Modeling the strength properties of Asphalt Concrete using NDT

Saad Issa Sarsam✉, Nazar Sajad Kadium

Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq

✉**Corresponding author**
Department of Civil Engineering, College of Engineering, University of Baghdad,
Iraq
Email: saadisasarsam@coeng.uobaghdad.edu.iq

ABSTRACT

Asphalt concrete is a composite and viscoelastic material consisting of aggregates, mineral filler and asphalt cement. Its mechanical behavior is complex due to its susceptibility of temperature, moisture, loading frequency, and strain level. The construction of asphalt concrete requires stringent quality control process while it is labor, cost and time consuming. Implementation of nondestructive testing NDT techniques could possess a sustainable solution for such issue. In this investigation, asphalt concrete specimens of wearing, binder and base courses have been prepared in the laboratory and subjected to Marshaland indirect tensile strength determination. Another group of specimens were subjected to resistance to moisture damage evaluation. Specimens have practiced ultrasonic pulse velocity traversing the specimen using pundit instrument before conducting the strength test. Test results were analyzed and modeled. A nonlinear statistical model relating ultrasonic pulse velocity with the strength properties of asphalt concrete was obtained. It was concluded that such models can explain (88.8) % of the variation in the strength properties respectively under the testing techniques implemented.

1. INTRODUCTION

Implementation of nondestructive test technique NDT and modeling the physical properties of asphalt concrete are considered as a sustainable issue. The main Methods of non-destructive test like Ultrasonic pulse velocity, impact echo, and surface wave spectral analysis were applied by many researchers to determine material properties, Arabani et al., 2009. The ultrasonic pulse velocity method of testing is one of the most widespread wave-based methods in nondestructive testing techniques (NDT). However, its potential for assessing the quality of asphalt concrete materials is limited because it is only based on measurement of wave velocity, Jiang, 2007. NDT was implemented for testing of concrete, while there has been ongoing research on the use of ultrasonic testing for asphalt concrete mixtures. However, no standard wave-based test protocol is available yet for quality assessment of asphalt concrete, Di Benedetto et al., 2001. The ultrasonic testing of asphalt concrete is difficult because the material is viscoelastic and susceptible to temperature variation. The composite characteristics of the materials result in scattering of waves and limit the penetration of waves into the object being investigated by Abo-Qudais and Suleiman, 2005. The principle is that the velocity of wave propagation depends on the elastic modulus, density, and Poisson's ratio of the medium concerned. In practice, however, the velocity-strength relationship is affected by the combined effect of aggregate size, air void, and moisture condition which can cause some degree of variability in the results, Witczak et al., 2002. It is known that asphalt concrete exhibits a non-linear behavior between stress and strain above a certain degree of deformation. At these levels of deformation, the material displays a viscoelastic-plastic behavior. At lower levels of deformation, asphalt concrete can have a linear viscoelastic behavior which greatly simplifies the difficult task to predict the stress-strain behavior of the material, Weldegiorgis, and Tarefder, 2014. The quality of asphalt concrete materials is often characterized by material properties such as dynamic modulus determined based on the simple performance tests recommended by the Federal Highway Administration (FHWA). The dynamic modulus test is the oldest test recently modified for use as a part of simple performance tests for the evaluation of the long-term performance of asphalt concrete mixture, Bonaquist et al., 2013. Sarsam and Kadim, 2018 investigated the volumetric properties of asphalt concrete wearing course using pulse velocity test. Specimens were prepared in the laboratory at various asphalt percentages and tested for pulse velocity, then subjected to indirect tensile strength and punching shear strength determination. It was concluded that implementation of non-destructive testing with the aid of pulse velocity is feasible for predicting the quality of asphalt concrete within the limitations of the testing program implemented. The good correlation between the pulse velocity and the volumetric and strength properties demonstrates the potential benefit of using the wave parameters for condition assessment of asphalt concrete.

The aim of this investigation is to model the strength properties of asphalt concrete with the aid of NDT. Specimens will be prepared and tested for strength, and resistance to moisture damage after practicing the ultrasonic pulse velocity test. A statistical model could be obtained relating the pulse velocity with the strength properties.

2. MATERIALS AND METHODS

Asphalt Cement

Penetration grade of (40-50) asphalt cement obtained from Dora refinery was implemented in this investigation; the physical properties of asphalt cement are shown in Table 1.

Table1 Physical Properties of Asphalt Cement

Test procedure as per ASTM, 2013	Result	Unit	SCRB, 2003 Specification
Penetration (25ᵒC, 100g, 5sec) ASTM D 5	43	1/10mm	40-50
Ductility (25ᵒC, 5cm/min). ASTM D 113	156	Cm	≥ 100
Softening point (ring & ball). ASTM D 36	49	ᵒC	50-60
After Thin-Film Oven Test ASTM D-1754			
Retained penetration of original, % ASTM D 946	31	1/10mm	< 55
Ductility at 25 ᵒC, 5cm/min, (cm) ASTM D-113	147	Cm	> 25
Loss in weight (163ᵒC, 50g,5h) % ASTM D-1754	0.175	%	-

Coarse and Fine Aggregates

Crushed Coarse and fine aggregates were obtained from Al-Nibaee quarry; Table 2 demonstrates the physical properties of aggregates.

Table 2 Physical Properties of Al-Nibaee Coarse and fine Aggregates

Property	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity (ASTM C 127 and C 128)	2.610	2.631
Apparent Specific Gravity (ASTM C 127 and C 128)	2.641	2.6802
Percent Water Absorption (ASTM C 127 and C 128)	0.423	0.542
Percent Wear (Los-Angeles Abrasion) (ASTM C 131)	20.10	-

Mineral Filler

The mineral filler used in this investigation is limestone dust which was obtained from Karbala plant. Table 3 exhibits the physical properties of the filler.

Table 3 Physical Properties of Filler (Limestone dust).

Property	Value
Bulk specific gravity	2.617
% Passing Sieve No.200	94

Selection of Asphalt Concrete Combined Gradation

The selected gradation in this work follows the SCRB, 2003 Specification. Dense gradation for asphalt concrete dense graded base, binder, and wearing courses, with (25, 19, and 12.5) mm nominal maximum size of aggregates have been implemented. Figure 1 shows aggregate gradations.
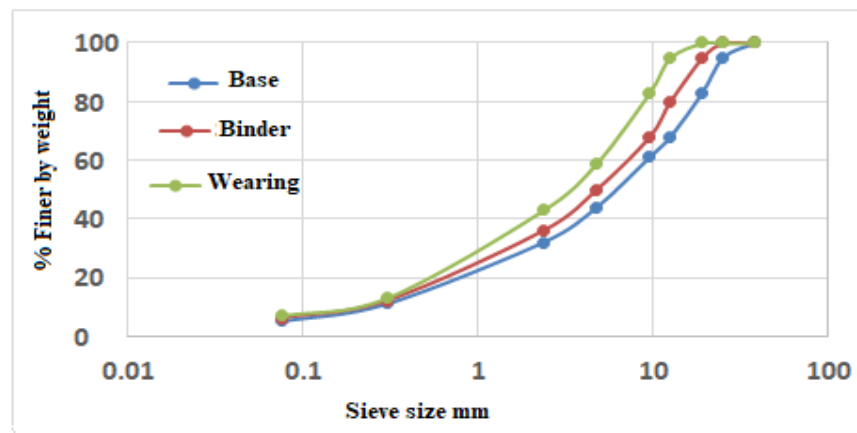

Figure 1 The implemented aggregate gradation according to SCRB

Preparation of Hot Mix Asphalt Concrete

Aggregates were dried in an oven to a constant weight at 110ºC, then sieved to different sizes, and stored separately. Coarse and fine aggregates were combined with mineral filler to meet the specified gradations of various asphalt concrete layers as per SCRB specifications. The combined aggregate mixture was heated to 150ºC before mixing with asphalt cement. The asphalt cement was heated to 150ºC, then it was added to the heated aggregate to achieve the desired amount and mixed thoroughly using mechanical mixer for two minutes until all aggregate particles were coated with thin film of asphalt cement. Marshall Size specimens were prepared in accordance with ASTM D1559, 2013 using 75 blows of Marshall hammer on each face of the specimen for binder and wearing courses. On the other hand, 50blows of Marshall hammer on each face of the specimen was implemented for base course. Specimens with optimum asphalt content and 0.5% of asphalt above and below the optimum have been prepared for each layer. Figure 2 shows part of the prepared asphalt concrete specimens.

Figure 2 Part of the prepared asphalt concrete specimens

Ultrasonic Pulse Velocity Measurement

The portable ultrasonic non-destructive digital indicating tester (Pundit) was implemented in this study. The device generates and receives ultrasonic waves and has a digital display of the results. A frequency of 54 kHz and accuracy of 0.1 was implemented through this study to measure the ultrasonic pulse velocity for the specimens. The direct transmission arrangement was used in this study. The pulser and receiver were placed on opposite specimen parallel surfaces according to ASTM C597, 2013. Calibration of the pundit was done before testing to check the accuracy of the transit time measurements. This is achieved by the calibration with the reference bar. A thin layer of Vaseline oil was applied on the surface of the tested points to act as a couplet between the transducer and the asphalt concrete specimen's surface and to prevent dissipation of transmitted energy. Eight readings were performed and averaged for each specimen. The ultrasonic pulse velocity test setup is demonstrated in Figure 3. All the prepared asphalt specimens have practiced the NDT before they were subjected to strength test.

Figure 3 Ultrasonic pulse velocity determination in process

Indirect tensile strength test

The indirect tension stress test as specified by ASTM, 2013 was conducted. The test was performed on the Marshal Size cylindrical specimens, 102 mm in diameter and 63.5 mm in height. The prepared Marshall Size Specimens of the three layers were subjected to the indirect tensile stress test at 25°C. Specimens were tested in triplicate, and the average value was considered for analysis.

Resistance to Moisture Damage test

The procedure of this test was conducted according to ASTM D4867, 2013 to assess the resistance to moisture damage of specimens. Six specimens were prepared for each layer, three of them experienced indirect tensile strength determination after placing in water bath at 25°C for 30 minutes, the average value of (ITS) was recorded as SI (ITS for unconditioned specimens). The other three specimens were placed in volumetric flask of 4000 ml filled with water at room temperature 25°C. specimens were subjected to air bubbles suction using a vacuum pressure of 3.74kPa for 10 minutes, then transferred and stored into deep freeze at -18°C for 16h, then specimens were placed for 24 hours in water bath at 60°C, then they were moved to water bath for 1 hour at 25°C after that the specimens experienced for indirect tensile strength determination and recorded as SII (ITS for moisture conditioned specimens). The tensile strength ratio TSR was determined according to ASTM D4867, 2013.

Marshal Stability and Flow

Parts of the prepared specimens have been subjected to Marshal Properties determination according to ASTM D1559, 2013.

Calculation of Moduli

The dynamic, seismic and elastic moduli of asphalt concrete were calculated based on the ultrasonic pulse velocity determination in the laboratory and the mathematical expressions provided by Weldegiorgis and Tarefder, 2014; Gudmarsson, 2014 and Di Benedetto et al., 2001.

3. STATISTICAL ANALYSIS AND MODELING

The statistical analysis was implemented in the development of the model relating the dependent variables (ultrasonic pulse velocity) to the number of independent variables including (Density, indirect tensile strength ITS@25C, TSR, Marshal Stability and flow, elastic, seismic and dynamic moduli). A statistical relationship between dependent and independent variables was the goal in mind of measuring future values of those predictors andinserting them into the mathematical relationship to predict future values of thetarget variable. It is desirable to give some measure of uncertainty for the predictions, typically a prediction interval that has some assigned level of confidence like 95%. Another task in the process is model building. Thus, a significant level of 0.05 was chosen. Model selection, fitting and validation are the basic steps of the model building process.

Identification of Dependent and Independent Variables of the Developed Model

To achieve the requirements of modeling, several variables were used. These variables are listed in Table 4.

Table 4 Independent and Dependent Variables Considered in Regression Analysis.

Independent Variables		
Abbreviation	Description	Unit
D	Density	gm/cm^3
ITS @25° C	Indirect tensile strength	kPa
TSR	Tensile strength ratio	%
S	Marshal stability	kN
F	Marshal flow	mm
Em	Elastic modulus	GPa
Dm	Dynamic modulus	GPa
SM	Seismic modulus	GPa
Dependent Variables		
UPV	Ultrasonic pulse velocity	mm/microsec.

Checking Sample Size

Sample size was checked as shown in Table 5 and calculated by using equation 1, Kennedy and neville, 1986.

Sample Size = (Z-score) ^{2} SD(1-SD) / (significant level) ^{2} ....(1)

Where:

Z-score: constant value corresponding to the confidence level (for confidence level of 95%, Z-score= 1.96.

SD: standard deviation

Significant level: 0.05

Table 5 Sample size for the model

Dependent variable	Standard deviation	Number of specimens N	Required sample size N
Ultrasonic pulse velocity (mm/microsecond)	0.386749	244	139

Checking for Outliers

The experimental work include collected data, the distribution of data contain of group concentrated within limited margin calculated from the frequency of data, but sometimes due to mistakes or other abnormal condition, a data set is considered as

extreme or outliers by checking those extreme values using Chauvinist's criterion and absolute tabulated sample size value as in Table 6. It was noticed that all tabulated values are more than the test results, thus, there are no outliers. To eliminate the data for modeling purposes to increase the R^2, the standardized residuals are removed from data matrix. The standardized residuals are an indication of how the residuals are large in the standard deviation units, and it is equal to the observed minus the estimated value and divided by the standard deviation. In the case of nonlinear regression, the residuals of high absolute value are removed resulted from observed minus estimated values, Montgomery and Peck, 2009.

Table 6 Chauvinist's test

Ultrasonic pulse velocity	N	Min.	Mean	Max.	S. D.	| (min. -mean)/s|	|(max. -mean)/s|	Tabulated
	244	2.420	3.673	4.850	0.386	3.242	3.042	3.038

Testing of Normality

Kolmogorov Smirnov (K-S) and Shapiro Wilk test was used to check the distribution of variables were used to developed model relate resilient modulus of asphalt mixture to numerals of variables. Herrin et al., 1995 stated that the K-S statistics D is based upon the maximum distance between F (y) and F n (y); that is equation 2. Table 7 shows the result of normality checking of the model.

D=max. [F(y) –Fn(y)] ....(2)

Where:

F(y) = Normal cumulative probabilities (From normal distribution table)

Fn (y) = Sample cumulative distribution function.

$$D^+ = Max. \left[\frac{i}{n} - F(yi) \right] \quad and, \quad D^- = Max. \left[F(yi) - \frac{i-1}{n} \right]$$

Since

$$D = Max (D^+, D^-)$$

Table 7 Result of One Sample K-S Test to the model

		Pulse velocity mm/microsec.	Density	ITS @ 25C (KPa)	TSR %	Marshal stability (KN)	Marshal flow (mm)	Elastic Modulus (GPa)	Seismic modulus (GPa)	Dynamic modulus (GPa)
N		244	244	244	244	244	244	244	244	244
Normal Parameters[a,b]	Mean	3.7468	2.5405	114.00	2.345	.9280	.340	7.4173	7.384	15.8959
	Std. Dev.	.31302	.65391	376.61	11.39	2.8204	1.18	7.8699	7.822	16.8658
Most Extreme Differences	Absolute	.071	.425	.529	.528	.526	.519	.352	.352	.352
	Positive	.071	.425	.529	.528	.526	.519	.352	.352	.352
	Negative	-.044	-.273	-.381	-.418	-.371	-.387	-.236	-.243	-.236
Test Statistic		.071	.425	.529	.528	.526	.519	.352	.352	.352
Kolmogorov-Smirnov Z		4.999	10.229	14.212	14.78	14.020	14.1	8.194	8.194	8.194
Asymp. Sig. (2-tailed)		.004[c]	.000[c]	.000[c]	.000[c]	.000[c]	.000[c]	.000[c]	.000[c]	.000[c]

Multicollinearity

SPSS software version (22) is employed to find the correlation between independent variables with one another using Multicollinearity (collinearity and intercorrelation). A statistical procedure using stepwise regression technique. The independent variables are eliminated according to the significant contribution of X variable on the produced model. The process is repeated with each variable until significant predictor variable remained and the insignificant ones are removed. This would suggest that those variables with high inter correlation may be eliminated according to the decision to add or remove a variable to improve the model; at that Point, interactions among the variables are considered. A correlation matrix is produced to determine the correlation coefficients for the Variables.

Model Adequacy Assessment

There are two approaches generally used to assess the adequacy of the proposed regression models, the first one is based on examining goodness of fit measures, where as the second approach is based on the graphical analysis of the residuals, also called diagnostic plots.

Goodness of Fit Measures

The measures of goodness of fit are aimed to quantify how well the proposed regression model obtained fit the data. The two measures that are usually presented are coefficient of multiple determinations (R^2) and standard error of regression (SER), Montgomery and Peck, 2009. The R^2 value is the percent variation of the criterion variable explained by the suggested model and calculated according to following equation 3.

$$R^2 = 1 - SSE/SST \dots\dots\dots\dots\dots\dots (3)$$

where SSE is the error sum of squares
SST is the total sum of squares

R^2 is bounded between 0 and 1; the higher the value of R^2, the more successful is the regression model in explaining y variation. If R^2 is small, an analyst will usually want to search for nonlinear model that can more effectively explain y variation. Because R^2 is always increases as a new variable is added to the set of the predictor variables and in order to balance the cost of using more parameters against the gain in R^2, many statisticians use the adjusted coefficient of multiple determinations, which is calculated as following equation (4).

$$AdjR^2 = 1-(n-1)/(n-(k+1)(SSE/SST) \dots\dots\dots\dots\dots (4)$$

where n is the sample size
k is the total number of the predictor variables

Adjusted R^2 adjusts the proportion of unexplained variation upward, which results in adj $R^2 < R^2$. The second measure, standard error of regression (SER), is calculated according to the following equation (5).

$$SER = \sqrt{SSE/(n-(k+1)} \dots\dots\dots\dots\dots\dots(5)$$

The divisor n-(k+1) in the above equation is the number of degrees of freedom (df) associated with the estimate of SER. In general, the smaller the SER value, the better the proposed regression model.

Predictive Model

Examination of the diagnostic plots presented for the model for nonlinear regression indicates the tendency of the developed model to underestimate the low model values and to overestimate the model values in the high range. Moreover, the predictive model produces negative values. Nonlinear relations are examined for Figure 4. Results of the obtained stepwise regression analysis are presented in Table 8. The obtained R^2 value is high and the standard errors of estimate are low. This is not the only reason; the almost nil difference in R^2 and standard error of Estimate is considered another good reason to the use of nonlinear.

Table 8 Statistical Summary for nonlinear regression Model

Model No.	Explained Variation (R^2)	Standard Error (SE)
Ultrasonic pulse velocity	0.888	0.119
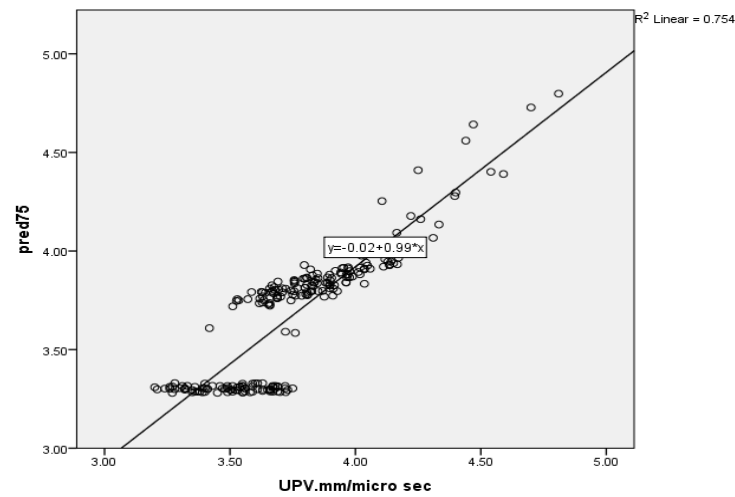
Plot, a, predicted vs measured
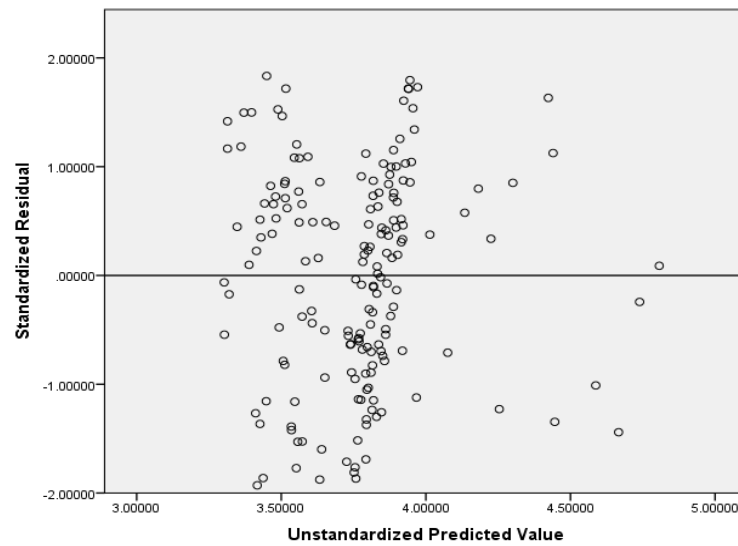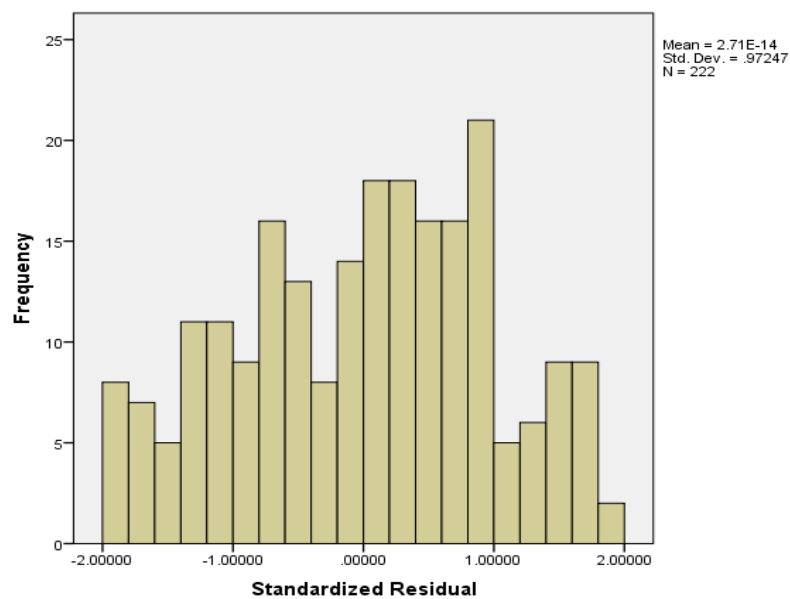

Plot, b, Residual vs measured

Figure 4 Diagnostic Plots for Residual vs measured Nonlinear Model

Stepwise Regression model

The best and commonly method used to determine parameter of prediction model is stepwise method, Kennedy and neville, 1986. This method computes the simple regression model for each independent variable. The independent variable is with the largest F-statistic, in other words, the smallest p-value is chosen as the first entering variable. SPSS software uses the F-statistics and the standard is usually set at F=3.8, which is chosen because the significant level is about 5 %. The standard is called the F-to-enter. If at least one variable exceeds the standard, the procedure continues. It then considers whether the model would be improved by adding a second independent variable. It examines all such models to determine which is best and whether the F-statistic of the second variable (with the first variable already in the equation) is greater than F-to-enter. If two independent variables are highly correlated, only one of them will enter the equation. Once the first variable is included, the added explanatory powerof the second variable will be minimal and its F-statistic will not be large enough to enter the model. Tables 9 show the Coefficients and summary of stepwise regression for the model.

Table 9 Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
	B	Std. Error	Beta			Zero-order	Partial	Part
(Constant)	3.382	.021		159.64	.000			
Flow (mm)	.204	.007	.963	27.524	.000	.649	.883	.794
Dynamic Modulus (GPa)	.040	.010	2.406	3.915	.000	.343	.258	.113
Elastic Modulus (GPa)	-.058	.022	-1.595	-2.590	.010	.337	-.174	-.075

a. Dependent Variable: UPV.mm/micro sec

Error analysis

For nonlinear model goodness, the homoscedasticity hypothesis assumes that the error is with constant variance, the standardized residual scatter plot as solve the problem, and by setting the estimated values of dependent variable on x axis and plotting the difference of observed value and theoretical value on y axis which is standardized residual, we can decide the goodness of the model. The pattern plots as demonstrated in Figure 5 are satisfactory and the residuals are randomly distributed.
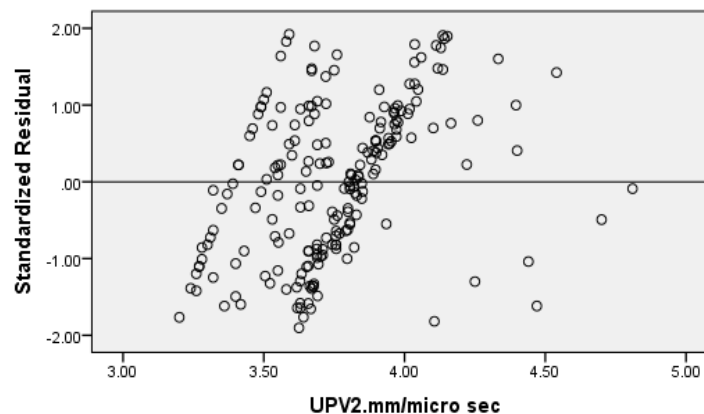

Figure 5 Scatter plot of Standardized Residual

Variance analyses of ANOVA test

To check the significant differences of the independent variables mean, the ANOVA is applied by F-test. The F -test called the test of linearity which determines by a straight line the deviations of means. Table 10 shows the ANOVA test for the model. The results show statistically significant relation since the p-value is less than 0.05, thus the overall variables used in regression (independent variables) are effective on the dependent variable. And by comparing the F ratio value with critical value from relative frequency distribution we decide the significances of results.

Table 10 ANOVA for the Model

Source	Sum of Squares	df	Mean Squares
Regression	2883.789	50	57.676
Residual	2.977	159	.019
Uncorrected Total	2886.766	209	
Corrected Total	26.473	208	

Checking of R-critical

A high correlation coefficient R value does not guarantee that the model fits the data well. The correlation between x and y is considered significant at the given probability level when the calculated R exceeds the tabulated R value. Table 11 demonstrates the calculated and tabulated R- value.

Table 11 Tabulated R-values for the model

Dependent	N.	R-calculated	R-tabulated
Ultrasonic pulse velocity	244	0.888	0.136

Model Limitation

The limitation of the data used to establish the model is presented in Table 12. The intention of the limitation is not to suggest that the modeling effort has not been successful. It merely serves to alert of the limitations of the data. Table 13 exhibits the developed model.

Table 12 The Intention of the limitation

Model	Maximum	Minimum	Mean
Ultrasonic pulse velocity (mm/microseconds)	2.74	1.88	2.297

Table 13 The Developed Model

Dependent variable	Developed Model
Ultrasonic pulse velocity	$500 + 0.656\,D + 0.065\,TSR - 0.062\,S - 1.051\,F - 0.365\,F^2 - 2.716\,EM + 0.386\,EM^2 - 1.447\,SM + 0.117\,SM^2 + 1.82\,DM - 0.102\,DM^2$

Where:

Dependent Variable:
Ultrasonic pulse velocity (mm/microseconds)

Independent Variables:
D = Density of Asphalt Concrete (gm/cm^3)
TSR = Tensile Strength Ratio (%)
S = Marshal Stability (kN)
F = Marshal Flow (mm)
EM = Elastic Modulus (GPa)
SM = Seismic Modulus (GPa)
DM = Dynamic Modulus (GPa)

## Measured and Predicted data for the Model

Figure 6 shows the predicted vs. measured data for dependent variable, the model is considered good because of the small variance of the points measured as compared with predicted values. Table 14 shows the statistics of the model data.

Table 14 Model Statistics

Variable	N	Std. deviation	Min.	Max.	mean	R^2	SEE
Ultrasonic pulse velocity	244	0.386	2.67	4.82	3.699	0.888	0.119

Validation of the Developed Model

The graphic plotting of observed and estimated data is a most useful method of evaluating the overall performance of a regression equation. If the point which result from the plot of estimated with observed data tend to stand nearby the line drawn at 45°, then the result model is considered satisfactory. This can be done by data splitting in to two sets. 70% of data are used to build the models and 30% of it is used for the validation process. Figure 7 show the resulting plot.
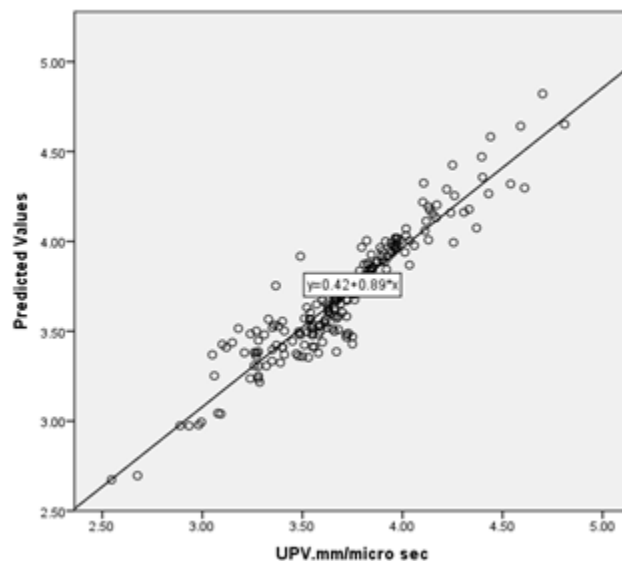
Figure 6   Scatter plot for predicted and observed values
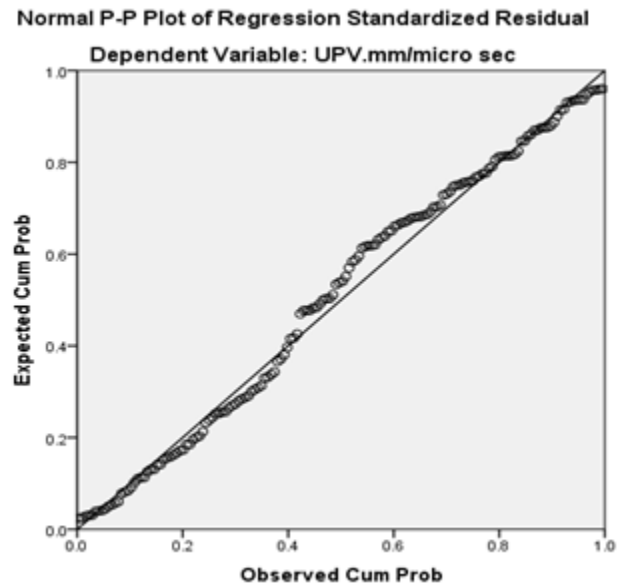
Figure 7 Estimated Value of the Model

4. CONCLUSIONS

Based on the limitations of the testing program, the following conclusions can be drawn.

1- The developed nonlinear statistical model can explain 88.8 % of the variations in ultrasonic pulse velocity among various strength properties.

2- The dynamic, seismic and elastic moduli of asphalt concrete exhibit high significant influence on ultrasonic pulse velocity among other strength parameters.

3- Moisture damage in terms of TSR and marshal stability exhibit the lowest influence on ultrasonic pulse velocity.

4- Such modeling is considered as a sustainable issue in predicting the strength properties of asphalt concrete, it can limit the testing requirements, time and cost of quality control.

Conflicts of Interest: The authors declare no conflict of interest.

REFERENCE

1. Arabani M., Kheiry P., & Ferdosi B. (2009). Laboratory Evaluation of the Effect of HMA Mixt Parameterson Ultrasonic Pulse Wave Velocities, Road Materials and Pavement Design, 10:1, 223-232.

2. Jiang Z. (2007) Innovative nondestructive testing (NDT) for condition assessment of longitudinal joints in asphalt pavements. MSc Thesis, University of Waterloo, Ontario, Canada.

3. Di Benedetto, H., Part, M.N., Francken, L., and De La Roche Saint André, C. (2001). Stiffness testing for bituminous mixtures. Mater. Struct. 34 (2), 66–70.

4. Abo-Qudais, Suleiman A. (2005). Monitoring fatigue damage and crack healing by ultrasound wave velocity. Nondestructive Testing and Evaluation; 20(2): 125-145.

5. Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H., (2002), Simple Performance Test for Superpave Mix Design, NCHRP Report 465,Transport Research Board, Washington D. C.

6. Weldegiorgis, M.T. and Tarefder, R.A. (2014). Laboratory investigation of asphalt concrete dynamic modulus testing on the criteria of meeting linear viscoelastic requirements, Road Ma-ter. Pavement Des., 15 (3), 554–573.

7. Gudmarsson A. (2014) Resonance Testing of Asphalt Concrete. PhD. Dissertation, KTH Royal Institute of Technology. Stockholm, Sweden.

8. Bonaquist, R.F., Christensen, D.W., and Sump W., (2003), Simple Performance Tester for Superpave Mix Design: First-Article Development and Evaluation, NCHRP Report 513, Transport Research Board, Washington D. C.

9. Sarsam SI, Kadim NS. (2018) Feasibility of Using Pulse Velocity to Evaluate Asphalt Concrete Properties. Journal of Advances in Civil Engineering and Construction Materials; 1(1): 51-63.

10. ASTM. American Society for Testing and Materials. (2009). Road and Paving Material, Vehicle-Pavement System, Annual Book of ASTM Standards, Vol.04.03.

11. SCRB, (2003), General Specification for Roads and Bridges, Section R/9 Hot-Mix Asphalt Concrete Pavement, Reverse Edition, State Corporation of Roads and Bridges, Ministry of Housing and Construction, republic of Iraq.

12. Kennedy, j., Neville (1986). Basic statistical methods for engineers and scientists, JW &Son, third edition.

13. Montgomery, D. C., & Peck, E. A. (2009). Introduction to Linear Regression Analysis, 2nd Edition, John Wiley & Sons, Inc., New York.

14. Herrin G. D., Scheaffer R., McClave J. T. (1995). Probability and Statistics for Engineers. The American statistician, Vol. 49 No.2, P.238.