estimates by two formulations ([9,13]) for columns and one formulation ([9]) for beams would appear to be having more similarity to the population mean (ensemble), with comparatively higher *p*-values. For other cases, the low *f*-value would indicate that those estimates would have 'significant' differences of mean from the population (ensemble). But there are limitations of such inferences based on significance tests as highlighted in literature [26,27] and therefore, the analysis is presented only for completeness and no inferences such as 'acceptable' or 'rejected' would be drawn from the results of this analysis. However, readers may note that the selection of the better suited PDF to represent the estimated concrete strength from RH is performed using Chi-square and K-S statistic and *p*-value is not considered due to aforementioned reasons.

Results obtained from USPV sample sets have shown somewhat low values of compressive strength while using most of the formulations [9,12,13].

4.4 Compressive strength of concrete from indirect tests: RH and USPV

Results obtained in earlier tables clearly show a higher standard deviation in estimated compressive strength values using USPV values with that of RH values which is in line with the earlier discussion in introduction part. The standard deviation from the indirect strength estimates from NDT (RH or USPV) are substantially higher than even the conservative values stipulated in IS code [28]. Invariably, the strength values obtained from correlation expressions developed using both RH and USPV values would involve uncertainties. However, the certain dominant aleatory type of uncertainties i.e., dependency on composition, heterogeneous nature and density of concrete incorporates comparatively higher uncertainties in estimation of compressive strength from USPV values, e.g., having same compressive strength but variation of density can influence the USPV value significantly. Further, consideration of single correlation in absence of sufficient number of core test results, can give rise to epistemic type of uncertainty in estimation of present-day strength of concrete. Therefore, this study has been conducted by considering multiple correlations from literature and carry out statistical comparative study by two different methods to conclude on the available present-day strength of different structural elements of the structure.

Comparison between the characteristic strength of concrete estimated by parametric and non-parametric methods are presented in Table 8 and Table 9 respectively for RH and USPV based calculations.

As a parametric approach, five percentile values of compressive strength (value with 95% confidence) were evaluated using the properties of Normal distribution (μ-1.65×σ), where μ: mean; σ: standard deviation.

In case of Log-normal distribution fitting the data better, logarithm of the data was used for the calculation and then anti-log was taken to obtain the characteristic strength (95% confidence value). In the non-parametric approach, the 95% confidence value has been obtained from the data directly, and this does not require any PDF or its parameters. Thus, the strength values obtained from this method would not be severely affected by the estimated parameters of distributions or high standard deviations.

The calibration curve obtained by Gehlot et al. [7] was based on concrete strength within a range of 25 MPa – 40 MPa, whereas the corresponding range for the relationship by Turgut [13] was 5 MPa – 55 MPa with a R^2 value 0.80. On the other hand, formulation of Raouf and Ali [12] was based on cube strength ranging from 15 MPa– 45 MPa and the one by Qasarwi [14] was for cube strength between 10 MPa and 40 MPa with R^2 value 0.88.

The standard deviation is observed to be as high as 80% of the mean value (column, Turgut [13]) which would make the calculated extreme percentile values very low or might actually be negative (Table 6). The strength obtained from USPV using expression given by Gehlot et al. [7] yields the lowest coefficient of variation for all members. Therefore, it can be said that the range of concrete strength used for calibration curve development along with mix quality could have a great impact on the accuracy of the estimated strengths from such correlation curves.

It is worth mentioning that large variations are observed in the mean or standard deviation of the strength estimates using different correlation expressions. Such wide variation of standard deviation could be due to the use of different range of parameters for development of the particular correlation expression which would include differences in grade of concrete, material constituent, curing regime, compaction protocol, number of data used, testing method, type of test (on existing building/laboratory test), and regional differences. This in turn would lead to the huge variation in obtained characteristics compressive strength value and decision would have to be based on logical judgement of the engineer for use of available correlation expressions in order to obtain present compressive strength of concrete in the existing building.

From Table 8 and Table 9, it can be observed that the characteristic strength values obtained from the parametric and non-parametric methods more or less match, except a few stray cases. This would strongly indicate that the fitted distributions represent the data quite well. However, it must be noted that the characteristic strength obtained from the N-curve [11] interpretation of RH resulted in quite low value between 10 MPa and 15 MPa, which seems improbable particularly, considering that all other formulations yield much higher values between 20 MPa to 24 MPa (beams); 23 MPa to 30MPa (columns); and 23 MPa to 28 MPa (slabs). A reason for this discrepancy could be the wide range of strength values (10 MPa to 100 MPa) for which the N-curve [11] was generated and the inaccuracies associated with its application for the present concrete. Considering the values obtained using parametric or non-parametric methods from the other three expressions, the minimum (conservative) characteristic strength would be 20 (20.49) MPa for beams; 23 (23.43) MPa for columns, and 23 (23.07) MPa for slabs.

Table 8 – Comparison of Characteristic Strength from RH

Literature	Characteristic Strength (MPa)	
	Parametric	Non-parametric
Beam		
Ref. [9]	24.23	21.58
Ref. [10]	22.79	22.50
Ref. [11]	12.55	11.37
Ref. [14]	22.58	20.49
Column		
Ref. [9]	29.90	30.18
Ref. [10]	23.43	23.46
Ref. [11]	15.49	15.66
Ref. [14]	27.03	27.26
Slab		
Ref. [9]	28.11	26.74
Ref. [10]	23.23	23.07
Ref. [11]	12.91	13.77
Ref. [14]	25.63	24.55

In case of strength estimate from USPV, all formulations except Gehlot [7] yield zero or close-to-zero values for both Normal and/or Log-normal distributions. Even for a 40-year-old structure, such unrealistic strength values indicate that the expressions used for converting the USPV results to compressive strength would not be applicable in this case, for some reason. Had the structure been constructed with M15 or M20 concrete, the minimum for reinforced concrete works, then also strength of 5 MPa or 7 MPa could only be possible for highly deteriorated concrete in structure, and this was not the case in the present building. For 40-year-old structure constructed using M15 or M20 concrete, the strength values obtained in non-parametric approach using Gehlot [7] formulation would be, for similar reasons, towards the lower end of the spectrum, and could just be possible. In want of any better estimate, following

Gehlot [7] relationship, the characteristic strength values would be 16 (16.90) MPa for beams, 19 (19.50) MPa for columns, 13 (13.80) MPa for slabs. Therefore, for overall structural analysis, the characteristic strength of 13 MPa would have to be adopted, which would be markedly lower compared to that obtained from RH correlation (20 MPa) earlier and could be improbable for the structure for reasons already mentioned. Due to aforementioned reasons, however, it is suggested that the characteristic strength values obtained by correlation expressions from USPV data is unsuitable for further application in re-evaluation of the structure. However, for completeness, characteristic strength obtained from correlation expressions using RH (recommended) and USPV (not recommended) are compared in Table 10.

Table 9 – Comparison of Characteristic Strength from USPV

Literature	Characteristic Strength (MPa)	
	Parametric	Non-parametric
Beam		
Ref. [7]	16.90	17.81
Ref. [13]	5.21	5.63
Ref. [12]	2.75	7.11
Ref. [9]	0.86	3.44
Column		
Ref. [7]	19.50	20.48
Ref. [13]	6.50	7.07
Ref. [12]	7.97	8.52
Ref. [9]	8.13	3.44
Slab		
Ref. [7]	15.08	13.80
Ref. [13]	3.18	4.03
Ref. [12]	5.09	5.45
Ref. [9]	2.89	3.41

Table 10 – Comparison of Characteristic Strength for Different Members from RH and USPV

Member	Characteristic Strength (MPa)		Remarks
	RH	USPV	
Beam	20	16	USPV strength 20% less than RH strength
Column	23	19	USPV strength 17% less than RH strength
Slab	23	13	USPV strength 43% less than RH strength
Overall Structure	20	13	Beam governs for RH; Slab governs for USPV. USPV strength 35% less than RH strength

4.5 Compressive strength of concrete from direct test: Core test on columns

Core test data is a better option for estimating compressive strength of concrete in existing structure. However, as core data is an outcome of semi-destructive test, it is done on a limited number of samples for strength evaluation in existing structure. For the present case, the number of samples in core test was six (out of which NDT was carried out only at five locations) and furthermore, cores were taken only from column locations. Therefore, the comparison of strength estimates from NDT (USPV / RH) and PDT (core) could be performed only for the columns in the structure under study. The strength from core test results was also evaluated by parametric and code-based approaches.

Table 11 – Strength from Core tests: Columns (6 nos.)

Mean (MPa)	Standard deviation [28] (MPa)	Parametric	Code based (BIS [3])
21.53	4.0	14.93	22.67

For the parametric approach the mean strength from the core test was used along with the standard deviation (4 MPa) from the Indian mix design standard [28] according to the mean strength (20 MPa – 25 MPa), with assumption of Normal distribution. The code-based method is performed according to the stipulations of the Indian national standard for concrete design [3] which has also been used by Karmakar et al. [29] in their retrofitting work in absence of sufficient NDT data. Results obtained using core test data has been summarized in Table 11where it may be highlighted that the parametric value obtained for the characteristic strength is much less than that estimated from IS code specifications [3]. This could be because of the assumption of Normal distribution in parametric estimation, which might not be suitable to the small number of core strength results in this case. The strength value obtained according to BIS [3] matches closely to the strength obtained from correlation with RH values over the entire structure (Section 4.4, Table 8), whereas it is higher than that of the strength obtained using correlation with USPV (Section 4.4, Table 9). Therefore, it is recommended that the strength obtained by BIS [3] method be adopted for the structure.

Considering the correlation expressions applicable for column NDT for RH [10] and USPV [7], the equivalent strength values are evaluated for the five cores, for which the NDT results were available. These are compared in Fig. 10 as a scatter plot, wherein it can be observed that the strength values from RH are closer to the core test results, when compared to the USPV results, which overestimates largely (almost double) in three out of five cases. Overestimation for RH strength estimates are limited to 25% to 30%, with one case of around 5% underestimation. These findings reinforce the earlier observation that the strength estimates from USPV would be quite unreliable for this structure.

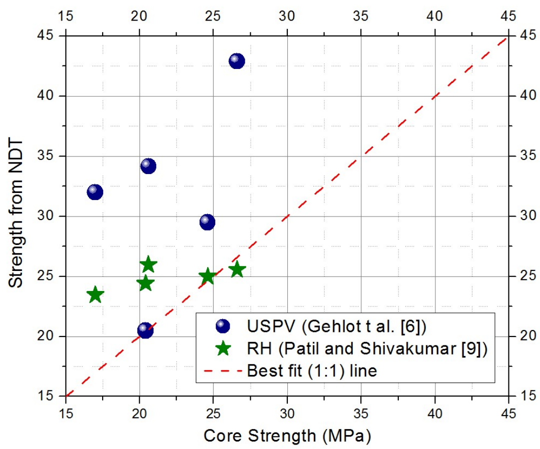

Fig.10 – Comparison of compressive strength from direct (core) test and indirect (RH / USPV) test for column

5. Discussion, observations and recommendations

This section summarizes the results obtained from the case study specific to the 40-year-old institutional building in consideration, with suggestions regarding concrete strength for re-analysis as well as incorporating uncertainties into the same for better confidence in the re-evaluation results. Furthermore, recommendations for addressing similar cases have been provided.

5.1 Discussion

There is one observation in the strength values estimated from NDT (RH and USPV) results using the various correlation expressions from literature, which deserves further elaboration. The variability (coefficient of variation: COV) of these strength estimates ranged from as low as 0.04 (Tables 3 and 4) to as high as 0.66 (Table 5) and 0.81 (Table 6). The Indian standard [28] recommends COV for compressive strength of concrete as 0.20 and 0.16 for grade of concrete M20 and M25 respectively. For concrete (mean strength: 25.8 MPa, Normal distribution) across the world, a COV of 0.18 (~ M18) has been suggested [30] after extensive literature review. Five out of the twelve strength estimates using RH and all twelve using USPV have COV higher than these recommended values. Even if the statistical tests do not reject the Normal distribution for these datasets, adopting Normal distribution could result in negative values for lower percentiles (say, 5 percentile or below) – and that would correspond to a physically impossible scenario, thereby indicating a limitation of the present study. This is another justification for recommendation against use of the USPV estimates in this case. Therefore, Normal distribution could be adopted for the RH datasets, but caution would be suggested.

5.2 Observations

This study has focused mainly towards selection of best correlation expression/s (from literature), recommended grade of different elements (beam, column, and slab) as well as the entire existing building, and ranges of variation.

1. From the present study, it has been observed that for columns, the estimated characteristic strength using the correlation expressions by Patil and Shivakumar [10] for RH (Table 8 – parametric: 23.43 MPa; non-parametric: 23.46 MPa) and Gehlot et al. [7] (Table 9 – parametric: 19.50 MPa; non-parametric: 20.48 MPa) for USPV gave better comparisons with characteristic strength estimated according to the IS code [3] from core test results (Table 11 – 22.67MPa). This is possibly due to the use of similar range of concrete grade with that of existing strength during the preparation of calibration curves. Readers must note that this comparison is performed for the characteristic strength obtained from NDT (RH) and the PDT (core), and not the individual test results (depicted in Fig. 10).
2. Conservative estimate of the grade of concrete can be considered 20 MPa for beams and 23 MPa for slabs and columns. Overall grade of concrete for this case can be considered as 20 MPa for structural analysis purpose. Design checks for individual members, if required, might benefit from use of the higher strength as found applicable for that particular element, should the designer choose to use different strength values for qualifying different members of the structure.
3. As it has been already explained in the earlier sections, there are various sources of uncertainties in estimated strength from only NDT data and these should be factored in any re-evaluation exercise conducted for the structure. One approach could be by using the maximum deviation from the mean compressive strength as seen in estimated value using different formulae for RH computations (around 43%). Thus, for structural re-analysis purposes, a range analysis can

be carried out to capture the statistical variation with a 45% increase (to check the range of responses) and decrease (strength criteria) in present grade of concrete estimated from RH results from the entire structure.

4. In this study, the concrete strength estimates from USPV were deemed unreliable. Otherwise, similar re-analysis could have been conducted using strength estimates obtained from USPV results.

5.3 Recommendations

The selection of the applicable correlation expression for strength estimation from NDT results, where structure specific expressions cannot be developed due to lack of direct test data, would not be straightforward – particularly when the actual design strength of the concrete in the structure is unknown. The reasons for this have been discussed in detail in the preceding sections of this article. It would be suggested to use a number of different correlation expressions from literature and analyze the results for arriving at the strength estimate. The procedure demonstrated in this case study could be one such indirect approach. Additionally, strength estimate from only indirect test (NDT) results would be fraught with many additional sources of uncertainties and due consideration should be given to the uncertainties for the final decision on the present strength of concrete in the existing building, and subsequent analysis of the structure for re-evaluation purposes. The approach suggested in this study is to analyze the structure for a variety of strength values, incorporating the variability observed in the indirect strength estimates for the structure.

6. Conclusions and Future scope

The study is an effort to shed some light on application of NDT test results for present strength estimate of concrete structures targeted towards retrofitting and rehabilitation purposes. In absence of sufficient numbers of direct (core) test results, indirect method has been demonstrated to arrive at a suitable correlation expression for strength estimation, and using these estimated values, statistical inference about the characteristic strength of concrete, using both parametric and non-parametric methods, has been presented. The following are concluded from the results obtained in the study:

a) Correlation of USPV or RH to the compressive strength could be sensitive to various factors such as the range of concrete grade, mix proportions, properties of ingredients, curing regime, compaction, etc. of the concrete originally used for development of the expressions. Therefore, proper care is advocated for selection of correlation expression for estimation of compressive strength using only NDT such as RH or USPV data, for cases where structure specific expressions could not be developed due to lack of direct test data.

b) Cases where only NDT data are available without sufficient core data for development of structure specific correlation expression, use of a random formulation from literature would add to the inaccuracy of estimated compressive strength, which is inherent in indirect strength estimates. To address this issue, different formulations can be initially employed to estimate the existing strength of concrete. Subsequently, the equation originated from the range of concrete strength closest to (and narrowest about) the estimated grade could be used for further analysis.

c) It is recommended to carry out structural analysis for re-evaluation for a range of values, by taking into account of the variations in estimated strength values, to capture the possible variation in response of the structure due to the uncertainty in the estimated strength. This would improve the confidence in estimated structural response by indirectly considering the uncertainties in NDT data as well as the selected correlation expression/s.

As a future scope of study, this work can be further extended to address the following limitations:

a) This study has considered total eight numbers (four for RH and four for USPV) of correlation expressions from literature, in order to arrive at the decision of obtaining present-day compressive strength of the existing structure. However, there are scores of other correlation expressions available in literature and consideration of more expressions may produce a wider bandwidth of estimated strength values for better representation of the associated uncertainties.

b) As was indicated in the Section 5.1, the high COV obtained for these strength estimates could result in negative strength values for lower percentiles, thereby being a limitation of this study and this aspect can be examined further.

c) There would be uncertainties in the NDT values due to sampling, instrument error, and human error, among others**.** However, this aspect was not considered in the present study. Incorporation of such sources of uncertainty in the strength estimates would help to arrive at better characteristic strength of concrete in existing buildings.

d) In the recent years, there has been a new concept of NDT data fusion wherein two or more NDT tests (say, RH and USPV) are used concurrently for strength estimation purposes and some results are promising better accuracy. Such expressions, though not used in the present study, may be explored for achieving better and more accurate estimations.

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Appendix: NDT Data

Beam											
RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)
41	3.20	34	3.34	41	1.25	36	3.47	41	2.70	37	1.90
41	4.29	37	2.91	37	2.56	28	2.50	41	2.92	32	2.77
40	3.63	37	2.93	40	3.08	32	2.71	38	2.65	39	3.62
39	3.04	37	3.04	40	4.22	26	2.62	38	2.28	38	2.93
48	3.20	39	3.92	35	3.43	38	2.33	46	3.49	36	5.23
40	3.80	38	3.73	37	2.80	31	3.29	43	2.62	42	4.90
38	3.62	44	3.97	43	2.16	30	3.20	39	4.38	39	3.84
32	3.53	44	3.74	45	3.54	39	3.08	28	4.26	42	3.70
38	3.00	49	3.37	37	3.45	31	2.34	28	2.06	34	4.19
32	3.13	38	3.06	41	3.49	38	3.03	37	2.07	-	-
28	2.89	36	2.45	41	3.09	47	2.09	36	2.90	-	-

Slab											
RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)
45	2.98	41	2.75	40	2.92	33	2.19	48	3.17	40	2.76
34	2.92	41	3.98	43	1.33	38	1.86	47	3.01	40	1.85
33	2.33	40	3.27	31	3.29	38	1.74	41	3.26	37	2.29
31	2.75	39	2.98	41	2.66	44	2.95	47	3.72	39	3.28
29	1.42	38	3.53	44	3.4	43	2.94	42	3.46	-	-
45	3.48	37	3.04	37	2.62	47	2.86	40	2.69	-	-

Column										
RH	USPV (km/s)	Equivalent Cube Strength from Core (MPa)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)	RH	USPV (km/s)
44	4.86	26.60	48	3.56	40	4.35	45	3.18	39	3.03
41	3.37	24.60	46	4.74	45	2.94	50	4.79	47	4.71
38	2.37	20.40	42	3.51	40	3.77	39	3.12	29	1.75
33	3.65	17.00	39	4.09	46	2.96	44	4.84	39	3.37
46	3.89	20.60	41	5.9	50	3.01	46	3.27	39	3.73
41	2.94	-	40	5.24	57	3.24	44	3.41	47	2.11
42	3.2	-	46	4.03	48	3.29	35	3	56	3.37
33	3.81	-	31	3.61	38	3.48	43	4.02	39	3.12
44	4.02	-	-	-	-	-	-	-	-	-