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Modeling the Influence of Surface Free Energy on the Durability of Modified Asphalt Concrete

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Abstract

Modeling the durability of modified asphalt concrete can assist in verification of suitable type of additives. The improvement in the properties of asphalt concrete due to implication of additives are proposed to last for the design life of the mixture, such durability issue is essential and should be checked before a decision is made. In this work, the influence of (7% sulfur and 10% carbon black) additives by weight of asphalt cement on the durability of asphalt concrete was investigated. The implication of such additives into the asphalt cement have been conducted using two different techniques, the cooking pressure vessel and the oven heating technique. Wilhelmy plate and sessile drop test methods have been implemented for verification of surface free energy of control and modified asphalt cement. Asphalt concrete Specimens of 102 mm in diameter and 63.5 mm in height have been prepared using the Marshall Compaction procedure. Specimens were separated into two groups; the first group was tested for temperature susceptibility at (25 and 40)°C. The second group was subjected to moisture damage according to modified Lottman procedure, then tested at high, moderate, and low testing temperatures of (60, 40, and 10)°C. Specimens were tested in triplicate and the average values were considered for evaluation and modeling. Test results were analyzed and modeled with the aid of IBM SPSS V 24 software. It was concluded that the obtained linear statistical models are beneficial in assessing the influence of mixing techniques and additives type on the surface free energy variables, physical and rheological properties of modified asphalt cement. The durability in terms of resistance of modified asphalt concrete to moisture damage and temperature susceptibility could be predicted based on surface free energy models developed.

Keywords

Asphalt Concrete, Durability, Moisture Damage, Temperature Susceptibility, Modeling, Surface Free Energy

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1. Introduction

With the increasing use of modifiers in asphalt cement, there is a great need for evaluating and modeling the effectiveness of modifiers and their duration in long term behavior. There are generally three major types of asphalt modification; either implementation of polymer and non-polymer additives or through chemical reaction. Non-polymer additives employed in asphalt modification include using of fillers, anti-stripping additives, extenders, antioxidants, and other materials such as Gilsonite, silicone and inorganic fibers. Polymer additives include plastics, elastomers, reclaimed rubbers and fibers. Chemical reaction modifications include vulcanization (asphaltic reaction with sulfur) and nitration reaction (asphaltic reaction with nitric acid) as reported by Isacsson and Lu, [1]. As a result, polymers have become extremely popular as modifiers to improve the performance of the asphalt mix. Sarsam, [2] had conducted a comprehensive testing program to study the possibility of digesting asphalt

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cement of penetration grade 40-50 with Nano materials. It was concluded that the digestion of asphalt cement with Nano materials (fly ash and silica fumes) reduces the stiffness modulus. Higher percentages of fly ash show high reduction in the modulus, while silica fumes exhibit lower reduction in the stiffness modulus. As stated by Qadir, [3] in a study on the performance of polypropylene fibres modified asphalt concrete, the polypropylene fibres were found to increase the Marshall Stability by almost 25%. The fibres were also determined to be effective against rutting at elevated temperatures and increase the Indirect Tensile strength by stiffening the mix at high temperature. However, at low temperature, the modification failed to perform effectively. One measure of a binder's durability is its ductility. Several studies report that a value of the 15°C ductility at 1 cm/min in the range of 2 to 3 cm corresponds to a critical level for age-related cracking in pavements, Woo et al, [4]. A comprehensive review of the literature was conducted by Jones et al, [5] found that although considerable research has been undertaken to understand the advantages and disadvantages of using recycled tire rubber to modify asphalt binders. It significantly improves various properties of asphalt such as elasticity, cohesion, stiffness, and adhesion. This leads to more stable pavement at warmer temperatures and more flexible at colder temperatures. An attempt has been made by Sarsam and Lafta, [6] to prepare the modified Asphalt cement for pavement construction in the laboratory by digesting each of the two-penetration grade Asphalt cement (40-50 and 60-70) with sulfur, fly ash, fumed silica, crumb rubber and Phospho gypsum. It was concluded that Sulfur additive provides the lowest creep stiffness at all the loading periods and for both asphalt grades, while crumb rubber additive shows the highest creep stiffness. Sulfur, Phospho gypsum, and fly ash increase the temperature susceptibility of both grades of asphalt cement, while Rubber and sulfur, improved the elastic properties of both grades of asphalt. Significant evidence that sulfur extended asphalt SEA pavement mixtures provide performance equal to conventional asphalt concrete mixtures as stated by FHWA, [7]. SEA mixtures can potentially be designed with softer asphalts and higher binder contents to enhance durability. Sarsam and AL-Lamy, [8] provided a comparative evaluation of pavement resistance to the phenomenon of fatigue cracking between modified asphalt concrete and conventional asphalt concrete mixes (under the influence of three percentage of Silica fumes 1%, 2%, 3% by the weight of asphalt content), and (changing in the percentage of asphalt content) by (0.5% ±) from the optimum. Modified asphalts tend to provide longer life and better pavement performance than conventional pavements as stated by Brovelli et al., [9]. Sarsam, [10] evaluated modified Asphalt cement specimens with different ingredients and studied the effect of such ingredients on rheological and physical properties, it was concluded that modified Asphalt cement prepared from (Asphalt cement, 10% rubber and 20%lime), or from (Asphalt cement, 5% sulfur, 10% rubber and 20%lime) and from (Asphalt cement, 20% lime and 2% recycling agent) satisfies the suggested specification requirements. Attoh-Okine et al, [11] investigated the influences of polymer modifications to asphalt rheology as compared to conventional asphalt pavement sections. The addition of 2% to 3% of polymers into the asphalt pavements have been known to enhance the engineering characteristics of asphalt which offers longer life expectancy, increased resistance to fatigue cracking, increased resistance to rutting, improved thermal-stiffness performance at high and low extreme temperatures, and increased resistance to stripping. The positive influence of surface free energy on predicting the properties of modified asphalt cement has been investigated and reported by Mirhosseini et al, [12]; Wang et al, [13]; Kakar et al, [14]; Sarsam and AL Azzawi, [15] and Sarsam and AL Azzawi, [16]. On the other hand, modeling the influence of surface free energy on the properties of asphalt cement was reported by Sarsam and AL Azzawi, [17]. The aim of this work is to model the influence of surface free energy on the durability of both asphalt cement and asphalt concrete modified with (7% sulfur and 10% carbon black) additives by weight of asphalt cement. Asphalt cement and modifiers will be prepared using two mixing and heating techniques (pressure vessel and oven heating), while asphalt concrete specimens will be tested for indirect tensile strength ITS and temperature susceptibility at (25 and 40)°C. The moisture damage will be investigated at high, moderate, and low testing temperatures of (60, 40, and 10)°C.

2. Materials and Methods

2.1. Asphalt Cement

In this study, Asphalt cement of (40-50) penetration grade which was obtained from Al-Dora refinery, south-west of Baghdad was implemented. The physical properties are shown in Table 1.

Table 1. Physical Properties of Asphalt Cement.

Property as per ASTM, [18]	Result	Unit	SCRB Specification, [19]
Penetration (25°C, 100g, 5 sec) ASTM D5-97	44	1/10mm	40-50
Softening Point (Ring & Ball) ASTM D5-36	51.5	°C	-------

Property as per ASTM, [18]	Result	Unit	SCRB Specification, [19]
Ductility (25°C, 5cm/min) ASTM D113-07	150	cm	>100
Rotational viscosity at 135°C (c. P. s)	427.2	c. p. s.	_____
Specific gravity at 25°C ASTM D-70	1.056	_____	(1.01-1.05)
After Thin-Film Oven ASTM D1754			
Retained penetration of original,% D946	90	%	>55%
Ductility at 25°C, 5 cm/min.	125	cm	>25
Loss in weight (163°C, 50g, 5h) ASTM D1754	0.22	%	< 0.75

2.2. Carbon Black

It was obtained from local market; the physical properties are listed in Table 2.

Table 2. Properties of Carbon black.

Property	Residue on Sieve No. 35	Pour density gm/liter	Ash content%	PH	Specific Surface Area (m^2/g)	Oil absorption number
ASTM	D-1514	D-1513	D-1506	D-1512	D-6556	D-2414
Test result	10	352.4	0.75	7.5-9	36	122

2.3. Sulfur

It was obtained from local market in solid form and crushed to powder in the laboratory; it has 98% of pure sulfur. The physical and chemical properties of sulfur are presented in Table 3.

Table 3. Properties of sulfur.

Melting point°C	117-120
Flash point°C	207 (closed cup)
Relative density (gm/cm^3)	2.07 at 25°C
PH	6 at 20°C
Viscosity (mm^2/sec)	8 at 140°C
Bulk density (kg/m^3)	0.90
Vapor pressure (mm Hg)	8 at 246°C 1 at 183.8°C

2.4. Coarse Aggregate

In this work, the crushed coarse aggregate was brought from Al-Nibaee quarry. It consists of hard, strong and durable pieces, free of coherent coatings. The gradation of coarse aggregate ranges between 19.0 mm and 4.75 mm according to SCRB R/9, [19] specification. The mineralogical composition of coarse aggregate is shown in Table 4, while the physical properties of the coarse aggregate are illustrated in Tables 5.

Table 4. Mineralogical Composition of Al-Nibaee coarse Aggregates.

Mineralogical Composition	Content%
Quartz	80.3
Calcite	10.92

2.5. Fine Aggregate

Fine aggregate was brought from Al-Nibaee quarry. The gradation of fine aggregates ranges between passing 4.75mm and retains on 0.075mm. It consists of tough grains, free from clay, loam or other deleterious substance. The physical properties of the fine aggregate are shown in Table 5.

Table 5. Physical Properties of Al-Nibaee Coarse and Fine Aggregates.

Property as per ASTM, [18]	Coarse aggregate	Fine aggregate
Bulk Specific Gravity (ASTM C127 and C128)	2.640	2.582
Apparent Specific Gravity (ASTM C127 and C128)	2.654	2.677
Percent Water Absorption (ASTM C127 and C128)	0.796	1.365
Percent Wear (Los-Angeles Abrasion) (ASTM C131)	18.1	……
Soundness loss by sodium sulfate,%	4.1	……..
Percent fractured faces	97	……..
Sand equivalent,%	……….	52

2.6. Mineral Filler

Limestone dust was implemented as filler material. It is thoroughly dry and free from lumps or aggregations of fine particles. The chemical composition is illustrated in Table 6, while the physical properties are shown in Table 7.

Table 6. Chemical composition of limestone dust.

Chemical composition	Cao	siO_3	MgO	SO_3	Loss on ignition
%	68.5	2.26	0.34	1.19	27.1

Table 7. Physical Properties of limestone dust.

Test	Physical properties
% Passing Sieve No. 200 (0.075 mm)	94
Apparent Specific Gravity	2.560
Specific Surface Area (m²/kg)	448

2.7. Preparation of Modified Asphalt Cement

Asphalt cement samples of various mixes types and percentages of additive have been prepared in the laboratory. Based on the literature review, three percentages of carbon black (5, 10, and 15%) and four percentages of sulfur (3, 5, 7, and 10%) have been implemented in this investigation. Two blending technique have been implemented; the first technique was with the aid of cooking pressure vessel of 6 liters capacity. The mixture was blended, and the pressure applied by the vessel was maintained to 1 bar (15 psi). Heating of the pressure vessel was maintained to 130°C, applied through electric hot plate with a thermostat control; 50 min were enough to obtain a homogeneous mix. The second technique was mixing with continuous stirring at 150°C for one hour. Similar procedure was implemented by Sarsam and Jasim, [20]. Figure 1 demonstrates the cooking pressure vessel implemented. After each mixing period, the pressure was unconfined through the safety valve, and the vessel cover was removed, swelling and formation of bubbles was detected after each mixing period indicating the chemical reaction occurred due to temperature and pressure. Figure 2 exhibits the prepared modified asphalt cement after the pressure vessel.

Figure 1. Cooking pressure vessel.

Figure 2. Modified asphalt cement.

2.8. Selection of Overall Aggregate Gradation

The gradations that was selected in this study follow SCRB R/9, [19] specification for Hot-mix asphalt paving mixtures usually used for wearing course with aggregate nominal size of (12.5 mm). Figure 3 show the gradation for wearing layer adopted.

2.9. Preparation of Modified Asphalt Concrete Specimens

The various fractions of aggregate as supplied from the mixing plant were dried to a constant weight at 110°C, then sieved to different sizes, separated into groups, as retained on each of the following sieve, (19, 12.5, 9.5, 4.75, 2.36, 0.3, 0.075) mm using dry sieve analysis. The material passing 0.075 mm was discarded and replaced by mineral filler (limestone dust). The aggregates were recombined according to the requirements shown in Figure 1 for wearing course. The overall aggregate mix was heated to 160°C, while the pure or modified asphalt cement was heated to 150°C, then added to the aggregates and mixed thoroughly for three minutes using mechanical mixer until asphalt had sufficiently coated the surface of the aggregates and a homogeneous mixture is achieved.

Optimum percentages of asphalt content obtained from previous work by Sarsam and Abdulhussain, [21] have been implemented for each type of modified asphalt. Specimens of 102 mm in diameter and 63.5 mm in height have been prepared using the Marshall Compaction procedure with 75 blows on each side of the specimen, ASTM D1559, [18]. The compaction temperatures were (150, 125, and 163)°C for control, sulfur treated, and carbon black treated mixtures respectively. The mold was left for 24 hours and then the specimen was extruded from the mold. Figure 4 demonstrates part of the prepared specimens. The prepared Marshall Size Specimens were divided into two sets, the first set was tested for temperature susceptibility at (25 and 40)°C using the indirect tensile strength ITS test as per ASTM, [18]. The second set was subjected to moisture damage according to modified Lottman procedure, then tested at high, moderate, and low testing temperatures of (60, 40, and 10)°C. Specimens have been tested in duplicate, and the average value was considered for analysis.

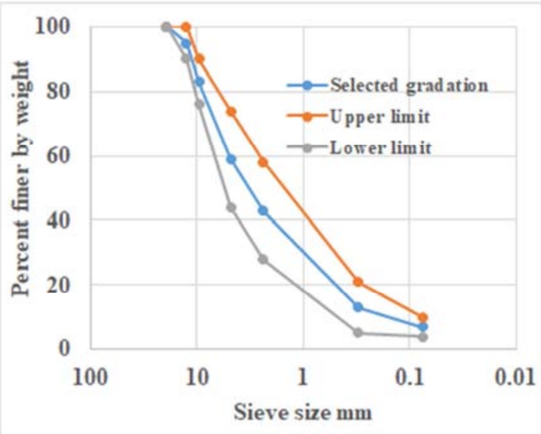

Figure 3. Combined gradation implemented, SCRB, [19].

Figure 4. Part of the prepared specimens.

2.10. Temperature Susceptibility and Moisture Damage

The indirect tensile strength test was determined according to the procedure of ASTM D6931, [18]; Marshall Size Specimens were stored in the water bath at 20°C for 30 minutes and then each specimen was centered on the vertical diametrical plane between the two parallel loading strips of 12.7 mm width. Vertical compression load at rate of 50.8 mm/min by Versa tester machine was applied until the dial gage reading reached the maximum load resistance. The indirect tensile strength (ITS) and the temperature susceptibility were calculated using ASTM D4123, [18]. The indirect tensile strength ratio test was performed to evaluate the moisture damage resistance of mixtures, and the procedure followed AASHTO, [22]. A set of specimens were conditioned by placing in volumetric flask 4000-ml heavy- wall glass filled with water at room temperature of 20˚C and then a vacuum of 3.74kPa was applied for 5 to 10 minutes to obtain 70%-degree level of saturation. The specimens were then placed in deep freeze at -18˚C for 16 hours. The frozen specimens were then removed and allowed to thaw for two hours at the laboratory environment, then conditioned for two hours at 20°C. Specimens were tested for indirect tensile strength and recorded as moisture conditioned ITS. The indirect tensile strength ratio TSR could be calculated according to AASHTO, [22].

3. Results and Discussions

Asphalt cement and asphalt concrete specimens were tested in triplicate, the average values were implemented in the analysis and statistical modelling.

3.1. Modeling the Influence of Mixing Technique on SFE Components of Modified Asphalt Cement

The measurement of surface free energy parameters was conducted using both Wilhelmy plate and sessile drop test methods. Test results show that pressure vessel heating improves the total surface free energy for the carbon black modified mixture CBMAC and sulfur modified mixture SMAC as compared to oven heating technique. To determine the influence of the contact angle measurements on the surface free energy for each modified asphalt cement type, linear regression analysis using IBM SPSS 4.7 was adopted. The predicted models are presented in Table 8, while the variables implemented are listed in Table 9.

Table 8. Models of SFE Prediction Based on Contact Angle.

Model Number		R^2
	Carbon Black Modified Asphalt Cement CBMAC	
1	(OH) WPSFE= 97.568+0.436 ϴW -4.806 ϴG +3.710 ϴEG	0.998
2	(PVH) WPSFE=98.821+0.403 ϴW -4.777 ϴG +3.699 ϴEG	0.989
3	(OH) SDSFE=50.873+0.320 ϴW -0.412 ϴG -0.328 ϴEG	0.998
4	(PVH) SDPSFE=46.968+0.629 ϴW -0.539 ϴG -0.532 ϴEG	0.999
	Sulfur Modified Asphalt Cement SMAC	
5	(OH) WPSFE=103.567+0.287 ϴW -4.444 ϴG+3.421 ϴEG	0.997
6	(PVH) WPSFE=99.741+0.379 ϴW -4.753 ϴG+3.688 ϴEG	0.998
7	(OH) SDSFE=50.893+0.568 ϴW -0.551 ϴG -0.502 ϴEG	0.999
8	(PVH) SDPSFE=23.741+0.854 ϴW -0.666 ϴG -0.298 ϴEG	0.999

Table 9. Variable for The Mixing Technique Impact Models.

Variable symbol	Name	Units	Type
ӨW	The contact angle with deionized water probe liquid		
ӨG	The contact angle with glycerol probe liquid	degrees	Independent Variables
ӨEG	The contact angle with ethylene glycol probe liquid		
WPSFE	Wilhelmy plate total surface energy	ergs/cm^2	Dependent Variables
SDSFE	Sessile drop total surface energy		
(OH) represent oven heating technique			
(PVH) represent pressure vessel heating technique			

The models exhibit the changes in surface energy parameters due to the addition of the carbon black powder and sulfur powder modifiers respectively. The models also consider the effect of the mixing and heating techniques implemented. Table 10 exhibit the descriptive statistics of the models. Similar modeling of SFE variables were reported by Sarsam and Jasim, [23] using another type of additives.

Table 10. Descriptive statistics of the models Variables.

Contact angle	Mean	Std. Deviation	N
ӨW	85.7576	2.3158	5
ӨG	78.9744	2.6943	5
ӨEG	58.5829	2.1904	5

3.2. Assessing the Influence of SFE on Physical and Rheological Characteristics of Asphalt Cement

The surface free energy defines the stripping characterizes of the asphalt cement. The assessment process was developed using the linear regression analysis of the potential parameter using the (IBM SPSS statistics 24). The model included the SFE as a dependent variable and the tested rheological and physical properties as the independent variables. Independent variables are displayed in Table 11. The developed models are listed in Table 12. Table 13 demonstrates the Descriptive Statistics for SFE for SD and WP methods.

Table 11. Independent Asphalt Cement Physical and Rheological Parameters.

Independent variable	Units of measurement
Penetration (P)	0.01 mm
Softening Point (SP)	ºC
Penetration index (PI)	---
Ductility (D)	Cm
Retained Penetration (RP)	0.01 mm
Retained Ductility (RD)	Cm

Table 12. Developed Models for SFE.

Model Number	For CBMAC using WP method for SFE	R^2
1	Total SFE= -3499.274+36.738 P+0.438 D +28.566 SP +21.649 RP -3.839 RD	0.970
2	Total SFE= -3489.469+0.165 D+133.176 PI +139.496 RP -14.990 RD	0.980
	For CBMAC using SD method for SFE	
3	Total SFE= -3499.279+36.486 P+0.317 D+28.488 SP +21.532 RP -3.627 RD	0.998
4	Total SFE= -3489.491+0.053 D+133.266 PI +138.861 RP -14.746 RD	0.990
	For SMAC using WP method for SFE	
5	Total SFE=-3499.881+0.285 P +20.936 D +0.591 SP +0.178 RP -0.061 RD	0.960
6	Total SFE=-3499.879+21.214 D -2.378 PI -0.076 RP -0.022 RD	0.980
	For SMAC using SD method for SFE	
7	Total SFE=-3499.885+0.608 P+20.252 D+2.188 SP +0.160 RP -0.020 RD	0.990
8	Total SFE=-3499.879+21.160 D+1.311 PI -0.207 RP+0.021 RD	0.990

It can be observed that the physical properties in terms of penetration and softening points exhibit significant influence on surface free energy SFE as compared to ductility. On the other hand, the rheological properties in terms of penetration index, retained ductility and retained penetration exhibit a great impact on SFE regardless of testing technique. Figure 5 demonstrates the influence of additives on the physical and rheological characteristics of asphalt cement. It can be noted that CBMAC shows lower penetration and ductility values, and higher softening points compared with the SMAC test results. The findings of mixture behavior agree with those reported by Cong et al, [24].

Table 13. Descriptive Statistics for SFE.

Descriptive Statistics for SD SFE				Descriptive Statistics for WP SFE			
Variables	Mean	Std. Deviation	N	Variables	Mean	Std. Deviation	N
Ductility, D	76.25	62.2166	4	Penetration, P.	67.4	15.0764	5
P. I	-.4647	1.0348	4	Ductility, D.	167.0	0.11	5
Retained penetration, RP	33.6275	4.33795	4	Softening Point, S. P.	46.0	3.6571	5
Retained Ductility, RD	74.2500	34.7311	4	Retained penetration, R P.	35.8560	4.8589	5
Total SD SFE	27.3205	1.6999	4	Retained Ductility, RD.	132.6	27.7542	5
--	---	---	--	Total WP SFE	41.1603	2.4089	5

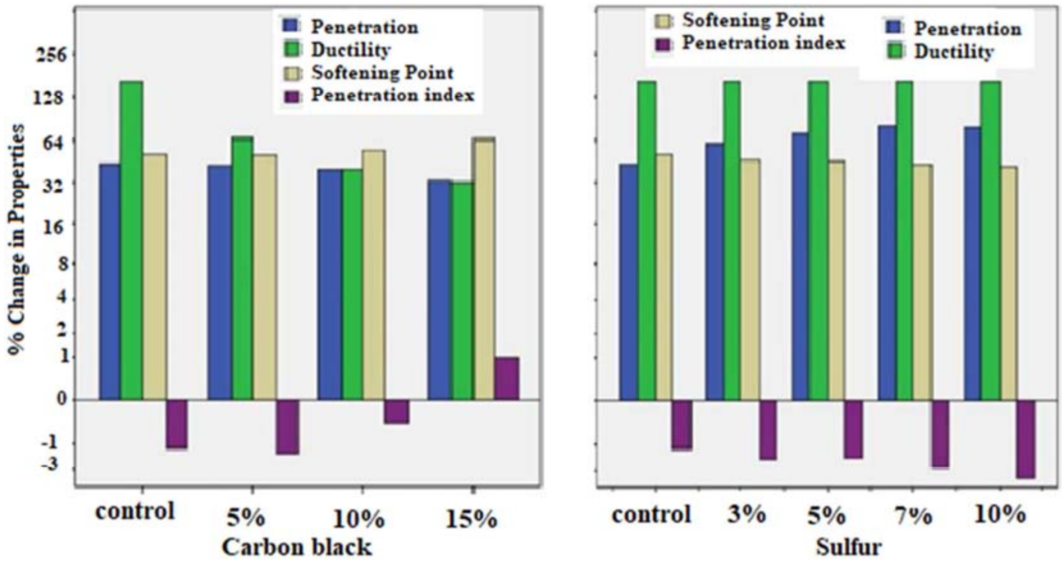

Figure 5. Influence of additives and mixing technique on the physical and rheological characteristics of asphalt cement.

3.3. Assessment of the Stripping Potential of Asphalt Concrete Based on The SFE Tests Results

The assessment program investigates the stripping potential relationship in terms of tensile strength ratio between different asphalt concrete parameters and the results of SFE. The stripping investigation depended on the tensile strength ratio (TSR) results, including three sets of temperature range conditioning (60, 40, and 10) ºC. The models below represents the predicted effect using linear regression, the model was not intended to present a full prediction for all modified asphalt contents and SFE results, rather than a presentation of the potential effect of suggested independent variables on the moisture damage results and thus the stripping characteristics for the three tested mixtures only. Similar findings were reported by Sarsam and AL Azzawi, [16]; Sarsam and Alwan, [25]; Caro et al, [26]; Haghshenas et al, [27] and Little et al, [28]. The models estimate the predicted TSR results from the findings of SFE and indirect tensile strength of the corresponding conditioning temperatures. The models are represented in Table 14 below. It can be observed that for sulfur modified asphalt concrete SMAC, significant influence of surface free energy SFE parameters (contact angles) on tensile strength ratio TSR could be detected as compared to carbon black modified asphalt concrete CBMAC regardless of the SFE testing technique.

Table 14. Durability in terms of Resistance to Moisture Damage Models.

Model Number		R^2
	For CBMAC mixture using WP method for SFE	
1	TSR 60°C = -45319.92 -36.342 ITS wet 60°c + 48.524 ITS dry 25°c+ 8.221 ΘW+7.562 ΘG +7.223 ΘEG	0.99
2	TSR 40°C = -45319.96 -15.423 ITS wet 40°c + 39.40 ITS dry 25°c+ 4.357 ΘW+4.133 ΘG +4.010 ΘEG	0.98
3	TSR 10°C= -45319.95 -17.850 ITS wet 10°c + 41.975 ITS dry 25°c+ 4.932 ΘW+4.650 ΘG + 4.497 ΘEG	0.99
	For CBMAC mixture using SD method for SFE	
4	TSR 60°C= -45319.91 -34.147 ITS wet 60°c + 47.099 ITS dry 25°c+ 10.111 ΘW+12.821 ΘG + 7.358 ΘEG	0.97
5	TSR 40°C= -45319.961 -15.050 ITS wet 40°c + 39.138 ITS dry 25°c+ 4.965 ΘW+5.580 ΘG + 3.708 ΘEG	0.99
6	TSR 10°C= -45319.954- 17.329 ITS wet 10°c + 41.556 ITS dry 25°c+ 5.727 ΘW+6.613 ΘG + 4.244 ΘEG	0.98
	For SMAC Mixture using WP method for SFE	
7	TSR 60°C = -45319.628 -94.928 ITS wet 60°c + 72.470 ITS dry 25°c+ 30.778 ΘW+29.141 ΘG + 29.424 ΘEG	0.99
8	TSR 40°C= -45319.343 -122.378 ITS wet 40°c + 83.112 ITS dry 25°c+ 53.553 ΘW+50.616 ΘG + 51.221 ΘEG	0.99
9	TSR 10°C= -45319.524 -101.721 ITS wet 10°c + 83.927 ITS dry 25°c+ 39.089 ΘW+36.986 ΘG + 37.368 EG	0.98
	For SMAC Mixture using SD method for SFE	
10	TSR 60°C= -45319.623 -96.206 ITS wet 60°c + 73.412 ITS dry 25°c+ 34.984 ΘW+28.274 ΘG + 21.825 ΘEG	0.99
11	TSR 40°C= -45319.327 -125.297 ITS wet 40°c + 85.040 ITS dry 25°c+ 61.813 ΘW+49.298 ΘG + 38.104 ΘEG	0.98
12	TSR 10°C= -45319.516 -103.472 ITS wet 10°c + 85.330 ITS dry 25°c+ 44.671 ΘW+35.951 ΘG + 27.731 ΘEG	0.98

From the models, it was concluded that SFE results had a significant effect on the results of TSR when the contact angle tested by both methods were introduced in the models. Figure 6 exhibit the impact of conditioning temperature and additives on TSR. Figure 6 demonstrates the impact of conditioning temperature on tensile strength ratio test results. The mixtures were tested for TSR at high 60 ºC, moderate 40°C and low 10°C temperatures, the results showed that SMAC can resist the moisture at low to moderated temperatures while the CBMAC could be used for different temperature ranges.

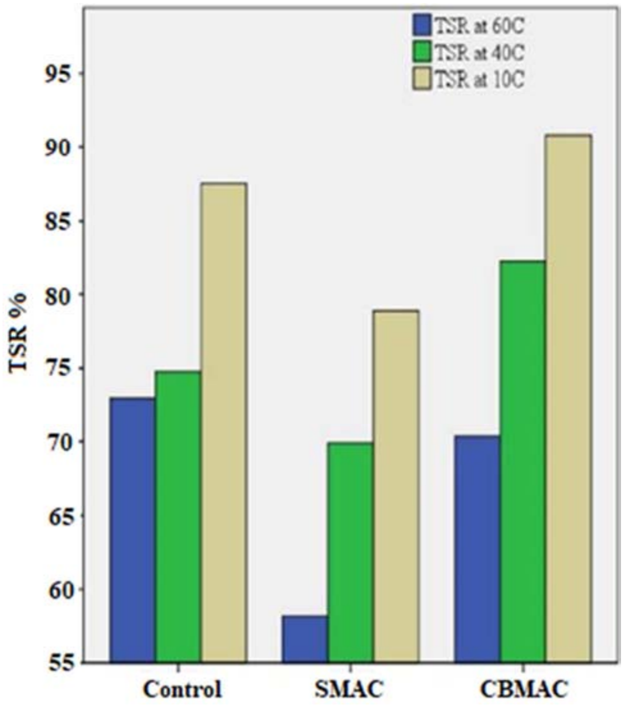

Figure 6. Impact of conditioning temperature and additives on TSR.

3.4. Assessment of Temperature Susceptibility of Asphalt Concrete Based on The SFE Tests Results

The results for durability in terms of temperature susceptibility TS was conducted and the specimens set were tested at 40°C and compared with the specimens set tested at 25°C. The Temperature susceptibility (TS) results were used as one of the durability potential related tests, the effect of surface energy on the results of the TS results was assessed using linear regression analysis with the following variables; the dependent variable is the TS in kPa/ºC, while the independent variables were the SFE form Wilhelmy plate and sessile drop, and the ITS at (25 and 40)°C. The following models were developed and listed in Table 15. On the other hand, Table 16 exhibit the range of variables implemented in the models. It can be noted that both modified mixtures show lower temperature susceptibility value with reduction of (12 and 7.3) % for CBMAC and SMAC respectively. The use of carbon black and sulfur powder results in a more temperature fluctuation resistance mixture. The temperature susceptibility test considered one of the durability test criteria.

Table 15. Durability in Terms of Temperature Susceptibility Models.

Model Number		R^2
	For CBMAC	
1	TS = -45319.932-27.633 ITS at 40°C +48.152 ITS at 25°C + 3.375 WPSFE total	0.96
2	TS = -45319.932-27.713 ITS at 40°C +48.272 ITS at 25°C + 1.049 SDSFE total	0.97
	For SMAC	
3	TS = -45319.647-92.339 ITS at 40°C +84.326 ITS at 25°C + 19.283 WPSFE total	0.95
4	TS = -45319.643-93.438 ITS at 40°C +85.234 ITS at 25°C + 13.791 SDSFE total	0.99

Table 16. Range of variables implemented in the TS models.

Mixture type	Control		SMAC		CBMAC	
Range of variable	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**
ITS, kPa.	1391.1	787.27	900.1	340.06	1487.8	956.01
Temperature suitability, kPa / ºC	40.256	38.23	37.336	36.00	35.451	34.50

4. Conclusions

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

1. Statistical regression analysis was introduced to produce models that explain the relationship between the studied physical and rheological parameters of asphalt cement and the results of the SFE tests results.
2. Regression models resemble the comparison between modified and control mixture properties and the corresponding difference in SFE parameters for asphalt cement on the asphalt concrete tests results.
3. The sulfur modified asphalt concrete satisfies the requirements of resistance to moisture damage at moderate and low testing temperature, while the carbon black modified mixture satisfies and improves the resistance to moisture damage at all of testing temperatures implemented.
4. Both modified mixtures show lower temperature susceptibility value with reduction of (12 and 7.3)% for CBMAC and SMAC respectively. The use of carbon black and sulfur powder results in a more temperature fluctuation resistance mixture.
5. Pressure vessel mixing, and heating technique improves the total surface free energy for the carbon black modified mixture CBMAC and sulfur modified mixture SMAC as compared to oven heating technique.
6. The physical properties in terms of penetration and softening points exhibit significant influence on surface free energy SFE as compared to ductility, while the rheological properties in terms of penetration index,

retained ductility and retained penetration exhibit a great impact on SFE regardless of testing technique.

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