Nondestructive Testing on Reinforced Concrete Structure: A Case Study

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***Abstract*—Non-destructive testing (NDT) is commonly implemented to determine the reliability of the concrete structure elements. In this study, we present a non-destructive diagnosis of structural members of an existing reinforced concrete building. Different types of *in situ* non-invasive tests such as Schmidt Hammer and ultrasonic pulse velocity together with invasive concrete coring were carried out to investigate the relation between rebound number/ultra sonic pulse velocity and concrete compressive strength by the following correlations: 1) Linear regression, 2) Exponential regression, and 3) Multiple nonlinear regression. Among these cases, the combined SonReb model yielded the most reliable estimates to predict the compressive strength, where a coefficient of determination (R^2) of 0.81 was obtained. However, the use of rebound hammer test only found to be not adequate for the estimation of compressive strength. Due to the exposure of the RC building to the harsh environment for long period (more than 30 years), data from 18 extracted cores were further analyzed to study the effect of carbonation on steel reinforcement. The presence of significant carbonation depth (~22 mm) and the large amounts of chloride lead to severe steel corrosion in several parts of the structure.**

***Index Terms*—Non-destructive tests, invasive and noninvasive tests, Compressive strength, Schmidt hammer, ultrasonic pulse velocity, SonReb, carbonation depth.**

I. Introduction

In recent years, nondestructive (NDE) tests have been widely used to estimate the in situ compressive strength, to study the safety and integrity and to conduct a preliminary structural assessment of existing reinforced concrete structures, and especially, the old and deteriorated ones. Results from earlier studies demonstrate a strong association between the Schmidt Hammer readings (R) and the in situ compressive strength (f_c) [1], [2]. On the other hand, combining different testing techniques (i.e. using SonReb) has been found to be more reliable method in estimating compressive strength, when compared to those obtained by simple methods [3], [4], [5], [6]. Unfortunately, the uncertainty of NDE test procedures, the age of structures, and the mechanical damage caused by cores drilling could affect the accuracy of the nondestructive test results [7]. There are three primary aims of this study: 1. To assess the accuracy of Schmidt Hammer in estimating in situ compressive strength of existing concrete structure; 2. To improve the reliability of NDT using SonReb method; and 3. To examine the effect of carbonation depth on structural elements. This investigation takes the form of a case-study on an abandoned 5 story building with a basement. The overall structure of this paper has been organized in the following order: a) the second section will discuss both the sources and methods of study, b) the third section will present the findings of the research and discuss the significant ones, and c) the final section will give a brief summary and critique of the findings.

II. Methodology

A. Compressive Strength Test

Concrete cylindrical cores from 3 beams and 15 columns were extracted in-situ by a diamond impregnated drill bit attached to a core barrel (Fig. 1c) based on the procedure outlined in ASTM C42 [8]. The concrete cylinders were prepared and tested in the lab to determine its compressive strength based on the procedure outlined in ASTM C39 [9] by applying an axial load over the cross-sectional area of the concrete cylinders until failure.

B. Schmidt Rebound Hammer (SRH) and Ultrasonic Pulse Velocity (UPV) Tests

The Schmidt rebound hammer (SRH) and ultrasonic pulse velocity (UPV) are widely used to investigate the strength uniformity of and to predict the compressive strength (f_{ck}) of concrete structures. Before conducting SRH and UPV tests, the concrete surface was thoroughly smoothed by an abrasive stone, and especially, in areas with rough texture to ensure a proper contact between the measuring device and the test surface. A total number of 16 SRH tests located near the extracted cores were carried out using Proceq SilverShmidt (Fig. 1a) according to ASTM C805 [10]. The mean rebound number was obtained from each test. Following Schmidt hammer test, structural members were tested for ultrasonic pulse velocity as described in BS EN 12504-4:2004 [11]. All UPV readings were taken directly (Fig. 1b) (i.e., the two transmitting and receiving transducers were opposite to each other). It is worthwhile noting that NDT results are

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highly affected by the type of aggregate and concrete mix proportions [12]. However, these properties were not known.

C. SonReb (SONic REBound) Method

The correlation of rebound number and ultrasonic pulse velocity with actual compressive strength was obtained using the double power low model

$$f_c = \text{a}\, UPV^{\text{b}}\, R^{\text{c}}$$

where f_c is the concrete compressive strength, [*MPa*]; UPV is ultrasonic pulse velocity, [*m/s*]; R is rebound value, (*S*); a, b, c are dimensionless correlation constants determined based on regression analysis from Proceq SonReb Excel sheet.

D. Carbonation Test

The carbonation test was carried out to determine whether the concrete cover is adequate to maintain the steel reinforcement from rust in the presence of both oxygen and moisture [13]. Following the British standard (BS EN 14630:2006) procedure [14], the indicator phenolphthalein was sprayed onto the surface of cylindrical cores immediately after extraction to measure the depth of the carbonated concrete. Thermogravimetric analysis (TGA) method is more accurate and used in few studies [15], [16], [17], [18]. If the pH value is equal or higher than 9, the indicator will give red-purple color, meaning that the concrete is non-carbonated. Otherwise, when the pH equals 7.5, the region of colorless depth is a clear indication of the full carbonation meaning that the passivating layer of iron oxide (Fe_2O_3) which protects embedded steel rebars from corrosion is destroyed [13]. The carbonation depth is measured as the distance between concrete surface and the carbonation front.

(a)

(b)

(c)

Figure 1. Nondestructive and noninvasive digital Schmidt Hammer (a) and UPV (b) tests; (c) invasive method to extract concrete cores from beams and columns

III. Results and Disscussion

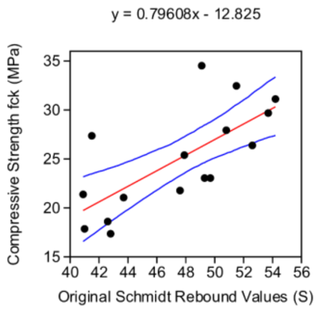
A. Compressive Strength Rebound Hammer Correlation

Linear and exponential regression have been set up and illustrated with data obtained from in situ compressive strength and rebound values. The number of tests is the correlation is n = 18. As seen in Fig. 2, and except a few outliers, a fair agreement is found between rebound hammer and the actual compressive strength results. The R^2 value and RMSE of linear regression are found to be 0.49 and 3.87, respectively, which indicate a non-significant correlation between rebound values and actual compressive strengths. The linear equation is

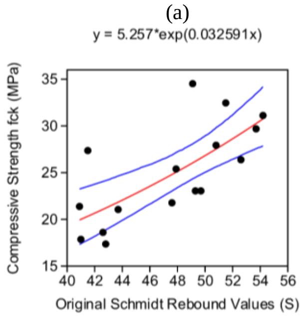
$$y = 0.8x - 12.8$$

where y is compressive strength and x is rebound number. It can be seen that there is a slight enhancement in the exponential regression, where R^2 and RMSE are 0.5 and 3.86, respectively, and its equation is

$$y = 5.3e^{0.033x}$$



(a)



(b)

Figure 2. Linear (a) and exponential (b) correlations between Rebound values and compressive strength. The red line depicts the regression curve and the blue lines represent the 95% confidence interval.

B. SonReb Method

Combined relation between UPV and rebound number has been carried out using SonReb method, which is based on multiple regression, in order to predict compressive strength. The derived regression equation is

$$f_c(\text{UPV}, \text{R}) = 2.45\ UPV^{-0.31}\ R^{1.25}$$

SonReb approach yielded a value of R^2 of 0.81, which indicates a significant correlation. Obviously, regression model achieved by the combination of UPV and rebound number had a better correlation than individual linear and exponential models (R^2 is ~0.5) of Schmidt hammer rebound (SHR) vs. compressive strength.

C. Carbonation Depth

Fig. 3 shows the phenolphthalein colorless (carbonated) depth of the extracted cores. Fourteen concrete samples out of 18 were carbonated, where 6 of them have a carbonation depth that approaches steel rebar which may severely affect the durability of concrete and cover thickness. Three samples had a significant depth ranging from 12 to 13 mm, which may cause reinforcement corrosion. On five samples, the depth of carbonation was not significant and ranged from 3 to 6 mm (Fig. 4). Only four samples were non-carbonated. Due to the long period (more than 30 years) of exposure to environmental variables (e.g. humidity) and weather conditions (e.g. rain), the carbonation depth was found to be high in most concrete specimens extracted from the building [19]. In addition, the public building is located ~900 m from the seashore. This can significantly accelerate the deterioration of concrete where carbon dioxide, as well as chlorides, can reach the steel reinforcement more rapidly and cause corrosion [20]. After noticing the widespread signs of steel corrosion in the retaining wall Fig. 5, the investigators removed the concrete cover and exhibited severe corrosion. The investigators also observed the presence of large localized amounts of chloride.

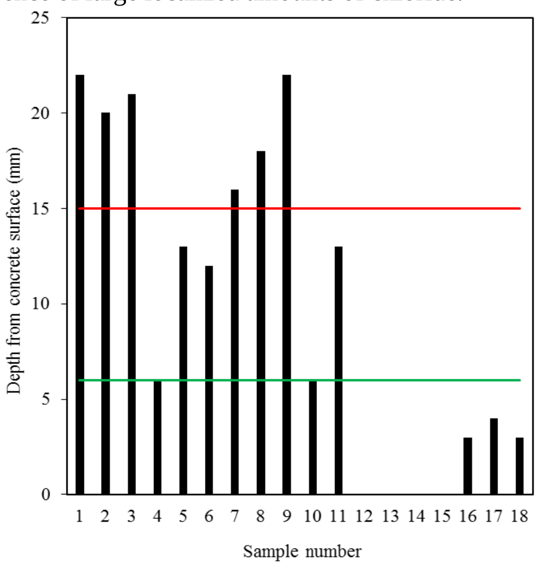


Figure 3. The carbonation depth of extracted core samples. The green and red lines are the limits of negligible and severe carbonation, respectively

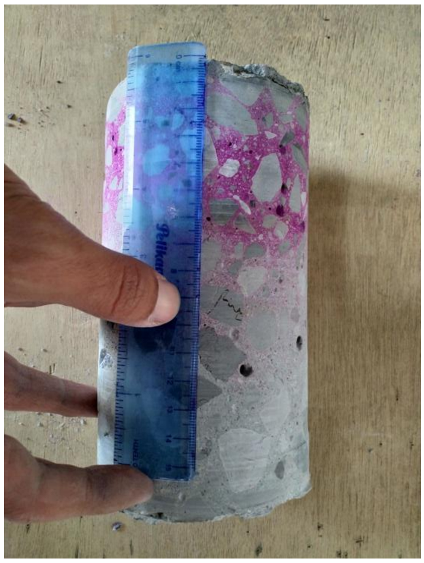


Figure 4. Concrete cylinder after spraying the phenolphthalein. Aggregates seems to be not vulnerable to onset of carbonation.

Figure 5. Severe corrosion of reinforcing bars in the retaining wall of the basement.

IV. Conclusion

The presented study analyzed the use of NDT to estimate the in situ compressive strength and studied the effect of carbonation depths on steel reinforcement. Several correlation models have been developed to study the relations between Schmidt hammer rebound (R), ultrasonic pulse velocity (UPV) and compressive strength (fc). When using UPV in addition to rebound values, a reliable SonReb model to predict the compressive strength was obtained with R^2 value of 0.81. However, the use of individual models, which correlates both fc and R, is seen to be not reliable where R^2 and RMSE are 0.5 and 3.86, respectively. The exposure of RC building to harsh environment for a long period led to severe corrosion in the steel reinforcement, and hence, had a direct impact to the durability of concrete. This can be seen from the results of the carbonation where most concrete samples were carbonated to a great depth.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Hasan A. Almuhanna and Ali K. Saleh conducted the research, participated in the data collection and drafted the manuscript. Noura A. Almutawa analyzed the data, performed the statistical analysis and wrote the paper. All authors read and approved the final manuscript.

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