Surface Free Energy for the Evaluation of Asphalt Binder Stripping

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Abstract

Stripping is one of the major distresses within asphalt concrete pavements caused due to penetration of water within the interface of asphalt-aggregate matrix. In this work, one grade of asphalt cement (40-50) was mixed with variable percentages of three types of additives (fly ash, fumed silica, and phosphogypsum) to obtained an modified asphalt cement to resist the effect of stripping phenomena .The specimens have been tested for physical properties according to AASHTO. The surface free energy has been measured by using two methods namely, the wilhelmy technique and the Sessile drop method according to NCHRP-104 procedures.

Samples of asphalt concrete using different asphalt cement and modified asphalt cement percentages(4.1,4.6 and 5.6) were prepared and tested for stripping phenomena by using Marshall Immersion method (The index of retained stability test(I.R.S) ≥75 %.

When using Sessile drop method the value of surface free energy of asphalt cement grade (40-50) was about 8.8 ergs/cm^2, while when using Wilhelmy technique the value of surface free energy of asphalt cement was 30.71 ergs/cm^2.

Finally, a mathematical relationship was obtained by using (SPSS) Software between the stripping asphalt concrete using conditioned and unconditioned specimens data (I.R.S) %, the contact angle, the total surface free energy for asphalt cement and modified asphalt cement with fume silica.

Keywords: Stripping, surface free energy, modified asphalt, fume silica

تقييم خصائص التقشر للأسفلت السمنتي بأستخدام مبدأ الطاقة السطحية الحرة

الخلاصة

تقشر الأسفلت عن الركام هو احد المشاكل الرئيسية التي تضعف الخرسانة الأسفلتية وذلك بسبب تغلغل الماء الى سطح الأسفلت والركام. في هذا البحث تم مزج نوع واحد من الأسفلت السمنتي (40-50) مع نسب متغيرة من ثلاثة انواع من المضافات (الرماد المتطايروالفيوم سليكا والفوسفوجبسوم) للحصول على أسفلت سمنتي محسن.

تم فحص النماذج للخصائص الفيزيائية اتباعا لمواصفة AASHTO الأميريكية للأسفلت السمنتي والمحسن وثم قياس الطاقة السطحية الحرة بأستخدام طريقتي(Wilhelmy Method and Sessilt Drop) بموجب مواصفة (NCHRP-104).

تم فحص نماذج الخرسانة الأسفلتية لأنواع الأسفلت الأسمنتي والأسفلت المحسن بالنسب 4.1,4.6,5.6 لقياس ظاهرة التقشر بأستخدام طريقة Marshall Immersion لأيجاد مؤشر بقاء الأستقرارية (I.R.S.%). ومن نتائج الفحوصات لوحظ ان طاقة الشد السطحي للأسفلت السمنتي (40-50) المحسوب بطريقةSessile Drop حيث كانت 8.8 ergs/cm^2 بينما اعطت طريقة Wilhelmy Method طاقة الشد السطحي المحسوبة بمقدار 30.71 erg/cm^2.وتم ايجاد علاقات رياضية تربط ظاهرة التقشر للنماذج(Conditioned and unconditioned) و(contact angle) مع طاقة الشد السطحي للأسفلت المحسن بالفيوم سيليكا.

الكلمات الرئيسية: التقشر ، الطاقه السطحيه الحره ، الاسفلت المحسن ، أبخره السليكا.

Introduction

General

Moisture damage in asphalt concrete pavements is considered as primary cause of distresses in the asphalt pavement layers. The exposure of asphalt pavement to water is often one of the major factors affecting the durability of HMA. The water induced damage in HMA layers may be associated with two mechanisms: loss of adhesion and/loss of cohesion. In the first mechanism, the water gets trapped between the asphalt and aggregate and strips the asphalt film away, leaving aggregate without asphalt film coverage. This happens because the aggregates have a greater affinity for water than asphalt binder. The second mechanism includes the interaction of water with the asphalt cement that reduces the cohesion within the asphalt cement. This will lead to a severe reduction in the asphalt mixture strength. **(Wasiuddin, (2007)).**

Mineral anti-stripping additives and liquid anti-stripping agents are commonly used to modify hot mix asphalt HMA components, asphalt binder and aggregate, to increase the resistance of HMA mixtures to moisture damage. Surface free energy, of a material is the amount of work required to create unit area of the material in vacuum. The total surface energy of a material is divided into three components, namely,: the Lifshitz–van der Waals component, the acid component, and the base component. Such components can be used in calculating the free surface energy for asphalt **(NCHRP-104)**, and there are several methods to determine the surface energy.

Methods for Determination of Surface Free Energy of Asphalt:

- Sessile Drop Method **(SDM).**
- Wilhelmy Plate Method **(WPM).**

Research Objective

The main objectives of this research work are:
(1). Studying the relationship between the surface free energy and stripping properties for asphalt cement and modified asphalt improved by three types of additives (fly ash, phpsphogypsum and fume silica). The source of fly ash is locally from the waste of factories, phospho gypsum from Phosphate plant usually available as waste, fume silica obtained from local market.

(2). Finding a mathematical relationship between the stripping of asphalt concrete using conditioned and unconditioned specimens data with (I.R.S) and the contact angle and the total surface free energy for asphalt cement and modified asphalt cement.

Stripping Test

Marshall Immersion Test:

Three sets of Marshall Specimens were prepared according to the method described by ASTM D 1559. Each set contains four groups (two Specimens, one dried (control) and another (condition).The Marshall Specimens were used to find the Index of Retained Stability (I.R.S) %. Each group contains two specimens subgroup; one is the average of three specimens (control specimens) which were subjected to immersion in water bath at 60 ˚C for 30 minute. The second is the average of three specimens (conditioned specimen) and were immersed in water bath at 14±2˚C for 24 hrs. Such procedure was also followed by **Zhou et al (2009) and Solaimanian et al (2003).**

Then the specimens were tested by using Marshall Device .The index of retained stability was calculated as the ratio of stability of water exposed specimens to the stability of control specimens using equation (1).**Yousif, (2003).**

$$\text{I.R.S}\,(\%) = \frac{S_2}{S_1} \times 100 \qquad (1)$$

Where:

S_1=Marshall Stability for control specimen (30 minutes immersion at 60˚C).

S_2=Marshall Stability for condition specimen (24 hours immersion at 14±2˚C, then 30 minutes immersion in water at 60 ˚C).

A minimum I.R.S (%) of 75% is often specified for satisfactory resistance to damage by moisture. **Yousif (2003).**

Figure (1) show the gradation of aggregate used for wearing course(SCRB)

Test Methods to Measure Surface Energy Components:

Surface energy is defined as the energy needed to create a new unit surface area of material in vacuum condition. Surface energy measurements are used to compute the adhesive bond strength between the aggregates and asphalt and cohesive bond strength in the binder. It is a suitable method for forecasting the moisture damage in asphalt mixtures. Therefore, this method seems to be capable of analyzing the effects of anti-stripping additives on the reduction of moisture damage. The ability to accurately determine surface free energy of asphalt binders and aggregates has been developed based on the **Van Oss theory. Cheng (2002). Table (1)** shows the Surface Energy Components of the Probe Liquids used throughout this investigation. **Figure (2)** shows the flow chart of the surface energy determination.

The total surface energy of a material is divided into three components, namely, the Lifshitz-van der Waals component, the acid component, and the base component **Cheng (2002).** The surface free energy, □^{total} of a material is determined by combining the polar and nonpolar components as follows:

$$\gamma^{total} = \gamma□□ + 2\sqrt{\gamma^{+}\gamma^{-}} \qquad (2)$$

Where:

γ^{total} = is the total surface free energy of the material.

γ□□= the Lifshitz-van der Waals.

γ^{+}= is the Lewis acid component.

γ^{-} =is the Lewis base component.

Several methods are proposed in the literature to measure the surface free energy of the asphalt-aggregate system. **Shah (2003)** studied the surface energy that aimed at assessing moisture damage. **Wasiuddin et al (2005)** studied that (SFE) of A HMA mix and its constituents (aggregate and binder) can be a valuable indicator of moisture damage in HMA. **Hefer; et al (2006)** studied the bitumen surface energy using contact angles measured with various liquids by the Wilhelmy plate.

Wilhelm Plate Device Method(WPD)

This method is used to measure dynamic contact angles of the asphalt binder with various probe liquids and to determine surface energy components of the binder. A glass slide (25.4mm× 76.2mm × 1mm) coated with the asphalt binder and suspended from a microbalance is immersed in a probe liquid. From simple force equilibrium conditions the contact angle of the probe liquid with the surface of the asphalt binder can be determined. **Bhasin et al (2007)**

The difference between weight of a plate measured in air and partially submerged in a probe liquid, ΔF, is expressed in terms of buoyancy of the liquid, liquid surface energy, contact angle, and geometry of the plate **Bhasin et al (2007)**. The contact angle between the liquid and surface of the plate is calculated from this equilibrium as follows:

$$\cos\theta = \frac{\Delta F + V_{im}\left(\rho_L - \rho_{air} g\right)}{P_t \gamma_L^{Tot}} \qquad (3)$$

Where:

Pt=is the perimeter of the bitumen coated plate.

□$_L^{Tot}$ =Is the total surface energy of the liquid.

θ = The dynamic contact angle between the asphalt binder and the liquid.

V_{im} =The volume immersed in the liquid.

P_L=The density of the liquid.

P_{air}= The air density.

g =The local acceleration due to gravitation.

The analysis for obtaining the contact angle is usually carried out by using the software of the testing device. Since the testing device was not available in our laboratory, a manual test procedure was followed instead of using the device. The glass slides were of dimensions (25.4mm× 76.2mm × 1mm) each was coated with asphalt binder or modified asphalt. Each slide was then immersed in the beaker that was filled with the different probe liquids slowly at a steady speed and then a picture was taken while the slide was in its last position in the liquid.

The digital balance with a capacity of (1000 g) was used having a sensitivity of 0.2gm. The glass beaker that is filled with probe liquid was placed on the balance and then was covered together with the balance to prevent the air effect. Then, the glass slide was linked with a clipper paper and downloaded at slow and steady speed inside the beaker. The balance reading was taken when the slide touches the liquid. However, the balance was not sensitive enough for this measurement and it was not possible to determine the value of the ΔF during the immersion and lifting and hence, Equation (3) cannot be used. Therefore the image processing software **(Comef 4.3)** was used to find a dynamic contact angle. A total number of slides were perpetrated of (48) slides. **Arabani (2010)** explained the theoretical and experimental concept of predicting moisture damage in asphalt concrete mixes by using the surface free energy (SFE) concept using dynamic Wilhelmy plate method. **Figure (3)** shows the contact angle between probe liquid and glass slide coated asphalt. A total number of slides were perpetrated of (48) slides.

Sessile Drop Method(SDM)

A probe liquid is dispensed over a smooth horizontal surface coated with asphalt binder. The image of the drop of liquid formed over the surface of the binder is captured by using a digital camera. Contact angles are obtained by analyzing the image using image processing software **(Comef 4.3)** software. A static Contact angles measured with different probe liquids are used with equations of work of adhesion to determine the three surface energy components of the asphalt binder. **[NCHRP -104(2006)],** A total number of slides were perpetrated of (48) slides.

A drop with a contact angle over 90° is hydrophobic. This condition is exemplified by poor wetting, poor adhesiveness and the solid surface free energy is low. A drop with a small contact angle is hydrophilic this condition reflects better wetting, better adhesiveness, and higher surface energy. **Figure (4)** shows the Output of the Comef 4.3 Software

Computing Surface Energies from Contact Angles

The surface energy component of a solid surface is determined by measuring its contact angles with various probe liquids. Typically more than three liquids are recommended to determine the three surface energy components of the solid. At least three probe liquids are recommended to be used in this test. These are water, glycerol, and formamid and all reagents must be high-purity grade (>99%). Contact angles must be measured for at least three replicates with each probe liquid for each type of asphalt binder and modifier asphalt. Probe liquids that have been selected not react chemically or dissolve with asphalt binders and are used to measure the contact angles with the binder.

The system of linear equations generated based on the above equations is shown below:

$$A\,x = B \tag{4}$$

Where:

$$A = \begin{bmatrix} \sqrt{\gamma_{l1}^{LW}} & \sqrt{\gamma_{l1}^{+}} & \sqrt{\gamma_{l1}^{-}} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ \sqrt{\gamma_{lm}^{LW}} & \sqrt{\gamma_{lm}^{+}} & \sqrt{\gamma_{lm}^{-}} \end{bmatrix} (m \times 3) \tag{5}$$

$$X = \begin{bmatrix} \sqrt{\gamma_{s}^{LW}} \\ \sqrt{\gamma_{s}^{-}} \\ \sqrt{\gamma_{s}^{+}} \end{bmatrix} (3 \times 1) \tag{6}$$

$$B = 0.5 \begin{bmatrix} \gamma_{li}(1 + cos\theta_1) \\ \cdots\cdots \\ \gamma_{li}(1 + cos\theta_m) \end{bmatrix} (m \times 1) \tag{7}$$

$$x = A^{-1}B \tag{8}$$

The propagated variance of error in the work of adhesion can be calculated for each liquid as follows in Equation (10) and a reasonable approximation of $\boldsymbol{\sigma_y}$ is 0.1ergs/cm^2

$$\sigma_w^2 = \sigma_y^2\{0.5(1 + cos\theta)\}^2 + \frac{1}{r}\frac{1}{(r-1)}\sum_{k=1}^{r}(\theta_k - \bar{\theta})^2\{-0.5\,\gamma\,\sin\bar{\theta}\}^2 \tag{10}$$

Where, is the total surface free energy value of the liquid shown in table (1), $\boldsymbol{\theta}$ is the average contact angle from $\boldsymbol{r}$ replicate measurements in radian, $\boldsymbol{\theta_k}$ is the contact angle from r replicate measurements. σ_θ^2 is the variance **θ** expressed in radians shown in Equation (3.10)

$$\sigma_\theta^2 = \frac{1}{r}\frac{1}{(r-1)}\sum_{k=1}^{r}(\theta_k - \bar{\theta})^2\{-0.5\,\gamma\,Sin\,\theta^-\}^2 \quad (11)$$

The matrices **A** and **B** are changed as follows:

$$A' = \begin{bmatrix} \frac{\sqrt{\gamma_{l1}^{LW}}}{\sigma_1} & \frac{\sqrt{\gamma_{l1}^{+}}}{\sigma_1} & \frac{\sqrt{\gamma_{l1}^{-}}}{\sigma_1} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \\ \frac{\sqrt{\gamma_{lm}^{LW}}}{\sigma_m} & \frac{\sqrt{\gamma_{lm}^{-}}}{\sigma_m} & \frac{\sqrt{\gamma_{lm}}}{\sigma_m} \end{bmatrix} (m \times 3) \quad (12)$$

$$B' = 0.5 \begin{bmatrix} \frac{\gamma_{li}(1+cos\theta_1)}{\sigma_m} \\ \cdots\cdots \\ \frac{\gamma_{li}(1+cos\theta_1)}{\sigma_m} \end{bmatrix} (m \times 1) \quad (13)$$

Then, determine the $(\mathbf{A'}^{T}\mathbf{A'})^{-1}$ matrix for each asphalt binder. The three diagonal elements of this matrix(c_{ii}) represent the variance of the square roots of the surface energy components (Lifshitz-van der Waals, base and acid component, respectively).

The variance estimate of the errors in the surface free energy components is obtained by propagation of errors as follows:

$$\gamma_{LW}^2 = 4X_i^2 C_{ii} \quad (14)$$

$$\gamma_{base(\gamma^-)}^2 = 4X_i^2 C_{ii} \quad (15)$$

$$\gamma_{LWacid(\gamma^+)}^2 = 4X_i^2 C_{ii} \quad (16)$$

Where, c_{ii} are diagonal elements of the $(\mathbf{A'}^{T}\mathbf{A'})^{-1}$ matrix.

Determination of Physical Properties:

In **table (3)** shows the physical properties of asphalt cement and modified asphalt cement were determined by using the following equations and shell nomograph. The table below illustrates such properties, **Sarsam et al (2000).**

$$\text{Penetration Index (P.I)} = \left[\frac{30}{(1+90\,k)}\right] - 10 \quad (17)$$

$$k = \frac{log800 - logpenetrationat77^\circ F}{[ringandball\,(softeningpoint^\circ F) - 77^\circ F]} \quad (18)$$

The value of penetration index indicates greater temperature susceptibility. Stiffness modules (SM) defines as the ratio stress/strain was obtained from shell nomograph at $T_{R\&B}$ 75°C and temperature of asphalt at 25°C and a frequency of 10 Hz.

Effect of Additives on Calculated Surface Free Energy by Sessile Drop Method

Surface free energy was determined for each type of asphalt binder based on Van Oss theory which separates the surface energy of asphalt into three components, namely, the Lifshitz-Van Der Waals component, the acid component, and the base component. **Figures (5), (6) and (7)** show the histograms of surface free energy of asphalt and modified asphalt. The surface free energy calculated was randomly when using asphalt modified with fly ash, fume silica and phosphor gypsum.

Effect of Additives on Calculated Surface Free Energy by Wilhelmy Plate Method

Surface free energy was determined for each type of asphalt binder based on Van Oss theory which separates the surface energy of asphalt into three components, namely, the Lifshitz-Van Der Waals component, the acid component, and the base component. **Figures (8), (9) and (10)** show the histograms of surface free energy of asphalt and modified asphalt. The surface free energy calculated was randomly when using asphalt modified with fly ash, fume silica and phosphor gypsum.

Effect of Additives on Stripping Potential Using Marshall Immersion Test The index of retained stability (I.R.S) % was calculated as the ratio of stability of water exposed specimens to the stability of dry specimens. A minimum I.R.S (%) of 75%is often specified for satisfactory resistance to damage by moisture. **Figures (11),(12),(13) ,(14) ,(15) and (16)** show the relationship between contact angle of water and (I.R.S) % and total surface free energy of asphalt cement (40-50) modified with fumesilica

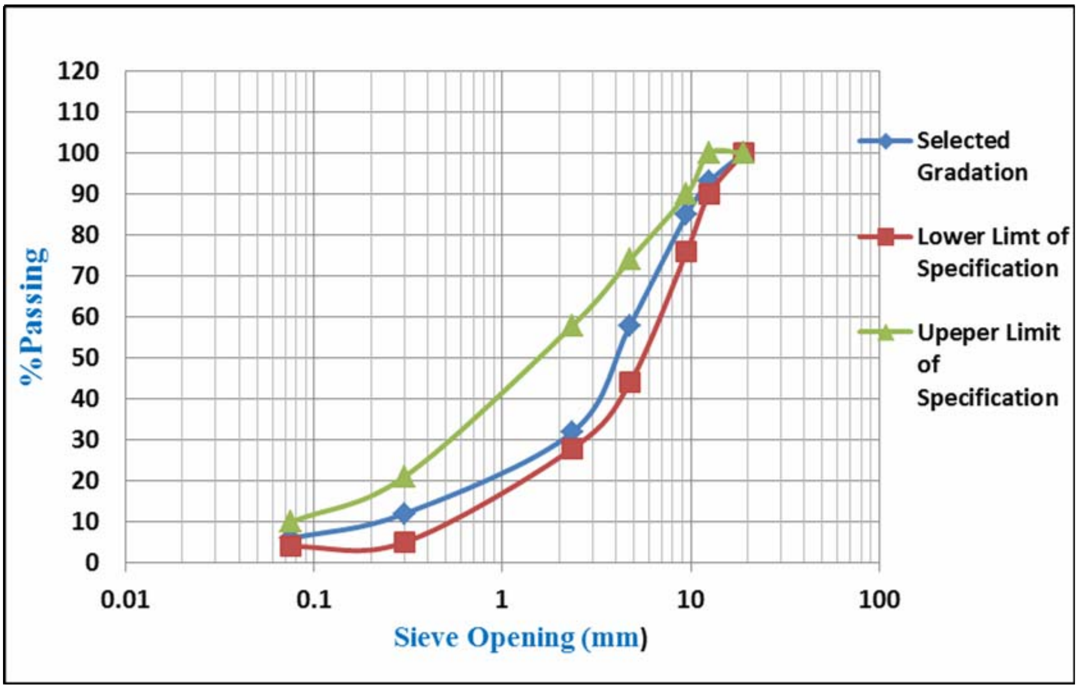


Figure (1) Gradation Curve of Aggregate Used for Wearing Course(SCRB)

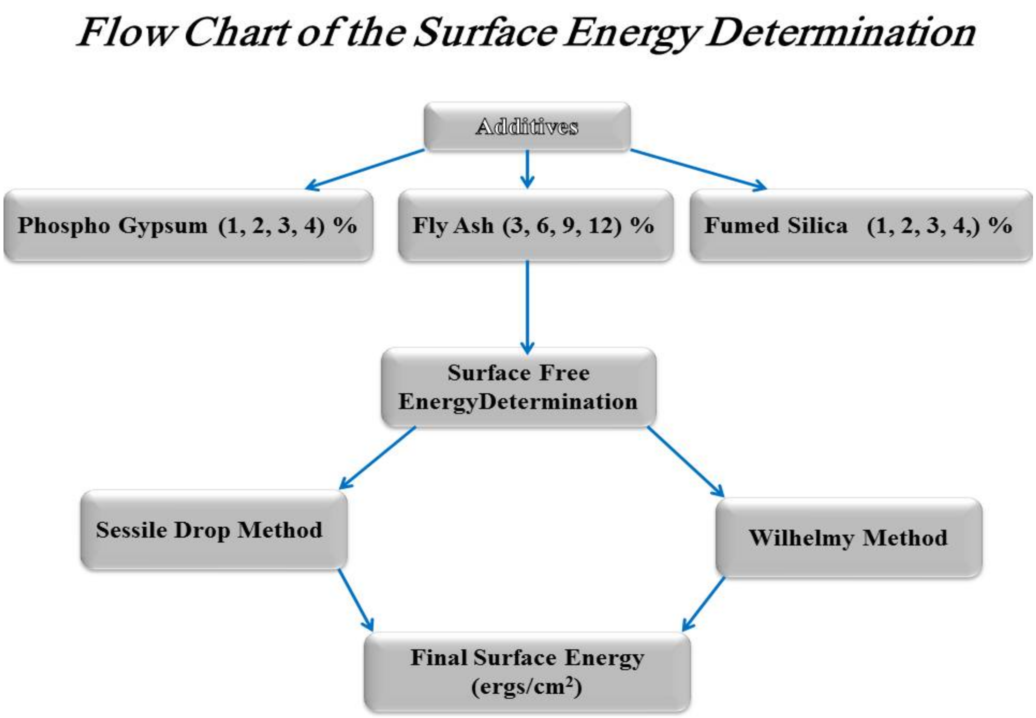


Figure (2) Flow Chart of the Surface free Energy Determination.

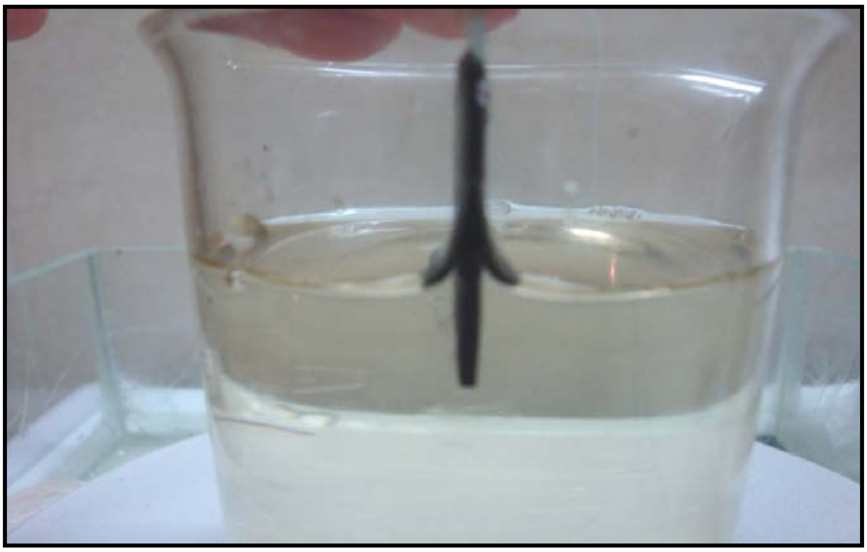


Figure (3) Contact Angle between Probe Liquid and Glass Slide Coated Asphalt

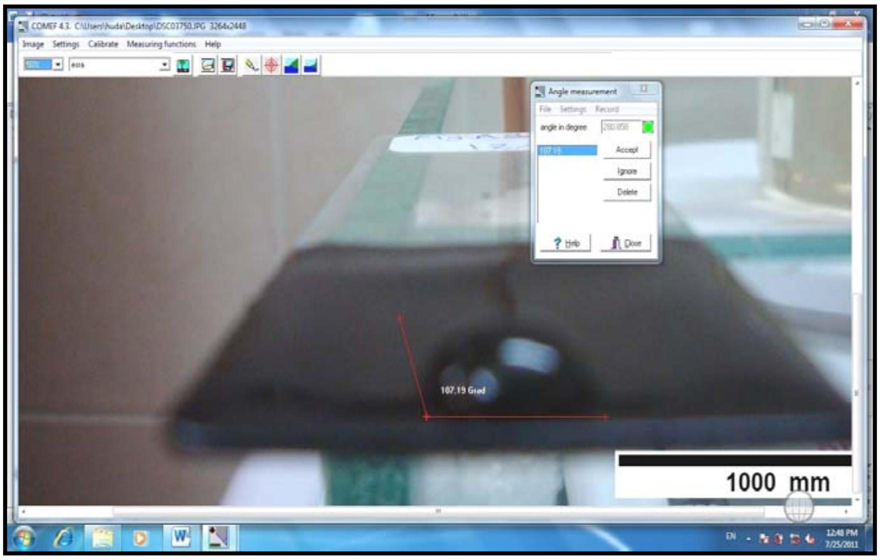


Figure (4) Output of the Comef 4.3 Software

Table (1) Surface Energy Components of the Probe Liquids [NCHRP 104 (2006)]

Probe Liquid	γ□□	γ^{+}	γ^{-}	γ^{Total} (ergs/cm^2)	Density g/cm^3
Water	21.8	25.5	25.5	72.80	0.997
Formamid	39.0	2.28	39.6	58.00	1.134
Glycerol	34.0	3.92	57.4	64.00	1.258

Table (2) Physical properties of Modified Asphalt Grade (40-50)

Asphalt(40-50)	penetration	Softening point (C°)	PI	SM(N/m^2)
control	46	51	-0.022	$1.0x10^8$
Fume Silica 1%	62	52	0.722	$8x10^7$
2%	47	51	-0.193	$1.8x10^8$
3%	37	57	0.491	$9x10^7$
4%	39	58	0.798	$0.5x10^8$
Phospho1%	26	52	-1.198	$5.5x10^8$
2%	30	53	-0.728	$3.0x10^8$
3%	33	55	-0.138	$2.0x10^8$
4%	44	57	0.889	$6x10^7$
Fly ash 3%	49.6	51.5	0.0671	$1.9x10^8$
6%	55.41	52	1.0517	$4.3x10^7$
9%	62	53.5	1.0517	$5.0x10^7$
12%	61.5	53.7	1.107	$4.8x10^7$

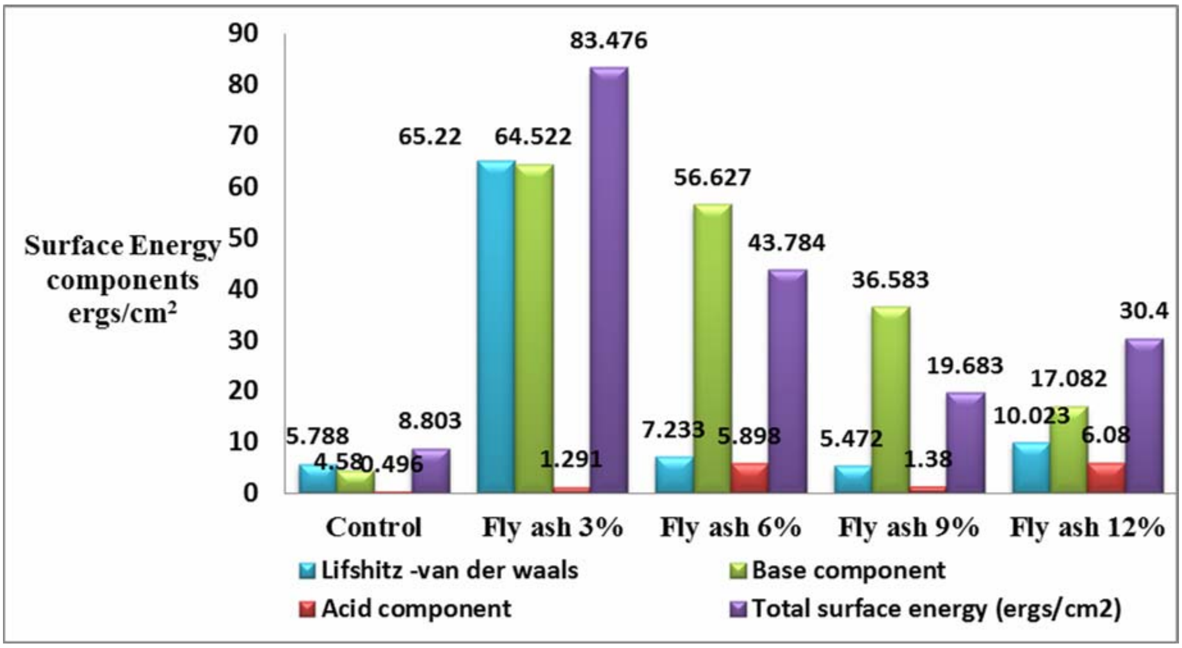


Figure (5) Effect of Fly ash on Surface Energy component of Asphalt binder by Sessile Drop Method

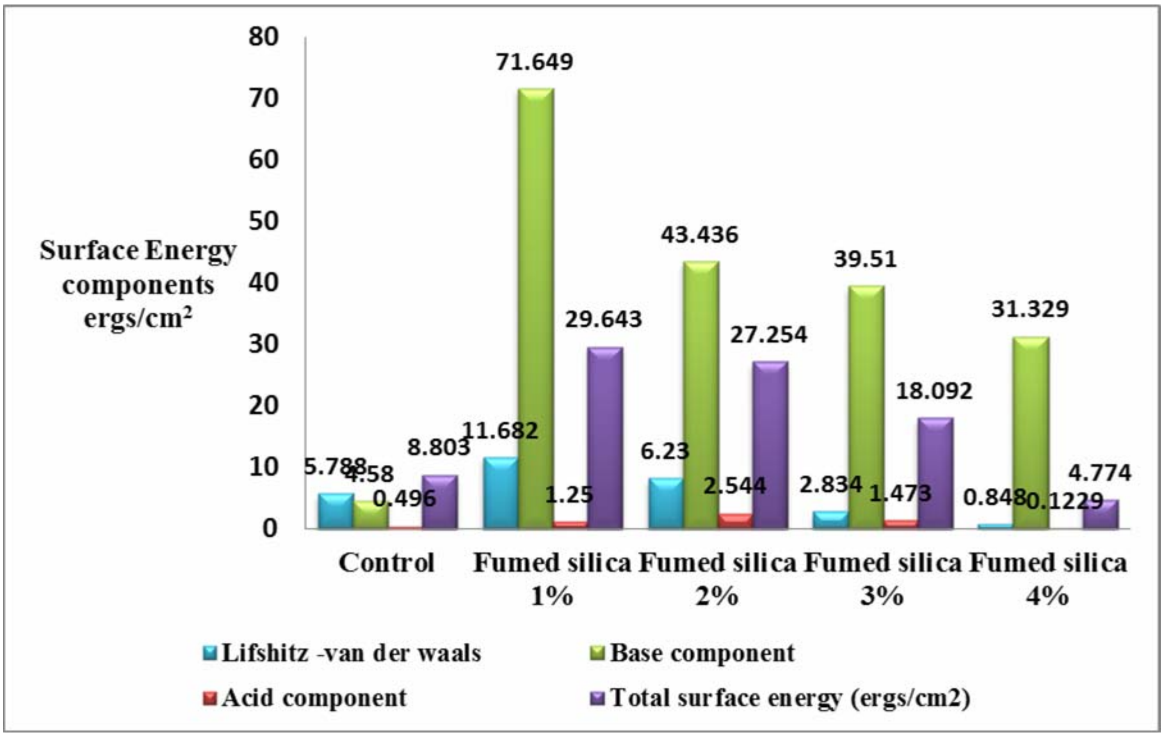


Figure (6) Effect of Fumed silica on Surface Energy component of asphalt binder by Sessile Drop Method

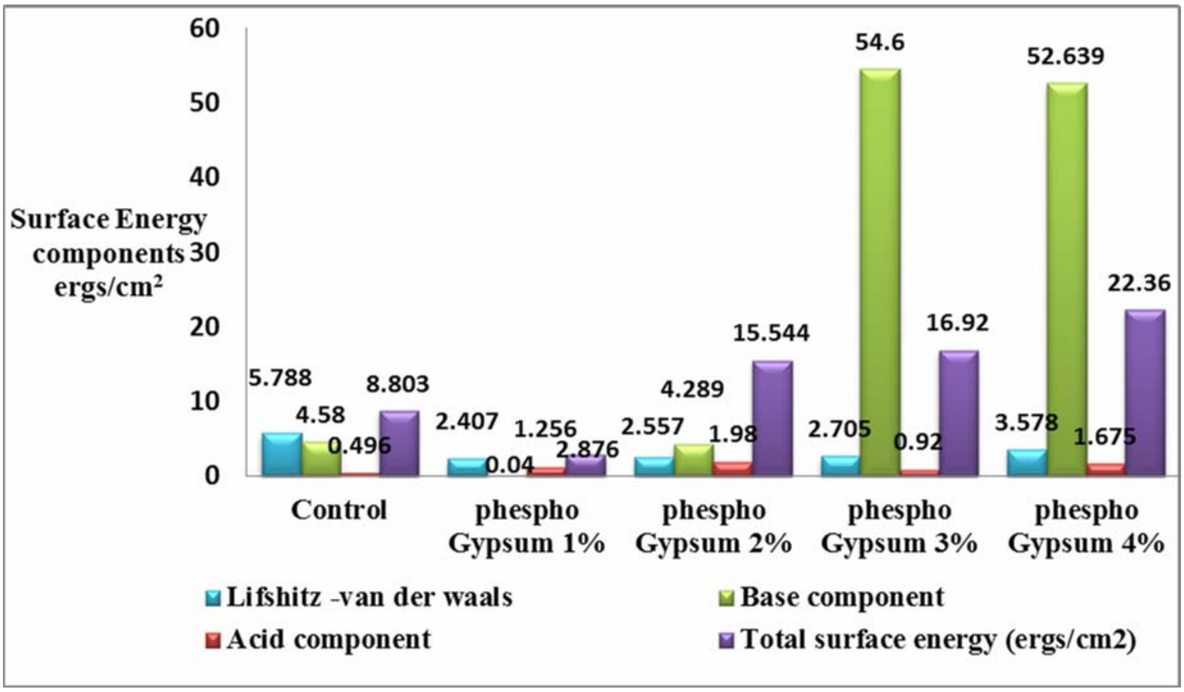


Figure (7) Effect of Phospho Gypsum on Surface Energy component of asphalt binder by Sessile Drop Method

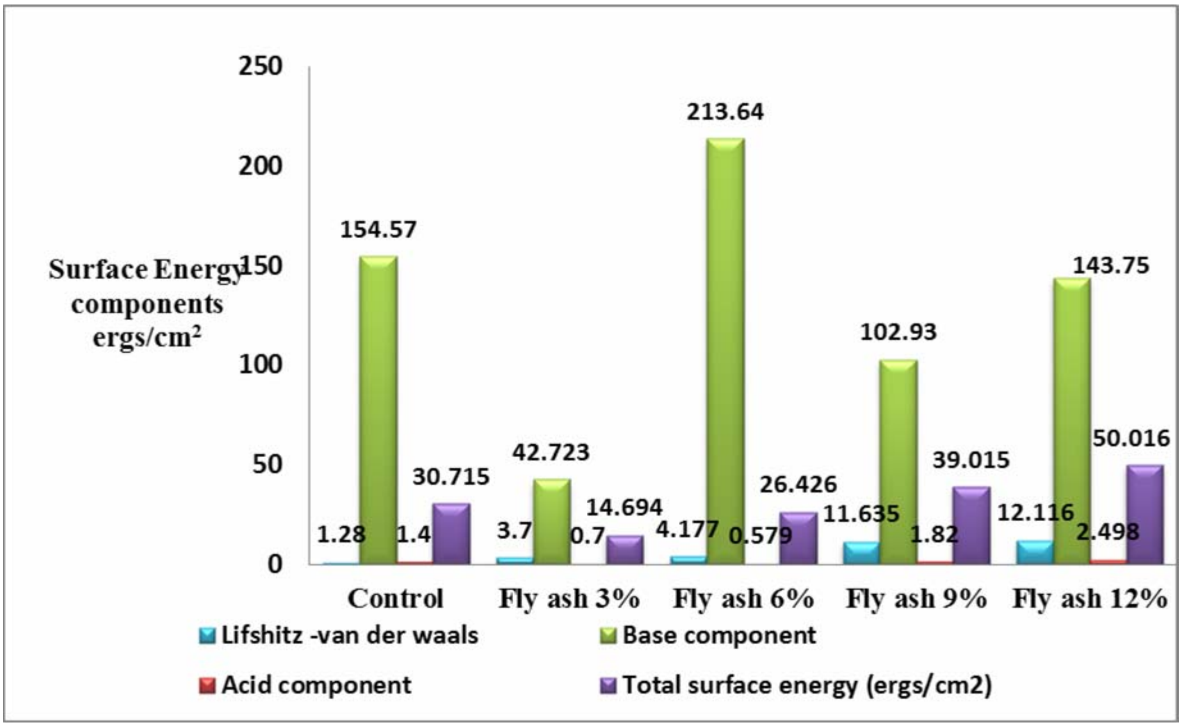


Figure (8) Effect of Fly ash on Surface Energy component of Asphalt binder by Wilhelmy Method

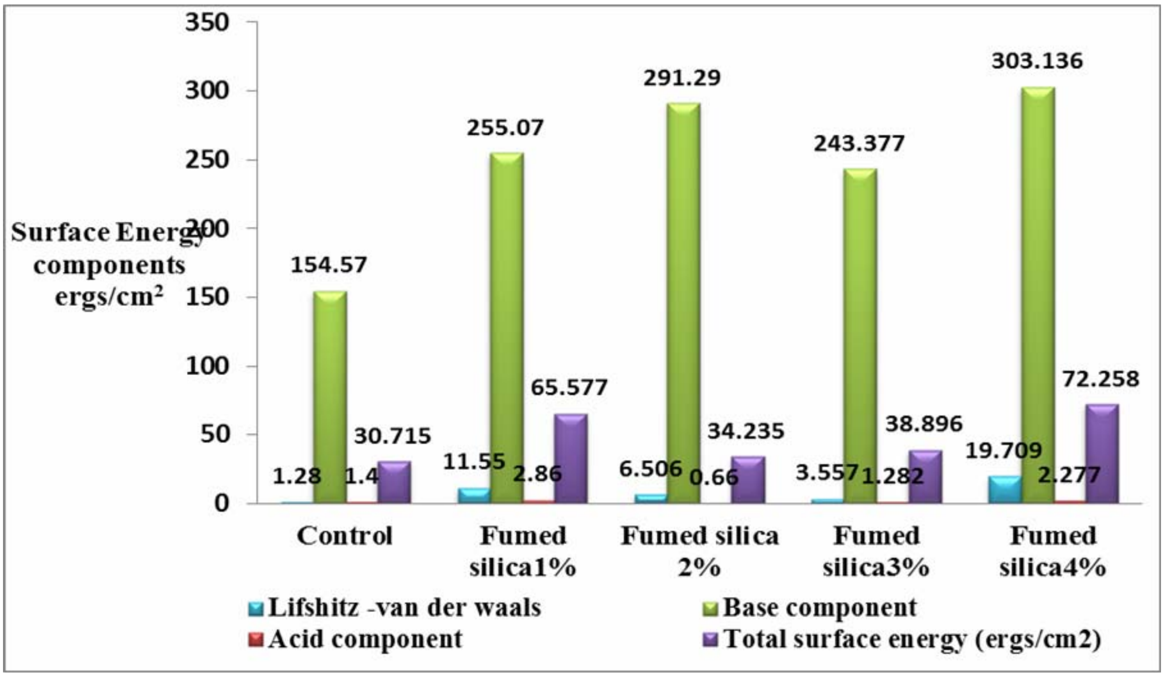


Figure (9) Effect of Fumed silica on Surface Energy components of Asphalt binder by Wilhelmy Method

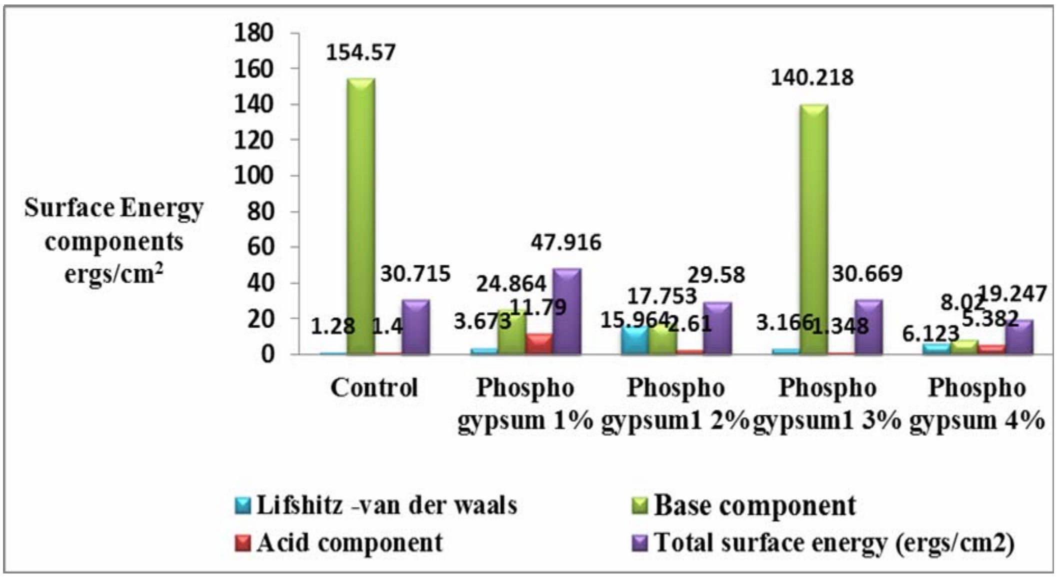
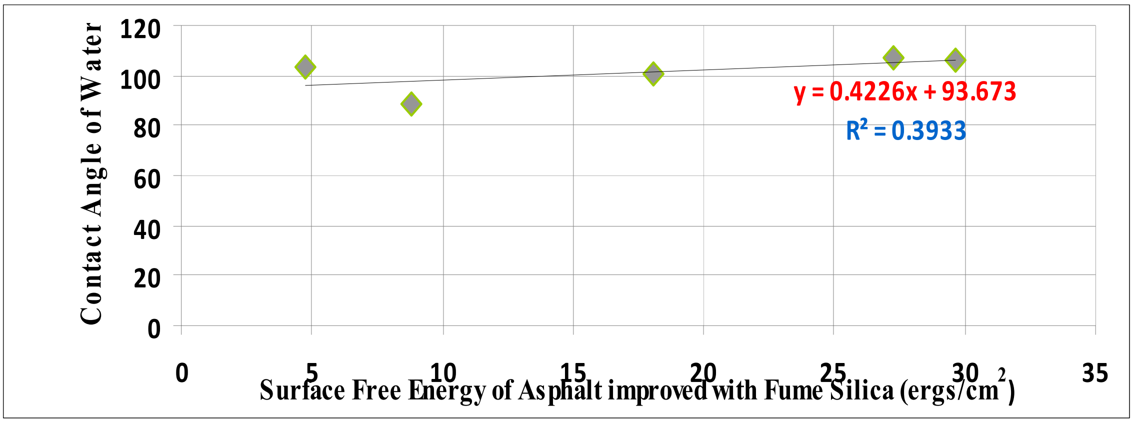


Figure (10) Effect of Phospho on Surface Energy components of Asphalt binder by Wilhelmy Method



Finger (11) Effect of fumed silica on contact angle

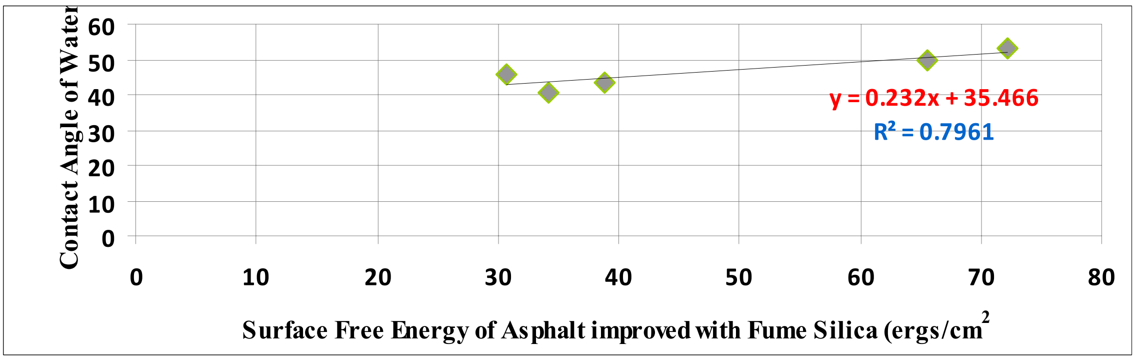


Figure (12) Effect of surface free energy on index of retained strength

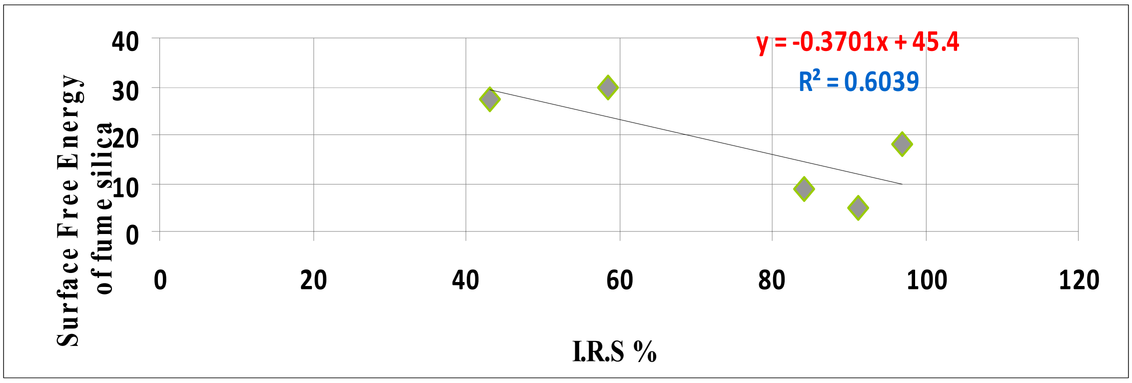


Figure (13) Surface Free Energy and I.R.S. % Relationship Using Sessile Drop Method

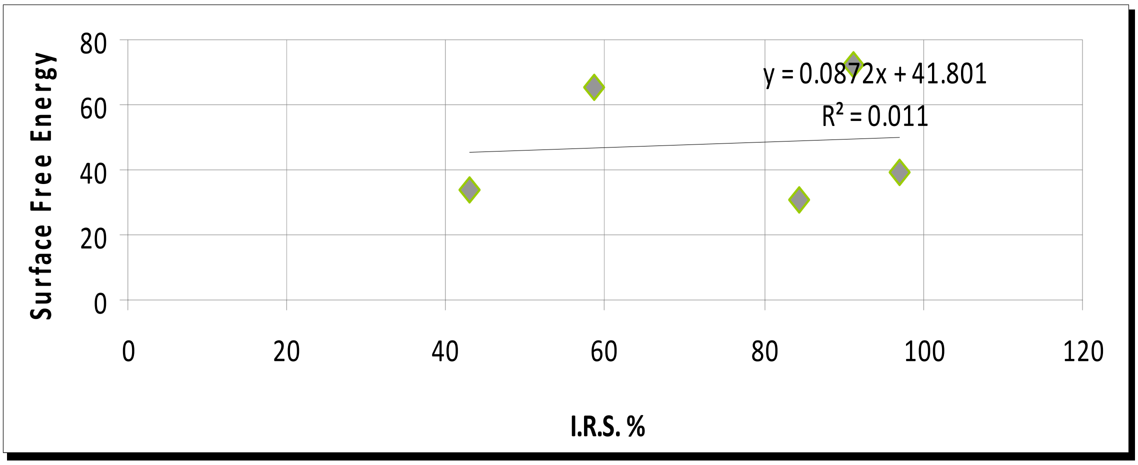


Figure (14) Surface Free Energy and I.R.S. % Relationship Using Wilhelmy Method

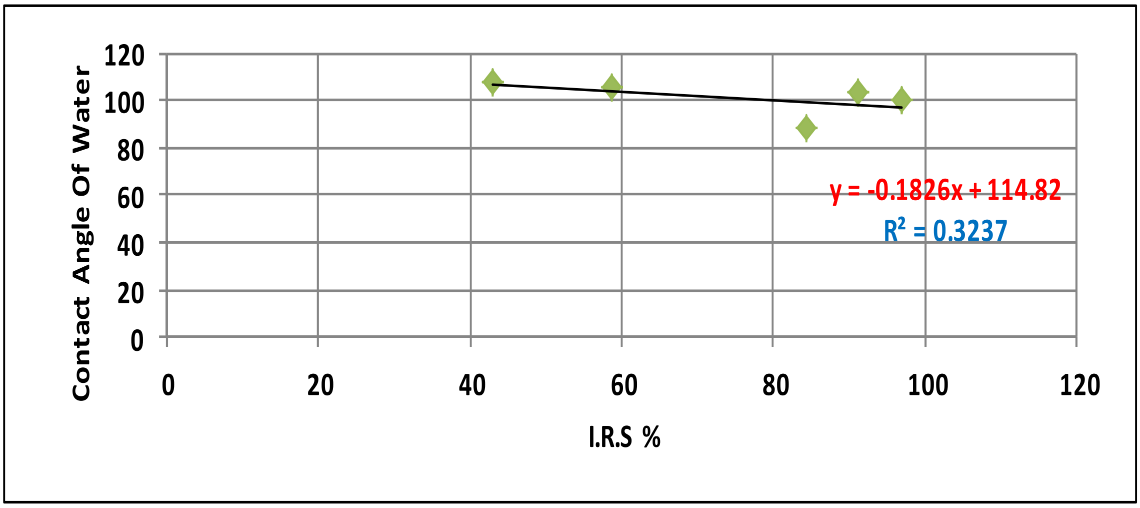


Figure (15) Contact Angle and I.R.S. % Relationship Using Sessile Drop Method

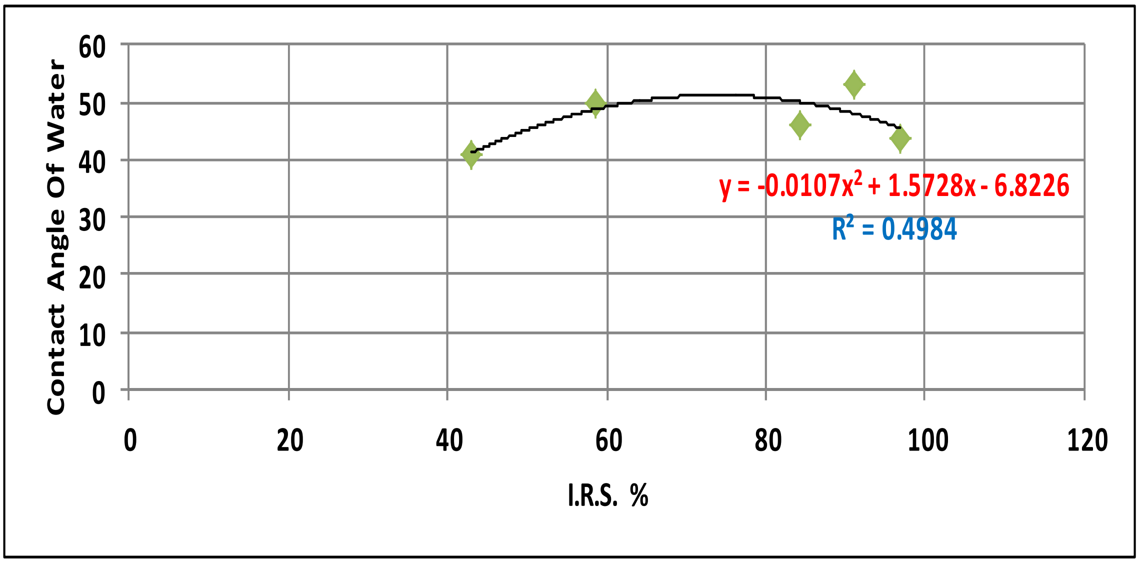


Figure (16) Contact Angle and I.R.S. % Relationship Using Wilhelmy Method

Modeling of Stripping Potential Using Surface Energy (Sessile Drop)

Linear regression is used to develop model for stripping (I.R.S. %), physical and rheological properties using SSPS statistics 17.0.
The dependent variable is % Index of Retained Stability **(%I.R.S).**

The independent variables are **SFESD, S.P, P, PVN, P. I, θ_w, θ_F, θ_G, SM.**

SFESD: Total surface free energy by sessile drop (ergs/cm^2).

P.I= penetration Index.

S.P =Softening point of asphalt cement (°C).

P=Penetration of asphalt cement.

θ_w =Average contact angle when using water as probe liquid(°).

θ_F=Average contact angle when using Formamid as probe liquid(°).

θ_G=Average contact angle when using Glycerol as probe liquid(°).

SM=stiffness modules of asphalt cement and modified asphalt (N/m^2).

It has been found that this model has an R^2 value of 0.871 and R of 0.933and the standard error of the estimated value of (42.70). The developed statistical model using SPSS software V. 17 is shown below in Eq.(19)

$$Y=-109816.12+2.4SFESD+217.2S.P-55.48P-941.89P.I+-3.484\theta_w+1.271\theta_F-1.865\theta_G+8.28x10^{-5}SM \quad (19)$$

Modeling of Stripping Potential Using Surface Energy (Wilhelmy Method)

The following variables will be included in the prediction of the model:

The dependent variable is % Index of Retained Stability **(%I.R.S).**

The independent variables are **SFEW, S.P, P, PVN, P. I, θ_w, θ_F, θ_G, SM.**

SFEW: Total surface free energy by Wilhelmy Method (ergs/cm^2).

P.I= penetration Index.

S.P =Softening point of asphalt cement (°C).

P=Penetration of asphalt cement.

θ_w =Average contact angle when using water as probe liquid(°).

θ_F=Average contact angle when using Formamid as probe liquid(°).

θ_G=Average contact angle when using Glycerol as probe liquid(°).

SM=stiffness modules of asphalt cement and modified asphalt (N/m^2).

It has been found that this model has an R^2 value of 0.827 and R of 0.909 and the standard error of the estimated value of (49.58).The developed statistical model is shown below in Eq.(20).

$$Y= -81267.65-2.16 SFEW+45.3 S.P-67.5P-109.44 P.I++ 1.9 \theta_W - 4.778 \theta_F+3.96 \theta_G +1.18x10^{-7} SM \quad (20)$$

It can be noticed that the following variables have the most positive effect on (I.R.S) % for both methods of surface energy. **Table (3)** shows the significance of such variables in descending order for Sessile drop and Wilhelmy Method.

Table (4.21) The Significant of such variables in descending order for both Method

Variable	Constant of (SDM)	Variable	Constant of (WPD)
P.I	941.89	P.I	109.44
S.P	217.20	P	67. 50
P	55.48	S.P	45.30
θ_w	3.48	θ_F	4.77
SFE	2.47	θ_G	3.96
θ_G	1.86	SFE	2.16
θ_F	1.27	θ_w	1.90
SM	8.28×10^{-7}	SM	1.11×10^{-7}

When using Sessile drop method the effect of surface free energy is significant as supported by high constant value of (2.47), while when using Wilhelmy technique the effect of surface free energy is less significant due to a lower constant value (2.16).

Conclusions

Based on the limitation of materials and test procedure in this work the following conclusions are drawn:

1. When using Sessile drop method the value of surface free energy of asphalt cement grade (40-50) was about8.8 ergs/cm^2, while when using Wilhelmy technique the value of surface free energy of asphalt cement was 30.71 ergs/cm^2.

2. The surface free energy values as calculated by Sessile drop method are higher than the values calculated by using Wilhelmy technique for both asphalt cement and modified asphalt when using fly ash. While the surface free energy values calculated by using Wilhelmy method are greater than those values calculated by using sessile drop method for both asphalt cement and modified asphalt when using fumed silica and phosphpo gypsum.

3. Higher surface free energy values were obtained when using base component of Van Oss theory as compared to the acid and Lifshitz -Van Der Waals for both methods.

4. Higher contact angle can be obtained when using sessile drop method and lower surface energy, while when using Wilhelmy technique we obtained lower contact angle and higher surface energy.

5. From the relationship between surface energy of the asphalt modified with fumed silica and the I.R.S. % when using sessile drop method it was found that the coefficient of determination (R^2) was 0.6.

6. From the relationship between the contacts angle of the asphalt modified with fumed silica and the I.R.S. % when using Wilhelmy technique it was found that the coefficient of determination (R^2) was 0.5.

7. The surface free energy concept should be considered when the stripping of asphalt concrete is under question.

LIST OF ABBREVIATION

I.R.S %: The index of retained stability.

SDM : Sessile Drop Method.

SFE: Surface Free Energy.

WPM: Wilhelmy Plate Method.

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