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Full Length Research Paper

Modeling of compressive strength of concrete using pulse velocity values from a non-destructive testing of concrete

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In this research, ultrasonic pulse velocity (UPV) and crushing strength tests were carried out. Major factors which affect the strength of concrete such as concrete mix, aggregate size, and water-cement ratio were considered such that the model obtained could be used for the determination of strength of concrete elements made under different conditions. Three proposed models were calibrated using some of the data generated in the laboratory. The models were verified and compared with two similar existing models using the remaining data. The following statistical parameters were adopted for the comparison; the square of the coefficient of correlation (R2), the root mean square error (RMSE), and the average relative error (AVE). The proposed and existing models produced significant values of coefficient of correlations (R2) of 0.9833, 0.9645, 0.9895, 0.9822 and 0.9645. The first proposed model generated the highest value of R2 (0.9895), and least values of root mean square error and average relative error (1.35 and 4.95%) respectively, while the remaining models yielded an appreciable range of errors. The performance of the first proposed model shows that the correlation between the compressive strength of concrete and pulse velocity values is a logarithmic function.

Key words: Non-destructive testing, ultrasonic pulse velocity, compressive strength, regression analysis, root mean square, average relative error.

INTRODUCTION

Casting of concrete during construction in some cases is carried out with certain uncertainties resulting from poor supervision and low-quality materials. It is imperative to carry out a non-destructive investigation after the setting of the concrete to check if the structure meets its predesigned characteristics. Non-destructive testing (NDT) is defined as the sequence of examining, testing or assessing materials, components or assemblies without destroying the serviceability of the part or system (Workman and More, 2012). The main aim of non-destructive testing is to evaluate the reliability of the component materials used without distorting or hampering the structure's ability to achieve the designed functions. Non-destructiveness is different from non-invasiveness. Testing methods which have no effect on the future usefulness of a part or the full structure can be

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considered as non-destructive even if there were invasive actions (Helal et al., 2015).

The most common tests on concrete structures can be categorized under non-destructive and partially non-destructive tests. The non-destructive testing creates no damage on the concrete such as ultrasonic pulse velocity and rebound hammer tests. Partially non-destructive testing creates little damage on the surface of the concrete such as core tests and pull-out and pull-off tests. The cost of carrying out non-destructive testing is by far less than that of partially non-destructive testing. It is important to carry out non-destructive testing of concrete elements of both old and new structures. To prevent some conceivable doubts especially when there are suspicions on the quality of supervision during construction, non-destructive testing when conducted should act as a quality assurance measure. For existing structures, non-destructive testing on the concrete is mainly to obtain the structural integrity and adequacy of the concrete which helps with the assurances on the safety of the structures. In words, if destructive testing is solely conducted by removing cores for the compression testing, the cost of coring and testing may only allow a relatively small number of tests to be carried out on a large structure which may be misrepresented. Non-destructive tests are widely applied to study mechanical properties and integrity of concrete structures (Helal et al., 2015; Ravindrarajah, 1997; Nazarian et al., 1997; Proverbio and Venturi, 2005).

The non-destructive machines are adapted for multiple data gathering during the testing. Different methods of non-destructive tests are interrelated with each other for improved diagnosis of defects in a concrete element and to economize the number of tests (Breysse, 2012). Compressive strength is a commonly used parameter for the assessment of the quality of concrete. Although the results obtained using the destructive methods of determination of compressive strength can be closer to the actual values, they have their own limitations; some of which are; the cost of execution, a limited number of samples, partial or total destruction of the concrete element. Cube or cylindrical samples cast from fresh concrete may not be identical to in-situ concrete because of curing and placement differences. The partially non-destructive coring method consumes a lot of time and resources, and its effect can lead to damage of part or the entire concrete structure under study (Mehta, 1986). These aforementioned major limitations of destructive testing are the reasons why non-destructive tests are normally preferred.

Schmidt rebound hammer test is one of the indirect measurement methods of the compressive strength of concrete. The manipulation of rebound hammer is easy while the interpretation of results obtained during the testing is also very simple. However, rebound hammer test is greatly influenced by the properties of the surface of the specimen. Estimation of compressive strength using Schmidt rebound hammer can only be accurate if the density of the concrete is constant at every point within the element. Its major limitation is that it does not reflect on the internal properties of the concrete element. Vacuum cast concrete elements have greater surface hardness than normal concrete cast. The performance of Schmidt hammer tests could be worse for vacuum cast concrete (Mehta, 1986; Erdal and Simek, 2006).

Ultrasound measurements provide a simple non-destructive and inexpensive method to evaluate the elastic modulus of concrete. In this method, the velocity of sound waves transmitted through the concrete specimen is measured. This velocity is dependent on the stiffness of the concrete specimen (Bungey, 1989; Malhotra and Carino, 2004). Pulse velocity measurements made on concrete structures may be used for quality control purposes with an advantage that they relate directly to concrete in the structure rather than to samples which may not be the true reflection of the concrete cast in-situ. Ideally, pulse velocity should be related to the results of tests on structural components and, if a correlation can be established with the strength or other required properties of these components, it should be desirable to make use of it. The relationship between ultrasonic pulse velocity and strength is affected by a number of factors including age, curing condition, moisture condition, mix proportion, type of aggregate and type of cement (BS 1881-203, 1986). The formulae proposed by different standards to estimate the dynamic modulus of elasticity from the resistance are very approximate (Baalbaki et al., 1992). The dynamic modulus of elasticity is strongly influenced by the aggregates, and cannot be determined accurately based on the strength, which depends mainly on the cement paste and the particle size (Honza, et al., 2002). For temperatures between -10 and +30°C, there is an increase in the dynamic modulus of elasticity of the concrete with temperature (Gardner, 1990; Marzouk and Hussein, 1990). Meanwhile, a number of models have been propounded based on rebound numbers and ultrasonic pulse velocity. These are as shown in Table 1.

Interpretation of Schmidt rebound hammer results can easily be done using the chart on the machine, while that of ultrasonic pulse velocity results has been a challenge in non-destructive testing of concrete. There is no information from the relevant standards on the direct interpretation of the results of ultrasonic pulse velocity tests in terms of compressive strength. Most of the results have been presented as a range of values. For example, Whitehurst (1951) published the following tentative classification for using pulse velocity as an indication of quality.

Table 2 has been quoted in many subsequent publications; however, Whitehurst (1951) warned that these values were established on the basis of tests of normal concrete having a density of about 24 kg/m^3 and that the boundary between conditions could not be

Table 1. Some existing single-variable models used for compressive strength estimation of concrete.

S/No	Equation	Explanation	Reference
1	$f_c = 1.2\times10^{-5} \times V^{1.7447}$	$f_c[MPa], V[km/s]$	Kheder (1998)
2	$f_c = 0.403R^{1.2083}$	$f_c[MPa]$	
3	$f_c = 36.72V - 1.29077$	$f_c[MPa], V[km/s]$	Qasrawi (2000)
4	$f_c = 1.353R - 17.393$	$f_c[MPa]$	

f_c= Compressive strength, V=ultrasonic pulse velocity, R=rebound number.

Table 2. Classification of ultrasonic pulse velocity.

Pulse velocity (m/s)	Condition
Above 4570	Excellent
3660 to 4570	Generally good
3050 to 3660	Questionable
2130 to 3050	Generally poor
Below 2130	Very poor

sharply drawn. It was also mentioned that rather than using these limits, a better approach would be to compare velocities with the velocity in a portion of the structure that are known to be of acceptable quality (Nicholas, 1997). In an effort to directly interpret ultrasonic pulse velocity tests, Ivan Ivachev interpreted results obtained through experimental procedures with EN 12504-4: 2004 and EN 2390-3:2009, and compare the results with theoretically calculated compressive strengths according to EN 1992 – 1- 1: 2004. The errors obtained ranged from 13.5 to 103.3% (Ivan, 2018). Another study was made on the improvement of compressive strength of concrete using the ultrasonic method. The parameters for interpretation are the dynamic modulus of elasticity of the concrete, bulk density of the concrete, and a factor k that depends on the quality of materials used. A recent study on non-destructive estimation of concrete elements using exact-size specimen (Watanabe et al., 2018) was good but very expensive, and forms one of the major limitations to this study.

This forms the basis of this research to look for the possibility of obtaining model(s) from the proposed models by using different mixes and different grades of coarse aggregate at different temperature ranges which to a certain level determines the compressive strength of concrete. The idea of using different materials and different grades is to obtain a universal model that can be applied no matter the nature and condition of materials used for the casting of concretes. These models will be compared with the existing ones to test their performance on independent data.

METHODOLOGY

Ultrasonic pulse velocity test

Descriptive research was adopted while quantitative study was conducted using statistical analysis of linear regression and two error analyses.

The equipment used was made up of an electrical pulse generator, an emitter transducer, a receiver transducer, an amplifier and an electronic timer for measuring the time taken by the ultrasound to move from the emitter transducer to the receiver transducer. The pulse velocity test was determined using cuboid specimens in accordance with the requirements of BS 1881-203:1986. The ultrasonic pulse velocity test meter is as shown in Figure 1 while the working principles are represented in Figure 2.

Description of the method

For this experiment, ultrasonic pulse velocity meter (V-C-400, V-Meter Mark IV) from James instrument and compressive-testing machine were used. While the former is a non-destructive testing instrument, the latter is a destructive testing machine. Varieties of commonly prescribed concrete mixes (1:1.5:3, 1:2:4, 1:3:6), sizes of coarse aggregate (10 mm – 20 mm) and water-cement ratio ranging between 0.5 – 0.6 were adopted. To balance these conditions, the V-meter was tuned to the frequency of 150 kHz. The size of concrete cubes ranges between 150 mm × 150 mm to 200 mm × 200 mm and the age range between 21 days and 56 days were adopted. The reason for adopting this is because in most cases, concrete reaches appreciable strength in 21 days while its maximum strength is also reached between 28 days and 56 days. About eighty (80) sample cubes were used for both calibration and verification of proposed models. For each of the cubes, two tests were carried out as aforementioned. To obtain the pulse velocity, the path length was measured and recorded into the V-Meter; also, the couplant was applied to the traducer scan areas on the opposite sides of the cuboid. After this, the traducers were placed firmly on

Figure 1. Ultrasonic pulse velocity.

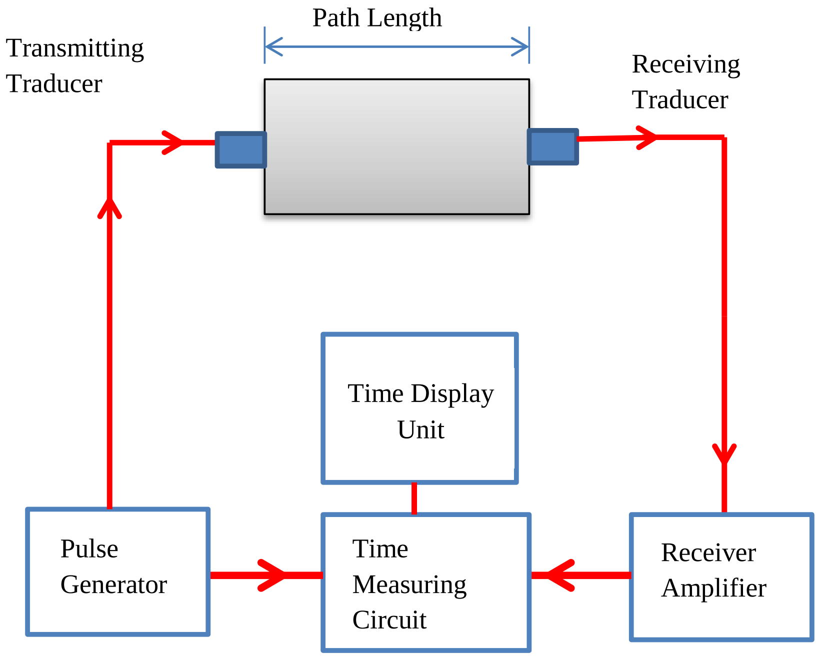

Figure 2. Schematic of ultrasonic pulse velocity method.

the areas where couplant has been applied and the pulse velocity was read from the display window of the V-Meter. It was repeated four more times on the specimen after which an average of the five readings was obtained. The cuboid was later taken to the compressive-testing machine where the compressive strength of the concrete was obtained. The same experiment was repeated on all the concrete cubes. This experiment was done under a different range of temperature, the water-cement ratio as mentioned above, different aggregate sizes (between 10 mm – 20 mm) and different curing conditions.

Proposed models

Three relationships were assumed as shown below:

$$f_c = Ae^{BV} \tag{1}$$

$$f_c = AV^n \tag{2}$$

$$f_c = AV + B \tag{3}$$

Where A, B and n are all constants, f_c = compressive strength of concrete (N/mm^2), V = pulse
Velocity (m/s).

In order to compare the performance of the existing equations and the proposed models in this study, three statistical parameters were employed as shown below:

i) The linear regression coefficients of correlations were calculated using the following representative of x, y (x represent abscissa, y represent ordinate).

$$R. = \sqrt{\frac{\left(n\sum xy - \sum x \sum y\right)^2}{\left(n\sum x^2 - \left(\sum x\right)^2\right)\left(n\sum y^2 - \left(\sum y\right)^2\right)}} \qquad (4)$$

ii) Average relative errors were calculated from the following equation:

$$\text{ARE} = \frac{100}{N}\sum_{i=1}^{p}\left|\frac{X_{e,meas} - X_{e,est.}}{X_{e,meas}}\right| \qquad (5)$$

Where $X_{e,meas.}$ is the measured variable, $X_{e,est.}$ is the estimated variable and N is the number of data points (Kapoor and Yang, 1989).

iii) Similarly, Root Mean Square Errors (RMSE) were calculated from the equation below

$$RMSE = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(f_{c_{est}} - f_{c_{mea}}\right)^2} \qquad (6)$$

Where n is the number of data points, f_{cest} is the estimated value of compressive strength, and f_{cmea} is the measured value of compressive strength.

RESULTS

Calibration of the models

To solve Equation 1 using natural logarithm, we use:

$$f_c = Ae^{BV} \qquad (1)$$

$$\ln f_c = \ln(Ae^{BV})$$

$$\ln f_c = \ln A + BV \qquad (7)$$

Where ln is natural logarithm, f_c is compressive strength, ln A is the intercept on the vertical axis of the graph representing minimum strength, B is the slope and V is ultrasonic velocity. A graph of $\ln f_c$ against V is as represented in Equation 3 using part of the data generated. The square of the coefficient of correlation (R^2 = 0.9725) is relatively high.

Also, to solve Equation 2, natural logarithm is applied at both sides of the equation as shown below:

$$f_c = AV^n \qquad (2)$$

$$\ln f_c = \ln(AV^n)$$

$$\ln f_c = \ln A + \ln V^n$$

$$\ln f_c = \ln A + n \ln V \qquad (8)$$

where ln is natural logarithm, f_c is compressive strength, ln A is the intercept on the vertical axis of the graph representing minimum strength, n is the slope and V is ultrasonic velocity. A graph of $\ln f_c$ against lnV is as represented in Figure 4. The square of the coefficient of correlation (R^2 = 0.9794) is also high.

$$f_c = AV + B \qquad (3)$$

Equation 3 is a direct relationship between compressive strength (f_c) and ultrasonic velocity (V) as evidenced in Figure 5. The constant A is the slope of the graph while B is the intercept on the vertical axis.

As stated earlier, the data generated was divided into two; while one part was used for the calibration of the models as described above, the remaining half was used for the verification of the models in conjunction with testing the performance of some of the existing models as contained in Table 3.

Figures 3 to 5 represent the results of the calibration of the proposed models (Equations 1, 2 and 3 respectively). The calibration of the models gave rise to the following models as shown below.

$$f_c = 5.76e^{0.0004V} \qquad (9)$$

$$f_c = 0.000044V^{1.6807} \qquad (10)$$

$$f_c = 0.0117V - 18.693 \qquad (11)$$

Verification of models

In order to test the performance of the models, the remaining parts of the data were used. The measured data were compared with the estimated (theoretical) values of the compressive strengths for the three proposed models as shown in Figure 6. The performances of two existing models were also studied as shown in Figure 7.

DISCUSSION

From the verification of the proposed models and in comparison with the existing ones, it is evident that it is always better to judge a model with other statistical parameters than depending only on regression analysis. This is because Qasrawi model and the 2nd proposed

Table 3. Summary of performance of the models.

Model	The coefficient of correlation (R^2)	Root mean square error (RMSE)	Average relative error (ARE) (%)
Kheder 1 (1998)	0.9833	5.10	20.49
Qasrawi 1 (2000)	0.9645	90.04	377.72
1st Proposed Model	0.9895	1.35	4.95
2nd Proposed Model	0.9822	19.22	72.91
3rd Proposed model	0.9645	2.14	8.85

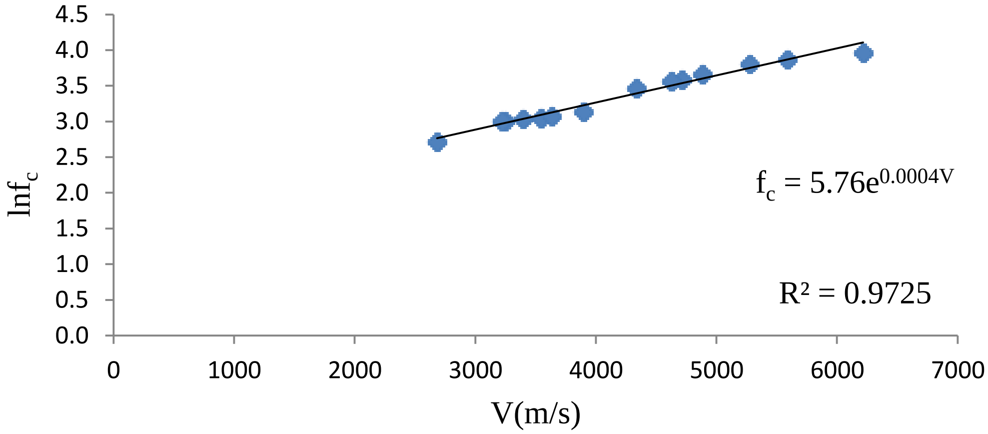

Figure 3. Variation of $\ln f_c$ against v.

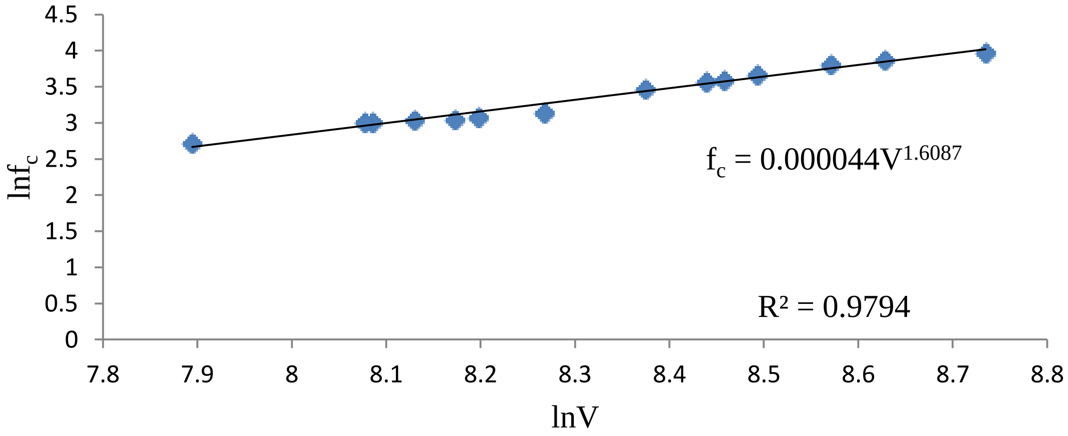

Figure 4. Variation of $\ln f_c$ against lnv.

model recorded appreciable values of coefficient of correlation of 0.9645 and 0.9822 but performed poorly in terms of root mean square and average relative error. In other words, the huge errors recorded by these two models show that they cannot be relied on for interpreting varieties of concrete. From Figures 6 and 7, it is clear that the estimated values of compressive strength using the Qasrawi and second proposed models went above the range. Unlike Qasrawi and Kheder models which must have been derived under some specific conditions, some key factors were considered during the generation of data used for derivation of the proposed models, which though are within certain limits but allow the model(s) to be used to analyze results of tests carried out on various concrete mixes and sizes of aggregates. In terms of coefficient of correlation, the first proposed model and Kheder

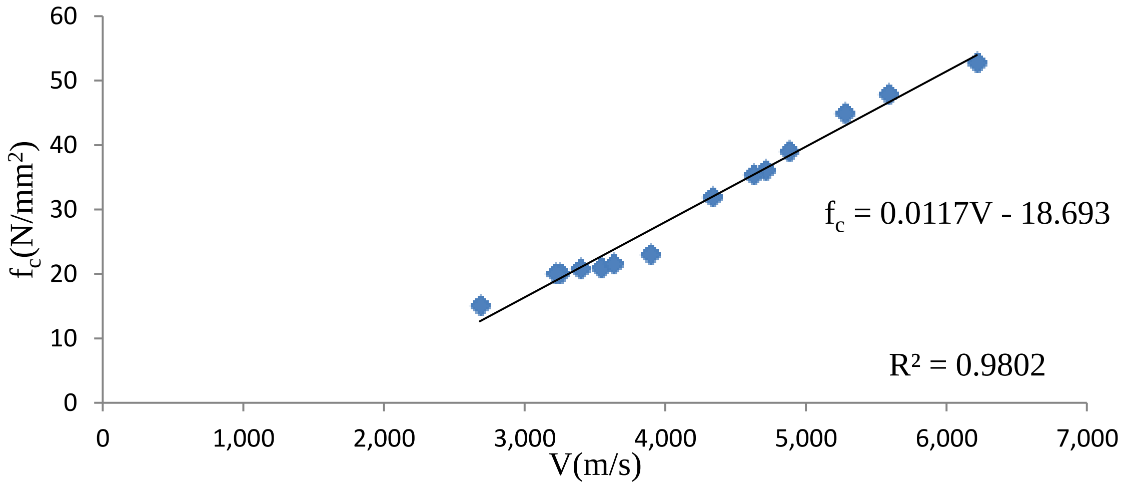

Figure 5. Variation of f_c against v.

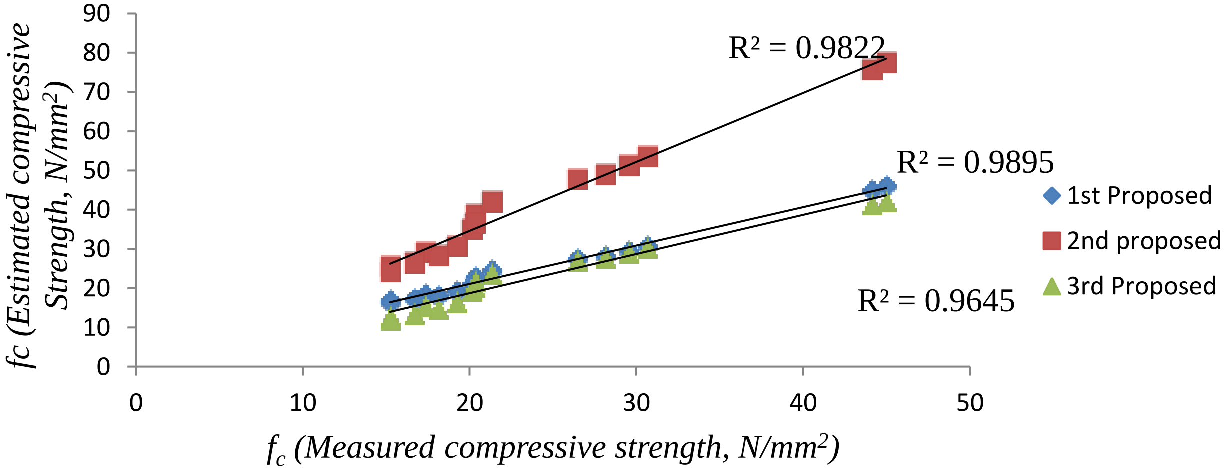

Figure 6. Performance comparison of two existing models.

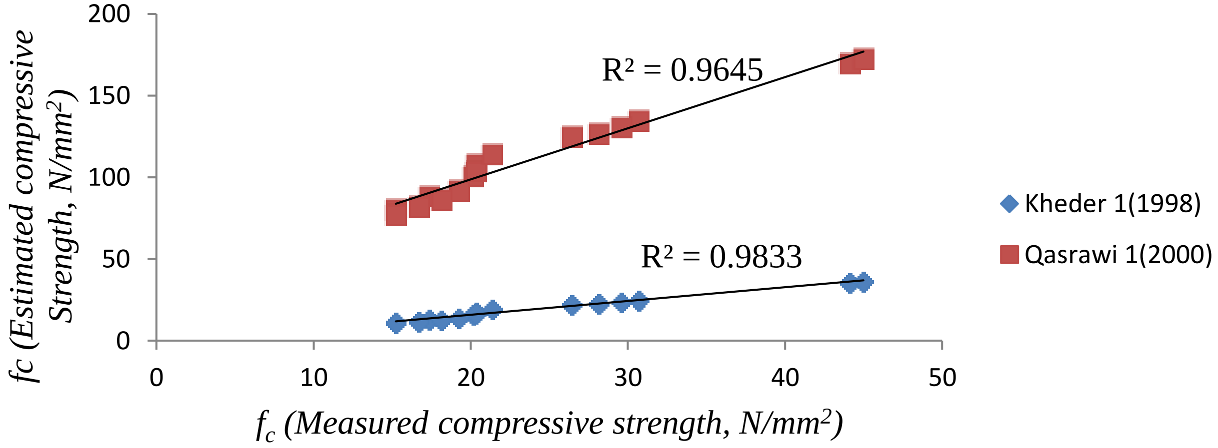

Figure 7. Performance comparison of three proposed models.

performed well. Just like Qasrawi model, Kheder recorded RMSE value of 5.10 and AVE value of 20.49% which might be due to some specific experimental conditions adopted during the generation of data used for the calibration of the model. The first proposed model produced the highest value of the linear regression coefficient of correlation and least values of both root mean square error (RMSE) and average error (AVE). The third proposed model and Qasrawi model have the least value of the coefficient of correlation when compared to other models. The third proposed model has the second least errors after the first proposed model. This implies that the relationship between pulse velocity and compressive strength of concrete is more of logarithmic function than a linear function.

Conclusion

The difficulty in the interpretation of pulse velocity results in relation to the compressive strength of concrete propelled this research. Several factors were considered during the experimental stage of this project for a possible universal application of the model(s) to concrete elements of different mixes. In general terms, the first proposed model can be adjudged effective when compared to others. The most important finding in this work is that the relationship between pulse velocity and compressive strength follows a logarithmic function. Future research will center on this relationship and possibly bring the coefficient of correlation to near unity and the errors near zero.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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