International Journal of Engineering & Technology, 7 (4.20) (2018) 113-117

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Empirical Formula for Assessment Concrete Compressive Strength by Using Ultrasonic Pulse Velocity

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Abstract

Statistical practical program was carried out to establish a fairly accurate empirical formula between compressive strength of concrete and ultrasonic pulse velocity. The work has a strong empirical base, but it is firmly governed by theory. In concrete, the compressive strength of concrete is related to the type, proportion and physical properties of aggregate but it is well known to be intensely affected by the properties of the cement paste, which relate, mainly, to the w/c ratio. The other variables such as age and density of concrete, salt content in fine aggregate and curing method have a relatively little effect on compressive strength of concrete. Therefore, the program involves field testing of reinforced concrete members that their w/c ratio and cube uniaxial compressive strength are known. The results were used as input data in statistical program (SPSS) to develop an empirical formula between the compressive strength of concrete and ultrasonic pulse velocity. The proposed formula was confirmed by the results of previous experiments. Although the relationship between the compressive strength of concrete and ultrasonic pulse velocity physically indirect, the statistical program revealed that the pulse velocity test could be used with acceptable error in evaluating the compressive strength of concrete.

Keywords: *Aggregate Content; Concrete strength; NDT; ultrasonic pulse velocity.*

1. Introduction

Essentially, the Non-Destructive Ultrasonic Pulse Velocity (UPV) test was created to assessment of concrete properties. In 1940, the first report of pulses velocity measurements through concrete was published in USA. A few years later, work was undertaken to improve this technic, which led into the modern (UPV) method using the natural frequency within the range 20-150 kHz. Traditionally, the UPV test can be used to inspect the homogeneity, the location of defects or cracks, estimate the dynamic modulus of elasticity, monitor the variations with time in characteristics of concrete as explain in the British Standard [1]. However, it is widely used to predict on site compressive strength of concrete in new and existing construction with acceptable reliability due to its relative simplicity, economical, safe, time saving and do not affect the functioning of structure.

In concrete, there is no direct physical relationship between the pulse velocity and strength, but the pulse velocity (V in km/s) is related to the dynamic modulus of elasticity (E_d in MPa), density (ρ in kg/m^3) and dynamic Poisson's ratio (v) of concrete by the following relation [2]:

BS 1881- 203:1986 $$V=\sqrt{\frac{E_d(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \quad (1)$$

In addition, the relationship between the static and dynamic modulus of elasticity (E_c&E_d) for concrete is generally linear. In literature, there are many linear expressions which relate (E_c) to (E_d) such as the equation in the British Standard [3] for natural aggregate concrete:

BS 8110-2:1985 $$E_c = 1.25E_d - 19 \quad (2)$$

Also, the cylindrical compressive strength of concrete (f_c in MPa) is related to its static modulus of elasticity (E_c **in** GPa) by standard expressions such as:

ACI 318M -2014 $$E_c = 0.043\rho^{1.5}\sqrt{f_c} \quad \text{for} \quad f_c \le 40\text{MPa} \quad (3)$$

ACI 363-2010 $$E_c = \left(3320\sqrt{f_c}+6900\right)\left(\frac{\rho}{2346}\right)^{1.5} \quad \text{for} \quad 21 \le f_c \le 83\text{MPa} \quad (4)$$

BS EN 1992-1-1:2004 $$E_c = 1.05\times 22000\left(\frac{f_c+8}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^{1.5} \quad \text{for} \quad 12 \le f_c \le 80\text{MPa} \quad (5)$$

Based on all the above, it should be expected that the direct relationship between the compressive strength of concrete and pulse velocity is high nonlinear and depend explicitly or implicitly on (dynamic or static) modulus of elasticity and density of concrete. Furthermore, the previous experimental tests showed that the slight increase of compressive strength in the low range of strength (i.e f_c<10MPa), go along with high increase in pulse velocity, whereas the condition is reflected at the upper range of strength (i.e f_c>20MPa) [4]. As a result, the direct relationship should has increasing nonlinearity as pulse velocity increase and the sensitivity of pulse velocity to change in strength decreases as strength increase.

The simplest and commonly used relationship between compressive strength of concrete and pulse velocity which satisfy the above requirements is the following form [5]:

$$f_c = Ae^{BV} \tag{6}$$

Where A and B are constants, f_c and V are as definition before. This relationship is affected by many factors including water/cement ratio, age of concrete, presence of cracks, moisture content, type, size and amount of aggregate in the concrete [6, 7]; some of them are significantly affecting the pulse velocity and minor effect on compressive strength such as the type and amount of aggregate in the concrete [8], whereas other factors may have reverse effect on the compressive strength and pulse velocity such as moisture content especially when concrete reach maximum degree of saturation, a sudden increase in pulse velocity will occur [9].

Even though the UPV method is not reliable to evaluate the compressive strength directly, however the interest in establishing suitable correlation between them is steady increasing. This correlation is not simple and sometime may be confusing due to the many factors which affect it. Different type of concrete with similar strengths may have different UPV and vice versa. These differences make challenging the interpretation of UPV measurements into reliable value of strength. Nevertheless, in literature numerous correlations to relate the pulse velocity with the compressive strength have been proposed. Most of them have the same form of Eq.(6) due to its simplicity and nature of nonlinearity as explain above. The following discussion will focus on the commonly used and recent expressions.

Jones (1962) [8] proposed the primarily relationship between pulse velocity (V in km/sec) and concrete strength (f_c in MPa) which has the same form of Eq.(6) above:

$$f_c = 2.8e^{0.53V} \tag{7}$$

Elvery and lbrahim (1976) [10] carried out experimental tests to study the effect of curing temperature in the range (1 to 60 ^oC) on the relationship between UPV and concrete strength for ages of about 3 h and over. Based on this study, they proposed an exponential equation to relate the strength of concrete (f_c in MPa) at age 28 day with UPV (V in km/sec) as follow:

$$f_c = 0.0012e^{2.27V} \tag{8}$$

Raouf and Ali (1983) [11] used the test results of 650 cubes of concrete to develop the relationship between cube strength (f_c in MPa) and UPV (V in km/sec) as follow:

$$f_c = 2.016e^{0.61V} \tag{9}$$

Sandor et al. (1990) [12] used Klieger's experimental results in 1957 to compare between the using of direct and surface ultrasonic velocity to estimate the strength of concrete. Then, they proposed the following relationship between direct ultrasonic velocity (V in km/sec) and strength of concrete (f_c in MPa) at age 7 day:

$$f_c = 0.0028e^{2.1V} \tag{10}$$

Nash't et al., (2005) [13] tested 161 cubes of concrete (150×150×150mm). They studied the effect of different curing condition on the relationship between concrete strength (f_c in MPa) and ultrasonic velocity (V in km/sec) for ages ranged (7 to 138 days). Based on the results of the study, they proposed the following equation:

$$f_c = 1.19e^{0.715V} \tag{11}$$

In comparison all the above equations, it is clear that it have the same form of Eq.(6), with different values for constant A and B. Since the using fixed values for A and B makes the equation as general equation for all types of mixture of concrete. This mean, a specific value of pulse velocity gives single value of compressive strength regardless of the types of mixture, but this value of compressive strength is only valid for specific mixture and may underestimate or overestimate for the others. Though, the main imperfection in this style of equations is that it suitable for specific type of mixture of concrete if specific values for A and B are used. In addition, the effect of factors which have significant effect on strength with minor change in pulse velocity did not taken in account which may lead to overestimate or underestimate in compressive strength. Furthermore, the relationship between compressive strength and UPV is not unique but rather affects particularly by the mix proportions, type of content of aggregate and w/c ratio [14-16]. Therefore, the UPV can be used to estimate strength of concrete provided that a calibration curve is present for each evaluated mixture [17].

Lin et al. (2007) [18] proposed mathematical models for estimating predicting cylinder strength of concrete (f_c in MPa) from pulse velocity measurement (V in km/sec) in the same form of Eq.(6), but with variable values for A and B constants based on aggregate content (CA). These models take the form:

$$f_c = 0.00055e^{2.5V} \quad \text{for} \quad \text{CA} = 1100 \text{ kg / m3} \tag{12}$$

$$f_c = 0.00106e^{2.37V} \quad \text{for} \quad \text{CA} = 1000 \text{ kg / m3} \tag{13}$$

The main deficiency of these models of equation is the limit number of values for aggregate content and interpolation for other values is relatively difficult since the trend of different models is dissimilar. In addition, the effect of density and age of concrete should be taken in to account [14].

Deshpande et al., (1996) [19] tested 200 cubes of concrete and proposed polynomial equation to relate compressive strength (f_c in MPa) with UPV (V in km/sec) and taking density (ρ in g/cm^3) and age of concrete (A in days) into account. The equation takes the form:

$$f_c = 7.833 + 0.403\rho^3 + 0.00021A^3 + 0.475V^2 \tag{14}$$

Even though this equation take effect some of important factor which can improve the estimation of strength, however it is clear that it overestimate or underestimate the strength value in the low and high range of pulse velocity respectively (i.e if (A=28 day, ρ=2.3 g/cm^3), f_c≈18MPa for V=1km/s and f_c≈34MPa for V=6km/s).

This paper aims to overcome the imperfection of the previous equations by using a modified form for commonly used equation (i.e Eq.6) and develop new procedure to calculate its parameters (i.e A and B) continuously with any change in concrete mixture type. In addition, the effect of most important factors which affect the compressive strength (i.e density, aggregate content, age of concrete) are included.

2. Experimental work

Over 300 cube specimens of concrete (which its mix proportions are known) from many real construction projects have been brought and tested in the Constructional Lab of Al-Dewaniyah technical institute. The cube test results were used to develop the proposed empirical formula to in-situ estimate of concrete strength from UPV measurement. The validity of the proposed formula was investigated using the data found in literature.

2.1. Materials

Materials used for making cube specimens include:

1. Two types of cement were used (Ordinary Portland cement (OPC) and Sulphate resisting Portland cement (S.R.P.C)) from different sources of factories in Iraq. All of them are satisfy the physical and chemical requirements of IQS 5-1984. The compressive strength is in the ranges (17 - 19 Mpa for 3 days) and (24 - 26 Mpa for 7 days).
2. Two natural types of sand and one type of gravel with different maximum size were used. The grading requirements and other characteristics for sand and gravel were all conforming to Iraqi Specification IOS 45 – 1980 and BS 882:1992. The grading requirements and other characteristics for sand and gravel were all conforming to Iraqi Specification IQS 45 – 1984 and BS 882:1992.
3. The mix proportions were varied depending on the design strength for each member in the projects which the cubes have been collected. The range of compressive strength is (12-60MPa). The maximum strength was determined according to BS 1881-Part 203-86.Table 1 shows an example of some site mixes.

Table 1: Example of some site mixes

Compressive Class	Cement kg/m^3	Water kg/m^3	Fine Aggregate (Sand) kg/m^3	Coarse Aggregate (Gravel) kg/m^3	Slump Class	Maximum Strength (MPa)
C16/20	240	168	927	984	S4	24
C20/25	300	180	1130	693	S4	32
C24/30	375	143	737	1107	S3	45
C24/30	385	146	736	1104	S4	48
C24/30	400	152	715	1073	S3	51
C24/30	350	147	785	1084	S4	46
C24/30	376	158	764	1055	S4	49
C24/30	375	150	760	1093	S4	52
C28/35	376	143	768	1105	S5	56
C28/35	385	154	525	1167	S5	58

2.2. Concrete sample tests

All cube specimens were cast in-situ in standard steel molds (150×150×150mm). After 24 h, the cubes were removed from its molds and brought to the Laboratory of (CL-O-DTI) for curing in water at 20 °C and tested at ages of 7, 14, 28, 60 and 90days.The UPV and traditional compressive strength tests were carried out according to BS 1881-Part 203-86. The UPV measurements were carried out by a commercially pulse meter available in the (CL-O-DTI). The transducer pair pf the pulse meter has a nominal frequency of 54 kHz. The transmitter and receiver of pulse meter were placed at the top and bottom surfaces of a cube specimen (i.e DUPV Test). The pulse is generated by a transmitter and sending through the concrete and received by a receiver. The travel time for the pulse to propagate is measure. The pulse velocity (*V* in km/s) is calculated using the measure time (t in µ second) and the path length (*L* in mm) by the following simple equation:

$$V = \frac{L}{t} \tag{15}$$

4. Experimental results

Figure.1 shows the test results for more than 300 cube specimens which have been test using two methods (UPV Test and Standard compressive strength test) simultaneously at ages 7,14,28, 60and 90 days).

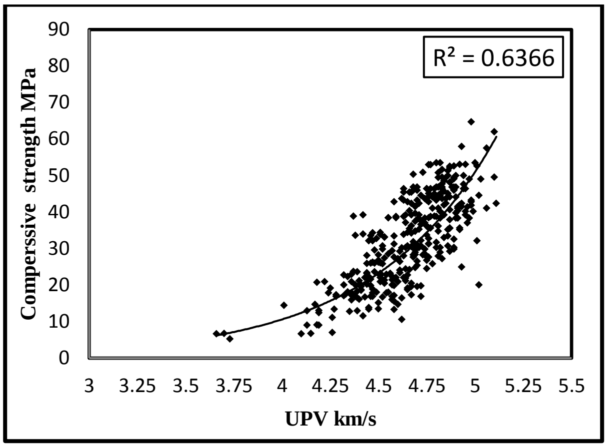

Fig.1: Experimental test results

Figure.(2) to Figure (5) show the effect of density (i.e dry density of concrete, aggregate content on the UPV and compressive strength at age 28 days only (i.e 60 results) .

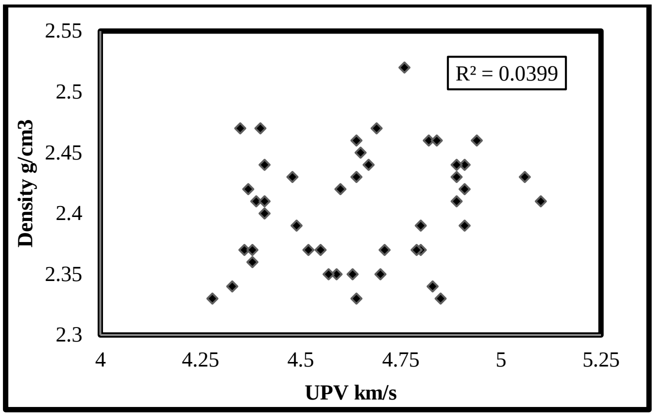

Fig.2: Experimental test results

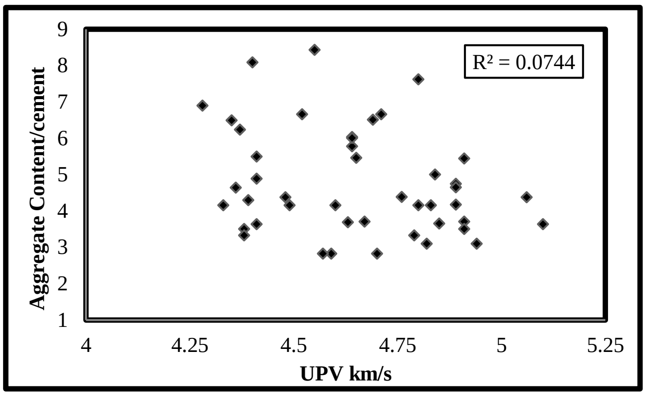

Fig.3: Effect of (Aggregate Content/Cement) on UPV

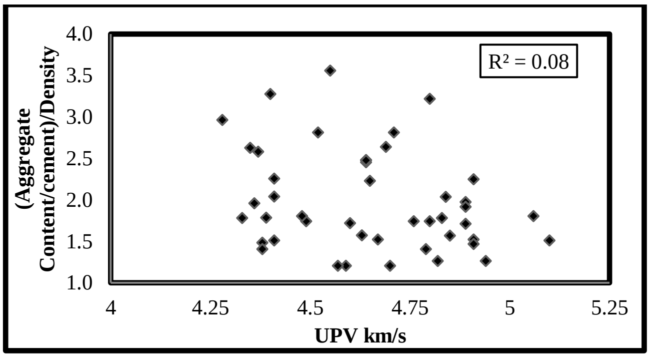

Fig.4: Effect of ((Agg.Co/Cement)/Density) on UPV

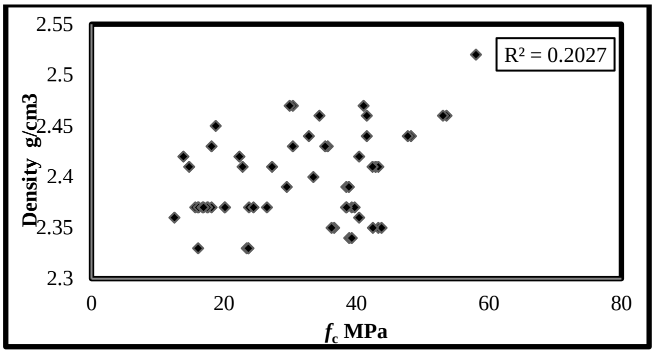

Fig.5: Effect of Density on f_c

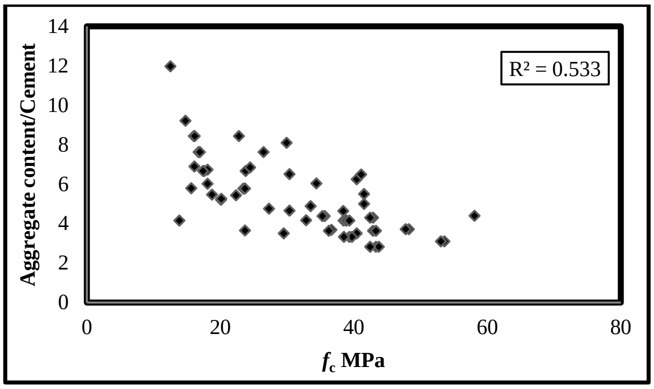

Fig.6: Effect of (Aggregate Content/Cement) on f_c

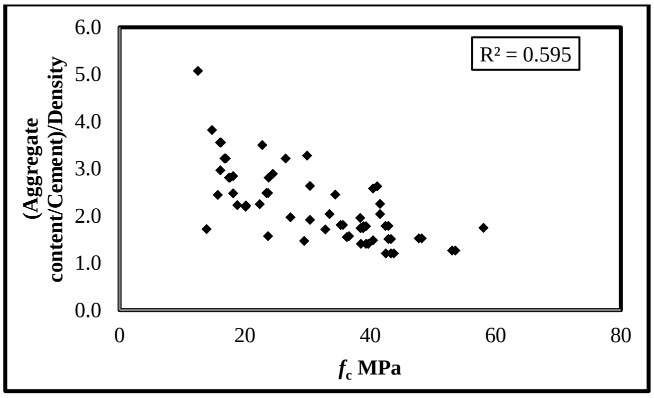

Fig.7: Effect of ((Agg.Co/Cement)/Density) on f_c

It is obvious from these figures that correlation between UPV and (dry density, aggregate content, (aggregate content/cement) and ((aggregate content/ cement)/Density)) have value of R^2 in the range (0.04-0.08) which it indicates the weak correlation between them. Also, the value of (R^2 =0.202) for the correlation between dry density and compressive strength of concrete indicates the same weak correlation between them. However, this behavior may be related to the narrow range of variation in dry density of concrete (2.3-2.5 g/cm^3). On other hand, ((aggregate content/cement)/Density) has apparent effect on compressive strength of concrete at age 28 days as it is clear from relative high value of (R^2=0.559). This result suggests that the percentage value of ((aggregate content/cement)/Density) should be taken into account in the calculation of parameters of the relationship between the UPV and the compressive strength of concrete. Furthermore, all previous figures were constructed depending on the results of compressive strength of concrete up to 60 MPa at age 28 day and for UPV in the range (3-5) km/s. Therefore the proposed empirical formula should be used for estimating compressive strength at age 28 day or more according to BS 1881- 203-86[2]. In addition, the effect of age of concrete more than 28 day on compressive strength of concrete may be taken into account by calculating the compressive strength of concrete at any age (t > 28day) using the following equation[20]:

$$f_c(t) = e^{0.25\left(1-\frac{28}{t}\right)^{0.5}} f_c(28) \quad (16)$$

4. Empirical formula between the UPV and compressive strength

For simplicity, the proposed empirical formula takes the commonly used relationship as explained before (i.e Eq.(6)) with some required modification. The suggest form as follow:

$$f_c = Me^{BV} \quad (17)$$

Where

f_c=cube compressive Strength in MPa

V=pulse velocity in km/sec

M=variable value depend on (density and aggregate content in concrete)

B=Constant

It is decided to fix the value of B and take the effect of density and aggregate content in M only to make this formula more simple and practical. The value of B and M are calculated from Fig.(6) and Fig.(7) by regression analysis using SPSS program. Fig.8 and table 2 summarized the linear regression results. The R^2 is 0.6032.

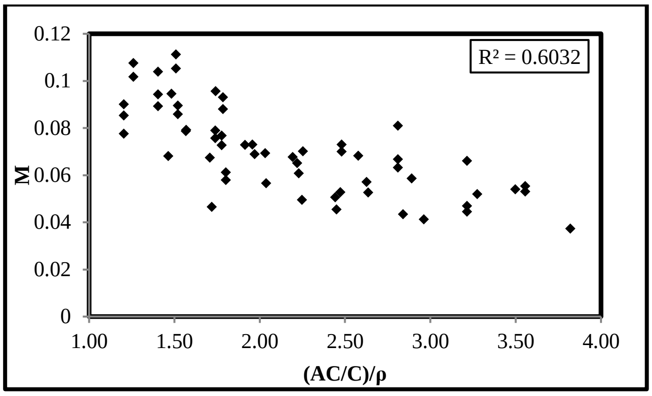

Fig.8: Regression graph

Table 2: Coefficients

Model	Unstandardized coefficients		Standardized coefficients	t	Sig
	B	Std Error	Beta		
1 (Constant)	0.108	2.305		33.761	000
(AC/C)/ρ	-0.0191	0.016	0.912	9.727	000

The best value of M (if B=1.3) can be calculated as follow:

$$M = 0.11 - 0.019\ ((AC/C)/\rho) \quad (18)$$

Where

AC/C=Aggregate Content to Cement Ratio, ρ=density of concrete in g/cm^3.The statistical analysis for all possible practical values for M indicate that the range of its value (0.03-0.15).

5. Validity of the empirical formula

The validity of the proposed empirical formula is investigated by using the experimental data of this study with some of available data in literature [11, 19, 21]. Fig.(9) shows the upper and lower bound of the empirical formula and it can be seen that most of data are located between this range.

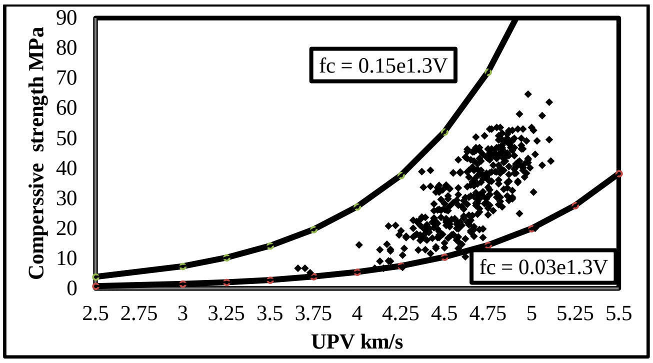

Fig. 9: The upper and lower bound of empirical formula

Fig.(10) compares between the upper and lower bound of the proposed formula with equations for other researcher in literature. It is obvious that the other equations can be considered as special cases for general proposed formula.

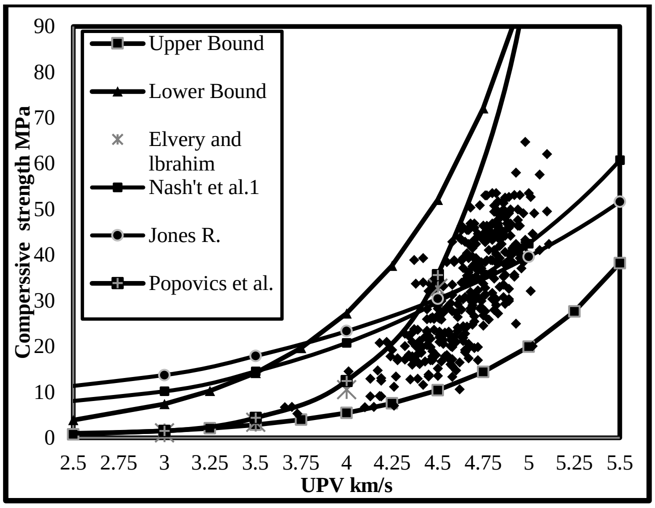

Fig. 9: Comparison between proposed formulas with other researcher's equations

Furthermore, the statistical analysis show that average value for (estimate strength/actual strength) for all data is (0.945) with maximum value (1.15) and minimum value of (0.79).

5. Conclusions and recommendations

Based on the results of this study, the following conclusions and recommendations can be drawn:

1. The estimating of compressive strength of concrete using equation with fix values of its parameter should be avoided because the relationship between compressive strength and UPV is not unique but rather affects particularly by the mix proportions.

2. The proposed empirical formula should be used for estimating the cube compressive strength up to 60 MPa and for age 28 days according to BS 1881- 203 -86.

3. UPV should be in range (3-5) km/s, otherwise the estimating of the concrete strength must be taken with caution.

4. The effect of age of concrete (t >28day) can be included in the empirical formula by multiplying the estimated compressive strength of concrete for 28day using proposed formula by factor suggested by BS EN 1992-1-1:2004.

5. All predicting equations (including the proposed formula) should be used for preliminary estimation purposes only

6. Other non-destructive methods (such rebound number) may be combined with UPV test results with appropriate procedure in order to improve the results.

7. Empirical formula should be used when enough information about density, aggregate content are available. If there is no information about these factors, it should be used with cautiously.

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