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Advancing concrete strength prediction using non-destructive testing: Development and verification of a generalizable model

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HIGHLIGHTS

- Models for compressive strength prediction solely based on NDT results were developed.
- Concrete strength classification using combined NDT results was proposed.

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ABSTRACT

Accurate prediction of concrete compressive strength is imperative for investigating the in-situ concrete quality. To avoid destructive testing, developing reliable predictive models for concrete compressive strength using nondestructive tests (NDTs) is an active area of research. However, many of the developed models are dependent on calibration and/or concrete past history (e.g. mixture proportion, curing history, concrete mechanical properties, etc.), which reduces their utility for in-situ predictions.

This paper develops predictive models for concrete compressive strength that are independent of concrete past history. To this end, ultrasonic pulse velocity (UPV) and rebound hammer (RH) tests were performed on 84 concrete cylindrical samples. Next, compressive strengths were determined using destructive testing on these cylinders, and predictive models were developed using NDT results. Furthermore, to ensure generalizability to new data, all models were tested on independent data collected from six different research papers. The results support combined usage of UPV and RH in a quadratic polynomial model structure. Therefore, the final model was proposed based on combining models from a threefold cross-validation of the experimental data. This model predicted the independent data with very good accuracy. Finally, a concrete quality classification table using combined RH and UPV is proposed based on a variant of machine learning k-means clustering algorithm.

1. Introduction

Estimating the in-situ compressive strength is imperative for evaluating the quality of existing concrete structures during their service lives. In many cases, however, the actual condition of the materials used in construction is highly variable, and no information exists regarding the specifications of the concrete. This information includes age, concrete ingredients, construction quality, curing method, and concrete mechanical properties. Non-destructive tests (NDTs) can be used in such situations to estimate the in-situ physical properties of concrete to circumvent the need for in-situ sampling and compressive testing of concrete cores [1]. Due to the increase in the need for assessment of damaged concrete structures, NDT has gained popularity in recent years, and many NDT methods are available such as cast in-place cylinder test, ultrasonic pulse velocity (UPV), rebound hammer (RH), and resonant frequency test [2]. The procedures for performing these NDTs are outlined in ACI 228.1R-13 [3]. This paper focuses on RH and UPV.

Rebound hammer testing is a simple NDT method that provides an approximate indication of concrete quality and is deemed as a supplementary and in-place technique for estimating compressive strength of cast-in-place concrete [4]. Test results are measured as rebound number (RN). Many researchers attempted to establish a relationship between RN and compressive strength [5–8]. Szilágyi et al. [5] added to the fundamental understanding of the rebound surface hardness of concrete by introducing a phenomenological constitutive model that can be formulated for the surface hardness of concrete as a time dependent material property. Their results indicated that RN is significantly affected by the near surface properties of the hardened concrete such as smoothness, carbonation, size and type of the aggregates, and age of the concrete. Similar

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results are reported by ACI committee 228 [6]. Hence, RH is considered as a non-electronic, supplementary, in-place technique to predict the compressive strength of hardened concrete [4,8]. Qasrawi [7] also reported the unsuitability of the individual use of rebound hammer to estimate concrete strength.

Ultrasonic pulse velocity (UPV) method measures elastic properties of concrete and has been used to estimate the quality of in-situ concrete including the dynamic modulus of elasticity and therefore, compressive strength [9–11]. Yildirim et al. [12] investigated the effects of water to cement ratio, maximum aggregate size, aggregate type, and fly ash addition on the dynamic modulus of elasticity of low quality concrete using UPV. Based on their results, a strong relationship was achieved between the modulus of elasticity and ultrasound pulse velocity. However, the UPV test has been generally used to detect discontinuities in hardened concrete and is more sensitive to internal properties including density of concrete [4]. The empirical issues of using this method such as materials constitutions and calibration are explained in [13,14].

A combination of NDTs therefore, may be advantageous for predicting concrete strength, because the results obtained from a single test, as discussed above, might be inconclusive [15]. However, early investigations on this combined usage yielded mixed results. For instance, Breysse [16] concluded that the effectiveness of combining the evaluation of two or more NDTs has been controversial. Moreover, Carvalho et al. [17] applied statistical techniques to evaluate the reliability of UPV and RH to evaluate the compressive strength of the concrete in bridges. Their results revealed lack of consistency in the correlation of UPV and RH on four tested bridges. ACI 228.1R-03 [6] also reported that a combination of NDTs only provides marginal improvements over a single method. Nevertheless, recently, there is a growing literature on documenting the advantages of application of multiple NDTs to increase reliability and accuracy of predictions [7,18–21]. Ravindrajah et al. [22] reported promising results on compressive strength estimation of recycled-aggregate concrete using combined UPV and RH. Kheder [23] investigated concrete strength prediction using UPV and RH in conjunction with concrete mix proportions and density. They compared their results with cores taken from actual structures, and observed good predictive accuracy. The advantage of using a combination of RH and UPV, for example, can be described by the fact that the results of each test is influenced by different properties of the hardened concrete [7,21,24,25]. A number of regression models using a combination of UPV and RH to predict compressive strength have been developed recently [26–29]. The seminal work by Huang et al. [19] developed a multivariate regression model to predict compressive strength using the combined UPV/RH for a comprehensive data on the mixture proportions, curing conditions, and age of the concrete. They showed that their proposed model yields more accurate predictions in comparison with other regression models.

The real conditions of the structures may be highly variable spatially due to the variability of materials received, their properties and sporadic supervision [1,7]. Therefore, realistically, information about concrete mixture proportions and construction might not be available for in-situ predictions. However, a look at the above body of work reveals most of the developed models use this information. In the present article, accurate predictive models for compressive strength of concrete specimens are derived using only NDT results. Through rigorous statistical tests with threefold cross-validation, both UPV and RN were determined statistically significant variables for predictive modeling. Therefore, a multivariate regression model based on a combination of these NDT results was proposed and verified for accuracy through prediction of independent data. Finally, concrete quality classification using RN and UPV is proposed based on unsupervised machine learning k-means clustering method.

2. Experimental procedures and independent data collection

A total of 84 concrete cylinders with unknown information about their age, mixing ratios, and without any prior knowledge of their expected compressive strength were first tested in a laboratory using the following NDTs.

The rebound hammer (RH) test was conducted in accordance with ASTM C805 [31]. The test began by a careful selection and preparation of the sample surface for testing. Once the plunger of the RH is pressed to the concrete surface, a spring-pulled mass rebounds back with a rebound distance. The extent of the rebound is a measure of the surface hardness. This measured value is designated as the rebound number (RN), which is on a graduated scale. At least 10 readings for each sample were performed and their average was used to determine the RN for each sample. A concrete with high strength and high stiffness absorbs less energy, leading to a higher rebound value and a higher RN [6].

The ultrasonic pulse velocity (UPV) test was conducted according to ASTM C597 [30]. The UPV test can be conducted by three different methods; direct, semi-direct, and indirect method, out of which the direct method is the most accurate method [3] and was used in this work. However, in the field, using a direct method is impractical, and the indirect method is used instead. This test determines the required time for a vibration pulse of an ultrasonic frequency to travel through a concrete specimen with known dimensions. The pulse velocity is, therefore, determined and reported. Based on the obtained velocity, the uniformity, quality, and strength of tested specimens can be estimated. The changes in the wave speed indicate the variability of the dynamic modulus of elasticity and the density of the material [3]. RH and UPV tests were repeated three times on each specimen and the average values were reported. All the cylinders were secured from movement and all the tests were conducted on the center of the surface of the cylinders.

After all the NDTs were conducted, the compressive strengths of all the specimens were destructively determined according to ASTM C39 [32]. For this test, the cylinders were placed in a compression machine and were loaded until failure and the maximum compressive strength was recorded for each concrete cylinder. The combination of UPV, RH, and compressive test results forms the “in-house” data for this study.

An additional 88 data points were also collected from six different research papers [26,33–37]. These data are termed the “independent” data, and will be used for testing the proposed models.

3. Data modeling and classification approach

For all of the analyses in this paper, the UPV reading was scaled by dividing by 10^3. We begin with single variable linear regression analysis to establish the relation between compressive strength with RN and UPV separately. A regression model is expressed as follows:

$$\boldsymbol{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \tag{1}$$

where $\boldsymbol{y}$ is the vector of responses, $\mathbf{X}$ is the matrix that collects all the exogenous variables, which are hypothesized to predict or influence the response, $\boldsymbol{\beta}$ is the vector of model parameters that will be estimated based on the available data, and $\boldsymbol{\varepsilon}$ is the vector of noise or random fluctuations. In this study, the response data are concrete compressive strengths, and exogenous variables include RN, UPV and possibly their exponents with an intercept (constant) term. Important assumptions in regression models are as follows. It is assumed that responses are independent, and the random noise vector is zero-mean, uncorrelated and follows normal distribution. This last assumption also means that the residuals from any fitted