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# Ultrasonic Pulse Velocity and Rebound Hammer Testing for Nondestructive Evaluation of Existing Concrete Structure

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## Abstract

*Nondestructive evaluation of existing structures is a vital part and an active area of research in civil engineering industry. Whenever modifications in a structure or its use are proposed the process begins with the evaluation of existing condition. Rebound hammer (RH) and ultrasonic pulse velocity (UPV) tests are the two readily available and easy-to-perform methods that are widely used in the industry. Current research work is focused on evaluation of an eight years old, half-built reinforced concrete building. The objective was to gather information to decide about the future construction and use. The study concludes that concrete is of reasonable quality and building is appropriate for future construction and use. However, one column in the basement has very poor quality concrete and needs strengthening. Paper also provides a comparison of existing regression models for the prediction of concrete strength based on RH and UPV test data.*

**Key Words:** *Nondestructive Testing, Ultrasonic Pulse Velocity, Rebound Hammer.*

## 1. Introduction

The major objective of nondestructive testing (NDT) is to assess the condition of structure without affecting its performance [1]. NDT methods have seen significant developments during recent decades [2,3]. However, most of the civil engineering programs have not yet incorporated NDT in their concrete education. For instance, in the U.S., less than 1 out of 12 civil engineering programs are teaching NDT in their concrete courses [2]. Bray (1993) suggested that NDT should be integral part of engineering education [4].

The ultrasonic pulse velocity (*UPV*) test and rebound hammer (*RH*) tests are commonly used to determine the in-place quality and strength of concrete. The combination of these two tests is also referred as SonReb. SonReb is very advantageous because *RH* test provides surface strength of concrete whereas *UPV* test reflects the inner properties of concrete [5]. Shariati et al. (2011) [1] concluded that *RH* test provides better prediction of concrete strength as compared to *UPV* test. Researchers [1, 6-8] have found that combined methods that refer to the use of two or more NDT methods can provide better prediction of in-place properties of concrete. Based on SonReb measurements, concrete strength can be predicted using three techniques: computational modeling; artificial neural networks and parametric multi-variable regression models. Several researchers [1, 5, 6, 8, 9, and 11] have developed regression models to predict concrete strength using *UPV* and rebound number (*RN*). Huang et al. (2011) [5] has provided a summary and comparison of these models and has also proposed her own model.

Current work is focused on establishing the strength and quality of concrete of an existing reinforced concrete building. The building had five existing stories (including one basement and one lower ground floor) with seven still to be constructed (Figure 1). Its construction started almost 8 years ago and was stopped after one year. During these seven years concrete had been exposed to severe temperature variations, humidity and rains. After these many years the construction work was planned resume. It was then imperative to perform NDT to determine out the existing condition of concrete because the decision of constructing seven more floors had to be based on the existing strength and quality of concrete. It was planned to adopt combined method consisting of *RH* and *UPV* tests. Critical columns, walls of lift wells and slabs were identified on all floors to perform these tests. Data from these two types of tests were then used to predict the concrete strength based on the previously available regression models.

**Fig. 1** View of the Partially Constructed Building under Study

## 2. Review of Testing Method

*RH* test provide an inexpensive, simple and quick method of obtaining an indication of concrete strength. *RH* test is based on the principle that the rebound of an elastic mass striking at the concrete surface depends on the hardness of the surface. On pressing the plunger of the rebound hammer against the concrete surface and then releasing, the spring-pulled mass rebounds. The magnitude of rebound is recorded as *RN*. *RN* is a measure of energy absorbed during the impact thus an indicator of concrete strength. *RH* test only provides an estimate of the strength of concrete near the surface. *RH* test is most likely influenced by the surface layer of concrete and therefore considered as an ‘indicator’ of concrete strength. Further, *RN* is affected by moisture content of concrete; surface smoothness; nature of coarse aggregate; age of concrete; and size, shape, and rigidity of concrete specimen [5]. Although any distinct relation between strength and hardness of concrete does not exist, however, such a relationship can be obtained for a given concrete [12]. ASTM C805 [13] provides detailed procedure for performing *RH* test.

*UPV* test equipment consists of two transducers: trainmaster and receiver. Transmitter generates a pulse of vibrations at an ultrasonic frequency which are received by the receiver. Knowing the distance between the transmitter and the receiver, ultrasonic pulse velocity is calculated which is used to estimate the properties of concrete. *UPV* test is mainly used for assessing the quality of concrete; detection of crack development and checking the deterioration due to environmental/chemical effects. *UPV* test has also been used to determine the residual strength of concrete and to assess damage [2]. Mirmiran and Wei (2001) [14] reported that continuous *UPV* monitoring is a feasible tool for damage assessment in concrete filled FRP tubes. Several researchers [15-17] have described the behavior of *UPV* in concrete; recent developments in NDT techniques; and application of *UPV* in concrete damage assessment. However, standard correlation between compressive strength of concrete and *UPV* does not exist [18]. Type of coarse aggregates is one of the major factors which influences the correlation between strength and *UPV* and also changes the elastic properties of concrete [19]. *UPV* test can be performed in three different ways: direct; semi direct; and indirect transmissions. Yaman et al. (2001) [20] conducted *UPV* tests on slab panels with direct and indirect transmissions. He concluded that direct and indirect *UPV* are statistically similar provided that the concrete has uniform properties along the surface and along the depth. Several standards provide guidelines for performing *UPV* testing for in-place assessment of hardened concrete [21-23]. Figure 2 presents the equipments used for the *RH* and *UPV* test.

(a) (b

**Fig. 2** NDT Equipment: (a) Rebound Hammer; and (b) Ultrasonic Pulse Velocity Tester

## 3. Experimental Work and Discussion

Total 40 *RH* tests were performed: 17 on columns; 12 on slabs; 10 on walls of lift wells; and 1 on a beam. The frequency and locations of the tests were decided in such a way that all floors would be covered. On each floor, tests were performed at 3 to 5 different locations, scattered in various parts of the floor. Table 1 provides a summary of *RH* test results and location of tests for all floors. The design strength of concrete for columns and lift wells was 28 MPa whereas for slabs it was 21 MPa. All the columns except four exhibited strength lesser than the design strength. The lowest strength was found in one of the basement columns which was 15.7 MPa. Such column with low strength concrete need thorough inspection through other testing methods like core test and be strengthened using appropriate strengthening techniques, if low concrete strength is confirmed. Average strength exhibited by columns was found as 40 MPa (without considering 15.7 MPa), with a peak strength of 52 MPa for a column on first floor. All the lift wells except one qualified the test with an average concrete strength of 43.6 MPa; and 30.4 MPa and 54 MPa as the lowest and the highest strength. Slabs at all floors also qualified the test with and average strength of 40.7 MPa and a highest and lowest of 47.1 and 35.3 MPa respectively.

(a)

(b)

**Fig. 3** Performance of Tests: (a) *UPV* Test on Slab; and (b) Rebound Hammer Test on Column

**Table1** Summary of Rebound Hammer Test Results

| Sr. No. | Structural Member | Location of Member | Avg. Rebound Number | Concrete Strength (MPa) |
|---|---|---|---|---|
| 1 | Column | Basement | 37 | 35.3 |
| 2 | Column | Basement | 38 | 37.3 |
| 3 | Column | Basement | 36 | 33.4 |
| 4 | Column | Basement | 34 | 30.4 |
| 5 | Column | Basement | 24 | 15.7 |
| 6 | Column | Lower Ground Floor | 41 | 43.2 |
| 7 | Column | Lower Ground Floor | 40 | 41.2 |
| 8 | Column | Lower Ground Floor | 39 | 39.2 |
| 9 | Column | Lower Ground Floor | 38 | 37.3 |
| 10 | Column | Lower Ground Floor | 36 | 34.3 |
| 11 | Column | Ground Floor | 40 | 41.2 |
| 12 | Column | Ground Floor | 43 | 47.1 |
| 13 | Column | Ground Floor | 42 | 45.1 |
| 14 | Column | Ground Floor | 39 | 39.2 |
| 15 | Column | First Floor | 40 | 41.2 |
| 16 | Column | First Floor | 41 | 43.2 |
| 17 | Column | First Floor | 46 | 52.0 |
| 18 | Wall Lift Well | Basement | 40 | 41.2 |
| 19 | Wall Lift Well | Basement | 34 | 30.4 |
| 20 | Wall Lift Well | Basement | 39 | 39.2 |
| 21 | Wall Lift Well | Lower Ground Floor | 44 | 48.1 |
| 22 | Wall Lift Well | Lower Ground Floor | 43 | 46.1 |
| 23 | Wall Lift Well | Lower Ground Floor | 46 | 52.0 |
| 24 | Wall Lift Well | Ground Floor | 40 | 41.2 |
| 25 | Wall Lift Well | Ground Floor | 47 | 54.0 |
| 26 | Wall Lift Well | Ground Floor | 38 | 37.3 |
| 27 | Wall Lift Well | Ground Floor | 43 | 46.1 |
| 28 | Slab | Basement | 36 | 39.2 |
| 29 | Slab | Basement | 34 | 35.3 |
| 30 | Slab | Basement | 34 | 35.3 |
| 31 | Slab | Lower Ground Floor | 41 | 47.1 |
| 32 | Slab | Lower Ground Floor | 40 | 46.1 |
| 33 | Slab | Lower Ground Floor | 36 | 39.2 |
| 34 | Slab | Lower Ground Floor | 39 | 44.2 |
| 35 | Slab | Ground Floor | 37 | 41.2 |
| 36 | Slab | Ground Floor | 38 | 42.2 |
| 37 | Slab | Ground Floor | 36 | 39.2 |
| 38 | Slab | Ground Floor | 38 | 43.2 |
| 39 | Slab | First Floor | 34 | 36.2 |
| 40 | Beam | Basement | 38 | 30.4 |

A total of 39 *UPV* tests were performed: 16 on columns; 12 on slabs; and 11 on walls of lift wells. Test observation of one column was ignored because direct transmission was not possible on that due to presence of masonry and the indirect transmission provided very low *UPV*. For all other columns and walls, direct transmission was used whereas indirect transmission was used for slabs because opposite faces of slabs were not accessible. Table 2 and 3 show the criteria of establishing concrete quality and summary of test results for columns, walls and slabs. Results for all the columns showed that concrete is of good quality except the one in the basement for which *UPV* was found as 1.31 km/sec. This is the same column which showed very low *RN* (24). Low *UPV* for this column confirms the results of *RH* test and emphasizes the need of strengthening. In case of walls, quality of concrete was generally good except at one location at the lower ground floor level, where *UPV* was only 2.0 km/sec. For slabs, because indirect transmission was used, *UPV* data may not be very reliable and cannot serve as decisive mean to establish concrete quality. *RH* test results are more trustworthy for slabs.

ACI 214R-11 [24] provides guidelines to evaluate data of the tests used for assessing condition of concrete. The analysis of strength test results presented in ACI 214R-11 assumes that test results follow normal distribution. Mathematically, normal distribution is defined by mean and standard deviation (SD). The property of normal distribution allows to estimate that what percentage of test data fall within multiples of standard deviation from the average. If 68.27% data lie within 1 standard deviation from mean and 95.45% of the data lie within 2 standard deviations the data are said to follow normal distribution [24]. Figure 4 and 5 present normal distribution (ND) plots for *RH* and *UPV* tests respectively. Only the data for columns and walls are used for plotting ND plots because *UPV* data for slab would not be very reliable due to indirect transmission. *RH* test and *UPV* test results for one very weak column at the basement (*RN* = 24, *UPV* = 1.3 km/sec.) are omitted from ND plot because it's *RN* and *UPV* were significantly lower as compared to other columns. ND plots (Figures 4 and 5) for *RH* and *UPV* tests show that the test data follow the normal distribution. In case of *RH* test the data is more scattered than the *UPV* tests. Scatter of *RH* test results indicates that surface properties of concrete show greater variation as the concrete grows old and remains exposed to changing environmental conditions. Whereas the inner condition of concrete is lesser influenced from the environmental conditions than the surface properties, therefore *UPV* data shows more concentration near the mean value.

**Table 2** Criteria for Classification of Concrete [25]

| Pulse Velocity (km/sec.) | Quality of Concrete |
|---|---|
| $UPV \geq 4.5$ | Excellent |
| $3.5 \leq UPV < 4.5$ | Good |
| $3.0 \leq UPV < 3.5$ | Medium |
| $UPV < 3.0$ | Doubtful |

## 4. Prediction of Concrete Strength

This section presents a comparison of previously available regression models proposed to predict concrete strength based on SonReb observations. Huang et al. (2011) [5] refitted eleven existing models using some calibration data and found that only five models were valid and the rest failed to satisfy the homoskedasticity and normality assumptions and/or have variable modeled incorrectly. In addition to these five models, she also proposed two models and provided a comparison of these seven models. Another models proposed by Shariati et al. (2010) was also found in literature and is also included in the comparison. Table 4, Table 5 and Table 6 present the previous models, data used in the models; and a summary of concrete strength predicted by using these eight models, respectively. Concrete strength is predicted only for columns and walls of lift wells, not for slabs. Because *UPV*'s for slabs were not reliable due to indirect transmission. Regression model (M5) proposed by Kherder (1999) [10] provides concrete strength closest to the design strength of 28 MPa with a difference of -1.8% for column. Predictions of concrete strength from Shariati's [1] model differ the most on higher side from the design strength (47.2% and 54% higher for columns and walls, respectively) whereas predictions from second model (M2) of Huang et al. (2011) [5] differ the most on the lower side (58.9% and 54.4% lower for columns and walls, respectively). These results contradict with the findings of Huang et al. (2011) [5]. She concluded that her model (M1) provides the best results among the seven models, which she compared. Such difference is understandable because the properties of current concrete including: age; moisture conditions; aggregate type; surface smoothness etc. may differ significantly from the concrete for which Huang used the calibration data. To improve the accuracy of the regression models, the aforementioned factor should also be incorporated in the models. Huang et al. (2011) [5] included water/cement ratio and age of concrete in her models. Trtnik et al. (2009) [26] proposed that aggregate type should be included in the model to get better prediction of concrete strength when *UPV* tests are used.

**Table 3** Summary of Ultrasonic Pulse Velocity Test Results

| Sr. No. | Structural Member | Location of Member | Avg. Pulse Velocity km/sec. | Quality of Concrete |
|---|---|---|---|---|
| 1 | Column | Basement | 1.3 | Doubtful |
| 2 | Column | Basement | 3.7 | Good |
| 3 | Column | Basement | 3.8 | Good |
| 4 | Column | Basement | 3.8 | Good |
| 5 | Column | Lower Ground Floor | 4.4 | Good |
| 6 | Column | Lower Ground Floor | 4.1 | Good |
| 7 | Column | Lower Ground Floor | 3.7 | Good |
| 8 | Column | Lower Ground Floor | 3.8 | Good |
| 9 | Column | Ground Floor | 4.0 | Good |
| 10 | Column | Ground Floor | 4.2 | Good |
| 11 | Column | Ground Floor | 4.0 | Good |
| 12 | Column | Ground Floor | 4.3 | Good |
| 13 | Column | First Floor | 4.0 | Good |
| 14 | Column | First Floor | 3.7 | Good |
| 15 | Column | First Floor | 4.2 | Good |
| 16 | Lift Wall | Basement | 4.1 | Good |
| 17 | Lift Wall | Basement | 3.0 | Medium |
| 18 | Lift Wall | Basement | 3.0 | Medium |
| 19 | Lift Wall | Basement | 3.7 | Good |
| 20 | Lift Wall | Basement | 3.3 | Good |
| 21 | Lift Wall | Lower Ground Floor | 4.4 | Good |
| 22 | Lift Wall | Lower Ground Floor | 2.0 | Doubtful |
| 23 | Lift Wall | Ground Floor | 4.7 | Excellent |
| 24 | Lift Wall | Ground Floor | 4.2 | Good |
| 25 | Lift Wall | Ground Floor | 4.3 | Good |
| 26 | Lift Wall | Ground Floor | 4.1 | Good |
| 27 | Slab | Basement | 2.4 | Results are not reliable due to indirect transmission |
| 28 | Slab | Basement | 2.6 | |
| 29 | Slab | Basement | 2.6 | |
| 30 | Slab | Basement | 3.0 | |
| 31 | Slab | Lower Ground Floor | 2.2 | |
| 32 | Slab | Lower Ground Floor | 2.6 | |
| 33 | Slab | Lower Ground Floor | 2.2 | |
| 34 | Slab | Lower Ground Floor | 2.2 | |
| 35 | Slab | Ground Floor | 2.2 | |
| 36 | Slab | Ground Floor | 2.0 | |
| 37 | Slab | First Floor | 1.6 | |
| 38 | Slab | First Floor | 1.9 | |

## 5. Summary and Conclusions

Nondestructive evaluation of an eight year old incomplete reinforced concrete building has been carried out using combination of *UPV* and *RH* tests. Based on experimental observations, strength of concrete is predicted using the previously available regression models. In the light of the test results, it can be concluded that the strength and quality of concrete is reasonable. Although the structure has been exposed to severe weather for several years but still the concrete is in good shape and the structure can be put to service in future. At few isolated locations, for instance in one of the columns in the basement, the strength of concrete is below the requirement. This column should be strengthened either by steel or concrete jacketing; or fiber reinforced polymer (FRP) wrapping, whichever is found suitable. Authors reinforce the findings of previous researchers that methods of NDT based on combination of more than one method are more suitable for in-place evaluation of concrete instead of using just one method. Test results of *RH* test show more scatter as compared to *UPV* tests which can be attributed to the fact that surface properties of concrete are more likely to alter over the period of time as compared to inner properties. In general, average *UPV* and *RN* for columns were found smaller than walls of lift wells. Concrete strengths predicted by previously available models provide scattered results, which could be due to the differences in the properties of concrete used for the development of models and the concrete of the structure under study. Model proposed by Kherder (1999) [5] predicted concrete strength closest to the design strength whereas results from models suggested by Shariati et al. (2011) [1] and Haung et al. (2011) [5] deviate the most from design strength on the higher and lower side, respectively. Although the results of column and walls provide reasonable information about concrete strength which can be used for future design, however strength of concrete slabs could not be determined with decent accuracy. The reason is that indirect transmission of *UPV* test was used because the opposite faces of slabs were not accessible. This emphasizes the need to develop reliable relationship between direct and indirect transmission of *UPV* test. Because high-strength concrete (HSC), ultra-high

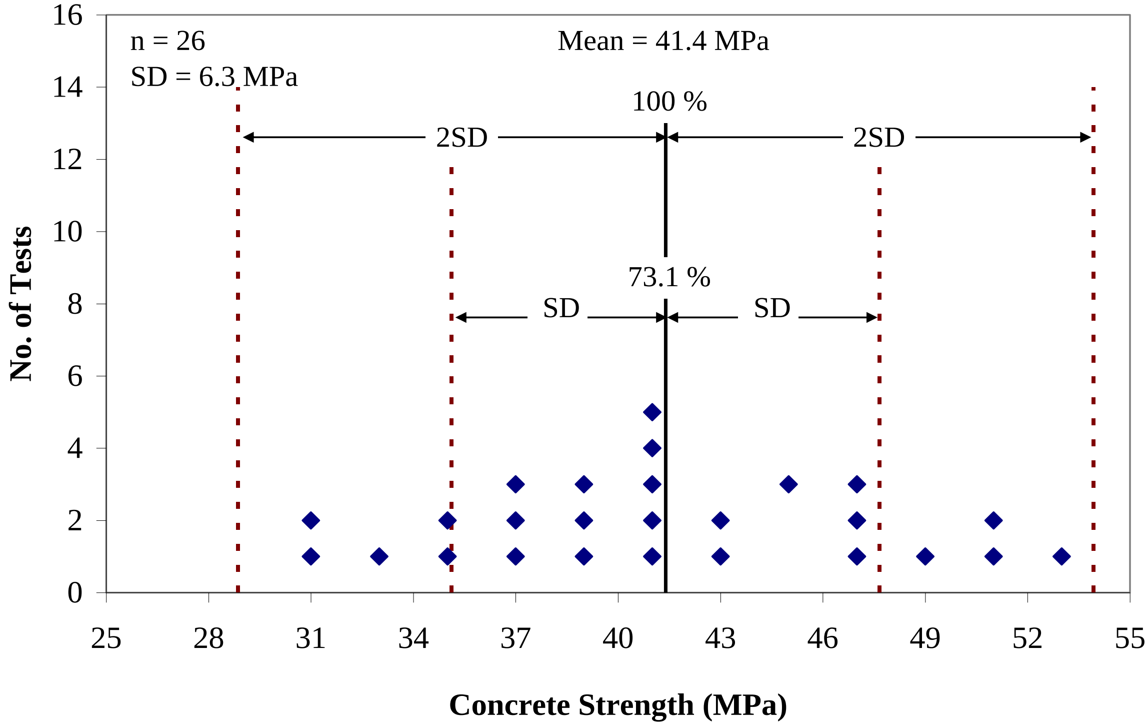


**Fig. 4** Normal Distribution Curve for Rebound Hammer Test on Columns and Walls

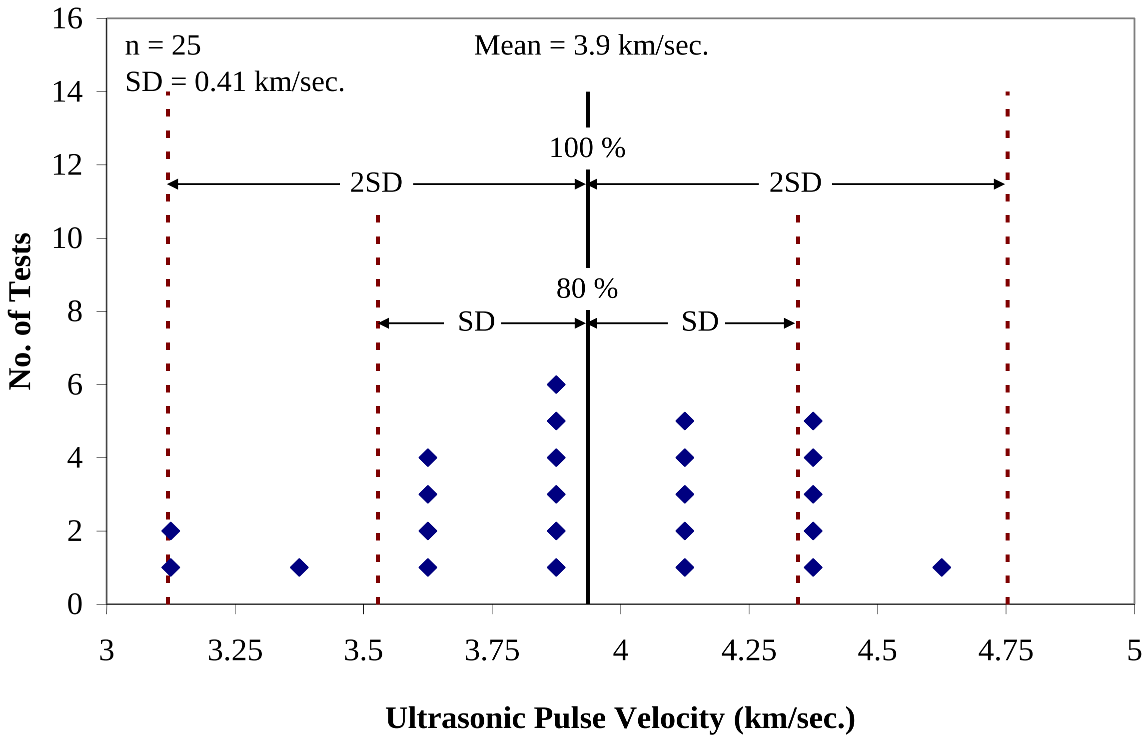


**Fig.5** Normal Distribution Curve for Ultrasonic Pulse Velocity Test on Columns and Walls

**Table 4** Model Proposed by Previous Researchers

| No. | Proposed by | Models |
|---|---|---|
| M1 | Haung et al. (2011) | $\sqrt{fc} = \theta_0 + \theta_1 RN^2 + \theta_2 UPV^3 + \theta_3 wc^{-0.5} + \theta_4 \ln(age) + \sigma\varepsilon$ |
| M2 | Haung et al. (2011) | $\sqrt{fc} = \theta_0 + \theta_1 RN^2 + \theta_2 UPV^3 + \sigma\varepsilon$ |
| M3 | Samarin and Meynink (1981) | $f_c = \theta_0 + \theta_1 RN + \theta_2 UPV^4$ |
| M4 | Wiebenga (1968) | $\ln f_c = \theta_0 + \theta_1 RN + \theta_2 UPV$ |
| M5 | Kherder (1999) | $\ln f_c = \theta_0 + \theta_1 \ln RN + \theta_2 \ln UPV$ |
| M6 | Kherder (1999) | $\ln f_c = \theta_0 + \theta_1 \ln RN + \theta_2 \ln UPV + \theta_3 \ln(unit\ weight)$ |
| M7 | Arioglu et al. (1994) | $\ln f_c = \theta_0 + \theta_1 [\sqrt{\ln(RN^3 . UPV^4)}]$ |
| M8 | Shariati et al. (1994) | $f_c . UPV = -173.04 + 4.07 UPV^2 + 57.96 UPV + 1.31 RN$ |

**Table 5** Summary of Relevant Data for Concrete

| | Columns | Walls |
|---|---|---|
| Average *RN* | 39 | 41 |
| Average *UPV* (km/sec.) | 3.79 | 3.89 |
| Unit wt. of Concrete (kN/m$^3$) | 2400 | 2400 |
| Water to Cement Ratio, *wc* (%) | 45 | 45 |
| Age (days) | 3285 | 3285 |
| Design Concrete Strength, $f_c$ (Mpa) | 28 | 28 |

**Table 6** Comparison of Concrete Strength Calculated from Various Models

| Model | $\theta_0$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\sigma$ | $\varepsilon$ | Columns | | Walls of Lift Wells | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Predicted Strength | Difference from $f_c$ Design | Predicted Strength | Difference From $f_c$ Design |
| | | | | | | | | MPa | % | MPa | % |
| M1 | -3.06 | 0.00027 | 0.024 | 37.04 | 0.24 | 0.5192 | 0 | 37.5 | 33.9 | 39.3 | 40.5 |
| M2 | 1.26 | 0.00015 | 0.035 | - | - | 0.8024 | 0 | 11.5 | ***-58.9*** | 12.8 | ***-54.4*** |
| M3 | -32.88 | 1.31 | 0.072 | - | - | - | - | 33.1 | 18.1 | 37.3 | 33.3 |
| M4 | -0.71 | 0.033 | 0.72 | - | - | - | - | 27.3 | -2.6 | 31.3 | ***11.8*** |
| M5 | -4.66 | 1.06 | 3.07 | - | - | - | - | 27.5 | ***-1.8*** | 31.4 | 12.1 |
| M6 | -21.12 | 1.01 | 2.28 | 2.29 | - | - | - | 31.2 | 11.6 | 34.9 | 24.5 |
| M7 | -10.89 | 3.57 | - | - | - | - | - | 34.2 | 22.1 | 38.3 | 36.6 |
| M8 | - | - | - | - | - | - | - | 41.2 | ***47.2*** | 43.1 | ***54.0*** |

strength concrete (UHSC), ultra-high performance concrete (UHPC) and fiber reinforce concrete (FRC) are now a days becoming more common, regression models for predicting their strength based on SonReb should also be developed and relationship between direct and indirect transmission of *UPV* for these should also be established.

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