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Compressive Strength Formula for Concrete using Ultrasonic Pulse Velocity

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Abstract — This paper investigates the relationship between the ultrasonic pulse velocity (UPV) and the compressive strength of concrete. The specimens used in the study were made of concrete with a varied cube compressive strength from 18 to 55MPa. Number of specimens was over 800 received from various construction projects of controlled concrete quality and tested by the Hawler Construction Laboratories (HCLabs) in Erbil, Kurdistan Region of Iraq, during the last half of 2014.

The UPV measurement and compressive strength tests were carried out at the concrete age of 28 days. The experimental results show that although the UPV and the compressive strength of concrete are related, no unique relationship can be established to cover all concrete specimens.

It is found, from a companion research, that with certain levels of concrete coarse aggregate content, certain clear relationships can be established.

This paper proposes the UPV - strength relationship formulas/curves for concrete having the range from 18 to 55MPa of concrete strength. These curves were verified to be suitable for prediction of hardened concrete strength with a measured UPV value. Other proposals found in literature are compared and discussed.

It is believed that the proposed formulas may be appropriately applied and used for the service of the local construction practice of the country.

Keywords: concrete strength; NDT; ultrasonic pulse velocity.

I. INTRODUCTION

Construction laboratories commonly provide ultrasonic pulse velocity (UPV) test to assess questionable concrete quality and strength. However, precise prediction of strength is difficult to obtain. This work attempts to set an acceptable recommendation based on a broad data from the local construction projects.

Many previous works made use of the UPV of concrete to predict compressive strength and it is of paramount importance in such research work to study the relationship between UPV and compressive strength⁽¹⁻⁵⁾. Pulse velocity is influenced by many variables, however, including mixture proportions, aggregate type, age of concrete, moisture content, and others.⁽¹⁾

The factors significantly affecting the concrete strength have little influence on UPV. As a result, a statistical study is important to tie strongly the UPV and compressive strength.

Although several previous studies⁽¹⁻⁵⁾ concluded that, for concrete with a particular mixture proportion, there

is a good correlation between UPV and the compressive strength; however, a relationship with a wide variation will be acquired if the data of UPV and the compressive strength of concrete having different mixture proportions are put together and analyzed.

No clear rules have been presented to describe how the relationship between UPV and the compressive strength of concrete changes with its mixture proportion. Therefore, there exists a high uncertainty when one tries to make use of UPV to predict the strength of concrete in different mixture proportions.

Thus, this study tries to adopt an influencing factor, the coarse aggregate content, as a medium to investigate the relationship between UPV and the compressive strength of hardened concrete. This paper uses over 800 concrete specimens and categorizes the specimens according to a strength range of (18 – 55) MPa. The UPV measurement and compressive strength tests were carried out at the age of 28 days.

II. RESEARCH SIGNIFICANCE

This paper proposes a new direction to establish a clear relationship formulas / curves between UPV and the compressive strength of concrete to improve the application of the UPV method on non-destructive evaluation of concrete strength in the construction projects in Iraq.

The importance of the established formulas stems from the fact that the over-800 investigated specimens are true practical specimens brought to the Hawler Construction Laboratories (HCLabs) from construction projects from all over the Kurdistan Region in Iraq. Proposal of a companion work along with other proposals found in literature are compared and discussed.

A recommendation is set for the HCLabs to follow, as the UPV test is continuously required by the construction projects officials.

III. EXPERIMENTAL DETAILS

A. Materials

Materials used for making specimens include ordinary Portland cement C, fine aggregate FA, coarse aggregate CA, and with or without high-range water-reducing admixture SP. The cement used was Portland Type I. River sand with and river coarse aggregate were used as fine and coarse aggregates, respectively. Both sand and river coarse aggregate were not from the same source. The grading curves for fine and

coarse aggregates were all conforming to Iraqi Specification IOS 45 – 1984⁽⁶⁾. The mix proportions are not known, however, most construction projects officials claim that they are based on ACI approach.⁽⁷⁾

B. Specimens

Over 800 concrete cube specimens were used in this study. Various concrete mix proportions were used most of which were based on ACI 211.1 – Reapproved 2009⁽⁷⁾. To simplify the analysis task, these cubes were having strength in the range (18 – 55)MPa, and their UPV should be > 3.5 km/s. It is widely agreed⁽⁸⁾ that concrete with UPV (2 to 3.5 km/s) is of very poor to doubtful quality, and that concrete with UPV (3.5 to >4.5 km/s) is of good to excellent quality.

All the specimens were cast in steel cube molds (150 mm) and kept in their molds for approximately 24 hours in the laboratory. After removing the molds, concrete cubes were cured in water at 20 °C and tested at ages of 28 days. The ultrasonic pulse velocity and compressive strength of three saturated surface dry SSD specimens were measured according to the specification of ASTM C 597 and ASTM C 39, respectively.

C. Equipment

The principle of ultrasonic pulse velocity measurement involves sending a wave pulse into concrete and measuring the travel time for the pulse to propagate through the concrete. The pulse is generated by a transmitter and received by a receiver.

As illustrated in Fig. 1, ultrasonic pulse velocities were measured by a commercially available pulse meter, used by the HCLabs* with an associated transducer pair through a direct transmission mode. The transducer pair had a nominal frequency of 54 kHz.

In the experimental work, the transmitter and receiver were placed at the top and bottom surfaces of a cube specimen, in parallel direction to the destructive load. Knowing the path length (*L*), the measured travel time (*t*) can be used to calculate the pulse velocity (*v*) as follows

$$v = L/t \dots \dots \dots (1)$$

where *L* is the travel path length of ultrasound in the cube. The concrete surface must be prepared in advance for a proper coupling agent. Firm contact of the transducers against the concrete surface is needed.

Direct velocity measurements were taken as the average of 10 readings for each cube tested. The direct path length for these measurements was through the cube thickness of 150 mm. Direct UPV was calculated as the ratio of the path length to the time of flight.

*Pulsonic Controls Instruction Manual 58-E4900.

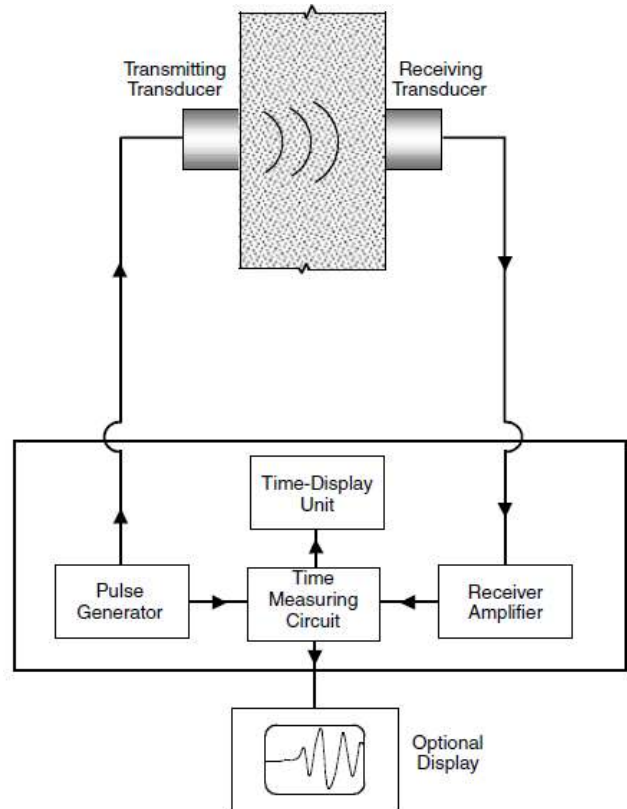


Fig.1 Schematic diagram of pulse velocity test circuit.⁽⁹⁾

IV. STATISTICAL STUDY

Statistical study was made on the direct UPV measurements for 848 cubes to evaluate and verify the normal distribution of the direct UPV measurements. The cumulative frequency distribution function is plotted in Fig. (2). For the 848 cubes with mean UPV of 4.06 km/s and standard deviation of 0.234, it can be seen that the direct UPV measurements are normally distributed.

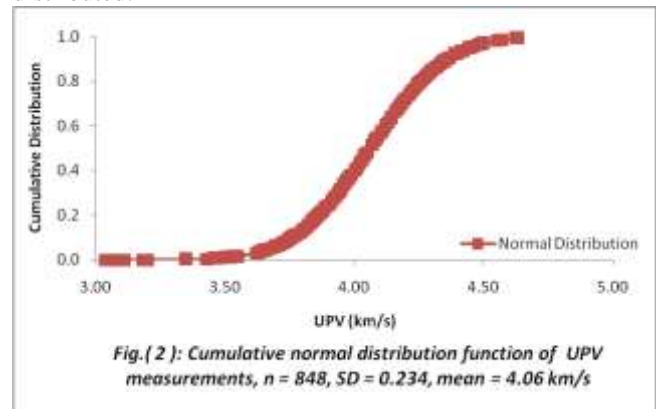


Fig.(2): Cumulative normal distribution function of UPV measurements, n = 848, SD = 0.234, mean = 4.06 km/s

V. RELATIONSHIP BETWEEN UPV AND 28-DAY STRENGTH OF CONCRETE CUBES

Fig.3 shows the relationship between UPV and strength at the age of 28 days of concrete cubes received by the HCLabs from various construction projects in Erbil during the last half of 2014 and tested

at age of 28 days. A relationship curve, equation 2, is drawn by exponential regression of all data points and its coefficient of determination R^2 equals 0.0813, as shown in Fig. 3.

$$f_{cu} = 11.804 \exp(0.2601v) \dots\dots\dots(2)$$

Because of the scattered distribution of data points, this relationship curve does not correlate the UPV with the strength of hardened concrete well, that is, a noticeable error may occur if one estimates the strength of concrete by using this relationship curve with a UPV value.

To improve the UPV-strength relationship of hardened concrete, it is important to consider the influence of coarse aggregate content of concrete specimens on the relationship. ^{(1), (10)}

The new approach treats the coarse aggregate content as a ruling factor in establishing the UPV-strength relationship of hardened concrete based on the fact that, for a particular coarse aggregate content, both UPV and strength of concrete are proportional to the density of hardened concrete.

The exponential regression was applied to establish the UPV-strength relationship. Fig. 4 shows the relationship between UPV and strength of hardened concrete having four coarse aggregate contents. In Fig. 4, four regression curves, based on a companion study ⁽¹⁰⁾ are associated with coarse aggregate contents of 1000, 1200, 1300 and 1400 kg/m³, respectively, and their corresponding coefficients of determination R^2 are 0.83, 0.87, 0.88, and 0.84, indicating good relevance between data points and the regression curves ⁽¹⁰⁾.

Fig. 4 reveals that, for concrete with a particular coarse aggregate content, both UPV and strength of hardened concrete are exponentially related but with different power.

Thus, when introducing coarse aggregate content as a key factor, one is able to better define the relationship between UPV and strength of hardened concrete.

The developed equations are ⁽¹⁰⁾

$$f_{cu} = 8.8793 \exp(0.4247v) \text{ for } CA = 1000 \text{ kg/m}^3 \dots\dots(3)$$

$$f_{cu} = 0.0574 \exp(1.6013v) \text{ for } CA = 1200 \text{ kg/m}^3 \dots\dots(4)$$

$$f_{cu} = 1.0332 \exp(0.8674v) \text{ for } CA = 1300 \text{ kg/m}^3 \dots\dots(5)$$

$$f_{cu} = 1.3908 \exp(0.7806v) \text{ for } CA = 1400 \text{ kg/m}^3 \dots\dots(6)$$

where f_{cu} and v represent the cube compressive strength (MPa) and the UPV (km/s), respectively.

In a more convenient way, the above equations can be rewritten as follows:

$$f_{cu} = 8.88 \exp(0.42v) \text{ for } CA = 1000 \text{ kg/m}^3 \dots\dots\dots(7)$$

$$f_{cu} = 0.06 \exp(1.60v) \text{ for } CA = 1200 \text{ kg/m}^3 \dots\dots\dots(8)$$

$$f_{cu} = 1.03 \exp(0.87v) \text{ for } CA = 1300 \text{ kg/m}^3 \dots\dots\dots(9)$$

$$f_{cu} = 1.39 \exp(0.78v) \text{ for } CA = 1400 \text{ kg/m}^3 \dots\dots\dots(10)$$

VI. COMPARISON WITH OTHER PROPOSALS

The equations set 7 to 10 are compared hereby with various proposals found in literature. Figs. (5), (6), (7) and (8) shows respectively; Naik and Malhotra equation ⁽⁹⁾,

$$f_c = (-109.6 + 33v) \text{ "cylinder"}$$

Raouf's equation ⁽¹¹⁾,

$$f_{cu} = 2.016 \exp(0.61v)$$

SonReb equation ⁽¹²⁾

$$f_{cu} = 2.756 \times 10^{-10} I^{1.311} (1000v)^{2.487}$$

and Lin et al equations ⁽¹⁾.

$$f_c = 0.00055 \exp(2.50v) \text{ "cylinder" "CA = 1100 kg/m}^3\text{"}$$

$$f_c = 0.00106 \exp(2.37v) \text{ "cylinder" "CA = 1000 kg/m}^3\text{"}$$

where f_{cu} and f_c represent the cube and cylinder compressive strength (MPa) and v the UPV (km/s), respectively. The curves show the cube compressive strengths (MPa) in which $f_{cu} = 1.2 f_c$

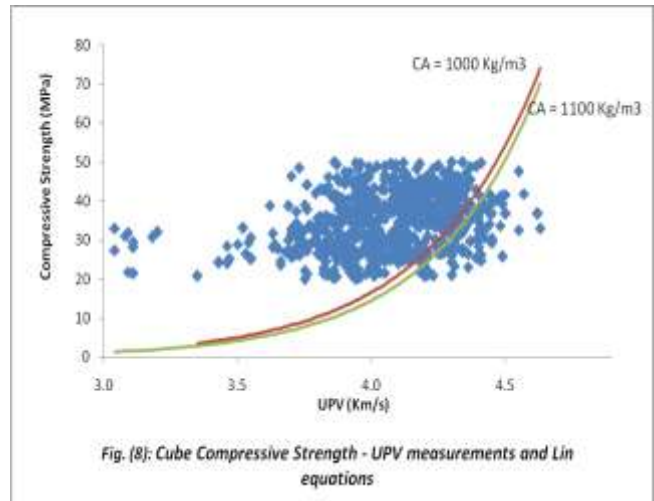
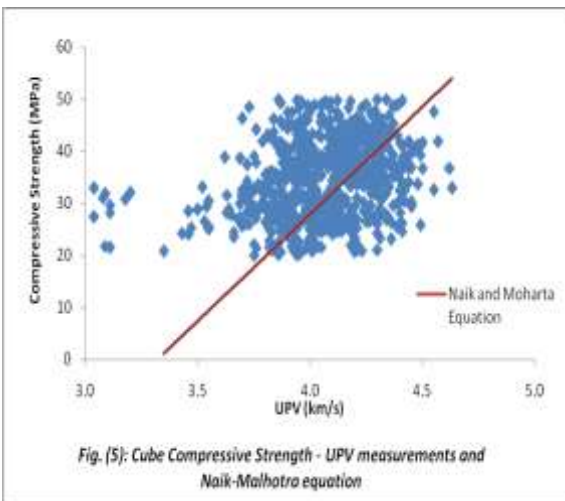
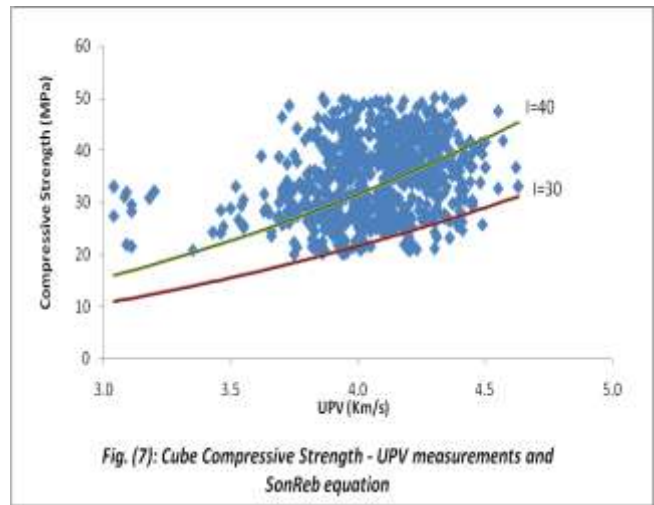
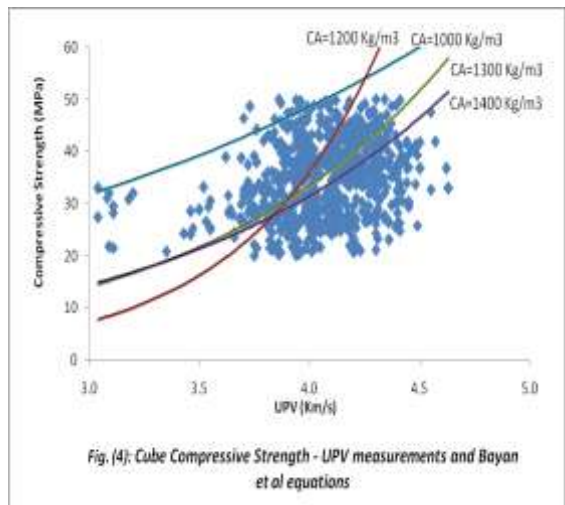
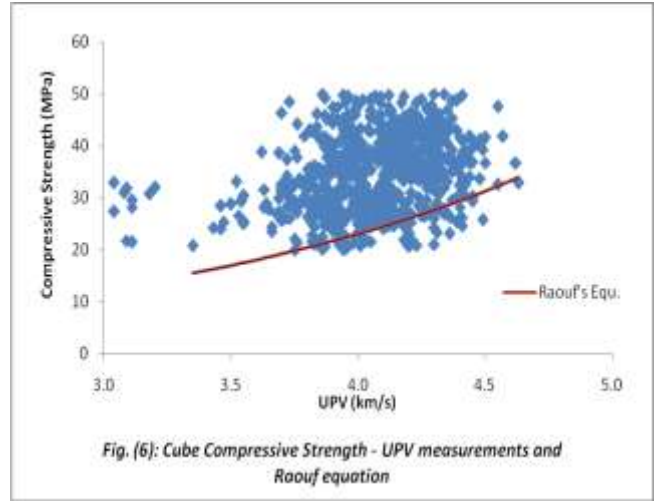
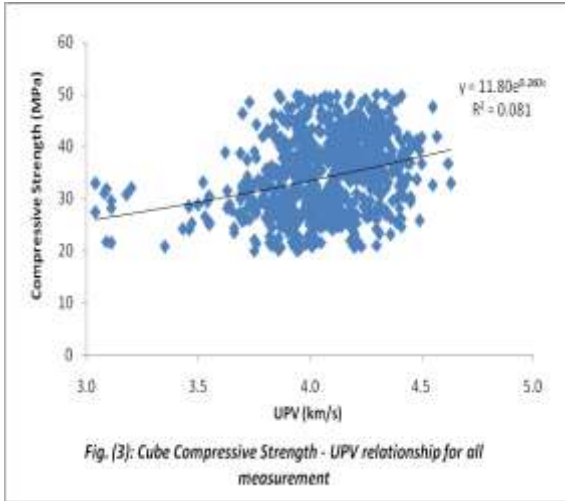
These equations are shown with the data collected in this work.

In comparison with the data of this work, it can be seen that most of the equations predicts a single value compressive strength on the average or on the lower part of data which may underestimate /overestimate the true value.

SonReb equation ⁽¹²⁾ predicts the values in which the data of this work would approximately lie above rebound number $I = 30$, and the equation lie in the approximate average of data points at rebound number $I=40$. It may be said that rebound number is helpful in indicating the strength condition of the tested concrete. With values of $I < 30$, the concrete may be considered poor.

Lin et al equations ⁽¹⁾ predict the local concrete compressive strength mostly on the lower side although they depend on the coarse aggregate content.

Equations (7) to (10) of this work seem of better prediction of the compressive strength of the local concrete specimens depending on the aggregate content value.



VII. PROPOSAL TO THE HCLABS

For the purpose of investigating a concrete with UPV test, as it is usually required by the construction officials, it is proposed hereby to the HCLabs officials to follow the following points to assess the concrete strength using UPV test:

1. UPV should be > 3.5 km/s, otherwise the concrete shall be considered poor and the strength is not conforming. Coring is recommended to be the deciding test.
2. The practice of HCLabs of conducting companion hammer test to obtain the rebound number (SonReb approach) is helpful. However, from the data of this work, rebound number values < 30 may indicate poor concrete.
3. Equations 7, 8, 9, and 10 are recommended. However, if no information on mix proportions is presented, the lower value of these equations shall be used as an assessment.

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