SIMULATING THE INFLUENCE OF SURFACE FREE ENERGY ON MOISTURE DAMAGE OF RECYCLED ASPHALT CONCRETE

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ABSTRACT

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Recycling is considered as a sustainable process for economic restoration of the pavement quality. However, the resistance of recycled asphalt concrete to the moisture damage was not deeply evaluated. In this investigation, asphalt cement was subjected to aging process in the laboratory, then the aged binder was recycled by digestion with (0.5, 1.0, and 1.5) % of polyethylene and crumb rubber. The recycled binder was implemented in the preparation of asphalt concrete Marshal specimens. The surface free energy of the control and recycled binder was determined using the Sessile drop method. Asphalt concrete Specimens were tested under repeated indirect tensile and double punching shear stresses with the aid of Pneumatic Repeated Load System (PRLS). Another group of specimens was tested for moisture damage, then subjected to the same loading sequence. Specimens were subjected to 1200 load repetitions under stress level of 0.138 MPa at 25 °C. The load was sustained for 0.1 second followed by 0.9 seconds of rest period. The permanent deformation was measured before and after moisture damage process for both testing technique. Regression analysis is used to simulate the influence of surface free energy on resistance to moisture damage and permanent deformation and a statistical model was developed using the SPSS Software. It was concluded that the obtained model can explain 82 % of the variation in moisture damage due to the influence of surface free energy.

KEYWORDS: Surface free energy; Simulation, Recycling; Asphalt Concrete; Moisture Damage; Deformation.

INTRODUCTION

Several models predicting the pavement performance have been analyzed, and it has been determined that the best predicting models are the ones formed using databases for the territory where they are intended to predict pavement properties, (Matic et al, 2016). Expression and mathematical models have been obtained for the determination of cyclic tensile strength of the asphalt concrete, which considers the damage accumulation and the history of loading. The obtained expression describes satisfactorily the cyclic tensile strength of the asphalt concrete and can be used for the prediction of fatigue strength of the asphalt concrete pavement, (Iskakbayev et al, 2017). A multi-objective nonlinear optimization model was established by (Zhou and Chen, 2019) according to the residual sum of squares of storage modulus and loss modulus from dynamic modulus test.

The results of statistical analysis indicated that the fitting curves of fractional models with fewer mechanical elements and fitting parameters were much smoother in comparison with the traditional integer model with many unknown parameters.

Therefore, the fractional model is more suitable to characterize the viscoelastic mechanical behavior of asphalt concrete within a wide frequency and temperature range. A new nonlinear, second order, hyper-elastic-visco-plastic-damage constitutive model in multi dimensions was developed by Panoskaltsis and Panneerselvam, (2007) and its theoretical foundations are presented. It was concluded that the model is used to analyze experiments for asphalt concrete both in the elastic as well as in the irreversible domain of the material.

Model's comparisons to experiments are very favorable. The experiments are analyzed both as homogeneous and as boundary-value problems. Experience and previous recycling processes made by many agencies, have indicated that the recycling of asphalt pavements is a very beneficial approach from technical, economic and environmental perspectives, (Ramanujam, 2000; Perez et al., 2004). (Silva et al., 2012) addressed that, using rejuvenator can improves the performance of the totally recycled HMA mixtures (i.e., longer life cycle), and reduces the mixing temperature (i.e., lower energy consumption), also it is necessary to have an adequate workability.

Asphalt pavement performance is related to cohesive and adhesive bonding within the asphalt-aggregate system, and the cohesive and adhesive bonding are related to the surface free energy characteristics of the system, the percentage of the surface area of aggregate that has been exposed to water can be calculated using the surface free energy concept after performing the controlled-stress test and can be used as a significant index to quantify the level of adhesive fracture (Kim et al, 2003). Pradyumna and Jain, (2016) describes the comparison of properties of mixture with recycling agents, which has been prepared in laboratory on the Recycled Asphalt Pavement (RAP) material, and their performance has been compared with virgin mixes. Various performance tests such as retained stability, Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR), and Resilient Modulus test have been carried out to compare the performance of modified RAP mixes and virgin mixes. It was concluded that the laboratory results indicate that the bituminous mixes with RAP and recycling agent provide better performance compared to virgin mixes.

It was observed by (Sarsam and Hamdan, 2019) that the surface free energy decreases after aging, while it increases after digestion with polymers. It was concluded that digestion of aged asphalt cement with polyethylene was able to retain the original surface free energy of asphalt cement before aging.

The influence of surface free energy on the properties of asphalt cement and how it is altered due to the addition of modifiers was investigated by (Sarsam and Abdulhussain, 2018). It was concluded that carbon black is more appropriate additive, it gives an ultimate total surface free energy increment of 7.7% and 6% as compared with 2.8% and 3.1% for sulfur when Wilhelmy plate and Sessile drop methods have been implemented respectively.

The aim of this investigation is to assess the influence of surface free energy on resistance to moisture damage of recycled asphalt concrete. A simulation model will be prepared by considering the permanent deformation under repeated tensile and shear stresses.

MATERIALS AND METHODS

Asphalt Cement

Asphalt cement of 40-50 penetration grade was obtained from Dora refinery; the physical properties as required by state commission of roads and bridges SCRB are listed in Table 1.

Table1. Physical Properties of Asphalt Cement

Test procedure as per (ASTM, 2013)	Result	Unit	SCRB Specification, 2003
Penetration (25°C, 100g, 5sec) ASTM D 5	40	1/10mm	40-50
Ductility (25°C, 5cm/min). ASTM D 113	167	Cm	≥ 100
Softening point (ring & ball). ASTM D 36	50	°C	50-60
Specific gravity at 25° C, ASTM D 70 – 03	1.04	-	-
After Thin-Film Oven Test ASTM D-1754			
Retained penetration of original, %, ASTM D 946	87	1/10mm	>55
Ductility at 25 ° C, 5cm/min, (cm) ASTM D-113	117	Cm	> 25
Loss in weight (163°C, 50g,5h) % ASTM D-1754	0.32	%	-

Crumb rubber

It was produced by mechanical shredding of used tires and was obtained from tires factory at AL-Najaf governorate, the rubber type is (recycled) from used tires. Table 2 shows the grain sizes distribution of crumb rubber.

Polyethylene

It was a low-density polymer, found to be suitable for blending with asphalt with a melting temperature not more than 180°C. Table 3 exhibits the mechanical and thermal properties of polyethylene as supplied by the manufacturer. No specification requirements yet exists for implementation in asphalt concrete.

Table 2. Gradation of crumb rubber

Sieve No.	Sieve Size(mm)	Passing by weight%
No.16	1.18	100
No.30	0.9	78
No.50	0.3	25
No.200	0.075	0

Table 3. Mechanical and thermal properties of low-density polyethylene

Properties	Unit	Value
Tensile strength	MPa	10
Tensile Elongation	%	>350
Flexural Modulus	MPa	8
Hardness (Shore D)	.....	50
Vicat Softening point	°C	88
Brittleness Temperature	°C	<175

Coarse and Fine Aggregate

The aggregate used in this work was obtained from the Nahrawan quarry. Crushed sand was used as fine aggregate (particle size passing sieve No.4 and retained on sieve No.200). The sizes of coarse aggregate range between 12.5 mm to 4.75 mm according to SCRB, 2003 specification. Table 4 shows the physical properties of aggregate.

Table 4. Physical Properties of Coarse and Fine Aggregate

Property	Value	(ASTM, 2013) Designation No.
Coarse Aggregate		
Bulk specific gravity	2.639	C127-01
Apparent specific gravity	2.614	C127-01
Water absorption %	1.323	C127-01
Wear % (los Angeles abrasion)	13.05	C131-03
Fine aggregate		
Bulk specific gravity	2.727	C128-01
Apparent specific gravity	2.710	C128-01
Water absorption %	3.333	C128-01

Selection of Aggregate Gradation

In this study, the selected gradation is that used for wearing course with 12.5 (mm) nominal maximum size according to (SCRB, 2003) specification. Table 5 shows the selected aggregate gradation.

Table 5. Gradation Limits of HMA Mixtures for Wearing Course (SCRB, 2003)

Sieve Opening (mm)	Sieve Size	% passing by weight of total aggregate	
		Selected gradation	(SCRB, 2003) specifications Limit For Wearing course (Type IIIB)
12.5	1/2"	100	100
9.5	3/8"	95	90-100
4.75	No.4	70	55-85
2.36	No.8	49.5	32-67
0.3	No.50	15	7-23
0.075	No.200	7	4-10

Mineral Filler

In this study, one type of mineral filler (Limestone dust) has been implemented. It was obtained from Al- Nahrawan factory. It is thoroughly dry and free from lumps or aggregations or fine particles, the physical properties are presented in Table 6.

Table 6. Physical Properties of Limestone Dust

Property	Limestone Dust
% passing sieve 200	96
Specific gravity	2.68

Aging of Asphalt Cement

To simulate the aging process of asphalt cement during its service life in the field, Asphalt cement was subjected to aging process using the thin film oven test apparatus as per (ASTM, 2013). Asphalt cement practices 163°C of heating for five hours in the rotating shelf of the oven. Asphalt cement was collected after the heating and cooled to room temperature. It was denoted as aged asphalt cement.

Preparation of Recycled Bitumen

Part of the aged asphalt cement was recycled by digestion with polyethylene, asphalt cement was heated to 150 °C and then blended with Low-Density Polyethylene with different percentages of (0.5 , 1 and 1.5 % by weight of asphalt cement) using

mechanical mixer, it was prepared in the laboratory at a blending speed of about 200 rpm and temperature of 160°C for 60 minutes to promote the physical and chemical bonding of the components.
Another part of the aged asphalt cement was recycled by digestion with crumb rubber using the wet process. The asphalt cement was heated to 150 °C and then blended with crumb rubber with different percentages of (0.5, 1 and 1.5 % by weight of asphalt cement) at a blending speed of about 1500 rpm for 60 minutes in the laboratory using mechanical mixer to promote the physical and chemical bonding of the components. During the blending process, the crumb rubber dispersed and reacts with the asphalt. Swelling and formation of bubbles could be observed after the blending process. Similar procedure was reported by (Sarsam and Jasim, 2018).

Surface Free Energy Determination by Sessile Drop Method
This test method was used for measuring contact angles and preparing samples to determine the three surface energy components of asphalt binders**.**

Preparation of Test Samples
The preparation of the test sample starts by heating the bitumen to mixing temperature, a small quantity of bitumen was poured on the substrate. The quantity of asphalt poured forms an area of approximately (5x5) cm in size, then left to cool for 24 hours at room temperature. By using micro syringe, a probe liquid was dispensed over the prementioned smooth horizontal surface coated with asphalt from the top of the sample position, the tip of the micro syringe needle was approximately 5 mm away. The image of the drop of the liquid formed over the surface of the binder was captured by a digital camera and the image was analyzed using (Comef 4.4) software and contact angles were obtained. With the aid of work of adhesion theory and mathematical models, the three surface energy components of the asphalt binder were determined. Three probe liquids were used to measure the contact angle (distilled water, glycerol, Formamid). The surface free energy component of asphalt binder was determined by measuring its contact angles with various probe liquids for at least three replicates with each probe liquid. The surface free energy was calculated using the mathematical models presented by (Little and Bhasin, 2006). Details of the testing and test results were published elsewhere, (Sarsam and Hamdan, 2019). Figure 1 exhibits schematic diagram of Sessile Drop Method while Figure 2 shows the images of the drop when using different probe liquids and different contact angles. On the other hand, Table 7 exhibit Surface Free Energy components of the Prob Liquids as obtained from (NCHRP 104, 2006).

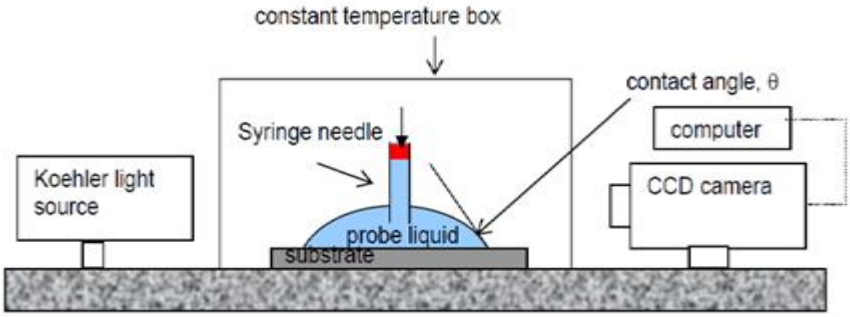


Figure 1. Sessile Drop Method, (Little and Bhasin, 2006)

Determination of Surface Free Energy of the Control and Recycled Binder
The surface free energy is required to measure work of adhesion between aggregate and asphalt binder. These quantities are related to moisture sensitivity and adhesive fracture properties of the asphalt binder. The three components of which the surface free energy

is composed for asphalt binder are the Lifshitz-van der Waals component, the Lewis base component and the Lewis acid component.

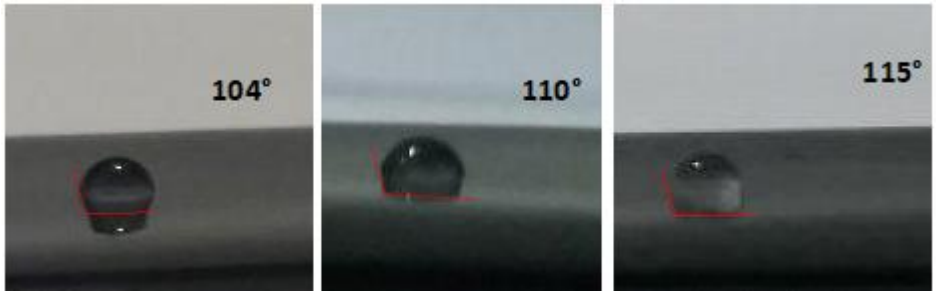


Figure 2. Variation of Sessile Drop Contact Angle with Prob Liquids

Table 7. Surface Free Energy Components of the Prob Liquids (NCHRP 104, 2006)

Prob liquid	γ^{Lw}	$\gamma +$	$\gamma -$	γ Total (ergs/cm^3)	Density (gm/cm^3)
Glycerol	34.0	3.92	57.4	64.00	1.258
water	21.80	25.50	25.50	72.8	0.997
Formamid	39.00	2.28	39.6	58.00	1.134

Preparation of Asphalt Concrete Specimens

The coarse and fine aggregates were dried to constant weight at 110 ºC, then separated into different sizes by sieves, and stored. Coarse and fine aggregates were combined with mineral filler to meet the specified gradation of wearing course. The combined aggregate mixture was heated to a temperature of 150 ºC before mixing with asphalt cement. The asphalt cement or the treated asphalt cement with polyethylene and crumb rubber was heated to the same temperature of 150 ºC, 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. The optimum asphalt content was determined as per the procedure above to be 5.3% by weight of aggregates. The prepared Marshall Size Specimens were divided into three sets, the first set was subjected to the repeated indirect tensile stress at 25 ºC, while the second set was subjected to repeated double punching shear stress at 25 ºC. The permanent deformation was determined after 1200 load repetitions. The third set was subjected to moisture damage as per the procedure by (AASHTO, 2013), and the tesnsile strength ratio TSR was determined**.** Specimens were tested in triplicate, and the average value was considered for analysis. Figure 3 presents part of the prepared specimens.

Figure 3. Part of the prepared specimens

Moisture Damage Test Process

This test was performed to assess the resistance to moisture damage of asphalt concrete mixtures; and the procedure of the test was conducted according to (ASTM D4867, 2013), and (AASHTO, 2013). A group of six specimens for each binder and recycling agent content were prepared, three specimens were tested for indirect tensile strength after storage in a water bath at 25ºC for half an hour; the average strength was considered as (un-conditioned specimens). The additional three specimens were conditioned through placing in volumetric flask (4000-ml) heavy weight- wall glass filled with water at room temperature 25˚C, and a vacuum of 3.74 kPa (28mm Hg) was applied to the flask for 10 minutes in order to attain (80 %) level of saturation. The specimens were covered with plastic sheets and stored in deep freezer at (-18˚C) for (16 hours). Then the specimens were placed into a water bath for (24 hours) at (60ºC) for thawing. After that, specimens were retained in a water bath on (25ºC) for (1 hour). Finally, specimens were tested for indirect tensile strength. The average value was considered as (conditioned specimens).

Repeated Indirect Tensile Stress Test

Specimens were subjected to the repeated indirect tensile stresses according to the procedure of (ASTM, 2013). In this test, the specimen was stored at room temperature of 25 ºC for one day; then the specimen was transferred to the pneumatic repeated load system PRLS chamber and fixed on the vertical diametrical level between the two parallel loading strips of (12.7 mm) in width as demonstrated in Figure 4. Asphalt concrete specimens were subjected to repeated indirect tensile stress for 1200 load repetitions at 25˚C. Such timing and test conditions were suggested by (Sarsam and Jasim, 2018). The load assembly applies indirect tensile stress on the specimen in the form of rectangular wave with constant loading frequency of (60) cycles per minutes. A heavier sine pulse of (0.1) sec load duration and (0.9) sec rest period was applied over the test duration. Before the test, dial gage of the deformation reading was set to zero and the pressure actuator was adjusted to the specific stress level of 0.138 MPa. A digital video camera was fixed on the top surface of the (PRLS) to capture dial gage reading. The average permanent deformation of duplicate specimens was considered. Figure 5 exhibit the PRLS implemented for load repetitions test.

Repeated Double Punch Shear Test

This test was implemented to measure the shear strength of asphalt concrete under repeated double punching shear action. Marshall specimens were conditioned in an oven for 30 minutes at 25˚C before the test. The test starts after fixing the specimen in the PRLS by application of central loading to the cylindrical specimen which is set vertically between the loading platens of the test machine and compressed by two steel punches. The diameter of steel punch is 25.4 mm was located concentrically on the top and bottom surfaces of the cylinder. The load assembly applies axial punching shear stress on the specimen in the form of rectangular wave with constant loading frequency of (60) cycles per minutes. A heavier sine pulse of (0.1) sec load duration and (0.9) sec rest period was applied over the test duration. Before the test, dial gage of the deformation reading was set to zero and the pressure actuator was adjusted to the specific stress level of 0.138 MPa. A digital video camera was fixed on the top surface of the (PRLS) to capture dial gage reading. The average permanent deformation of duplicate specimens was considered. Figure 4 shows repeated Double Punch test setup.

Figure 4. Repeated ITS and DPS testing

Figure 5. PRLS System

ANALYSIS AND MODELING

Modeling the Role of Surface Free Energy on Moisture Damage of Recycled Asphalt Concrete

The SPSS software V-25 was utilized for developing the model by adopting different variables which influence the model. Statistical prediction model is defined as a mathematical function or regression equation that characterize the deterministic variation in the response variable (dependent variable) according to other variables (independent variables) in addition to the random constituent (error) that follows a specific probability distribution. (Sarsam and Al-Sadik, 2014). Multiple linear regression is utilized when a model is a function of more than one predictor variable. At a suitable confidence level, the obtainable data and the basic assumptions of regression analysis can provide the highest coefficient of determination (R^2) and lowest mean square error for a given data thus to obtain proper model. A confidence level of 95 percent and significant level of 0.05 were selected. If the significance level is very small (less than 0.05), then the correlation is considerably significant. The value of R^2 represents the proportionality of dependent variable variance that is accounted for by its linear relationships with the independent variables and it is restricted between 0 and 1; the higher, the more successful is the regression model in clarifying the depended variation. The data should be fissured into two sets; Model building set and Predicted set (qualified as a validation which is used to evaluate the rationality and predicted ability for the selected model. For building the model, 75% of the original data is used, while 25 % were implemented for validation process.

Model Building Process

To build a model, there are several processes which should be followed such as distinguishing the dependent variables, tabulating potential predictors, inquiring in case the necessary conditions are satisfied or not, and use of Statistical software for assessing the model as reported by (Matic et al, 2016). The choice of the preferable model is based on the statistical output. To build any model, the following condition should be carried out regarding normality of residuals which indicates the distances between the points and the line. Multiple regressions presume that these distances are disseminated in a normal distribution with a mean of zero, (Zhou and Chen, 2019). The Linearity is the relation between the dependent and independent variables which could be estimated as a straight line. Then the homogeneity and independence of residuals should not be correlated to independent variables and should be normally distributed with egalitarian variance.

Identification of the Dependent and Predictor Variables

To forecast the model, different variables are used; these variables are **(**SFE) surface free energy (erg/cm^2), **(**DITS) Permanent Deformation under Repeated Indirect Tensile Stress (mm), **(**DDP) Permanent Deformation under Repeated Double Punching shear stress (mm), and (TSR) tensile strength ratio (%).

Sample size calculations

Sample size can be computed using the following equation, (Sarsam and Al-Sadik, 2014).

$$N=\left(\frac{CV*T}{E}\right)^2 \quad \text{---------- (1)}$$

Where:
N= Sample size,
E= Error of the mean,
T= T-statistics,
CV=Coefficient of variance.

The sample size was calculated after fissuring 75 % of data to build the model, it can be noted that (N) required is less than the sample size as shown in Table 8, therefore the sample size is accepted.

Table 8. Sample Size Determination

Model	Std. dev.	N implemented	N required
TSR	6.93	42	38

Checking for Outliers

Outlier occurred when one or more of the observation data is obviously diverse from all others. By using Chauvinists' criterion, the outliers and influential observations are checked to inspect the outliers of data used for accuracy (Sarsam and Al-Sadik, 2014). Table 9 shows the results of these tests; it can be noted that all tabulated values are higher than the results, therefore there is no outliers.

Table 9. Result of Chauvinists Test of Outliers for SFE models

Dependent variable	X min	X max	Mean (X´)	Std. Deviation	$\left\lvert\frac{Xmin - X'}{S}\right\rvert$	$\left\lvert\frac{Xmax - X'}{S}\right\rvert$	$\left\lvert\frac{Xmax - X'}{S}\right\rvert$ tabulated
TSR	3.21	21.84	10.75	6.93	1.088	1.600	2.478

Normality test

Kolmogorov-Smirnov (or K-S test) is used to test if the variables are normally distributed. The K-S statistics D is founded upon the extreme distance between F(y) and Fn (y), (Sarsam and Al-Sadik, 2014).

$$D = \max.\,[F(y) - Fn\,(y)] \quad \text{---------- (2)}$$

Where
F(y) = Normal cumulative probabilities (From normal distribution table).
Fn (y) = Sample cumulative distribution function.

$$D^+ = \text{Max.}\left[\frac{1}{n} - F(yi)\right] \quad \text{----------(3)}$$

and, D^{-}= Max. $\left[F(yi) - \frac{i-1}{n}\right]$ ---------- (4)

Since: D=Max (D^{+},D^{-}) ----------(5)

Table 10 shows the results of Kolmogorov-Smirnov test for dependent predicted TSR model. Based on these results, the (K-S) computed values are lower than the critical D values, the conclusion for that is the normal distribution of the data. Where (a) indicates that the data distribution is normal; (b) is calculated from data; (c) is the Lilliefors significance correction and (d) is obtained from Kolmogorov Smirnov table.

Table 10. Kolmogorov-Smirnov Results for TSR Model

Variables		TSR
Normal $Parameters^{a,b}$	Mean	10.755
	Std. Deviation	6.93
Most Extreme Differences	Absolute	0.208
	Positive	0.208
	Negative	-0.192
Test Statistic(k-s) D value		0.208
Critical D $value^{d}$		0.220
Asymp. Sig.(2-tailed)		0.000^{c}

Multicollinearity

SPSS software version (25) was utilized for identifying the multicollinearity between the independent variables via correlating between them with each other. Confidence level of 95 percent is employed. Based on significance of independent variables and on the intercorrelation analysis, the independent variables are eliminated one after another. The correlation coefficients are determined, and this matrix can be seen in Table 11 for TSR model. The process is iterated till significant predictor variable remained; at that point interactions among the variables are considered. To find the correlation coefficient for the variables, a correlation matrix is generated and by using SPSS software, the correlation coefficients among all of the variables are computed while the correlation matrix is setup, The decision is based on adding or deleting a variable weather that the variable develops the model or not.

Table 11. Correlations matrix

Variables		SFE	DITS	TSR	DDP
Pearson Correlation	SFE	1.000	-0.207	0.254	-0.507
	DITS	-0.207	1.000	0.708	0.171
	TSR	0.254	0.708	1.000	0.328
	DDP	-0.507	0.171	0.328	1.000

Regression Modeling

Regression modeling is used for determining the relation between two or more numbers of variables to estimate the best model and via using a statistical method. When a model is a function of more than one variable, the multiple linear regressions is applied to find the adequate model.

Stepwise Regression Procedure

The procedure has been done by computing the simple regression model for every independent variable. SPSS software version 25 uses the F-statistics and the standard is commonly set at F=3.84, because the significant level is about 5 %. The standard is

named the F-to-enter. The procedure continues by computing (p-values) for all variables at each step and compared to the F to remove, thus, deciding whether to add another independent variable or not. The results of analysis of variance ANOVA and summary of stepwise regression, for different possible models can be explained in Table 12. For the model and from table, it can be observed that the value of F statistic (for third option) was greater than value of F standard (3.84) that leads to (p- value) less than 0.05, thus all independent variables enter in the equation of this model. Based on Table 13, it can be noted that the standardized coefficients for (DDP) (ß=-0.720,p< 0.05) is significant, the standardized coefficients for (DITS)(ß=--0.865,p<0.05) is significant, and the standardized coefficients for (TSR) (ß= 1.103, p<0.05) is significant, this explained that the three independent variables are factors to SFE model (model 2).

Table 12. ANOVA Result for the Model

ANOVA						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	506.191	1	506.191	13.812	.001
	Residual	1465.904	40	36.648		
	Total	1972.095	41			
2	Regression	896.207	2	448.104	16.243	.000
	Residual	1075.887	39	27.587		
	Total	1972.095	41			
3	Regression	1626.027	3	542.009	59.515	.000
	Residual	346.067	38	9.107		
	Total	1972.095	41			

Table 13. Coefficients of regression analysis for the model

Coefficients						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	18.125	2.192		8.269	.000
	DDP	-354.306	95.333	-.507	-3.717	.001
2	(Constant)	-60.151	20.905		-2.877	.006
	DDP	-462.317	87.559	-.661	-5.280	.000
	TSR	.994	.264	.471	3.760	.001
3	(Constant)	-150.412	15.682		-9.591	.000
	DDP	-503.786	50.521	-.720	-9.972	.000
	TSR	2.329	.213	1.103	10.942	.000
	DITS	-568.900	63.550	-.865	-8.952	.000

Model Limitation

Table 14 described the limitation of the data used to build the model. The objective of the limitation is not to propose that the modeling effort has not been successful. It simply serves to alert of the limitations of the data.

Tables 14. Results of Limitation Data Used for SFE Model 2

Variable	DITS	DDP	TSR
Minimum	0.01122	0.01010	73
Maximum	0.05118	0.04000	84.7

Mean	0.02996	0.02079	81

Goodness of Fit

For measuring Goodness of fit, there are two measures; Coefficient of determination (R^2), and Standard error of regression (SER). R^2 represents degree of association between independent and dependent variable, domain from (0 to 1). The Standard Error of Estimate (SEE) is defined as a square root of residual mean square. To be more accurate, forecasting will be achieved when the statistical value is small, the equations of (R^2 and SER) are listed below. Table 15 illustrates the results of (R^2 and SEE) for TSR model.

Table 15. Correlation Coefficient and Standard Error for the Model

Model	R Square	Adjusted R Square	SEE
TSR	0.825	0.811	3.017

Validity of Developed Model

The validation steps have been done either by gathering new data or by splitting the data into more than one part. The first part of split data is appropriating sample which is used to construct the model. The second part of split data is named validation sample which is used to determine the performance of model. From the essential sample, the appropriating sample is selected without substitute by using simple random sampling process which considers (75) % of the original sample and the (25) % of the original sample is used as validation sample. The validity of developed model can be evaluated by multiple linear regressions which can represented by standard statistical methods.

Diagnostic (Q-Q) Plots

The relation between the estimated and observed values for (SFE) models can be sketched by (Q-Q) plots and which is a good technique for evaluating the performance of regression equation by using (25) % of the data which is fissuring from the basic data , Figure 6 show the graphical (Q-Q) plots for the model .

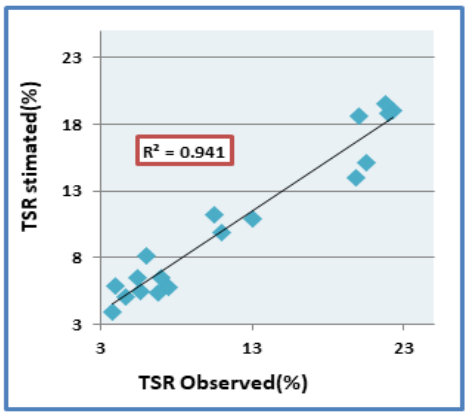
Residual Analysis

The variation between an observed value (yi) and the predicted value (yi′) as explained by (ei = yi − yi′), which is named a residual (ei), and by subtracts the mean value of residuals (zero) from each residual and dividing by the estimated standard deviation, standardizing residuals can be founded, thus for validation of regression model. There is one residual for each data point. The sum of distances above the line are equal the sum of distances below the line, therefore, the mean and the sum of residuals are equal to zero. The following requirements including the probability distribution of the residuals should be satisfied for the validation of regression model regarding the mean of error distribution is zero, and the probability of error distribution is normal, (Sarsam and Al-Sadik, 2014). Table 16 shows the relation between standardized residual versus standardized predicted value for modified model and the properties of standardized residuals.

Table 16. Residuals statistic properties of TSR Model

Residuals Statistics					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	.76113	22.7701	10.755	6.297	42
Residual	-7.131	4.30548	-.000	2.905	42
Std. Predicted Value	-1.587	1.908	.000	1.000	42
Std. Residual	-2.363	1.427	.000	.963	42

Figure 7 show the histograms of the model and the corresponding P–P plots. The distribution has normal looking. It is satisfactorily symmetrical and doesn't appear pointy or flat –with small deviation, so it is a good result. Therefore, the distribution of residuals is normally distributed, the P–P plot noticed that the data points all located very close to the 'ideal' diagonal line and tend to be in angle 45° which consider it a good result for the validation of model. Figure 8 represent the scatter plot for the model, it can be observed that the data point fall near the straight line (zero line) thus a strong correlation between variables of the model.



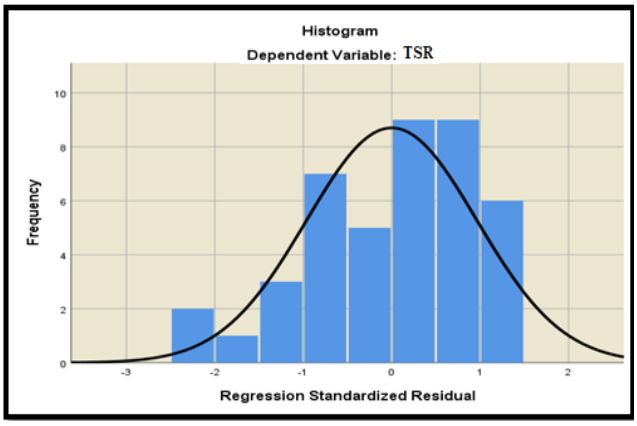
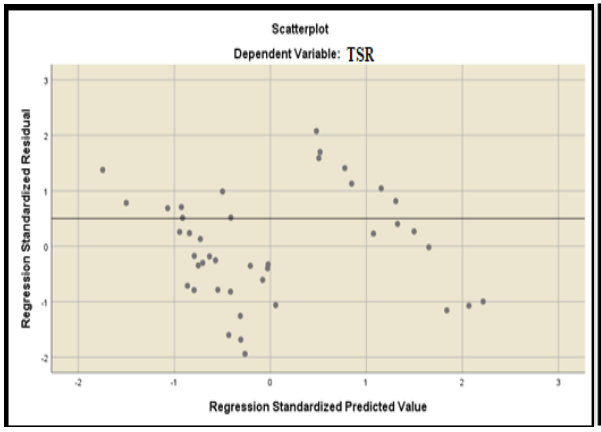


Figure 6. Observed and Estimated TSR **Figure 7.** Model Histograms and P–P plots

Whilst Figure 9 shows the estimated value of the model. The results presented in Table 16 and the Figures are showing that the error probability distribution is normal with zero mean for the modified model.



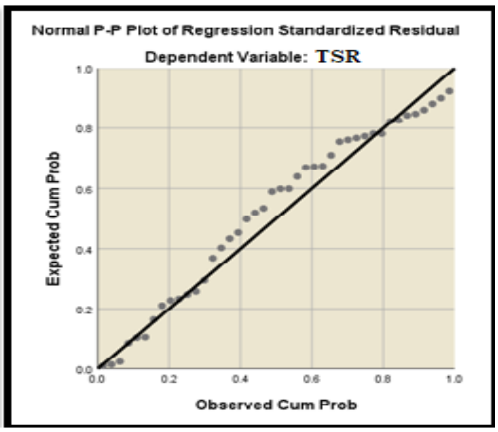


Figure 8. Scatter Plot for TSR **Figure 9.** Estimated value of TSR Model

Checking of R –Critical

R- value describe the coefficient of correlation between x and y and can be considered significant at given probability level when R- tabulated less than R- computed, high (R-

Value) does not give a guarantee that the model fits the data well. R computed = 0.908> R Tabulated = 0.304 (n=42, df=n-2=40). Therefore, there is sturdy correlation between independent variables and predicted variables in these models.

Analysis of Results

The analysis of results and the computations of standard error regression, and coefficient of determination for surface free energy (SFE) models are shown in Table 17. The coefficient of determination for tensile strength ratio is found to be (0.825) with a standard error of (.027). From these results obtained, it seems that there is good correlation between observed and estimated values for the model.

Table 17. SFE Model with Correlation Coefficients and SER

Regression Model	R^2	Adj. R^2	SER
TSR (%) = 64.58 +216.31 DDP+ 244.26 DITS + 0.429 SFE	0.825	0.811	.027

Where:
TSR % = Tensile strength ratio
DDP = Permanent Deformation under Repeated Double Punching Test (mm)
DITS = Permanent Deformation under Repeated Indirect Tensile Strength Test (mm)
SFE = Surface free energy (erg/cm^2)

CONCLUSIONS

Based on the analysis of test results and limitations of materials, the following conclusions can be drawn.

1- The developed statistical model of resistance to moisture damage is based on permanent deformation under repeated tensile and shear stresses and surface free energy of the binder.
2- The model can explain 82.5 % of the variations in tensile strength ratio with reasonable standard error of estimate of (0.027).
3- The model can be utilized for asphalt concrete mixtures within the limitations of materials regardless of the modifiers used and recycling process adopted.

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