Predicting the Strength of Submerged and Saturated Concrete Structures using Non-Destructive Ultrasonic Pulse Velocity Testing

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ABSTRACT

Concrete has long been a fundamental material in the construction of diverse structural forms due to its high strength and adaptability. As a result, ensuring concrete quality and continuous monitoring of structural health has become a critical concern for engineers and structure owners aiming to extend service life. Accurate structural assessment requires precise evaluation of mechanical properties, particularly compressive strength. Among the available techniques, Non-Destructive Testing (NDT) offers a means to assess these properties without inflicting damage on the structure. One widely adopted NDT method is Ultrasonic Pulse Velocity (UPV) testing, which measures the time it takes for ultrasonic waves to travel through the material. This velocity is strongly influenced by concrete's density and moisture content, both of which affect compressive strength. Consequently, it is vital to establish an empirical equation that accounts for varying moisture conditions when estimating compressive strength. In this study, a Proceq Ultrasonic Pundit Lab (+) device was employed to test 80 concrete cubes under submerged, saturated, and dry conditions. These cubes were subsequently tested using a compression machine to determine their actual compressive strength. Each UPV measurement was paired with its corresponding strength value to derive an empirical prediction model. The resulting equation was initially calibrated using dry-condition data and subsequently adjusted utilizing correction coefficients for different moisture levels. The findings demonstrate that the proposed equation is a robust and reliable tool for predicting the compressive strength of concrete in non-dry states.

Keywords-non-dry concrete strength; soaked concrete; underwater concrete; ultrasonic-pulse-velocity; non-destructive-testing

I. INTRODUCTION

Concrete technology has gone through major and important developments especially in concrete design and application since it was first invented. These developments have contributed to its widespread use in a broad range of structures—from basic foundations to skyscrapers and large-scale hydraulic systems, such as water tanks and dams [1, 2]. All these structures require consistent quality control and ongoing structural health monitoring throughout their service life [3]. However, standard concrete samples, such as cubes or cylinders, do not often accurately represent the in-situ concrete due to variable site conditions [4]. They more accurately reflect the concrete from the truck mixer rather than the poured structural element itself. Most concrete structures must be assessed for various purposes, including condition monitoring, structural modifications, or forensic investigations. For this reason, NDT methods have been developed to inspect both substructure and superstructure components without damaging them. Engineers often face diverse conditions when evaluating existing concrete—ranging from extremely dry elements, such as bridge girders exposed to the environment, to submerged components, like the walls of dams or water tanks. Since ultrasonic testing operates by measuring the time ultrasonic waves take to travel through a material (i.e., their velocity), the moisture content significantly influences wave propagation and, in turn, the measured compressive strength. Therefore, extensive testing is necessary to assess these effects and to derive an accurate empirical model for predicting compressive strength under different moisture conditions. When supported by well-calibrated equations, NDT methods can provide highly reliable results. However, multiple samples must be examined under various scenarios to ensure accuracy. For example, during the renovation of an existing structure, an examination of whether its service life should be extended or new loads should be accommodated, such as additional floors or equipment thorough structural evaluation, is required. This involves determining the actual capacity of the structure before implementing modifications. Among the mechanical properties to be assessed, compressive strength is of primary importance. Consequently, its accurate estimation is essential in any structural evaluation. As previously mentioned, using drilled cores is a reliable method to determine the in situ compressive strength of concrete. Moreover, the extracted cores can be utilized to determine other important concrete properties, such as density, water absorption, and tensile strength [4]. The American Society for Testing and Materials (ASTM) has established well-standardized guidelines for sampling and testing methods [25]. Although this test has many advantages, it has certain drawbacks, since it is considered expensive and laborious. Moreover, if sampling is performed improperly, it might damage the critical structural elements of the building and endanger the durability of the structure [5, 6]. Unlike destructive testing, NDT avoids damaging the concrete, as the structure remains intact during the tests. Therefore, nondestructive tests, such as the Schmidt rebound hammer and UPV tests, can be employed as alternatives. However, the evaluation method for these types of testing mainly depends on the testing devices and predictive equations calibrated using an unlimited database [5, 7]. Hence, utilizing such equations is doubtful, considering that they are applied to several types of concrete created using different mix proportions and being cured under various conditions [7-9]. Therefore, the current research was initiated based on practical needs to fill the gaps in the literature with missing pieces of knowledge.

Researchers have utilized NDT techniques to establish correlations between concrete quality and strength through regression analysis models. These models predict the structural integrity of concrete based on UPV and rebound hammer measurements, and have been widely applied in structural health monitoring and performance evaluation of concrete structures [10–16]. The primary goal of this study was to establish an equation or relationship that can accurately predict the compressive strength of concrete when submerged or saturated with water. It is essential to emphasize the necessity of conducting this research so that its findings will be employed to evaluate and monitor crucial structures while they are functional and under different moisture conditions. In this study, 80 concrete cubes were examined. This examination includes different pulse velocity readings for various cube water contents (submerged, saturated, or dry). A hypothesis has been introduced to meet practical needs, and is interpreted based on basic physics, stating that the velocity of sound waves changes depending on the medium's density. All prepared cubes were ND-tested and then crushed to determine their compressive strength. These compressive strengths were compared with the NDT-measured values. Subsequently, these paired values were idealized to extract a reliable empirical fitted equation correlating the NDT values with the concrete compressive strength.

II. MATERIALS AND METHODS

To accurately predict the compressive strength of submerged or saturated concrete, a comprehensive and carefully designed testing program was implemented. Concrete cubes with a wide range of strength grades, from M15 to M60, were prepared for this purpose. To enhance the reliability and consistency of the results, all samples were tested at an age of over 160 days' time point chosen to ensure that the concrete had reached a stable strength state. Each cube was first subjected to NDT using advanced UPV equipment to measure the internal wave velocity. Following this, the same cubes were tested for compressive strength utilizing a standard compression testing machine. The employed UPV equipment was a Proceq —Ultrasonic Pundit Lab (+), whose specifications are listed in Table I. The distance between the probes is entered before testing, with the calculated velocity being displayed based on Velocity = Distance /Time. There are three approaches to utilize the UPV in measuring/evaluating the wave velocity passing through the concrete structure. The first one is the direct transmission method, where the props' faces are opposite and aligned along the same axis. This method is the most preferred and reliable one. The second one is the semi-direct method, where props could be placed on perpendicular surfaces (faces). The third one is the indirect method in which props are facing the same direction, but should be placed twice. It should be noted that the second and third methods are less preferred than the first one. In this research, the direct method has been deployed. The surfaces of all samples were prepared for aural connection by applying grease on the transducer contact area facing the cube surface, with the samples tested utilizing UPV while they were dry. All samples were numbered, and their measured wave velocities were recorded accordingly. Subsequently, all the cubes were placed in a water container and kept under water for a week. Subsequently, the samples were subjected to UPV testing in water after waterproofing the UPV transducers and cables using plastic membranes. Sufficient pressure was applied to the transducers toward the faces of the tested cubes to ensure good contact and stable measured readings. The recorded velocities were again documented for the numbered samples. Next, all the samples were removed from water, and their surfaces were dried for immediate testing. Thus, three datasets were collected (dry, submerged, and wet-saturated samples). The samples were then crushed, and their compressive strength was evaluated and documented. Cubes were crushed using a standard concrete cube compressive machine, where the cube is placed between two steel plates. After that, compressive force is applied until the cube fails, and the failure force is then recorded.

III. EXPERIMENTAL DATA ANALYSIS RESULTS

The measured UPV values were plotted against the corresponding compressive strengths of the crushed cubes to determine the correlation between these parameters. Figures 1, 2, and 3 depict these relationships for dry, saturated, and submerged samples, respectively. The analysis of these relationships revealed significant variations in the UPV and compressive strength values depending on the conditions of the concrete samples. In order to achieve a rational prediction for the concrete compressive strength of the dry cubes based on the UPV, a nonlinear regression analysis has been conducted. The nonlinear regression analysis in this research has involved several manipulations to form an equation that precisely fits the data presented in Figure 1. The prediction equation is:

$$f_c' = 2.43e^{0.5469V} \tag{1}$$

where Y is the compressive strength of the test cubes (15 cm ×15 cm × 15 cm) in MPa, and V represents the measured wave velocity in km/s.

TABLE I. PUNDIT (PROCEQ PUNDIT LAB (+)) SPECIFICATIONS

	**Processing unit/Sensor**
Bandwidth	20 to 500 kHz
Technology	UPV
Measuring resolution	0.1 µs
Pulse voltage	1125 to 1500 V (UPV)
Receiver gain	1×, 10×, 100×, AUTO, Punt* Lab+ up to 1000×
Nominal transducer frequency	24 - 500 kHz
Pulse shape	Square Wave
Pulse delay	-
Number of channels	1
PC software	Pundit Link unlocks the full Pundit Lab+ capabilities
Display	79 x 21 mm passive matrix OLED
Memory	> 500 measured values
Connections	USB connection to PC
Measurement modes	Pulse velocity
	Surface velocity
	Data logging
	E-modulus
	Compressive strength correlation
	Crack depth
Measuring range	Up to 15 m, depending on concrete quality
Special features	Open interface
	Special Features: Integrated amplifier gain stage, Real-time stamp
Transducers	Available Proceq transducers: 54 kHz, 150 kHz, 250 kHz, 54 kHz exponential, 500 kHz, and 250 kHz Shear Wave. Connect third-party transducers up to 24 kHz, 54 kHz, 150 kHz, 250 kHz, 54 kHz Exponential, 500 kHz, and 40 kHz shear wave dry point Contact.

The forecasting equation consistency has been proved, and the results are presented in Figure 4. This equation is a valuable tool for predicting the compressive strength of dry concrete structures based on UPV measurements. Each concrete cube was subjected to a series of tests under three distinct conditions: submerged, saturated, and dry. The resulting data were organized into tables to enable a detailed comparison of how moisture content affects both ultrasonic wave velocity and the corresponding compressive strength. Since the prediction equation was originally developed using data from dry samples, it was necessary to introduce correction factors to adjust them for varying moisture levels. Therefore, it is important to figure out a modification factor that connects the compressive strength of dry samples to the ones of different moisture content. This has been achieved by employing an exponential smoothing technique to reach a rational average factor for the tabulated data (dry, saturated, and submerged). Figures 5-7 depict the correction factors and their corresponding equations, which are $D_{ryUPV} = 1.031947S_{aturatedUPV}$ and $D_{ryUPV} = 1.12672S_{ubmergedUPV}$. The aforementioned correction factors are essential to accurately predict the compressive strengths of saturated and submerged concrete structures. The accuracy of the prediction model was validated through a reverse-calculation approach, using the correction factors to estimate the actual compressive strength of the moist samples. The predicted values exhibited strong agreement with the experimentally measured strengths, confirming that the developed equation is both effective and reliable for estimating the compressive strength of saturated and submerged concrete. In-general, the outcome of this study proposes a significant comprehension of the concrete behavior under different moisture conditions and provide a practical method for assessing its mechanical performance through non-destructive means.

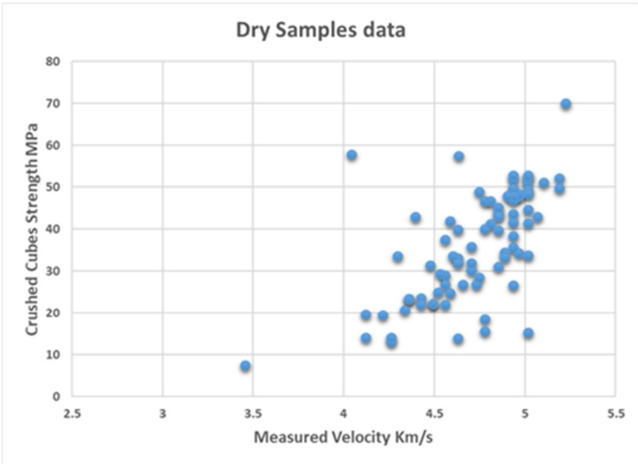

Fig. 1. Compressive strength of dry samples as a function of their UPV readings.

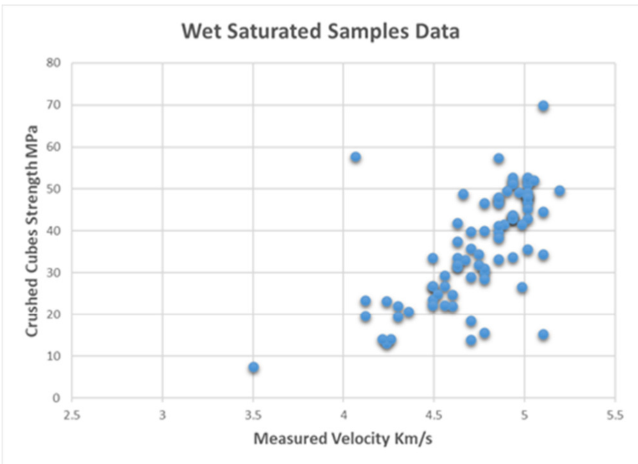

Fig. 2. Compressive strength of wet samples as a function of their UPV readings.

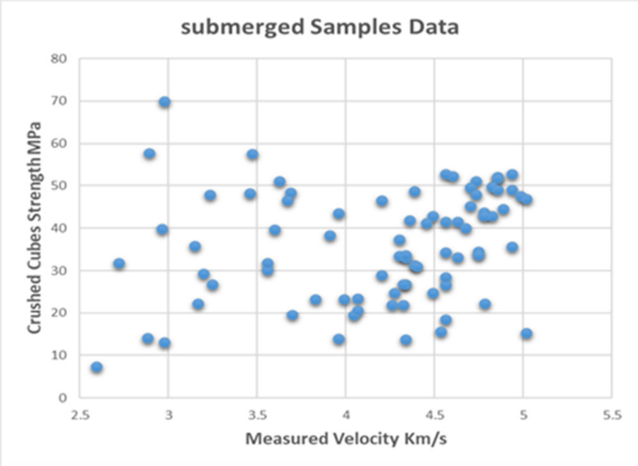

Fig. 3. Compressive strength of submerged samples as a function of their UPV readings.

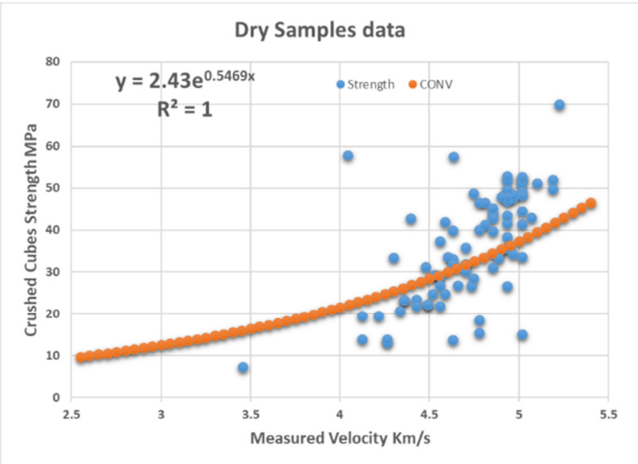

Fig. 4. Prediction equation fit through the dry sample data.

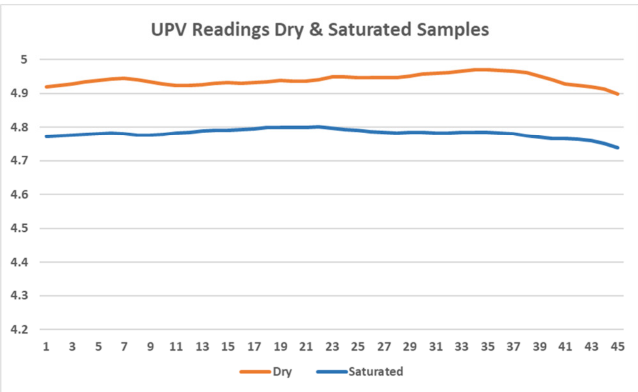

Fig. 5. Comparison between UPV reading of dry and saturated samples prior to smoothing.

IV. DISCUSSION

This research outcome validates that the presented empirical equation which is derived based on UPV measurements is a beneficial and powerful tool for predicting concrete structure compressive strength. Concrete mechanical properties can be evaluated by utilizing the NDT methods (UPV) which offers accurate, practical and reliable approaches the structural assessment without any damage triggered on neither the structures nor the materials. This capability makes UPV particularly valuable for structural health monitoring, enabling more efficient maintenance planning and reducing associated costs and risks. A key strength of this technique is its adaptability; it offers a cost-effective solution for assessing concrete under varying moisture conditions. In this study, correction coefficients were successfully developed to relate compressive strength in dry concrete to that in saturated and submerged states. This advancement allows for the in-situ evaluation of critical concrete elements, even while they remain operational and exposed to water. The study highlights the value of NDT techniques, particularly UPV, in evaluating concrete performance and structural integrity. The prediction equations and correction factors developed herein offer practical tools for assessing the compressive strength of moisture-affected concrete. In addition, the current proposed model has been compared with existing prediction equations presented in the literature [17-24]. Extremely deviated models have been omitted, and then the others have been compared utilizing Normalized Root Mean Square Error (NRMSE) technique. Figures 8-10 illustrate the comparative performance and confirm the high accuracy and reliability of the proposed equation.

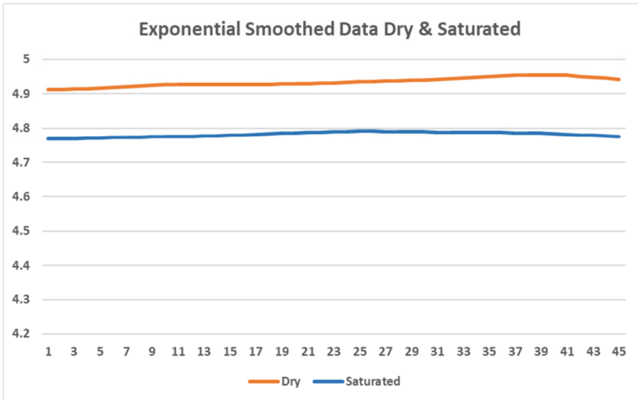

Fig. 6. Comparison between UPV readings of dry and saturated samples after smoothing.

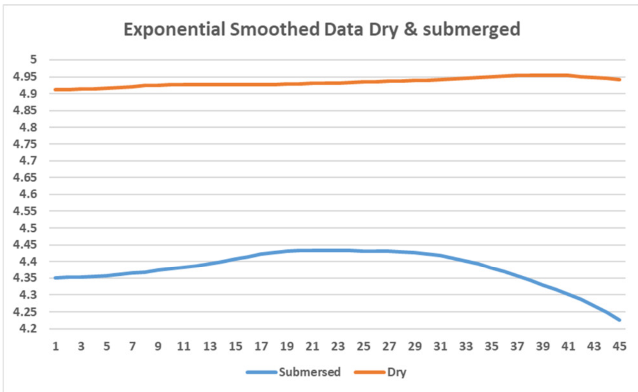

Fig. 7. Comparison between UPV readings of dry and submerged samples after smoothing

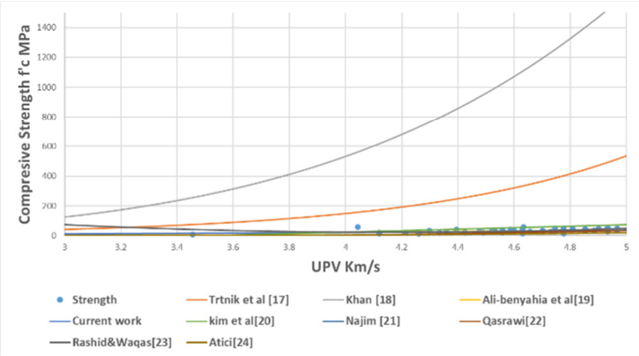

Fig. 8. Comparison of the current work equation with other works.

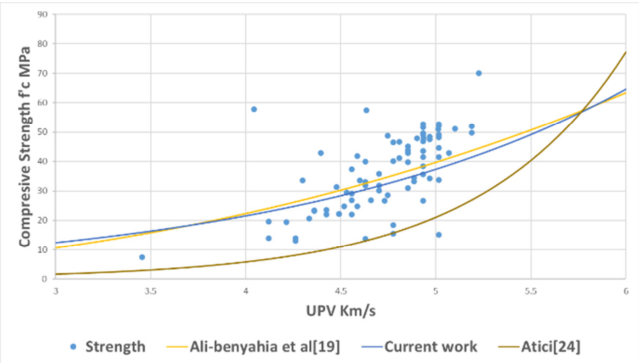

Fig. 9. Comparison of the current work equation with other research work, showing a tendency to behave similarly.

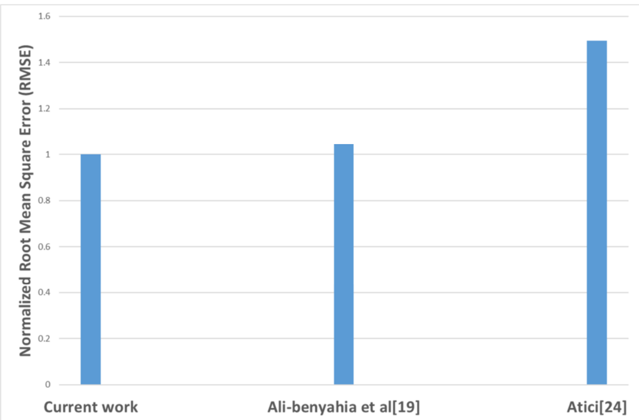

Fig. 10. NRMSE illustrates the fit of the current work equation.

V. CONCLUSIONS

Achieving a reliable approach for predicting the compressive strength of concrete structures exposed to water or super-humid environment was the aim of this study. Wave velocity has been measured utilizing UPV technique for 80 concrete cubes which were in different moisture conditions (dry, saturated and submerged). These measurements were then used to formulate an empirical equation correlating wave velocity with compressive strength. The resulting model was initially calibrated with dry-conditioning data and subsequently adjusted using correction coefficients to account for different moisture levels. This approach offers a dependable and efficient means of estimating the compressive strength of concrete structures in varying environmental conditions. The formulated predicating equation has influential practical application in the areas of civil and construction engineering. This is mainly emphasized in evaluating critical infrastructure, such as water tanks, dams, and bridge piers. Employing such a precise non-destructive approach for structural evaluation helps experienced engineers in detecting and addressing structural issues before they get complicated. Additionally, this research enhances the understanding of the relationship between UPV readings and concrete compressive strength.

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