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Concrete strength by combined nondestructive methods Simply and reliably predicted

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Abstract

The author's experience in the estimation of concrete strength by combined methods of nondestructive testing is summarized in this paper. Both the traditional well-known rebound hammer and ultrasonic pulse velocity tests were used in the study. Various charts showing the results are presented. All charts show the 95% prediction intervals, thus enabling professionals to predict concrete strength simply and reliably. Unlike other work, the research ended with one simple chart that requires no previous knowledge of the constituents of the tested concrete. The method presented is simple, quick, reliable, and covers wide ranges of concrete strengths. The method can be easily applied to concrete specimens as well as existing concrete structures. The final results were compared with previous ones from literature and also with actual results obtained from samples extracted from existing structures. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The direct determination of the strength of concrete implies that concrete specimens must be loaded to failure. Therefore, the determination of concrete strength requires special specimens to be taken, shipped, and tested at laboratories. This procedure may result in the actual strength of concrete, but may cause trouble and delay in evaluating existing structures. Because of that, special techniques have been developed in which attempts were made to measure some concrete properties other than strength, and then relate them to strength, durability, or any other property. Some of these properties are hardness, resistance to penetration or projectiles, rebound number, resonance frequency, and ability to allow ultrasonic pulses to propagate through concrete. Concrete electrical properties, its ability to absorb, scatter, and transmit X-rays and gamma rays, its response to nuclear activation, and its acoustic emission allow us to estimate its moisture content, density, thickness, and its cement content. However, the term "nondestructive" is given to any test that does not damage or affect the structural behavior of the elements and also leaves the structure in an acceptable condition for the client. Malhotra [1] presented a comprehensive literature survey for the nondestructive methods normally used for concrete testing and evaluation. However, a successful nondestructive test is the one that can be applied to concrete structures in the field, and be portable and easily operated with the least amount of cost.

Leshchinsky [2] summarized the following advantages of nondestructive tests, as compared to core testing:

1. A reduction in the labor consumption of testing.
2. A decrease in labor consumption of preparatory work (such as tedious work associated with determining location and diameters of reinforcement bars).
3. A smaller amount of structure damage in testing.
4. A lower probability of such structural damage which may cause the need for reinforcement.
5. A possibility of testing concrete strength in structures where cores cannot be drilled (thin-walled, densely-reinforced, etc., ...).
6. An application of less expensive testing equipment.

These advantages are of no value if the results are not reliable, representative, and as close as possible to the actual strength of the tested part of the structure.

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Among the available nondestructive methods, the rebound hammer and the ultrasonic pulse velocity testers are the most commonly used ones in practice. This is true in many developing countries where the lack of technology and funds requires the optimization of available methods and techniques. Also, in many developing countries, records of tested concrete constituents may not be available, or the available data lack some of the requirements for strength estimation by means of ultrasonic pulse velocity (or any other nondestructive testers).

In this work, the author used the combination of the rebound hammer and the ultrasonic pulse velocity testers in order to arrive at a suitable, reliable simple chart for strength evaluation in such countries; assuming that no records about tested concrete are available. A summary about the two tests, showing their advantages and disadvantages, is presented.

2. Rebound hammer

The rebound hammer test is described in ASTM C805 [3] and BS 1881: Part 202 [4]. The test is classified as a hardness test and is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges. The energy absorbed by the concrete is related to its strength [5]. Despite its apparent simplicity, the rebound hammer test involves complex problems of impact and the associated stress-wave propagation [6].

The test method starts by the careful selection and preparation of the concrete surface to be tested. Once the surface is chosen, it should be prepared by an abrasive stone so that the test surface is ground smooth. Then, a fixed amount of energy is applied by pushing the hammer against the test surface. The plunger must be allowed to strike perpendicularly to the surface. The angle of inclination of the hammer affects the result. After impact, the rebound number should be recorded. At least 10 readings must be taken from each tested area.

There is no unique relation between hardness and strength of concrete but experimental data relationships can be obtained from a given concrete. However, this relationship is dependent upon factors affecting the concrete surface such as degree of saturation, carbonation, temperature, surface preparation and location, and type of surface finish. The result is also affected by type of aggregate, mix proportions, hammer type, and hammer inclination. Areas exhibiting honeycombing, scaling, rough texture, or high porosity must be avoided. Concrete must be approximately of the same age, moisture conditions and same degree of carbonation (note that carbonated surfaces yield higher rebound values). Amasaki [7] presented the effect of carbonation on the rebound number. Grieb [8] showed the effect of type of aggregates on the rebound number and hence the estimated strength. Willetts [9] presented the effect of moisture content of concrete on the results of the rebound hammer test by comparing dry and tested samples. It is necessary to take 10 to 12 readings over the area to be tested because the test is sensitive to the presence of aggregate and voids immediately underneath the plunger [10].

It is clear then that the rebound number reflects only the surface of concrete. BS 1881: Part 202 [4] suggests that the measured number is an indication of about the first 30-mm depth of concrete. According to Teodoru [11], the results obtained are only representative of the outer concrete layer with a thickness of 30–50 mm.

Due to the difficulty of acquiring the appropriate correlation data in a given instant, the rebound hammer is most useful for rapidly surveying large areas of similar types of concrete in the construction being considered. Neville [12] presented the benefits of using the rebound hammer in concrete and stated that the test **all alone** is not a strength test and the exaggerated claims of its use as a replacement for compression test should not be accepted.

3. Ultrasonic pulse velocity

The test is described in ASTM C597 [13] and BS 1881: Part 203 [14]. The principle of the test is that the velocity of sound in a solid material, V, is a function of the square root of the ratio of its modulus of elasticity, E, to its density, d, viz.:

$$V = f\left(\frac{gE}{d}\right)^{\frac{1}{2}}$$

where g is the gravity acceleration.

The method starts with the determination of the time required for a pulse of vibrations at an ultrasonic frequency to travel through concrete. Once the velocity is determined, an idea about quality, uniformity, condition, and strength of the concrete tested can be attained.

It is clear from the previous equation that velocity is dependent on the modulus of elasticity of concrete. Relationships between pulse velocity and modulus of elasticity of concrete are given in Refs. [9,12,15,16]. Monitoring the modulus of elasticity for concrete through the results of pulse velocity is not normally recommended. On the other hand, it has been shown that the strength of concrete and its modulus of elasticity are related [17,18].

In the test, the time the pulses take to travel through concrete is recorded. Then, the velocity is calculated as:

$$V = \frac{L}{T}$$

where V = pulse velocity (m/s), L = length (m), and, T = effective time (s), which is the measured time minus the zero time correction.

Table 1
Quality of concrete as a function of the USPV

USPV (m/s)	>4500	3500–4500	3000–3500	2000–3000	<2000
Concrete quality	Excellent	Good	Doubtful	Poor	Very Poor

The zero time correction is equal to the travel time between the transmitting and receiving transducers when they are pressed firmly together.

The ultrasonic pulse velocity results can be used:

(a) to check the uniformity of concrete,
(b) to detect cracking and voids inside concrete,
(c) to control the quality of concrete and concrete products by comparing results to a similarly made concrete,
(d) to detect the condition and deterioration of concrete,
(e) to detect the depth of a surface crack, and,
(f) to determine the strength if previous data are available.

Table 1 is suggested by Whitehurst [19] and shows the use of velocity obtained to classify the quality of concrete.

Since strength is the major property in structural concrete, measured velocity was related to strength, and plots of velocity vs. strength were obtained. However, the test result is sensitive to surface properties, presence of steel reinforcement, presence of voids and cracks, properties of aggregates, and mix proportions [1,3,5,11,20,21]. According to Sturrup et al. [22], factors other than concrete strength can affect pulse velocity, and changes in pulse velocity may overshadow changes due to strength. Hence, there is no unique relationship between pulse velocity and strength; variations were found between results when wet and dry pastes, mortars and concrete were used.

The test is fast and easy to perform. Thus, it can be considered as a successful site test for quick comparative studies. Yun et al. [21] showed that the pulse velocity test results showed the lowest degree of correlation among the five different tests used to estimate the strength of concrete. Kheder [23] and El Shikh [24] found little correlation between ultrasonic pulse velocity and strength under general conditions. Compared to the rebound number test, Kheder showed that the ultrasonic pulse velocity test was less reliable in predicting concrete strength if the concrete constituents are not known.

4. Combined methods

When variation in properties of concrete affect the test results, (especially in opposite directions), the use of one method alone would not be sufficient to study and evaluate the required property. Therefore, the use of more than one method yields more reliable results. For example, the increase in moisture content of concrete increases the ultrasonic pulse velocity but decreases the rebound number [12]. Hence, using both methods together will reduce the errors produced by using one method alone to evaluate concrete. Attempts have been done to relate rebound number and ultrasonic pulse velocity to concrete strength [23,25,26]. An equation for predicting concrete strength by means of combined methods is shown in Ref. [23]. Unfortunately, the equation requires previous knowledge of concrete constituents in order to obtain reliable and predictable results.

5. Research program

The actual conditions of the sites show high variations of the materials received. These include variations in

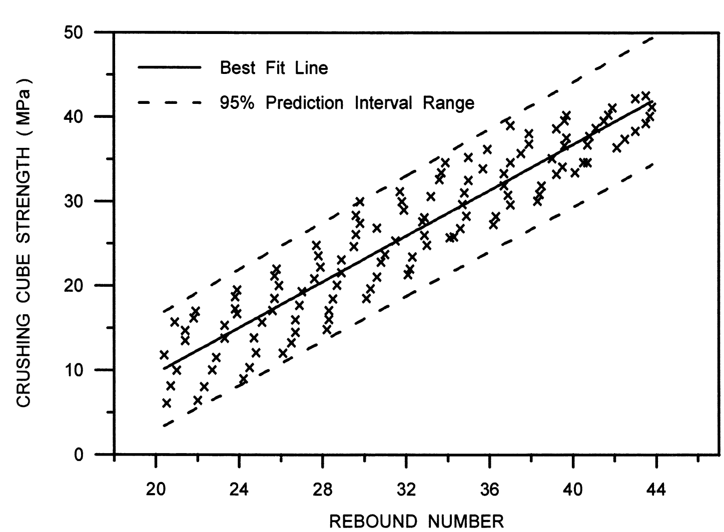

Fig. 1. Relationship between rebound number and crushing cube strength.

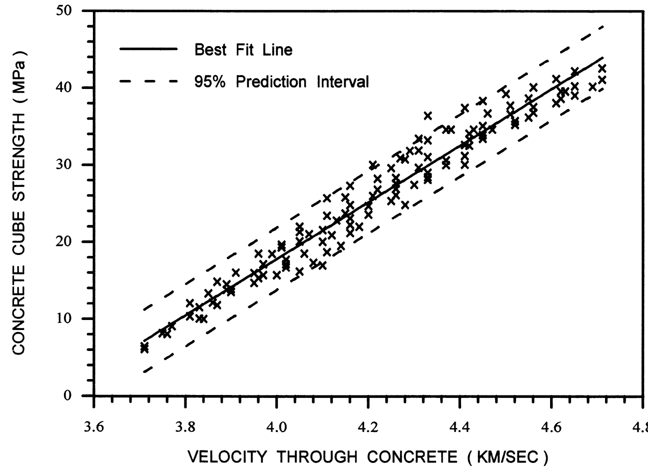

Fig. 2. Relationship between ultrasonic pulse velocity and crushing cube strength.

concrete quality and in the quality of workmanship, lack of technology in some cases, incorrect volume measurements of the quantities used in mixes, discontinuous supervision, and incorrect methods of concrete production usually ending in low to medium degree of quality control [27]. Therefore, it was necessary to design and follow a research program that does not depend on the previous history of the tested specimen.

The aim of the research was to obtain a simple plot between rebound number, ultrasonic pulse velocity through concrete and the crushing strength of concrete. The chart should be as simple as possible in order to be easily used by engineers who work on-site. Also, the chart was used later for strength evaluation of some samples of concrete. The procedure that was followed during experiments consisted of the following steps:

1. Various concrete mixes were used to prepare standard cubes of 150-mm side length.
2. Concrete cubes of unknown history made under site conditions were also brought from various sites for testing.
3. All cubes were immersed under water for a minimum period of 24 h before testing.
4. Just before testing, the cubes were rubbed with a clean dry cloth in order to obtain a saturated surface dry sample.
5. Once drying was complete, each of the two opposite faces of the cube were prepared for the rebound hammer test as described in the specifications.
6. The cubes were positioned in the testing machine and a slight load was applied. The rebound number was obtained by taking three measurements on each of the four faces of the cube. The rebound hammer was horizontal in all measurements. The results of the rebound number test were evaluated according to the rules of the ASTM C 805 [3].

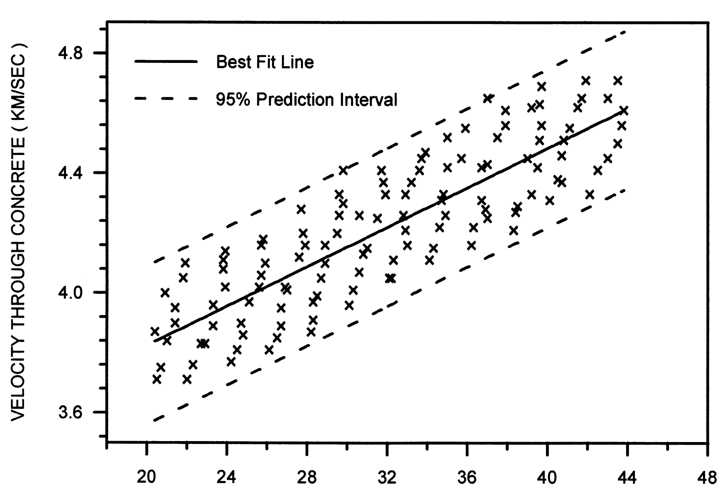

Fig. 3. Relationship between rebound number and ultrasonic pulse velocity.

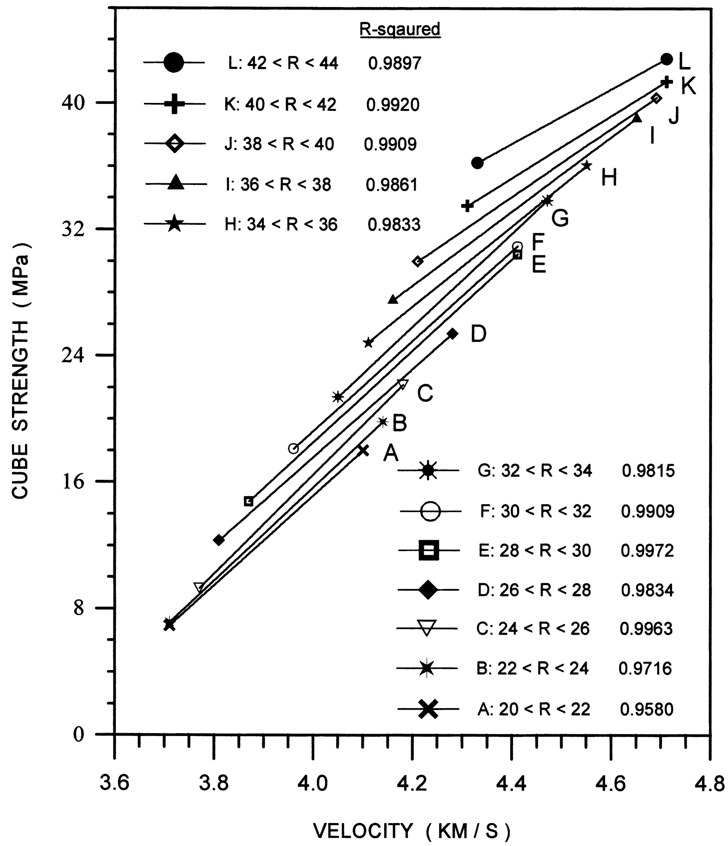

Fig. 4. Relationship between ultrasonic pulse velocity, rebound number and crushing strength of concrete (combined method).

7. Once the rebound hammer test was complete, each of the two surfaces was prepared for the ultrasonic pulse velocity test as described in the specifications. Care was taken so that there was no effect of the notches produced by the hammer. The time was measured on each of the two opposing surfaces and the average was recorded.
8. Once nondestructive testing on each cube was completed, the cube was loaded to failure and the maximum load was recorded.

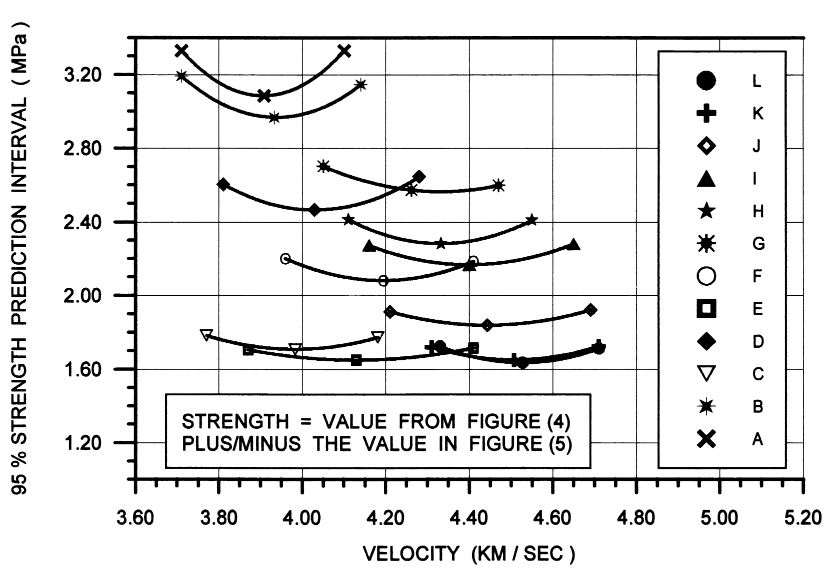

Fig. 5. The 95% prediction intervals for values in Fig. 4.

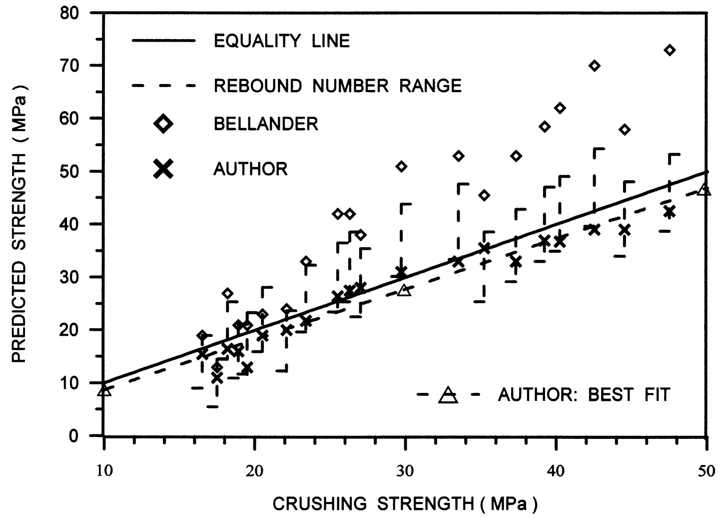

Fig. 6. Comparison of results using various methods.

9. Results were plotted as shown in Figs. 1, 2, 3 and 4.
10. New samples were obtained (either at laboratory or on-site conditions) and were tested in the same way in order to check the results obtained from the plots. These results were also added to the previous plots until reliable results were obtained. In each case, statistical analysis was performed [28] and the 95% prediction interval was plotted against the best-fit lines. The 95% prediction intervals for the values of Fig. 4 are plotted in a special figure (Fig. 5) in order to obtain accurately the values without confusion with the best-fit lines.
11. Twenty samples were taken from structures, equivalent cube strength for each sample was obtained and the results were plotted in Fig. 6. They were also compared with other results as shown in both plots.

N.B.: All samples were made from local materials, which consisted of the following:

1. Ordinary, pozzolanic or sulfate resisting portland cements.
2. Aggregate of local natural sources or crushed hard limestone.

6. Results and discussions

Test results are shown in Figs. 1–6.

Fig. 1 shows the relationship between rebound number and the crushing cube strength of concrete. The best-fit line representing the relationship is given as:

$$S = 1.353\text{RN} - 17.393$$

where S is strength (MPa) and RN is the rebound number. The r^2 value was found to be 0.88. The 95% prediction interval is also shown. It is clear that the interval is quite large.

Fig. 2 shows the relationship between the ultrasonic pulse velocity test result and the crushing cube strength of concrete. The best-fit line representing the relationship is given as:

$$S = 36.72\text{USPV} - 129.077$$

where USPV is the pulse velocity (km/s). The r^2 value was found to be 0.9562.

From the data obtained in both Figs. 1 and 2, it is clear that the line fit in Fig. 2 showed better correlation. The range of the 95% prediction interval is narrower than that shown in Fig. 1. The variations were not large and this was attributed to the fact that the tested cubes were all saturated surface dry when tested and there was little variations in the type of the materials.

Fig. 3 shows the relationship between the measured ultrasonic pulse velocity and the corresponding rebound number for the tested specimens. The best-fit line representing the relationship is given by:

$$\text{USPV} = 0.0329\text{RN} + 3.166$$

The r^2 value was found to be 0.7358. It is clear that the 95% prediction interval is quite wide, which means that no direct relationship can be obtained between the variables. The only conclusion is that there is a general trend for the velocity to increase with the increase in rebound number.

Fig. 4 shows the relationship between the ultrasonic pulse velocity test result and the cube strength of concrete for various values of the rebound number. In the plot, the rebound number was arranged in groups of increment of 2. Straight line relationships were obtained as shown in the figure. The r^2 values of all the lines in Fig. 4 were above 0.95. However, the r^2 alone is not a sufficient indication of the adequacy of the plots [28]. Therefore, the 95% confidence interval was calculated for all the lines in Fig. 4 and the results were plotted in Fig. 5. The use of this plot takes into account the variation in results obtained in the two tests

Table 2
Percent of tested samples deviating from observed values

Deviation from observed value (%)	0–4	4–8	8–12	12–16	16–20	>20
Number of test results	4	6	6	2	0	2
Percent of samples	20%	30%	30%	10%	0%	10%
Commutative Analysis						
Deviation from observed value (%)	0 and < 4	0 and < 8	0 and < 12	0 and < 16	0 and < 20	> 20
Number of Test Results	4	10	16	18	18	20
Percent of Samples	20%	50%	80%	90%	90%	100%

involved in the study. A much better correlation is obtained when using the combined method as compared with the previous "all alone" methods. It is clear that the range is quite small and hence, the predicted strength would probably lie as read from Fig. 4.

For example, if the velocity is 4.2 km/s and the rebound number ranges between 28 and 30, then Line (E) in Fig. 4 must be chosen. From Fig. 4, the expected mean cube strength is 24 MPa. Also, using Fig. 5, the 95% confidence interval will be ± 1.65 MPa. Hence, the expected strength is 24 ± 1.65 MPa.

The application of the method to 20 samples taken from existing structures is presented in Fig. 6. Fig. 6 also shows comparison of results obtained using the following:

(a) the use of the plot given in the hammer catalogue,
(b) the use of the combined method and the plot given by Bellander [25],
(c) the use of the combined method obtained by the author and shown in Fig. 4, and
(d) the crushing compressive strength of concrete.

The test was performed according to BS 1881: Part 120 [29]. It is clear from the figure that the predicted values are close to those of the observed crushing compressive strength (after adjusting the values to estimate cube strength). Eighteen results (90% of the tested samples) lay within + 4.56% to −15.34%. On the other hand, two values (10% of tested samples), showed more than 30% deviation. Both samples had low strength (below 20 MPa). When plotting the 95% predicted values, it was found that the equality line passed only through 60% of the values (the range was omitted from the chart to reduce the congestion of the plots). However, this can be attributed to the narrow range of prediction. The deviation between actual results and predicted results may be attributed to the fact that samples from existing structures are cores and the crushing compressive cube strength was obtained by using various corrections introduced in the specifications. Also, measurements were not accurate and representative when compared to the cubes used to construct the plots in Fig. 4. The results of cumulative analysis are shown in Table 2.

Table 2 shows the percentage of samples deviating from observed value as compared to the total number of tested samples (20 samples).

From Fig. 6, it is also clear that all the results obtained lay in the range provided by the hammer. However, this range is high, which makes no direct estimation of the strength of concrete. For example, a measured average rebound number of 31.5 resulted in a range of 19.7−32.3 MPa. This is, of course, a high range of prediction. It is also clear that Bellander's values are far away from actual results. Also, it is clear that most of the results presented by the author, using Fig. 4, lie close to the actual crushing strength and most of them are less than the actual values. This gives some degree of safety using Fig. 4 but, unfortunately, the safety margin is unpredictable.

7. Conclusions

From this study it can be concluded that:

1. The use of rebound hammer alone is not suitable to estimate and predict the strength of concrete. High variations are obtained, which makes engineering judgment quite difficult.
2. When compared to the rebound number, the ultrasonic pulse velocity method seems to be more efficient in predicting the strength of concrete under the conditions of the work. However, the use of such method alone would not give good reliable prediction of the strength of concrete.
3. The use of the combined methods produces results that lie close to the true values when compared with other methods.
4. The lower strengths of concrete showed higher prediction intervals and hence, less predictable strength by the combined methods.
5. The use of the combined methods yields more reliable and closer results to the actual strength. The 95% prediction interval is quite narrow, which enhances engineering judgement.
6. Better results of prediction of strength is obtained for estimated crushing cube strengths exceeding 20 MPa.

7. The method can be extended to test existing structures by taking direct measurements on concrete elements.

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