



Comparison of Nondestructive Testing Method for Strength Prediction of Asphalt Concrete Material

Hashem Al-Mattarneh ^{1*}, Mohammed Dahim ²

¹ Civil Engineering Department, Yarmouk University, Irbid, Jordan.

² Civil Engineering Department, King Khalid University, Abha, Asir, Saudi Arabia.

Received 24 September 2020; Revised 14 December 2020; Accepted 24 December 2020; Published 01 January 2021

Abstract

Concrete is one of the most common construction materials used in rigid pavement, bridges, roads, highways, and buildings. Compressive strength is one of the most important properties of concrete, which determines its quality. This study aims to present the use of a new surface dielectric method to estimate concrete compressive strength. Six concrete mixtures were produced with compressive strengths ranging from 30 to 60 MPa. Compressive strength and strength development were determined during 28 days of curing. All concrete mixes were tested using the ASTM standard. The dielectric properties, ultrasound velocity, and rebound number of all concrete mixes were also measured at each day of curing. The results obtained from the proposed dielectric method in predicting the compressive strength of concrete were compared with the rebound hammer and ultrasonic velocity that are frequently used to evaluate the compressive strength of concrete. The dielectric method shows a higher square correlation coefficient than the other two methods. The results also indicate that combined more than one method of nondestructive techniques will lead to higher prediction and could help to reduce some errors associated with using a certain method alone. The result indicate that the finding of this study could lead to help in reducing the time of evaluating concrete during construction and could also provide tools for practicing engineer to take decision faster with more confidence level on quality of concrete.

Keywords: Ultrasound Pulse Velocity; Rebound Hammer; Dielectric Sensor; Compressive Strength; Concrete; Strength Development.

1. Introduction

Concrete is a dominant construction material used in rigid pavement, bridges, and building. This is because its excellent in resisting and carrying compressive load [1-3]. Several nondestructive testing methods were used to predict and evaluate compressive strength of concrete to overcome the problems associated with the conventional destructive standard methods [4-5]. Standard method is slow take longer time and the rapid construction of concrete structure raised the need for reliable faster method. Determining the compressive strength of concrete has become the field of research and development for many studies by researchers, and it is often considered the main and most important criterion for judging the quality of concrete [6-7]. Several different methods have been developed and proposed for Non-Destructive Testing (NDT) to determine the compressive strength, durability, and various conditions of concrete [8-11]. An excellent review of nondestructive testing method for concrete material could be found in work collected by ACI 228 report [12] and handbook on nondestructive testing of concrete [13]. Examples of these methods are surface hardness methods [14], penetration resistance method [15], pullout method, break-off method [16], maturity method,

* Corresponding author: drhashem2010@yahoo.com; hashem.mattarneh@yu.edu.jo

 <http://dx.doi.org/10.28991/cej-2021-03091645>



© 2021 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

pull-off method, resonant frequency method, and ultrasound pulse velocity method [4-5,17]. But it has not been adopted by engineers and institutions specialized in developing standard specifications to determine the compressive strength of concrete [18-19].

Among the invasive nondestructive methods available, the Schmidt Hammer method is the one most used in field and practice. It has been accepted worldwide as an indicator test to evaluate the relative strength of concrete materials in site due to its speed, ease of implementation, simplicity, portable instrument, cheap in terms of cost, and nondestructive nature. To date, still all international standards do not allow using this method for strength determination [18]. Despite the intensive use of Rebound Hammer (Schmidt Hammer) due its simplicity, several factors affecting the Rebound Number (RN) obtained in testing concrete. The factors affecting RN could be classified according factors related concrete mix proportions such as aggregate type, water/cement ratio, admixtures, and cement type. Other factors classified according concrete conditions such as moisture content, curing condition and age, concrete maturity, and surface carbonation [14].

Another widely used nondestructive testing method for assessment of concrete material and determine the relative strength and quality of concrete is the Ultrasound Pulse Velocity (UPV) [19]. Ultrasound have been used to determine the elasticity, density, and relative strength of concrete. To date, the engineers and standard specification does not recommend ultrasound method to be used to determine the absolute compressive strength except in certain condition. This is due to many other factors affecting ultrasound velocity in concrete and the heterogenous nature of concrete [20-21]. Despite the wide used of UPV method for concrete durability and homogeneity limited use of UPV method for strength prediction has been reported. This is because several factors affecting UPV method have been reported in literature. These factors are type of cement, water/cement ratio, hydration degree, cure conditions of the concrete, presence of reinforcement, fissures, temperature, dimension of aggregate and concrete cracks [4-5, 7].

In the last two decades, several researchers investigate the use of dielectric methods to determine concrete compressive strength and evaluation several properties of concrete based on the dielectric properties of concrete. These dielectric methods measure the dielectric properties of materials and develop a relationship between dielectric properties of material like concrete with physical and mechanical properties of materials such as compressive strength. The dielectric properties of the material represent the response of the material to an applied electric field. When the material exposed to an AC current, the material absorbs amount of energy from electric field this is called dielectric constant of the material and part of the energy is lost in the material as conductance current this is called dielectric loss factor. These two dielectric properties of material could be measure using several dielectric and electromagnetic sensors. Several electromagnetic sensors were used by researchers to determine the electromagnetic and dielectric properties of concrete. Examples of the dielectric sensors are free-space method [22, 23], Resonant cavity method [24], time domain reflect meter [25], waveguide microwave method [26], capacitive electrode method [27-28] and ground penetration radar [29]. Capacitive electrode method is simple, low cost, portable and the electrode could be modified to suite the testing condition. Therefore, this method will be used in this study and the results will be compared with the most used two nondestructive testing method for assessment compressive strength of concrete.

This study presents the use of surface dielectric sensor to estimate the compressive strength of concrete and compare the prediction level with ultrasound pulse velocity and rebound hammer method. The proposed method is simple to use, fast low cost, portable and does not affected by the condition of concrete surface like other methods. The dielectric method has been investigated to predict compressive strength of concrete. Dielectric properties could represent the evolution of microstructure more than other nondestructive testing method [8, 26].

2. Nondestructive Testing Methods

In this study, three nondestructive testing method were used to evaluate compressive strength of asphalt concrete material. The first two method were the most used nondestructive method namely rebound hammer method and ultrasound method while the third proposed method is the dielectric method. These three methods will be explained in the following subsections.

2.1. Rebound Hammer Method

Ernst Schmidt proposed a method of testing concrete strength in 1948. This method based on the surface hardness of concrete and called rebound hammer or Schmidt hammer. The basic principles of the hammer assume that the strength development of concrete strength associated with the increasing surface hardness of concrete. After 40 years of creating the hammer and testing it on a large scale globally, around 50,000 Schmidt hammers have been sold worldwide [18, 30-34]. Figure 1 presents schematic and photo of rebound hammer. When the rebound hammer is placed perpendicular to the concrete surface, the spring-controlled mass (plunger) is pressed against the concrete surface and then the bounce or rebound of the plunger is measured from the concrete surface. The amount of rebound depends on the hardness of the concrete surface. The retracement is read along a predefined scale and is consider as the rebound number or the rebound indicator.

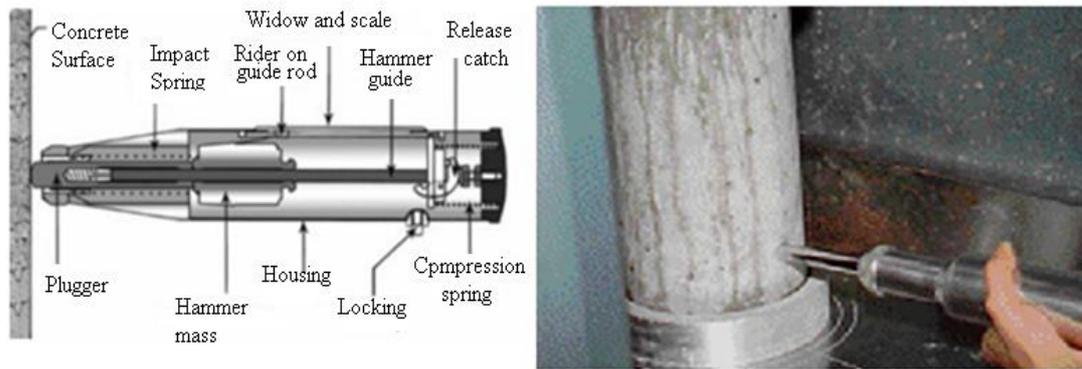


Figure 1. Schematic and picture of rebound hammer

Statistical regression formula is used to relate the rebound number as a measure of concrete surface hardness with concrete compressive strength. A linear relationship is mostly proposed to determine the relationship between strength and rebound number. The results rebound number obtained from rebound hammer is affected by several other factor which does not have similar effect on strength. These factors include moisture condition of concrete, aggregate type and properties, concrete surface condition, carbonation of concrete and cement type [18, 32].

2.2. Ultrasound Pulse Velocity Method

The compressive strength of concrete can be estimated by ultrasound pulse velocity calculation. The speed of ultrasound waves in concrete can be measured by sending a sound wave from the transmitter that is in contact with the concrete to the receiver that is also in contact with the concrete, which is separated by a distance that the concrete fills. The ultrasound device measures the time required for the sound wave to travel through the concrete from the transmitter to the receiver. Then the velocity of the ultrasound is calculated by dividing the distance between the transmitter and the receiver by the measured time. This method is described in ASTM C597-16 [19]. The velocity of the ultrasound in concrete can be used to determine the quality of the concrete and also to evaluate several factors specific to the concrete such as modulus of elasticity, crack depth, and internal defects. As for the compressive strength of concrete, it can be estimated by finding a relationship between ultrasound pulse velocity and compressive strength by examining several samples of concrete with different compressive strength. Since the velocity of ultrasound in concrete is affected by many factors other than compressive strength, such as water content and type of aggregate, estimating the precise compressive strength of concrete using ultrasound velocity alone is difficult and imprecise and is not recommended by many studies [4-5, 32-34]. Figure 2 represents the schematic diagram and picture of ultrasound method.

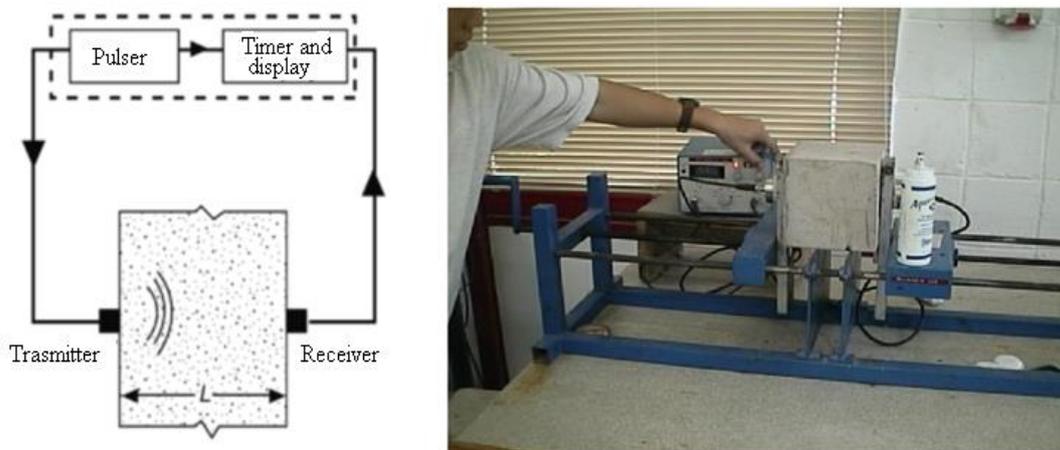


Figure 2. Schematic and picture of ultrasound pulse velocity

2.3. Dielectric Method

The dielectric method used in this study is the capacitance dielectric method. This method used two electrodes to excite the concrete material by AC current and measured the impedance of concrete material under testing. The dielectric properties of concrete will be calculated from the measured impedance. Two techniques of capacitor dielectric sensor were used. These techniques are parallel plate dielectric sensor and surface dielectric sensor. These

two techniques could be used to measure the dielectric properties of concrete. The detail description of the dielectric methods could be found in previous published work [35-40]. The dielectric methods used in this study is given in Figure 3.

The response of material to electric field depends on the electromagnetic properties of the material called complex permittivity. This property has real part called dielectric constant which represent the energy absorbed by the material due to polarization of the microstructure of the material. The imaginary part is called the loss factor represent the energy loss due to free electron in the microstructure and form current conductance. The complex permittivity generally represented relative to the air complex permittivity make it dimensionless. Relative permittivity of material could be given by Equation 1:

$$\epsilon^* = \epsilon' + j\epsilon'' \tag{1}$$

Where ϵ^* is the complex permittivity, ϵ' is the dielectric constant of the material and ϵ'' is the loss factor of the material. Dielectric nondestructive method based on exciting the material by electromagnetic signal such as AC current and determine the dielectric constant and loss factor of the material. These properties will change with the change of the material condition and structures. During hydration process, material microstructure will change from paste semiliquid to solid material. This change can change dielectric constant and loss factor of the new material formed by hydration process.

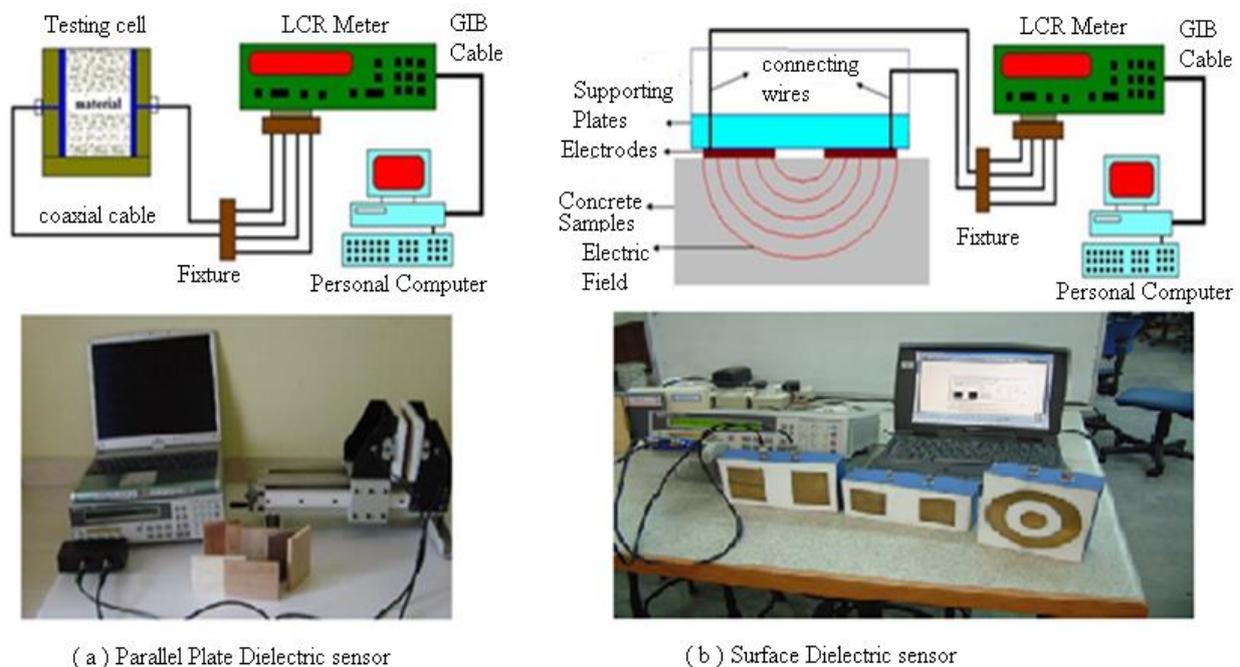


Figure 3. Schematic and picture of capacitor electrode dielectric sensors

2.4. Calibration and Validation

The proposed new dielectric method was calibrated and validated before used to measure dielectric properties of concrete. An open/short calibration standard method build in the LCR meter and developed by HP were used to calibrate the surface dielectric sensor [41]. Another method is used for calibration. This method called the standard material calibration. Teflon material is used as standard material to calibrate the surface dielectric sensor. The dielectric properties of Teflon (2.063) are in good agreement with the values reported (2.1) in literature [42]. The difference between the measured dielectric of Teflon using the proposed sensor and actual value is very small (less than 2% at all frequency from 100 kHz to 1 MHz). Methyl alcohol is used to validate the dielectric sensor. The dielectric properties of methyl alcohol is measured using surface dielectric sensor. The dielectric properties of methyl alcohol at 25°C was 9.0 - i7.0 [42]. The measured value using the proposed dielectric method was 8.79 - i6.71. The error was about 2%. UPV also calibrated before it used to measure the ultrasound velocity in concrete samples. The standard calibration provided by the manufactured was used to calibrate UPV instrument using the rode with known ultrasound velocity.

3. Research Methodology

Several concrete mixes were prepared using the guide provided by ACI211. Six asphalt concrete mixes were prepared to relate and evaluate the three proposed nondestructive testing methods in prediction of asphalt concrete strength. Three mixes were used to assess the development of compressive strength of asphalt concrete using Rebound hammer, Ultrasound pulse velocity and dielectric properties. The detail of the mixes and testing is presented in the next subsections. Figure 4 explain the flowchart of the research methodology used in this study.

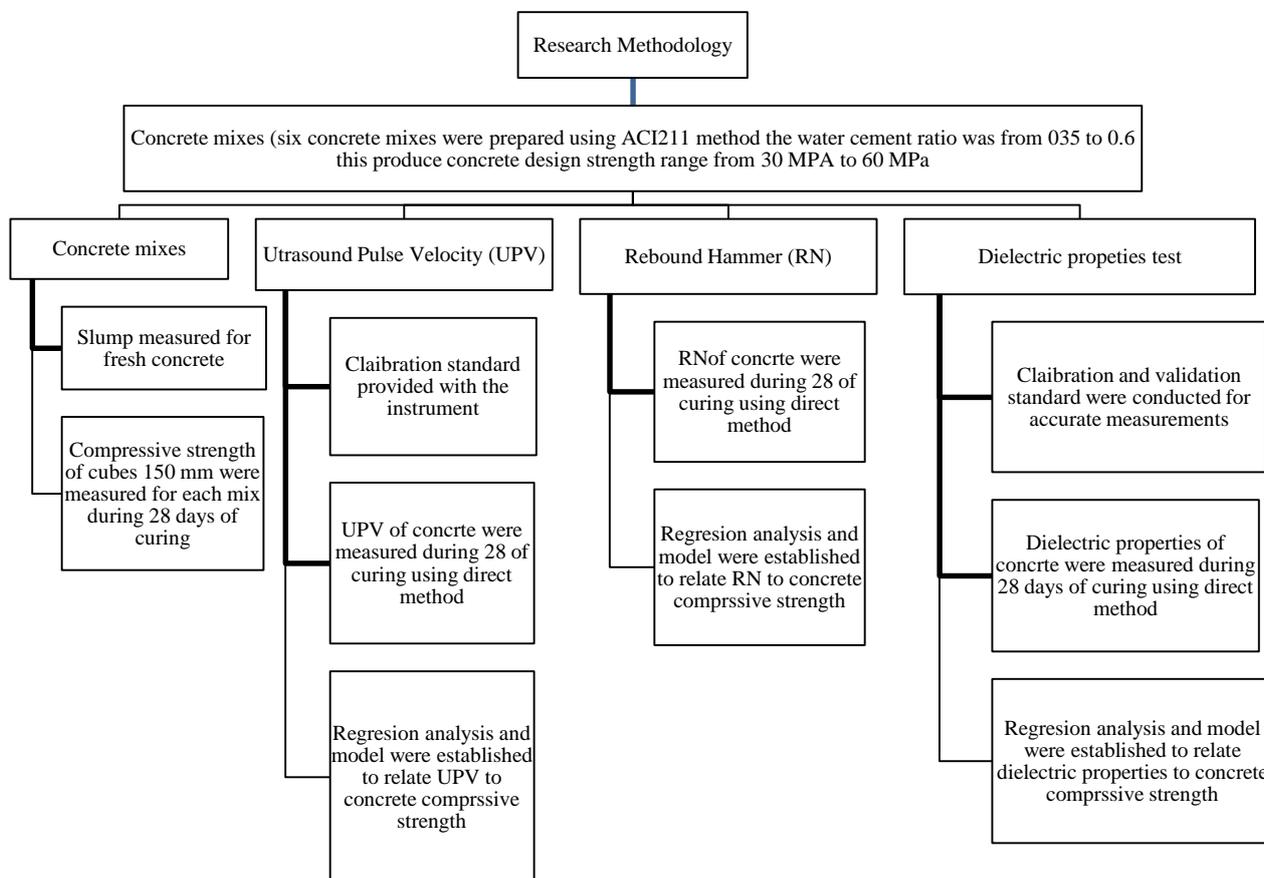


Figure 4. Flowchart of research methodology conducted in this study

3.1. Concrete Material

Using the mix proportion method suggested by ACI211, six asphalt concrete mixes have been produced. All mixes were prepared using ordinary Portland cement, limestone aggregate and sand. The mix proportion is given in Table 1 and the grading of limestone aggregate and sand are presented in Figure 5.

Table 1. Asphalt concrete mix proportion, slump and compressive strength at 28 days

| Code of Concrete mix | Water cement ratio (w/c) | Ratio of Cement to Aggregate | Ratio of sand to coarse aggregate | Slump (mm) | Compressive strength at 28 days |
|----------------------|--------------------------|------------------------------|-----------------------------------|------------|---------------------------------|
| C35 | 0.35 | 1:5 | 2:3 | 20 | 63.1 |
| C40 | 0.40 | 1:5 | 2:3 | 35 | 57.8 |
| C45 | 0.45 | 1:5 | 2:3 | 75 | 46.1 |
| C50 | 0.50 | 1:5 | 2:3 | 120 | 37.6 |
| C55 | 0.55 | 1:5 | 2:3 | 145 | 32.0 |
| C60 | 0.60 | 1:5 | 2:3 | 160 | 30.8 |

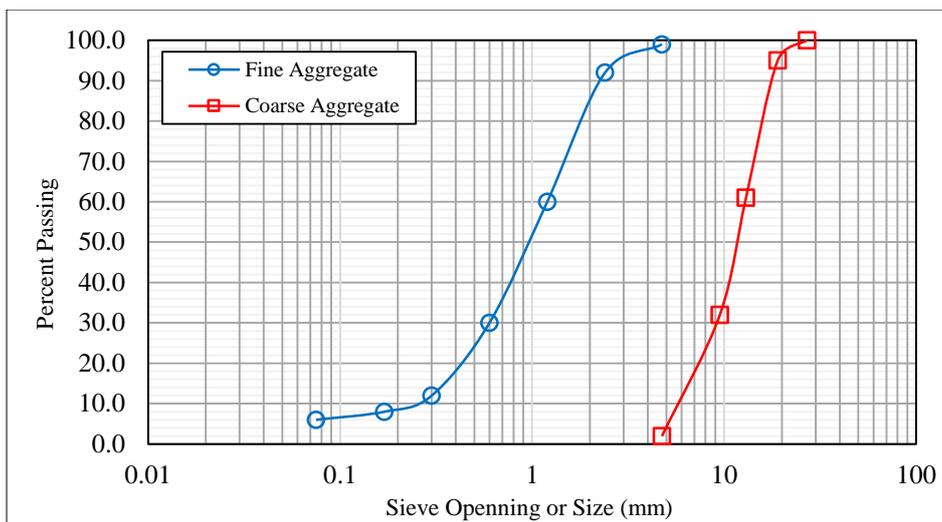


Figure 5. Sieve analysis for grading of sand and coarse aggregate

3.2. Testing Procedures

To evaluate strength development of concrete, compressive strength of asphalt concrete was measured at 1, 3, 5, 7, 11 14, 21 and 28 days for three mixes C40, C50 and C60. At each day of testing the ultrasound pulse velocity and the rebound number were measured. All concrete samples were cubes 150 mm. After 28 days compressive strength test, rebound number and ultrasound pulse velocity were performed for all six concrete mixes. The results of strength development of concrete are shown in Figure 6.

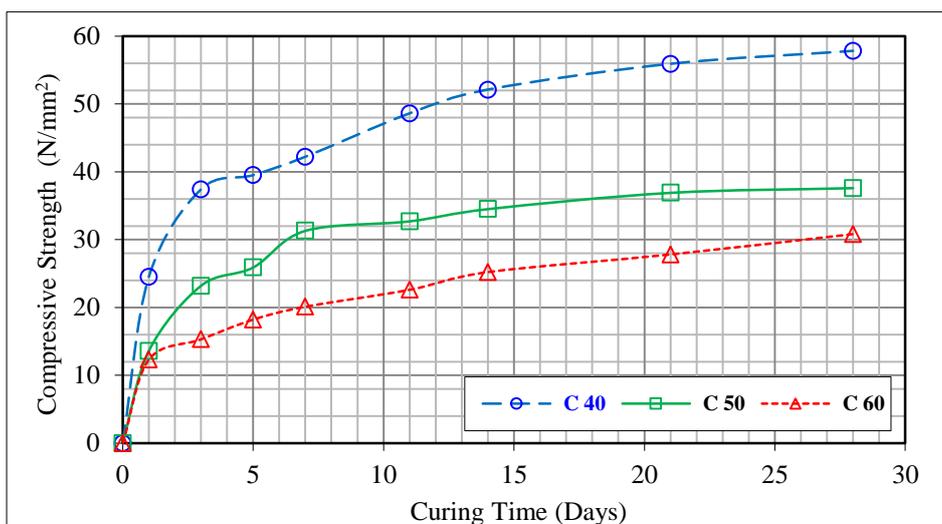


Figure 6. Compressive strength versus curing time

The results in Figure 6 shows that compressive strength of concrete increases with increasing curing time. The early age of concrete indicates high rate of gaining strength due high hydration process of cement. The hydration process converts the gel of cement paste to form the CSH product which form the strength of solid concrete material.

4. Results and Discussion

All concrete mixtures were tested with a rebound hammer, ultrasound velocity, and dielectric method for 28 days because concrete is usually designed with a measured compressive strength on 28 days. The concrete was tested on cubes with a side length of 150 mm on the same days as the compressive strength of the concrete measured. The following sections presents the results obtained in this study.

4.1. Results of Rebound Hammer

The rebound numbers of the three concrete mixes C40, C50 and C60 during the 28 days of curing are shown in Figure 7. The result shows an increase of the rebound number with increasing curing age. This was attribute to the strength gain over hydration time, which increases the surface hardness of concrete specimens. The regression analysis

of the relationship between the rebound number and the curing time is given in Figure 6 also. The best fit statistical model to relate the rebound number to the curing time is logarithmic and could be given by Equation 2.

$$RN = a \ln(t) + b \tag{2}$$

Where RN is the rebound number, t is the curing time, a, and b are constant represents the model parameters. The correlation is significance at 0.05 limit. The square correlation coefficients were 0.9307, 0.9642 and 0.94 for concrete mixes C40, C50 and C60 respectively. The results also indicate that in the first 7 days the variation of surface hardness is high. Therefore, using rebound hammer in this age of concrete is not reliable and could lead a larger error. After 7 days the rebound hammer work more consistent due to surface hardness development in concrete. This finding is in good agreement with literature [14, 30].

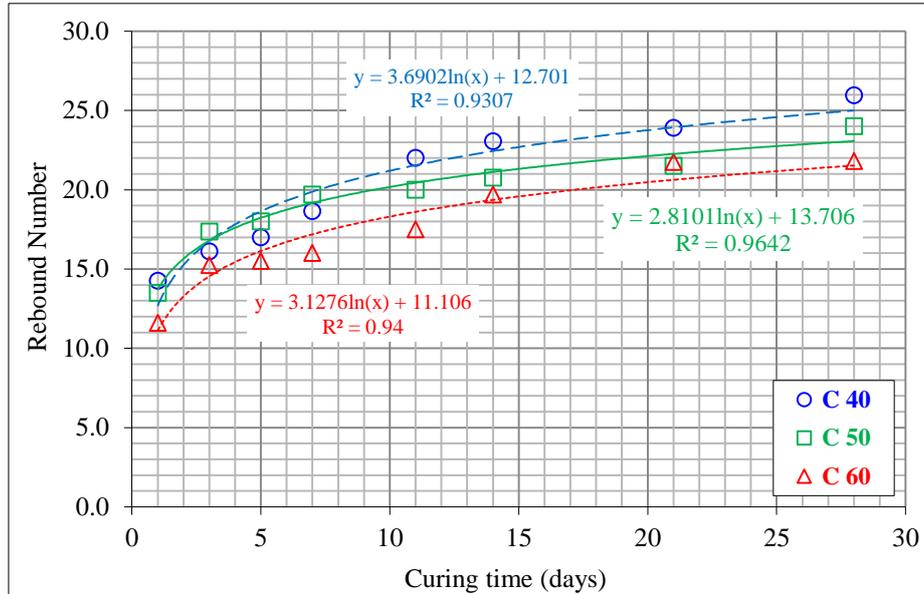


Figure 7. Rebound number versus curing time

The relationships between the RN and compressive strength development during curing time of concrete are given in Figure 8. The results of regression analysis are also summarized in Table 7. The best fit relationship based on statistical analysis is linear model with square correlation coefficients 0.9402, 0.9452 and 0.9525 for concrete grade C40, C50 and C60 respectively. The linear relationship between compressive strength development and rebound number (RN) is given by Equation 3 and presented in Figure 7.

$$f_{ct} = a + b (RN) \tag{3}$$

Where f_{ct} is the compressive strength at time t, RN is the rebound number, a, and b are model constant.

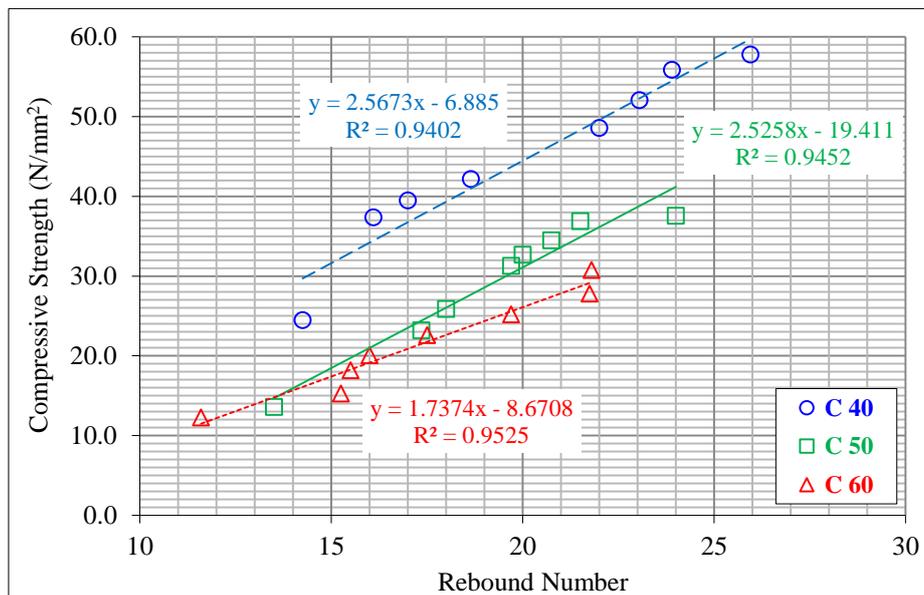


Figure 8. Relationship between compressive strength development and rebound number

4.2. Results of Ultrasound Pulse Velocity

The ultrasound pulse velocities of concrete specimens are shown in Figure 9. The results showed that the ultrasonic velocity decreased with increasing curing time. This was due to the decreasing free water in the concrete specimen due to evaporation and hydration process. The measured UPV could be used to indicate the strength development of concrete. When concrete age less than 7 days, the ultrasound velocity (UPV) does not reflect the strength development very well due to higher moisture condition of concrete. Moisture condition of concrete is seeming the dominant factor affecting UPV. After 7 days the UPV measurements reflect the strength development of concrete more than early ages. The relationship between strength development and UPV using statistical analysis were established. This is confirmed with another study in literature [5, 33, 34]. The best model fit the data was logarithmic and given in equation (4) and presented in Figure 9.

$$UPV = a \ln(t) + b \tag{4}$$

Where UPV the ultrasound velocity at time t, t is the time age of concrete, a, and b are constant model parameters.

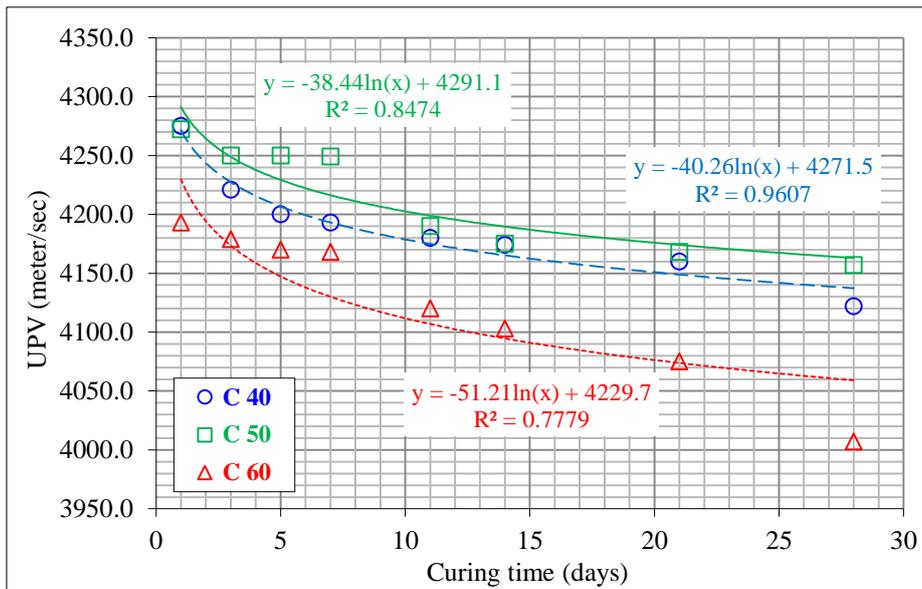


Figure 9. Ultrasound velocity versus curing time

The relationships between the UPV and compressive strength development are given in Figure 10. The results of regression analysis are summarized in Figure 10. The relationship takes the linear form and is presented in Equation 5.

$$f_{ct} = a + b (UPV) \tag{5}$$

Where f_{ct} is the compressive strength at time t, UPV is the ultrasound velocity, a, and b are model constants.

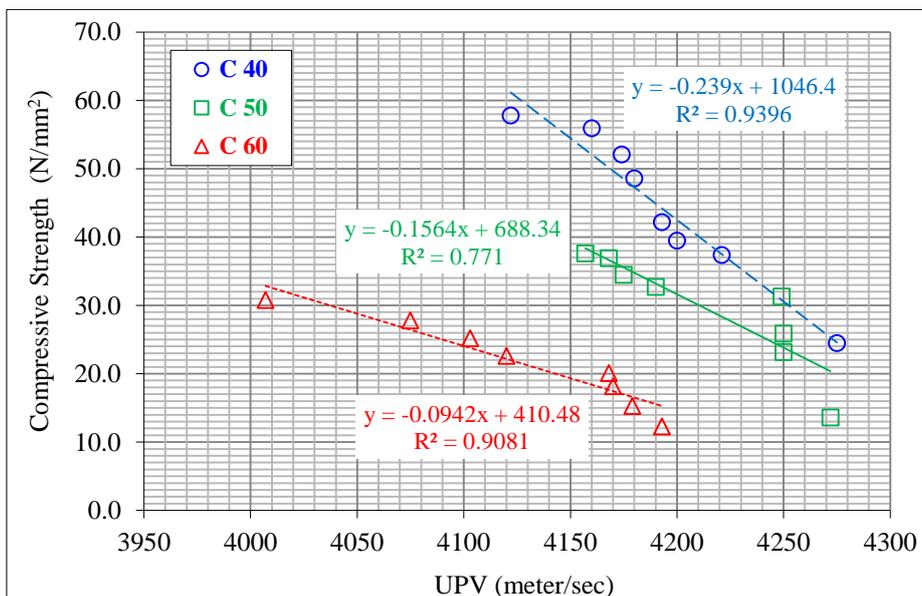


Figure 10. Relationship between compressive strength development and ultrasound velocity

4.3. Results of Dielectric Properties

The results of dielectric constants presented in Figures 11 indicate a rapid decrease in the values of dielectric constants during the first 7 days, particularly for the higher water cement ratio (w/c) specimens. This was expected due to bleeding, hydration of cement which convert free water into bound water and subsequent evaporation of free water from the surface of the concrete specimens. After 7 days the rate of decreasing was slow and after 21 days up to 28 days the dielectric properties become almost constant. After 21 days, most of the remaining water in the specimens was bound water. This would indicate that the dielectric constant measurements of concrete were indicative of hydration process, which directly related to w/c and compressive strength. It was clear that a trend of increasing values of dielectric constants was observed for decreasing w/c and higher strength. The change of dielectric constants of specimens is w/c dependent and it could be used to determine w/c in the early stages of curing. Also, since the difference between the final values of dielectric constants for each w/c was experimentally measured, this value was used to determine the w/c of hardened concrete, and subsequently was used to identify its final compressive strength. Same trend was observed for loss factor of concrete indicate that both dielectric constant and loss factor could be used estimate concrete strength.

To better visualize the above discussion and to establish the relationship between dielectric constants, loss factors and curing time, a statistical analysis using nonlinear regression analysis was performed. Several relationships were investigated including linear, power, exponential, quadratic, and logarithmic model. The relationships between the dielectric constants, loss factors and the curing time were established for the three water cement ratios 0.40, 0.50 and 0.6. The regression results and the square of the correlation factor (R^2) are presented in Figure 10. The best relationships between dielectric constants and curing time were exponential function while the best relationships between loss factors and the curing time were power function. These relationships are given in Equations 6 and 7.

$$\epsilon' = a + b(t) + c(t)^2 \tag{6}$$

$$\epsilon'' = d (t)^e \tag{7}$$

Where ϵ' is the dielectric constant, ϵ'' is the loss factor, t is the curing time age, a, b, c, d and e are model constant parameters. These models have a high correlation factor and the minimum square correlation obtained from the six models is 0.9703 which is higher than all values obtained for RN and UPV.

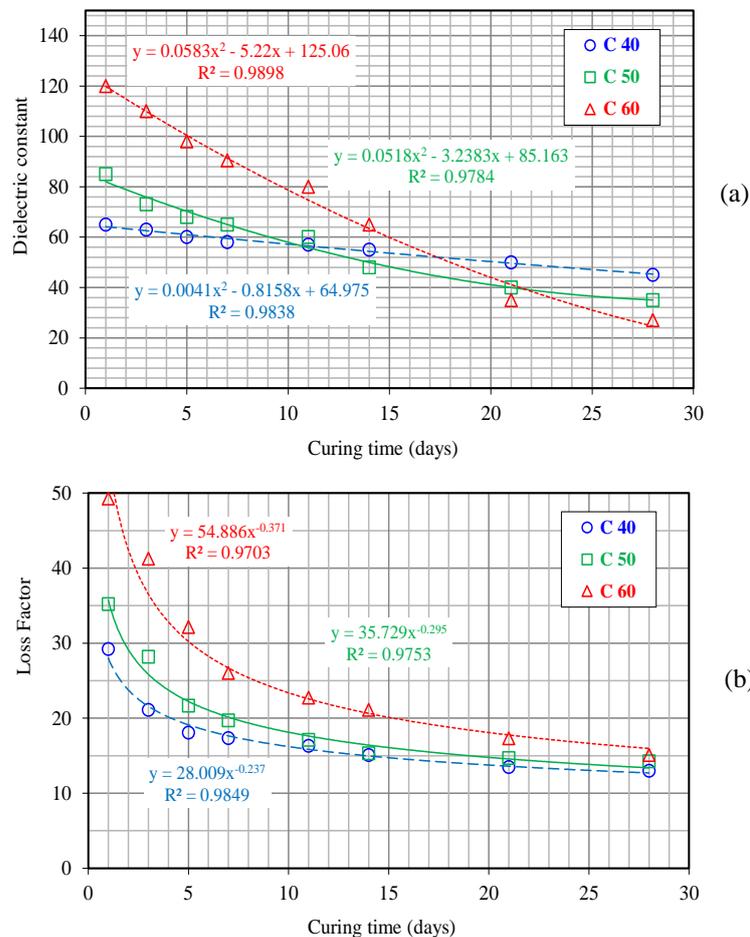


Figure 11. Dielectric properties versus curing time; a) Dielectric constant versus curing time; b) Loss factor versus curing time

To determine the relationship between compressive strength development of three grade concrete C40, C50 and C60 and concrete dielectric properties known as dielectric constant and loss factor, several statistical models were investigated and the best model fit the data was quadratic equations. The model equations for dielectric constant and loss factor are given by Equations 8 and 9 and the models are presented in Figure 12.

$$f_{ct} = a + b(\epsilon') + c(\epsilon')^2 \tag{8}$$

$$f_{ct} = d + e(\epsilon'') + g(\epsilon'')^2 \tag{9}$$

Where f_{ct} is the compressive strength development, ϵ' is the dielectric constant, ϵ'' is the loss factor, a, b, c, d, e, and g are models constant parameters. These models were significant in predicting strength development of concrete and the square correlation coefficients are high and close to 1. In stational regression analysis R^2 equal 1 representing a perfect fit. This indicate that dielectric method is more superior in predicting strength development in concrete than the other two methods RN and UPV.

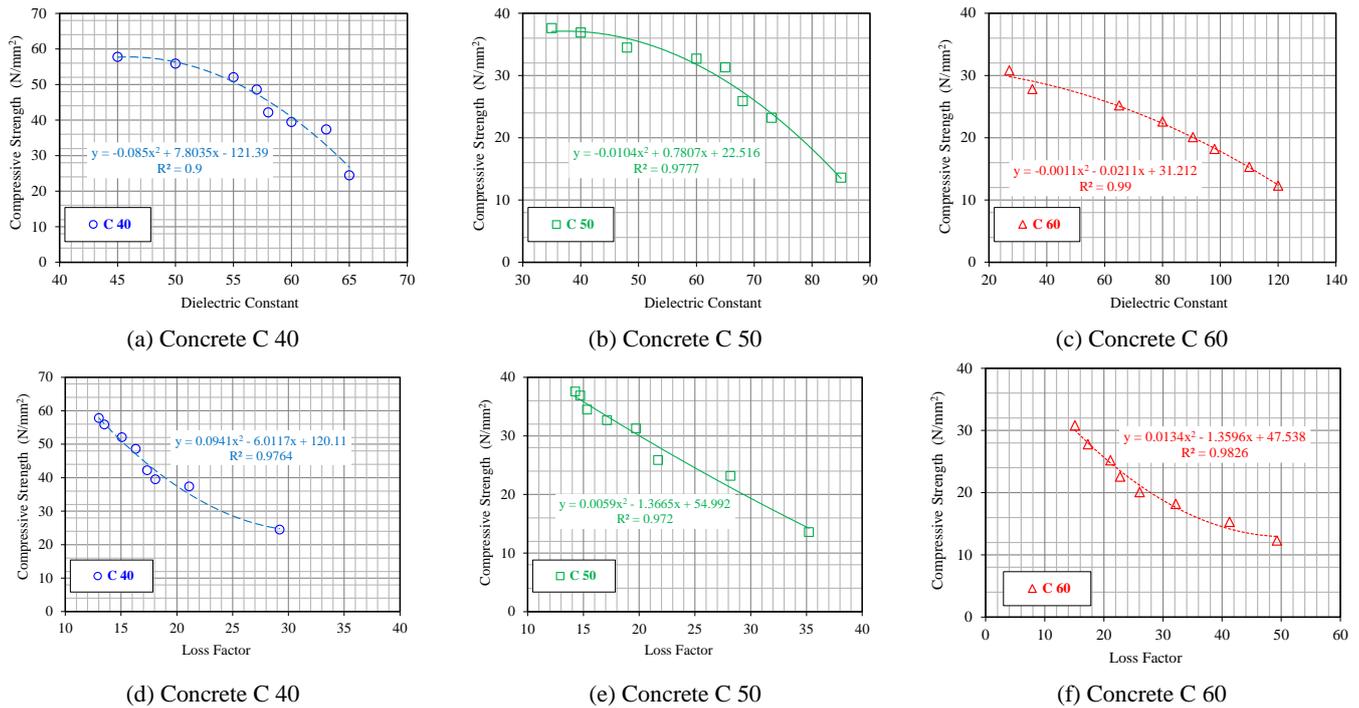


Figure 12. Relationship between compressive strength development and dielectric properties

4.4. Comparison of Nondestructive Methods

In previous section, the development of compressive strength at different curing time was evaluated using RN, UPV and dielectric properties. Dielectric properties were the best to relate and indicate the development of concrete compressive strength. Dielectric properties show butter response to the hydration process of concrete and associated with converting free water to bound water in concrete. The comparison of the square correlation coefficients to relate the three nondestructive parameters of three nondestructive methods with the compressive strength development of concrete is given in Table 2.

Table 2. Comparison of the correlation coefficients for each nondestructive method

| Code of Concrete mix | Square correlation coefficient (R^2) | | | |
|----------------------|--|---------------------------|---------------------|-------------|
| | Rebound Number | Ultrasound Pulse Velocity | Dielectric Constant | Loss Factor |
| C40 | 0.9402 | 0.9396 | 0.9528 | 0.9764 |
| C50 | 0.9452 | 0.7710 | 0.9777 | 0.9720 |
| C60 | 0.9525 | 0.9081 | 0.9900 | 0.9829 |

The relationship between concrete compressive strength after hydration almost completed have been evaluated. The RN, UPV and dielectric properties were measured of six concrete mixes after 28 days of curing at the same day the compressive strength was obtained. The six concrete mixes represent a wide range of concrete where the strength was range from 30 MPa to about 60 MPa. The relationship of the three nondestructive methods used in this study with designed concrete compressive strength after 28 days of curing were established and presented in Figure 13. Statistical

regression analysis to relate the nondestructive parameters of the three methods with compressive strength were linear model. This agrees of many studies and same models provided by rebound hammer and UPV produced by manufacturer. The linear models and its quality control R^2 are also presented in Figure 13.

Compared the results of UPV and RN of concrete specimens with the results that had been obtained from the proposed systems presented in the previous sections, it was clear that the dielectric properties of concrete specimens measured by the proposed systems were more sensitive to the hydration of concrete materials and could lead to a better estimation of concrete strength and strength development. The measured dielectric properties of concrete show the higher correlations with curing time, compressive strength, and strength development than the correlations with UPV and RN.

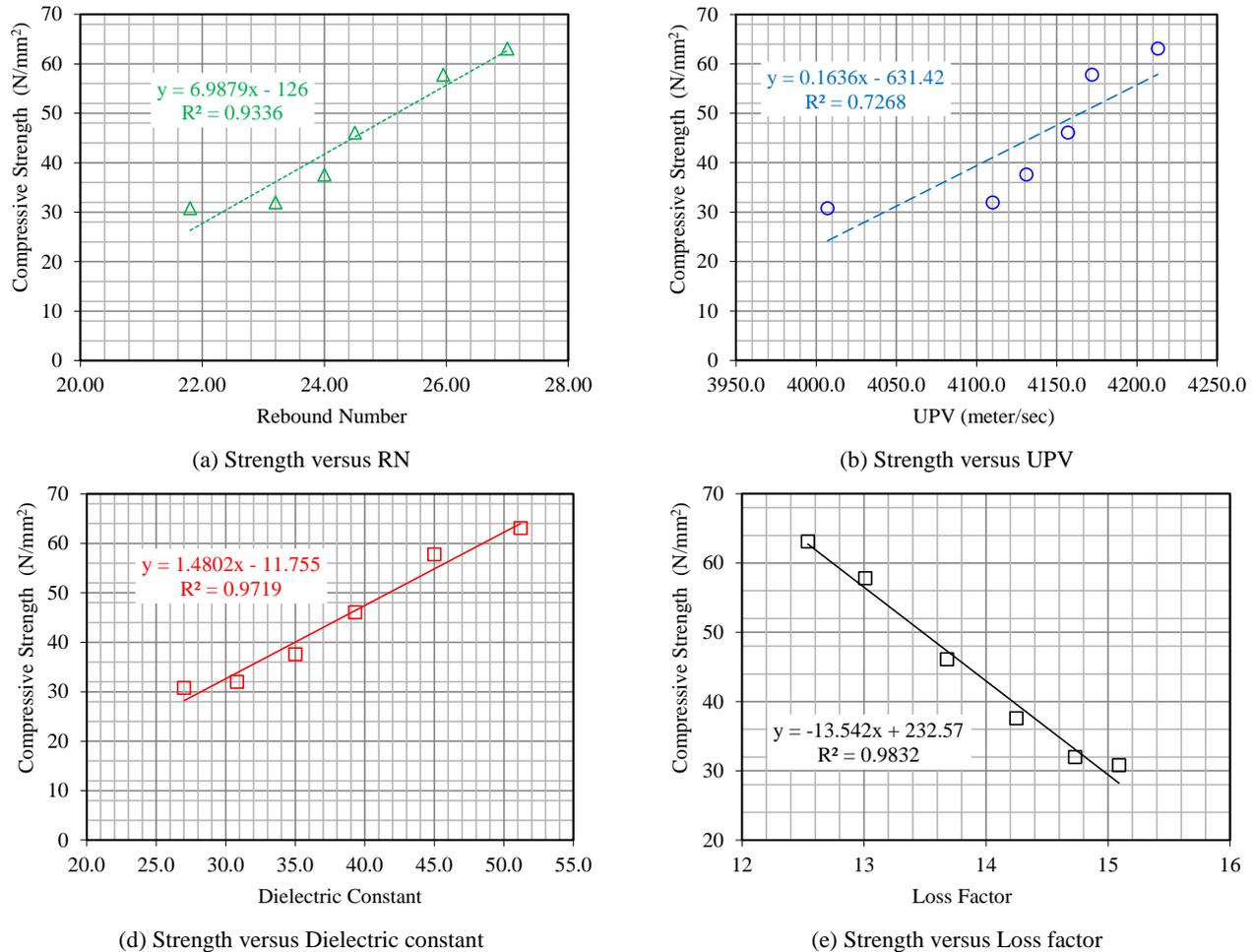


Figure 13. Comparison the relation between nondestructive testing parameters and compressive strength

5. Conclusions

The results obtained in this study show that dielectric properties of concrete measured using the proposed surface dielectric sensor is a promising nondestructive and invasive tool for assessment and determination of concrete compressive strength. The relationship between dielectric constant, loss factor and concrete compressive strength were significant and the fit square correlation coefficients were 0.9719 and 0.9832, respectively. The study also could lead to the following additional conclusion:

- All nondestructive testing method use in this study including rebound hammer, ultrasound pulse velocity and dielectric method could be used to estimate concrete compressive strength and strength development of concrete with different accuracy.
- Rebound number shows problem in assessing concrete strength at early age due to soft surface of concrete and high moisture content. This problem could be vanished after seven days of curing, but the estimated strength of wet surface could lead to underestimate of strength if this method is used.
- Ultrasound pulse velocity is significantly affecting by moisture condition of concrete especially in the first few days of curing. The moisture condition of concrete could lead to overestimate of compressive strength using UPV.

- Dielectric method based on the measured dielectric constant and loss factor of concrete shows excellent level of prediction compressive strength and strength development. This method indicates higher capability to determine concrete compressive strength than RN and UPV.
- Even the proposed surface dielectric sensor method provides excellent results in prediction compressive strength but further studies is necessary to evaluate other factors not consider in this study such as temperature, cement and aggregate type deteriorated concrete before using this sensor.

6. Declarations

6.1. Author Contributions

Both authors Al-Mattarneh and Dahim designed the sensor and conducted the testing, analyzed. Both authors performed the calculation, wrote the manuscript and editing the final version of this article.

6.2. Data Availability Statement

The data used to support the findings of this study are included within the article. Any other additional information used to support the findings of this study are available from the corresponding author upon request.

6.3. Acknowledgements

The authors thank their universities Yarmouk University and King Khalid University for using the lab facilities.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

- [1] Ambroziak, Andrzej, and Patryk Ziolkowski. "Concrete Compressive Strength under Changing Environmental Conditions during Placement Processes." *Materials* 13, no. 20 (October 14, 2020): 4577. doi:10.3390/ma13204577.
- [2] Paul Krauss. "Review of Properties of Concrete, 5th Ed. by A. M. Neville" *Journal of Performance of Constructed Facilities* 28, no. 3 (June 2014): 630–630. doi:10.1061/(asce)cf.1943-5509.0000595.
- [3] Albayati, Amjad H., and Waleed Arrak Turkey. "The Effect of Using Sustainable Materials on the Performance-Related Properties of Asphalt Concrete Mixture." *Civil Engineering Journal* 5, no. 12 (December 1, 2019): 2727–2737. doi:10.28991/cej-2019-03091444.
- [4] Hong, Seonguk, Sangki Yoon, Jonghyun Kim, Changjong Lee, Seunghun Kim, and Yongtaeg Lee. "Evaluation of Condition of Concrete Structures Using Ultrasonic Pulse Velocity Method." *Applied Sciences* 10, no. 2 (January 19, 2020): 706. doi:10.3390/app10020706.
- [5] Estévez, Esteban, Domingo Alfonso Martín, Cristina Argiz, and Miguel Ángel Sanjuán. "Ultrasonic Pulse Velocity—Compressive Strength Relationship for Portland Cement Mortars Cured at Different Conditions." *Crystals* 10, no. 2 (February 22, 2020): 133. doi:10.3390/cryst10020133.
- [6] Lucyna Domagała, "Size Effect in Compressive Strength Tests of Cored Specimens of Lightweight Aggregate Concrete." *Materials* 13 (2020): 1187. doi:10.3390/ma13051187
- [7] Godinho J. P., Desouza Junior T. F., Medeiros M. H. F., Silva M. S. A., "Factors influencing ultrasonic pulse velocity in concrete." *IBRACON Structures and Materials Journal Volume 13, Number 2, (2020): 222-234.* doi:10.1590/s1983-41952020000200004.
- [8] Al-Mattarneh H. M. A., Ghodgaonkar D. K., and Majid W. M. B.W. A. "Determination of Compressive Strength of Concrete Using Free-Space Reflection Measurements in the Frequency Range of 8–12.5 GHz." *Proceedings of Asia-Pacific Microwave Conference, Microwave for New Century, (2001), National Taiwan University, Taipei, Taiwan, R.O.C.*
- [9] Al-Mattarneh H. "Determination of chloride content in concrete using near- and far-field microwave non-destructive methods" *Corrosion Science* 105 (2016): 133–140. doi:10.1016/j.corsci.2016.01.010.
- [10] Al-Mattarneh H., Ghodgaonkar D. K., and Majid W. M. B. W. A. "Microwave sensing of moisture content in concrete using open-ended rectangular waveguide" *Subsurface Sensing Technology and Application* 2(4) (2001): 377–390. doi:10.1023/A:1013217017554.
- [11] Al-Mattarneh H. "Electromagnetic quality control of steel fiber concrete" *Construction and Building Material* 73 (2014): 350–356. doi:10.1016/j.conbuildmat.2014.09.101.
- [12] ACI 228.2R-98 "Nondestructive Test Methods for Evaluation of Concrete in Structures" (June 1998): 1-61.

- [13] Malhotra V. M. and Carino N. J. "Handbook on Nondestructive Testing of Concrete, Second Edition" (2004) CRC Press.
- [14] Antonio Brencich, Rossella Bovolenta, Valeria Ghiggi, Davide Pera, Paolo Redaelli. "Rebound Hammer Test: An Investigation into Its Reliability in Applications on Concrete Structures." *Advances in Materials Science and Engineering Volume 2020* (2020): 1-11. doi:10.1155/2020/6450183.
- [15] Raffaele Pucinotti, "In situ concrete strength assessment: Influence of the aggregate hardness on the Windsor probe test results" *Journal of Building Appraisal* Vol. 5(1) (March 2009): 75–85. doi:10.1057/jba.2009.14
- [16] Ghang Lee, Hunebum Ko and Jongsung Won, "Effectiveness of a Simplified Pullout Test Using a Post-Installable Break-Off Bolt" *Research in Nondestructive Evaluation* 24 (Jan 2013): 1-17. doi:10.1080/09349847.2012.675117
- [17] Helal J., Sofi M., and Mendis P. "Non-Destructive Testing of Concrete: A Review of Methods" *Electronic Journal of Structural Engineering* 14(1) (January 2015): 97-105.
- [18] ASTM C803-90, "Standard Test Method for Penetration Resistance of Hardened Concrete" *Annual book of ASTM standards Vol.04.02*, Philadelphia, American Society for Testing and Materials, (1990).
- [19] ASTM C 597-16 "Standard Test Method for Pulse Velocity through Concrete; American Society for Testing and Materials" *Annual book of ASTM standards Vol.04.02*, West Conshohocken, PA, USA, (2016).
- [20] Krzysztof Schabowicz "Non-Destructive Testing of Materials in Civil Engineering." *Materials* 12 (2019): 1-13. doi:10.3390/ma12193237
- [21] Seonguk Hong, Sangki Yoon, Jonghyun Kim, Changjong Lee, Seunghun Kim and Yongtaeg Lee "Evaluation of Condition of Concrete Structures Using Ultrasonic Pulse Velocity Method." *Applied Sciences* 10 (2020): 1-19. doi:10.3390/app10020706.
- [22] Al-Mattarneh H., and Dahim M. "Physical and mechanical properties of microwave absorber material containing micro and nano barium ferrite" *Advanced Materials Letters* 10(4) (2019): 259-262. doi:10.5185/amlett.2019.2226.
- [23] Al-Qadi I. L., Ghodgaonkar D. K., Varadan V. K., and Varadan, V. V. "Effects of moisture on asphaltic concrete" *IEEE Transactions on Geoscience and Remote Sensing* 29 (1991): 710–717. doi: 10.1109/TGRS.1991.817705.
- [24] Johri G. K., and Roberts J. A. "Study of the dielectric response of water using a resonant microwave cavity as a probe." *Journal of Physical Chemistry* 94(19) (1990): 7386–7391. doi: 10.1021/j100382a014
- [25] Roth C. H., Malicki M. A., and Plagge R., Empirical evaluation of the relationship between soil dielectric constant and volumetric water content and the basis for calibrating soil moisture measurements by TDR, *Journal of Soil Science* 43 (1992):1-13. doi: 10.1111/j.1365-2389.1992.tb00115.x.
- [26] Zoughi R., Gray S., and Nowak P. S. "Microwave nondestructive estimation of cement paste compressive strength" *ACI Materials Journal* 92(1) (1995): 64–70.
- [27] Dahim M., Al-Mattarneh H., and Ismail R. "Simple capacitor dielectric sensors for determination of water content in transformer oil." *International Journal of Engineering and Technology* 7(3.32) (2018): 157-160.
- [28] Dahim M, Ismail R, Al-Mattarneh H, Hatamleh R, "Determination of leachate pollution content in soil using in-situ dielectric measurement." *Advanced Materials Letters* 10(4) (2019): 298-301. doi: 10.5185/amlett.2019.2253.
- [29] Feng Zhou, Zhongchang Chen, Hai Liu, Jie Cui, Billie F. Spencer, and Guangyou Fang. "Simultaneous Estimation of Rebar Diameter and Cover Thickness by a GPR-EMI Dual Sensor." *sensors* 18 (2018): 1-15. doi:10.3390/s18092969.
- [30] Quoc-Bao Bui. "Assessing the Rebound Hammer Test for Rammed Earth Material" *Sustainability* 9 (2017): 2-10. doi:10.3390/su9101904.
- [31] Peng Deng, Yan Sun, Yan Liu, Xiaoxiao Song, Revised Rebound Hammer and Pull-Out Test Strength Curves for Fiber-Reinforced Concrete *Advances in Civil Engineering, Volume 2020*, (2020): 1-12. doi:10.1155/2020/8263745.
- [32] Panagiotis G. Asteris, Vaseilios G. Mokos. "Concrete compressive strength using artificial neural networks." *Neural Computing and Applications* 32 (2020):11807–11826. doi:10.1007/s00521-019-04663-2.
- [33] Saman Hedjazi, Daniel Castillo, "Relationships among compressive strength and UPV of concrete reinforced with different types of fibers." *Heliyon* 6 (2020): 1-12. doi:10.1016/j.heliyon.2020.e03646.
- [34] A Ndagi, A A Umar, F Hejazi, M S Jaafar, "Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review." *IOP Conf. Series: Earth and Environmental Science* 357 (2019): 012015. doi:10.1088/1755-1315/357/1/012015
- [35] Al-Mattarneh H. "Enhancement of Parallel Plate Sensor for Electromagnetic Characterization of Material." *European Journal of Scientific Research* 120(3) (March 2014): 348-359.
- [36] Al-Mattarneh H. "Surface Electromagnetic Sensor for Evaluation of Construction Material" *European Journal of Scientific Research* 120(3) (March 2014): 360-369.

- [37] Al-Mattarneh H. M., Nuruddin M. F., Shafiq N. and Dahim M. A. "Dielectric Dispersion Characteristics of Unsaturated Sand Contaminated by Diesel." *Journal of Material Sciences & Engineering* 6(3) (2017): 1-6. doi:10.4172/2169-0022.1000345.
- [38] Al-Mattarneh H., Ismail R. M. A., Nuruddin M. F., Shafiq N. and Dahim M. A. "Characterization of Pb and Cd contaminated sandy soil by dielectric means." *Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering (ICCOEE 2016, Malaysia, 15-17) (Aug 2016)*.
- [39] Al-Qadi A., Mustapha N. K. B., Al-Mattarneh H., and Al-Kadi Q. "Central composite design models for workability and strength of self-compacting concrete" *Journal of Engineering and Applied Science* 4(3) (2009): 177-183.
- [40] Dahim M, Abuaddous M, Ismail R, Al-Mattarneh H, Jaradat A, "Using a Dielectric Capacitance Cell to Determine the Dielectric Properties of Pure Sand Artificially Contaminated with Pb, Cd, Fe, and Zn." *Applied and Environmental Soil Science*, Vol 2020 (2020): 8838054. doi:10.1155/2020/8838054.
- [41] Hewlett Packard, "Dielectric Constant Measurement of Solid Materials." *Application Note 380-1*, (1999).
- [42] Arthur V. H., "Dielectric Materials and Applications, Artech House" (1995).