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Prediction of The Chemical Composition and Physical properties of Aged Asphalt Cement

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Abstract

In the present work a modification was made on three equations to represent the experiment data which results for Iraqi petroleum and natural asphalt. The equations have been developed for estimating the chemical composition and physical properties of asphalt cement at different temperature and aging time. The standard deviations of all equations were calculated.

The modified correlation related to the aging time and temperature with penetration index and durability index of aged petroleum and natural asphalts were developed. The first equation represents the relationship between the durability index with aging time and temperature.

$$\log_e(DI) = a_1 + 0.0123\left(2\log_e T - a_3\left(\frac{1}{30}t^2 + \frac{1}{2}t\right)\right)$$

The second equation represents the relationship between the penetration index with aging time and temperature.

$$\log(PI)_e = b_1 - 0.2013(T - (b_3 + b_4 t))^2$$

The third equation represents the relationship between the durability index with penetration index.

$$\log_e \log_e(PI) = a - 0.5627\log_e(DI)$$

The values of penetration index and durability index for all aged samples were compared with predicted values. These correlations give a percent of error in the range of 1.2 to 7.4%.

Kew word: chemical composition of asphalt, physical properties of asphalt, asphalt properties, and durability of asphalt

Introduction

Evaluation of asphalt physical and chemical properties is of great importance since they are directly related to the performance of asphalt pavement. asphalt, which remains after vacuum distillation of crude oil, is a complex mixture of Organic and inorganic compounds. Such compounds may be separated into asphaltenes, saturated compounds, polar aromatic compounds, and naphthene aromatic compounds [1]. Asphaltenes are defined as the black-colored fraction of bitumen that is insoluble in n-heptane. Asphalt is an extremely versatile material and its usage is widespread from paving, road building, and roofing to protective coating and hydraulic structures. Asphalt has these and various other uses as a result of certain properties it possesses like its ductility, durability, cohesiveness, its adhesive nature and its waterproof nature [2]. These properties vary greatly among different types of asphalt just as petroleum differs according to where it is obtained. Processes employed in asphalt manufacture include atmospheric-vacuum distillation, air-oxidation, solvent extraction or precipitation, chemical treatment and blending of individual stocks[3].

Natural bitumen is usually byproduct that have petroleum base and they produced from underground storages stones or they will rise up on its surface by ground layers. If bitumen rises on the ground surface it can constitute bituminous springs and if stay inside the ground and closed its force path it will be solidified and oxidized and extremely it will make a solid and hard substance that called mineral bitumen. Gilsonite is mineral bitumen, black and brittle, which is easily crushed into powder [4]. Natural bitumen is used in different industries such as petroleum production road making, found, making covers and making colors but natural bitumen directly is not used in this industry and usually it is added to the base material in the form of additive material. This combination can have different purposes like improvement of physical or chemical properties produce production with more variety or produce production with less final cost. In the petroleum derivation process that can mentioned to the shale stabilization. These additives have not any kind of effects on swelling pressure. Also, their significant bulk size prevents them from entering shales and effectively blocking pore throats. Therefore, filtrate invasion and mud pressure penetration will proceed unretarded [5].

Ishaiet[6,7] have adopted the durability index to reflect the relationship between aging and the internal colloidal structure of an asphalt . This index is given by the ratio of the sum of the asphaltenes and saturates to the sum of the polar aromatics and naphthene aromatics (equation 1).

$$DI=\frac{A+S}{PA+NA} \qquad \ldots(1)$$

Where, A is the asphaltenes content, S is the saturates content, PA is the polar aromatics content and NA is the naphthene aromatics.

Thus if the rate of deviation of the colloidal condition from the optimum or the initial could be considered as representing a measure of the susceptibility of the asphalt to durability problems , then the durability index could play a useful role[8].

The asphaltenes and polar aromatics fraction are considered the solid portion and, therefore, as the phase dispersed in an oily medium supplied but the resins components. Asphaltenes phase are thought to be convert by a sheath of high–molecular –weight, aromatic resin acting as a stabilizing solvating layer. There is a gradual reduction in the resinous character of a medium in a direction away from the center of a micelle. A stabilized micelle would not normally precipitate unit a solvent is added to reduce the peptizing power of the dispersion medium, thus affording the asphaltenes the freedom to agglomerate and precipitate. This idea presents asphaltenes as being some discrete particles already existing in the asphalt ; according to Boduszynski[8] et al., however , it is the non-polar solvent that upsets the solubility equilibrium of the system and causes the most polar compound types to agglomerate and precipitate as a Asphaltenes [9]. Simulation of aging time of asphalt cements is a widely used procedure in asphalt cements characterization for predicting the durability response to plant mixing and paving under controlled laboratory conditions. There are numerous equation for evaluating the aging time of asphalt cement.

Anderson [10] is used an exponential model for predicting the aging time of asphalt cement, represented as equation 2 and 3.

$$\log_e(p(t,T)) = a_1 + a_2(T - (a_3 t^2 + a_{4t})) \quad \ldots(2)$$

$$C(t,T) = b_1(T - (b_4 t^2 + b_5 t))^2 + b_2(T - (b_4 t^2 + b_5 t)) + b_3 \quad \ldots(3)$$

Where, t is the aging time in thin film oven test; T is the temperature; a_1 and a_2 are the model coefficients for predicting the physical properties of asphalt cements, a_3 and a_4 are the temperature shift coefficients , b_1 , b_2, and b_3 are the model coefficient for evaluating the chemical properties of asphalt cements, b_4 and b_5 are the temperature shift coefficient .The coefficients a_1, a_2, b_1, b_2, and b_3 are obtained using least squares regression of equations 2 and 3 and using the temperature shift coefficients a_3, a_4, b_4, and b_5 .Anderson found that the error are higher close to the middle range of temperature (30-46^{o}C) as well as at extreme low and high temperature. This predictions can be improved if this models are used for the high temperature and intermediate temperature; however, this will result in an increased complexity of the models and associated shift factors. The error is insignificant except at the lowest test temperature of 7^{o}C, which reflects the inability of the model to capture this extreme range.

Brule B. [11] suggests a definite relation between the durability index and asphalt viscosity or penetration of asphalt cement. This relation is equation 3-4 contained two parameters.

$$\log_e(n) = a + b(DI) \quad \ldots(4)$$

Where, a and b are the parameters of equation 4; n is the viscosity or penetration of the asphalt cements ; and DI is the durability index of the asphalt cements .This equation is applied on asphalt cements (paving grade) for evaluating the durability index at any viscosity or penetration. The parameters a and b are obtained using least square method of equation 4. Brule found that a strong correlation exists between the durability index and physical property (viscosity and penetration). This correlation is a confirmation of the fact that asphalt rheology is a direct consequence of the interaction of the fractional components and that the durability index summarizes the overall colloidal character of an asphalt during aging.

Eyring [10] developed an a approximate theor, for the estimation of viscosity as a function of temperature. This theory is based on the physical properties of the heavy liquids or semi-solid. Amin and Maddox [12, 13] reviewed the common correlation used for the prediction of the heavy liquid viscosity. Benson [14] addressed the relation between low temperature cracking of asphalt pavements in Texas, and asphalt hardening. Nine test sections were evaluated in detail and relationship between asphalt physical properties and performance established. Good correlations were found between the viscosity at 25^{o}C, aging index, and air voids with performance. Laboratory mixture samples17 in. in diameter by 2 in. deep was compared using a Texas gyrator compactor. These laboratory samples were called pizzas. Pizzas were aged in the field in two locations with different levels of solar radiation and precipitation. Control sets were stored in the laboratory. After three years the pizzas were cored, tested for resilient modulus, and penetration and viscosity tests, both at 25°C were carried out on the recovered asphalt. The majority of pizzas were regular dense mix. However, a set of 15 was made using an antihardening additive. This was a combination of paraphenyciene diamine antiozonates and ultraviolet light inhibitors, at a treatment level of 1%. Benson also conducted the ``Actinic Light Test`` on asphalt samples. The test was conducted on 10 micron films with the following conditions: 95°C, 18 hours, and 100 micro-watts/cm^3 of 3660 angstrom wavelength radiation. These are identical to the condition reported by Kemp and Predoehi. The thin film oven test was also conducted [13,14].An excellent feature of Benson's study is the hardening models developed. These were developed for viscosity and penetration and take the form of equation 5 and 6.

$$\nu = at^b \qquad \ldots(5)$$

$$P = c + d(t) \qquad \ldots(6)$$

Where, ν is the kinematic viscosity at 25°C, P is the penetration at 25°C, t is the time (months), and a, b, c and d are the coefficients of equation 5 and 6. Benson notes that the key to applying this model is to predict the parameter, ``c`` and ``d``, and that ``d`` is a measure of short-term hardening. Since when t is equal to one month.

$$P = c + d\ln(1) = c \qquad \ldots(7)$$

The parameter ``c`` relates to the curvature and represents long-term aging susceptibility. A predictive equation for ``c`` was developed from multiple regression analysis, yielding

$$c = 0.52(ORP) - 2 \qquad \ldots(8)$$

where, ORP is the original penetration.

The aim of the present work deals with study a method for prediction a relationship between the aging time and temperature with durability index and penetration index. Also, study a method for prediction a correlation between the durability and penetration index for aged natural and petroleum asphalt cements at different aging time and temperatures.

Experimental

Three grades of petroleum asphalt are supplied from Daura refinery, while two grades of natural asphalt is brought from Hiit city. The physical and chemical properties of these asphalt cements are presented in table 1 and 2**.**

Penetration Test

Penetration (ASTM-D1754) is a test for the consistency of asphalt. It is based on a standard needle entering asphalt under fixed conditions. The depth of the peneteration of the standard needle into the material to be tested within 5 seconds, with a load of 100gm at 25°C is measured in this standard tests. The penetration is measured in 0.1 mm.

Group Composition Separation Test

Group composition (ASTM-D2024) for all petroleum and natural and aged asphalts are determined by adsorption chromatography. A glass percolation column (20 mm diameter, 400 mm height) was filled with 300 gm activated alumina F20. A 500 ml separating funnel containing the deasphaltened sample was put in the top of the column.

Durability Test

The standard thin film oven test (ASTM-D1754) has been employed to aged the asphalt film at different temperatures and times for various types of petroleum and natural asphalt cements. All aged samples have been tested for penetration, kinematic viscosity, softening point, heat loss, and solubility in trichloroethylene. Separation of asphaltenes, polar-aromatics, naphthene-aromatics, and saturates were carried on all aged samples. The changes in physical properties and chemical composition properties of asphalt cements due to the effect of heat and air are evaluated by thin film oven test .In all tests 3.2 mm film thickness of asphalt cements is placed in cylindrical pans in an ovenmaintained at temperatures 150, 163, and 175°C for aging intervals 5, 10, 15, 20, 25 and 30 hours. Changes in the various physical and chemical properties after oven aging are then determined.

Result and Discussion

Ishaiet [6, 7] summarized the chemical composition of petroleum and natural asphalt cement according to the durability index. The durability index was calculated by equation 1 which correlated with DI.

In this investigation a correlation 9 has been developed for prediction chemical composition of asphalt cement according to the DI base as a function of aging and temperature. The correlation was tested on a range of temperature 150 to 175°C and a range of aging time 5 to 30 hours.

$$\log_e(DI) = a_1 + a_2\left(2\log_e T - a_3\left(\frac{1}{30}t^2 + \frac{1}{2}t\right)\right) \quad \ldots(9)$$

where, T and t are the aging time (hours) and temperature (°C), respectively, a_1, a_2, and a_3 are the parameter of equation 9.

The mean and standard deviation error for prediction of durability index by using equation 9 is calculated by statistical method. The values of empirical parameters of equation 9 with SD and error for each aged samples of asphalt cements are summarized in table 3. This table indicates that the correlation is yielded lowest value of mean and standard deviation for all aged asphalt cements. Figures 1 to 3 show the observed value and predicted value of durability index with aging time at 150°C. These figures report that a strong correlation exists between the durability index and aging time. Therefore, the correlation 9 simple to use and gives results in good agreement with experimental values. The prediction values are reported in table 4 to 6.

The parameter a_2 in equation 9 represents the slope of this equation. The values of parameter a_2 is ranged from 0.0067 to 0.0164. This parameter can be considered as a constant value. An average slope for all aged asphalt was 0.0123. This average value could be used as the value of parameter a_2 and it gives the best percent of error between the experimental and predicted durability index of aged asphalt cement. Then the equation 9 could be written as:

$$\log_e(DI) = a_1 + 0.0123\left(2\log_e T - a_3\left(\frac{1}{30}t^2 + \frac{1}{2}t\right)\right) \quad \ldots(10)$$

Equation 10 contains two parameters a_1 and a_3 which can be calculated by least square method. These calculated parameter and percent error are summarized in table 7. The percent error was ranged from 2.5 to 5.45, so this equation gives better agreement with experimental values, than equation 9.

To predict the physical properties of an asphalt cement as a function of aging time and temperature, the penetration index is used. Equation 3 can be used to predict the physical properties is represented by penetration index proposed originally by A. Shalabiy [15]. A modification of equation 3 was done to obtain equation 11.

$$\log(PI)_e = b_1 + b_2\left(T - (b_3 + b_4 t)\right)^2 \quad \ldots(11)$$

where, PI is the penetration index, b_1, b_2, b_3, and b_4 are the parameters of equation 11, t is the aging time (hour), and T is the temperature (^{o}C). The parameters of equation 11 are obtained using least square method. The values of parameters, standard deviation and percent of error for equation 11 are shown in table 8. The parameter b_2 is represented the slope of equation 11. It is seen from the table 8, that the equation 11 gives acceptable agreement with experimental data, where the percent of error for all aged samples is ranged from 1.5 to 6.5. The parameter b_2 in equation 11 represents the slope of this equation. From table 8 it is interesting to note that the values of parameter b_2 in equation 11 can be considered as a constant value by taking the average slope for all aged asphalt. This average value of the slops is equal to –0.2013. Then equation 11 become as follow:

$$\log(PI)_e = b_1 - 0.2013\left(T - (b_3 + b_4 t)\right)^2 \quad \ldots(12)$$

The values of parameters, SD, and the percent of error for equation 12 are summarized in table 9. It is seen from the table 9, that the equation 12 gives acceptable agreement with experimental data, where the percent of error for all aged samples is ranged 2.2 to 7.4. To avoid using a single component fraction to estimate the behavior of an asphalt in the aging process. Ishaiet [6, 7] favor the use of the durability index in terms of its colloidal stability during aging. Thus durability index can be correlated with the physical character of asphalt by measuring the penetration index. The penetration index summarize the softening point and penetration of asphalts. Equation 4 can be used to predict the physical properties with chemical composition is proposed originally by Brule B[11]. In this work a modification for equation 4 was done and equation 13 was obtained for all aged asphalt cement.

$$\log_e \log_e(PI) = a + b\log(DI) \quad \ldots(13)$$

where, PI is the penetration index , DI is the durability index and a and b are the parameters of equation 13.

The values of the parameters, SD, and percent of error of equation 13 based on experimental data of aged asphalt are summarized in table 10. This table indicates that equation 13 gives acceptable agreement with experimental data, where the percent of error ranged from 1.4 to 5.3. Equation 13 indicates that the parameter b are represented the slope of this equation. This slope for all aged asphalt can be considered as one value by taking the slop average. The value of the parameter b is ranged from –0.3401 to –0.8102%. Therefore, the value average of b is –0.5627. So the final equation becomes:

$$\log_e \log_e(PI) = a - 0.5627\log(DI) \quad \ldots(14)$$

The values of parameter a, the percent of error, and SD for equation

14 are summarized in table 11. This table indicate that the results calculated by equation 14 were very satisfactory with a percent of error ranged from 1.2 to 5.9 %.

Conclusions

Three equations are developed to predict the chemical and physical properties of natural and petroleum asphalt.

1. The first equation is developed to evaluate the durability index with aging time at a wide range of temperature.
2. The second equation is developed to evaluate the penetration index with aging time at a wide range of temperature.
3. The third equation is developed to evaluate the durability index with penetration index for all aged asphalt cement.

Nomenclature

A asphaltenes (% by wt.)
DI Durability index
N Naphthene aromatic content, (%, by wt.)
P Penetration, (0.1 mm)
PA Polar aromatic content, (%, by wt.)
PI Penetration index
S saturation content , (%, by wt.)
SP Softening point. oC
SD Standard deviation
T Temperature, (oC)
t Aging time, (hour)

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Table 1, Physical and chemical properties of petroleum asphalt cements

Test		Petroleum Asphalt grade			Test Method
		40-50	60-70	21-30	
1	Penetration (0.1mm)	48	68	22	ASTM-D5
2	Softening Point R&B(^{o}C)	51	50	87	ASTM-D36
3	Kinematic Viscosity at 135^{o}C (cSt)	443	356	1042	ASTM-D2170
4	Solubility in Trychloroethylene (% wt.)	99.7	99.8	99.1	ASTM-D86
5	Fractional Composition (%wt)				ASTM-D2024
	Asphaltenes	21.2	17.9	34.1	
	Saturates	21.3	16.3	22.3	
	Naphthene-aromatics	44.5	45.9	30.5	
	Polar-aromatics	11.5	20.9	13.0	
6	Thin Film oven Test				ASTM-D1754
	Loss by Heating (% wt.)	0.3	0.5	0.3	
	Penetration (0.1mm)	36	46	16	
	Softening Point(^{o}C)	54	55	90	

Table 2, Physical and Chemical properties of natural asphalt cements

Test		Natural Asphalt grade		Test Method
		49	35	
1	Penetration (0.1mm)	49	35	ASTM-D5
2	Softening Point R&B(^{o}C)	66	78	ASTM-D36
3	Kinematic Viscosity at 135^{o}C (cSt)	428	625	ASTM-D2170
4	Solubility in Trichloroethylene (% wt.)	88.6	89.2	ASTM-D86
5	Fractional Composition (% wt.)			ASTM-D2024
	Asphaltenes	17.9	10.2	
	Saturates	9.7	17.9	
	Naphthene-aromatics	53.4	49.7	
	Polar-aromatics	19.9	21.9	
6	Thin Film oven Test			ASTM-D1754
	Loss by Heating (% wt.)	2.0	2.5	
	Penetration(0.1mm)	39	28	
	Softening Point(^{o}C)	68	83	

Table 3, The parameters of equation 9 for aged natural and petroleum asphalt cements at different temperatures

Asphalt grade	Temperature, ^{o}C	a_1	a_2	a_3	SD	Error, %
60-70	150	-0.79699	0.00671	-1.50124	0.46	4.53
60-70	163	-0.73535	0.00736	-1.50213	0.47	4.67
60-70	175	-0.74339	0.00903	-1.52960	0.48	6.58
40-50	150	-0.47818	0.01047	-1.24173	0.49	7.56
40-50	163	-0.39966	0.01032	-1.24530	0.45	3.58
40-50	175	-0.37199	0.01100	-1.25480	0.46	2.54
21-30	150	+0.09746	0.00889	-1.05035	0.24	2.65
21-30	163	0.007867	0.01608	-0.88926	0.15	8.11
21-30	175	+0.01623	0.01611	-0.92119	0.4	7.68
35	150	-1.08704	0.00794	-1.67659	1.03	7.58
35	163	-1.06080	0.00811	-1.70790	3.15	7.64
35	175	-1.05859	0.00791	-1.75119	1.25	6.68
49	150	-1.06488	0.00706	-1.67414	0.26	8.22
49	163	-1.04464	0.00726	-1.70882	0.25	8.95
49	175	-0.99915	0.00772	-1.71534	0.28	8.65

Table 4, Predicted value of durability index with aging time for aged asphalt cement grade 60-70 and 40-50

Aging time, hour	Predicted DI of asphalt grade 60-70 at 150°C	Predicted DI of asphalt grade 60-70 at 163°C	Predicted DI of asphalt grade 60-70 at 175oC	Predicted DI of asphalt grade 40-50 at 150°C	Predicted DI of asphalt grade 40-50 at 163°C
0	0.496	0.519	0.727	0.727	0.752
5	0.542	0.584	0.818	0.818	0.874
10	0.591	0.652	0.917	0.917	1.002
15	0.643	0.720	1.025	1.023	1.130
20	0.697	0.787	1.142	1.322	1.256
25	0.755	0.852	1.267	1.427	1.376
30	0.8163	0.914	1.462	1.434	1.482

Table 5, Predicted value of durability index with aging time for aged asphalt cement grade 40-50 and 21-30

Aging time, hour	Predicted DI of asphalt grade 40-50 at 175°C	Predicted DI of asphalt grade 21-30 at 150°C	Predicted DI of asphalt grade 21-30 at 163oC	Predicted DI of asphalt grade 21 -30 at 175°C	Predicted DI of asphalt grade 35 at 150°C
0	0.7974	1.2300	1.3258	1.3425	0.3993
5	0.9241	1.4256	1.5146	1.5564	0.4187
10	1.0591	1.5125	1.7324	1.79252	0.4413
15	1.1998	1.6325	1.9567	2.0435	0.4672
20	1.3440	1.7626	2.2024	2.3145	0.4971
25	1.4884	1.8923	2.4671	2.5934	0.5314
30	1.8780	2.0425	2.7467	2.8874	0.5708

Table 6, Predicted value of durability index with aging time for aged natural asphalt cements grade 35 and 49

Aging time, hour	Predicted DI of asphalt grade 35 at 163°C	Predicted DI of asphalt grade 35 at 175°C	Predicted DI of asphalt grade 49 at 150°C	Predicted DI of asphalt grade 49 at 163°C	Predicted DI of asphalt grade 49 at 175°C
0	0.4016	0.4027	0.3715	0.3732	0.3856
5	0.4273	0.9395	0.4169	0.4246	0.451
10	0.4622	0.4837	0.4661	0.4635	0.5186
15	0.5082	0.5376	0.5176	0.5413	0.587
20	0.5672	0.6029	0.5695	0.5985	0.6548
25	0.6442	0.8266	0.5224	0.6552	0.7106
30	0.7427	0.7799	0.6764	0.7092	0.7762

Table 7, The parameter of equation 10 for aged natural and petroleum asphalt cement at different temperature

Asphalt grade	Temperature, °C	a_1	a_3	SD	Error, %
60-70	150	-1.8616	-0.0818	1.52	2.56
60-70	163	-1.7631	-0.1123	1.54	2.42
60-70	175	-1.8183	-0.0899	1.58	2.45
40-50	150	-1.4484	-0.1056	1.54	4.26
40-50	163	-1.3898	-0.1044	1.53	4.65
40-50	175	-1.3801	-0.1265	1.52	4.87
21-30	150	-0.9123	-0.0759	0.67	5.36
21-30	163	-0.8513	-0.1162	0.68	5.25
21-30	175	-0.8382	-0.1207	0.65	5.45
35	150	-2.1208	-0.1082	0.82	3.52
35	163	-2.1073	-0.1126	0.56	3.85
35	175	-2.1247	-0.1125	0.58	3.47
49	150	-2.1205	-0.0962	0.82	3.67
49	163	-2.1128	-0.10088	1.34	2.56
49	175	-2.0703	-0.1076	1.35	2.41

Table 8, The parameters of equation 11 for aged natural and petroleum asphalt cements at different temperatures

Asphalt grade	T, °C	b1	b2	b3	b4	SD	Error, %
60-70	150	5.1997	-0.5242	7.6657	1.0670	2.3400	4.2500
60-70	163	3.2452	-0.2114	3.9908	0.3823	1.4890	4.6700
60-70	175	3.2538	-0.0216	3.8575	0.0477	1.4567	5.3700
40-50	150	4.8011	-0.5097	7.6389	1.0554	1.9200	5.6480
40-50	163	1.3542	-0.6350	0.0889	0.8419	2.0642	5.7854
40-50	175	1.2701	-0.0042	3.0526	0.3056	2.0365	6.4820
21-30	150	5.3118	-0.5166	7.6336	1.0530	2.3564	2.3450
21-30	163	2.0095	-0.0082	3.6363	0.1635	2.5845	5.4558
21-30	175	1.8267	-0.0017	2.0263	0.2548	2.5687	2.3542
35	150	1.8266	-0.0018	1.9732	0.2474	2.9860	1.6500
35	163	1.9791	-0.0042	1.0886	0.1434	2.3580	7.3500
35	175	1.9642	-0.0048	0.4029	0.1719	1.5680	1.5680
49	150	5.7338	-0.5463	7.7209	1.0865	1.8650	6.1350
49	163	1.70915	-0.0024	3.7670	0.3149	1.025	6.1235
49	175	1.73552	-0.0028	5.7351	0.3866	1.0265	1.9860

Table 9, The parameters of equation 12 for aged natural and petroleum asphalt cements at different temperatures

Asphalt grade	T, °C	b1	b3	b4	SD	Error, %
60-70	150	-11.0929	-2.9345	-0.0029	1.2800	4.3658
60-70	163	-10.9520	-2.8250	-0.0050	1.3589	4.9867
60-70	175	-11.3116	-2.8559	-0.0062	1.2568	6.2365
40-50	150	-11.3676	-2.9655	-0.0041	2.2356	4.3255
40-50	163	-11.3468	-2.7983	-0.0042	2.2568	5.2365
40-50	175	-11.3683	-2.6324	-0.0041	2.8670	3.6569
21-30	150	--2.5898	-1.3417	0.0028	2.2654	2.21658
21-30	163	-2.02278	-1.7356	0.0076	2.5689	5.3658
21-30	175	-2.9255	-0.9369	0.0063	3.1256	3.0023
35	150	-2.4660	-1.3695	0.0018	2.2365	5.7890
35	163	-14.2725	-3.8974	0.0028	5.2356	7.3500
35	175	-22.2107	-5.8224	0.0030	3.5659	2.0576
49	150	-23.8407	-6.3238	0.0018	1.2256	6.2350
49	163	-20.6682	-5.5119	0.0021	2.9867	4.2356
49	175	-30.4734	-7.5612	0.0021	2.3654	2.3659

Table 10, The parameters of equation 13 for aged natural and petroleum asphalt cements at different temperatures

Asphalt grade	T, °C	A	B	SD	Error, %
60-70	150	1.1038	-0.5323	0.2660	2.3546
60-70	163	0.9974	-0.7845	0.5623	1.5680
60-70	175	1.0039	-0.7792	0.5433	3.2564
40-50	150	1.1190	-0.5763	0.3000	1.3568
40-50	163	1.1284	-0.6415	0.6701	2.3250
40-50	175	1.1421	-0.6103	0.9911	4.2350
21-30	150	1.8407	-0.3403	0.3837	3.5600
21-30	163	1.9016	-0.5022	0.5863	4.0020
21-30	175	2.0062	-0.7900	0.7460	5.0102
35	150	1.3461	-0.5139	0.4914	5.3260
35	163	1.3613	-0.4874	0.51263	4.2200
35	175	1.2729	-0.5110	0.7461	4.3265
49	150	1.3711	-0.3750	0.5687	4.0025
49	163	1.3407	-0.4014	0.8925	5.0002
49	175	1.3346	-0.5291	0.54821	3.4520

Table 11, The parameter of equation 14 for aged natural and petroleum asphalt cements at different temperatures

Asphalt grade	T, °C	A	SD	Error, %
60-70	150	1.0893	0.3660	1.2356
60-70	163	1.0849	0.6523	1.9820
60-70	175	1.0764	0.7213	3.0254
40-50	150	1.1195	0.3120	1.3023
40-50	163	1.1259	0.6103	3.5680
40-50	175	1.1195	1.0911	4.9720
21-30	150	1.9445	1.0330	3.72562
21-30	163	1.9332	0.6860	5.1240
21-30	175	1.8660	0.8250	5.32102
35	150	1.3087	0.3568	5.9250
35	163	1.3093	0.5613	4.0010
35	175	1.2942	0.5681	4.0001
49	150	1.2365	1.3568	5.3200
49	163	1.2301	0.9925	4.0025
49	175	1.3128	0.5531	3.4520

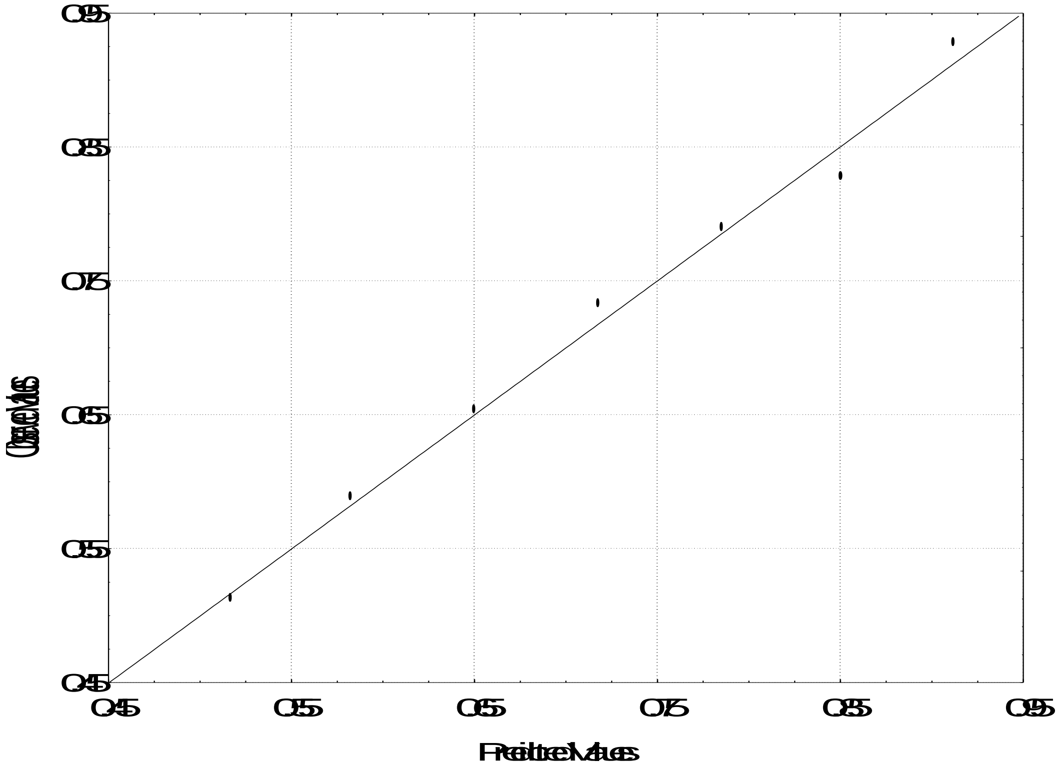

Fig. 1, Observed and predicted value of durability index for aged asphalt cement grade 60-70 at 150°C

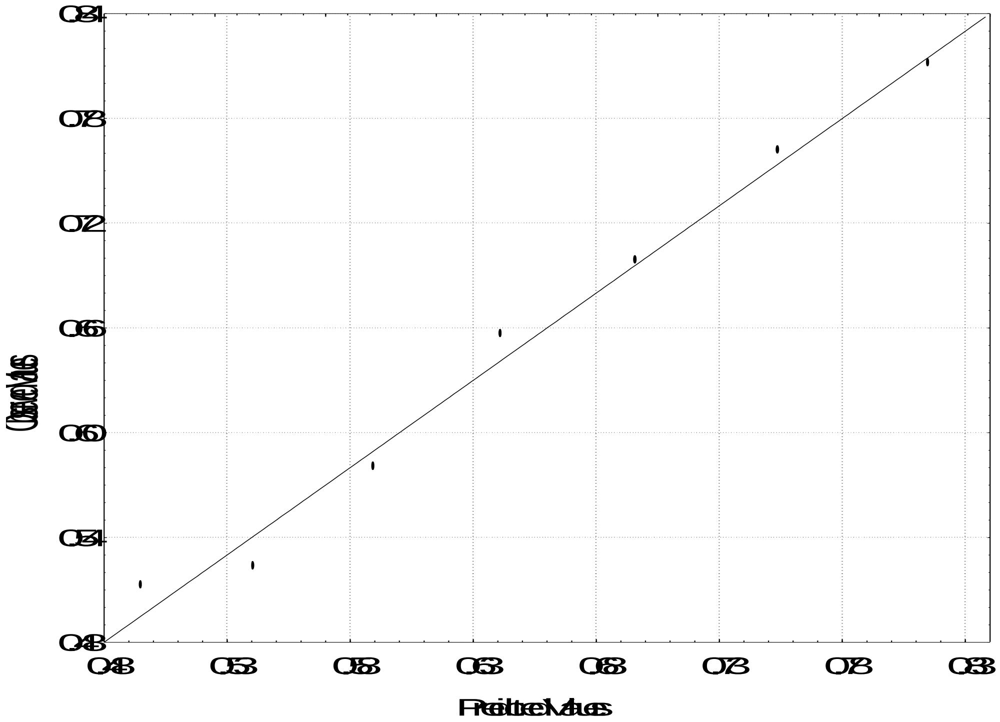

Fig. 2, Observed and predicted value of durability index for aged asphalt cement grade 60-70 at163°C

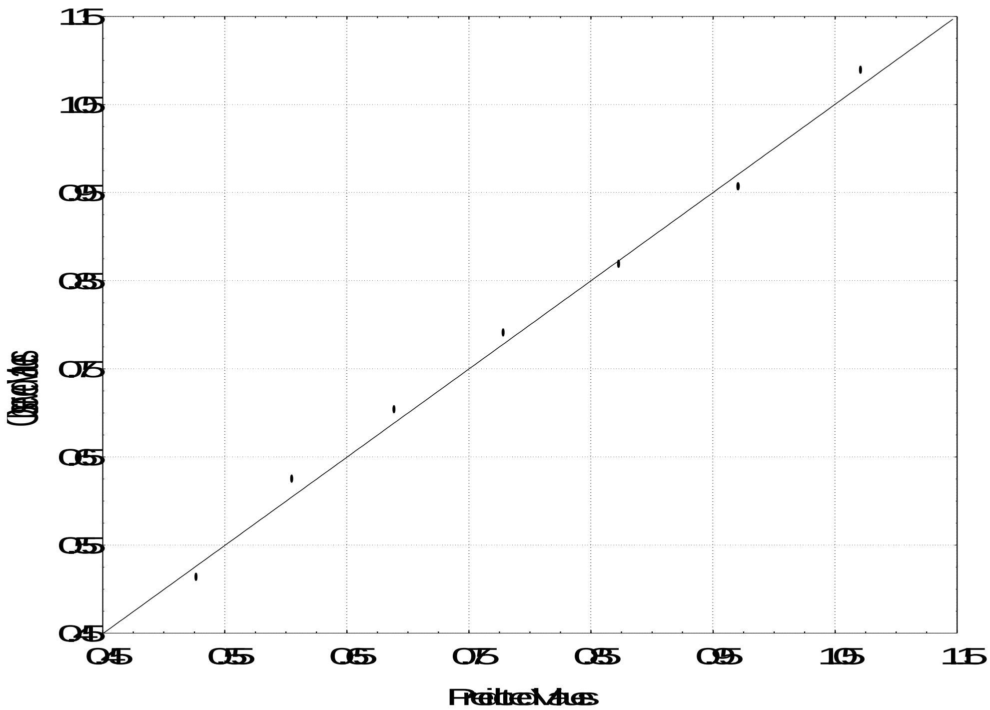

Fig. 3, Observed and predicted value of durability index for aged asphalt cement grade 60-70 at 175°C