International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:12, No:6, 2018

Investigation of Physical Properties of Asphalt Binder Modified by Recycled Polyethylene and Ground Tire Rubber

Sajjad H. Kasanagh, Perviz Ahmedzade, Alexander Fainleib, Taylan Gunay

***Abstract*—**Modification of asphalt is a fundamental method around the world mainly on the purpose of providing more durable pavements which lead to diminish repairing cost during the lifetime of highways. Various polymers such as styrene-butadiene-styrene (SBS) and ethylene vinyl acetate (EVA) make up the greater parts of the all-over asphalt modifiers generally providing better physical properties of asphalt by decreasing temperature dependency which eventually diminishes permanent deformation on highways such as rutting. However, some waste and low-cost materials such as recycled plastics and ground rubber tire have been attempted to utilize in asphalt as modifier instead of manufactured polymer modifiers due to decreasing the eventual highway cost. On the other hand, the usage of recycled plastics has become a worldwide requirement and awareness in order to decrease the pollution made by waste plastics. Hence, finding an area in which recycling plastics could be utilized has been targeted by many research teams so as to reduce polymer manufacturing and plastic pollution. To this end, in this paper, thermoplastic dynamic vulcanizate (TDV) obtained from recycled post-consumer polyethylene and ground tire rubber (GTR) were used to provide an efficient modifier for asphalt which decreases the production cost as well and finally might provide an ecological solution by decreasing polymer disposal problems. TDV was synthesized by the chemists in the research group by means of the abovementioned components that are considered as compatible physical characteristic of asphalt materials. TDV modified asphalt samples having different rate of proportions of 3, 4, 5, 6, 7 wt.% TDV modifier were prepared. Conventional tests, such as penetration, softening point and roll thin film oven (RTFO) tests were performed to obtain fundamental physical and aging properties of the base and modified binders. The high temperature performance grade (PG) of binders was determined by Superpave tests conducted on original and aged binders. The multiple stress creep and recovery (MSCR) test which is relatively up-to-date method for classifying asphalts taking account of their elasticity abilities was carried out to evaluate PG plus grades of binders. The results obtained from performance grading, and MSCR tests were also evaluated together so as to make a comparison between the methods both aiming to determine rheological parameters of asphalt. The test results revealed that TDV modification leads to a decrease in penetration, an increase in softening point, which proves an increasing stiffness of asphalt. DSR results indicate an improvement in PG for modified binders compared to base asphalt. On the other hand, MSCR results that are compatible with DSR results also indicate an enhancement on rheological properties of asphalt. However, according to the results, the improvement is not as distinct as observed in DSR results since elastic properties are fundamental in MSCR. At the end of the testing program, it can be concluded that TDV can be used as modifier which provides better rheological properties for asphalt and might diminish plastic waste pollution since the material is 100% recycled.

***Keywords*—**Asphalt, ground tire rubber, recycled polymer, thermoplastic dynamic vulcanized.

Sajjad H. Kasanagh is with the Civil Engineering Department, University of Ege, Izmir, 35100 Turkey (phone: +90-537-6893173; fax: +90-232-3425629; e-mail: hassanpour.sajjad@gmail.com).
Perviz Ahmedzade is with the Civil Engineering Department, University of Ege, Izmir, 35100 Turkey (phone: +90-533-7212423; fax: +90-232-3425629; e-mail: perviz.ahmedzade@ege.edu.tr).
Alexander Fainleib is Institute of Macromolecular Chemistry of the National Academy of Sciences of Ukraine (NASU), Kyiv, Ukraine (phone: +380-44-5595372; fax: +380-44-5595372; e-mail: fainleib@i.ua).
Taylan Gunay is with the Civil Engineering Department, University of Ege, Izmir, 35100 Turkey (phone: +90-532-4016021; fax: +90-232-3425629; e-mail: taylan.gunay@ege.edu.tr).

I. Introduction

ASPHALT binder is a viscoelastic material which shows viscous liquid at higher temperatures, half solid at intermediate temperature, and it is very stiff and brittle at lower temperatures [1].

The external distresses exposed to flexible pavements due to traffic loading or environment or other factors eventually cause permanent deformation, fatigue cracking, and low-temperature cracking. The asphalt binder has a key role on the performance of flexible pavements during service life. However, many of asphalt pavements distresses are related to properties of binder used in the pavement itself [2].

Permanent deformation is the most common type of pavement distresses showing up as accumulated longitudinal grooves due to repetitive traffic-loading accompanied by environmental effects. Similarly, fatigue cracking is typically associated with aged pavement and caused gradually by a large number of repetitive traffic–loading stressing a pavement to the limit of its life [3].

A few research groups have conducted some studies in order to improve the physical and rheological properties of asphalt binder by employing modifiers [4]-[6].

One of the principal roles of asphalt modifiers is to increase the resistance of asphalt binder against permanent deformation such as rutting by either or both of two methods, increase the high-temperature stiffness of the asphalt binder, or increase the elasticity of the asphalt binder. The modifiers such as SBS and EVA are used satisfactorily in asphalt binder, and favorable results have been reported [7], [8]. However, in order to decrease the eventual highway cost, some waste and low-cost materials such as recycled plastics and ground rubber tire have been attempted to utilize in asphalt as modifier which are more economical than manufactured polymer modifiers. On the other hand, the usage of recycled plastics has become a worldwide awareness in order to decrease the pollution made by waste plastics. Hence, finding new areas for employing recycled plastics has been aimed by research teams in order to diminish polymer manufacturing and eventually plastic pollution [9]-[11].

In this paper, TDV were used to provide an efficient modifier for asphalt which decreases the production cost as well and finally might provide an ecological solution by decreasing polymer disposal problems. TDV used as modifier was obtained from recycled post-consumer polyethylene and GTR. TDV used as a modifier in this work was synthesized by the chemists in the research group. After the synthesis, five different modified asphalt samples were prepared by adding of 3, 4, 5, 6, 7 wt.% TDV.

A comprehensive testing program was applied to base (control) and TDV modified binders including basis test methods such as penetration and softening point which are used for determination of the stiffness of asphalt, and RTFO tests in order to age the asphalt binders.

The high temperature PG of binders was determined by Superpave tests conducted on original and aged binders. The MSCR tests, where elastic ability of asphalt also takes into consideration, and also regarded as new method for determining PG of binders were applied to the asphalt samples. The differences between the Superpave test methodology and MSCR findings were also discussed.

II. Experimental Procedure

A. Materials

The asphalt used as binder having penetration of B 50/70 was obtained from Tupras Refinery. TDV was used as modifier synthesized in laboratory. The synthetization of thermodynamic vulcanize was done by continuous extrusion method in which grounded tire rubber was introduced into polyethylene matrix. TDV was synthesized by a component having 40% waste PE, 25% EPDM, 35% ground rubber tire (30% of natural rubber, 30% of SBR, 20% of BR, 20% of IIR and IIR). These components were mixed in a twin-screw extruder with a speed of 60 rpm for 45 minutes.

B. Sample Preparation

Asphalt samples having TDV modifier were prepared in laboratory by using high shear mixer. To this end, the binder having B50/70 was heated in oven for 120 min, at 160 °C and then poured into a temperature-controlled flask set to 160 °C at 700 rpm. TDV modifier was added to asphalt binder at intervals at the first 15 min of mixing. Following the ending of 15-minute adding process, mixer rate was adjusted to 1800 rpm and the components mixed for 45 min. At the end of the sample preparation, TDV modified asphalt binder having 3, 4, 5, 6, 7 wt.% of modifier was obtained. The binders used in this research were coded as below;

Base Asphalt - 'BA'
Base Asphalt + TDV %3 - 'A3TDV'
Base Asphalt + TDV %4 - 'A4TDV'
Base Asphalt + TDV %5 - 'A5TDV'
Base Asphalt + TDV %6 - 'A6TDV'
Base Asphalt + TDV %7 - 'A7TDV'

III. Testing Program

A. Conventional Physical Tests

Penetration and softening point tests were carried out on asphalt binders, and penetration index of the material was also calculated by means of penetration and softening point values.

B. Aging of Binders

The short–term aging processes of the base and modified asphalts are performed with the rolling thin film oven test (RTFOT) according to EN 12607–1 standard. The binders are aged at 163 °C for 75 min in the oven using eight standard bottles, and each bottle is filled with about 35 grams of asphalt [12]. After the RTFOT, which simulates the changes in the physical properties of binder during the storage, the mass loss is calculated to understand the effects of the short-term aging. The Superpave specification for RTFOT–aged binder implies that maximum weight loss after short–term aging process should not exceed 1% by weight of binder [12]. Loss of weight was calculated by:

$$\text{Mass loss (\%)} = (\text{Initial mass} - \text{Final mass} / \text{Initial mass}) \times 100$$

C. Dynamic Shear Rheometer Test

The Anton Paar Smart Pave Plus dynamic shear rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures. It measures the complex shear modulus (G*) and phase angle (δ) by subjecting a small sample of binder to oscillatory shear stresses while sandwiched between two parallel plates in the DSR rheometer in stress-controlled mode at a frequency of 10 rad/s. Original and aged samples are tested using 25 mm diameter plates and a gap of 1 mm.

Rutting parameter (G*/sinδ) of asphalt binders at intermediate to upper pavement service temperatures was calculated. According to SHRP standards, G*/sinδ of original binder should exceed to 1 kPa, whereas 2.2 kPa of G*/sinδ is needed for aged binder at least for the current test temperature. If the sample provides that condition, then test temperature is increased by 6 ^{o}C and runs again. This process repeats until failure. The last testing temperature where an abovementioned condition is provided by the material is named as high temperature PG of binder [13], [14].

D. MSCR Test

MSCR tests are performed according to ASTM D7405-100 standard on aged samples. 25-mm parallel plates and 1 mm of gap between plates was used as test geometry. In this test, the sample is place to rheometer, and constant creep stress of 0.1 kPa and 3.2 kPa for 1.0 second duration and followed with zero stress duration for 9.0 seconds duration is applied to the asphalt binders. At the end of the MSCR test, data are exported to Excel sheet in order to do analysis. As shown in Fig. 1, a certain amount of deformation occurs in the binder during the loading period of 1.0 second. Some of the deformation is returned, and some deformation is permanently stored during the 9.0-s recovery period [15], [16].

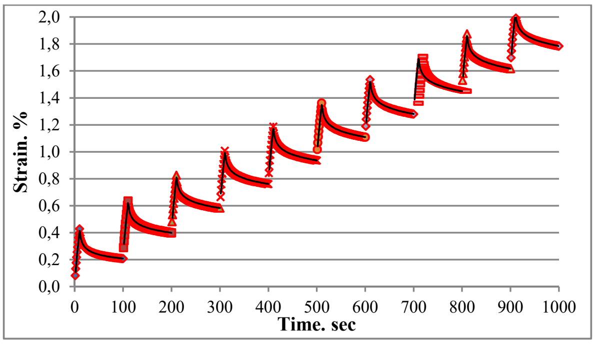

Fig. 1 MSCR time dependent deformation curve

The criterion for determining the high temperature grade in the SHRP method of an aged sample implies that the sample which should have a rutting parameter (G*/sinδ) of at least 2.2 kPa was developed in the MSCR test criteria as illustrated in Table I. In addition, the PG grading code adopted by SHRP is changed with the new MSCR grading criteria. The new specification limits are provided in Table III. Accordingly, for different traffic levels are defined as; standard (S), heavy (H), very heavy (V), and excessively heavy (E). Moreover, a Specific non–recoverable creep compliance (J_{nr}) limits are provided [16].

TABLE I
ASPHALT BINDERS PG GRADING BASED ON MSCR TEST

Traffic type	Traffic level/speed	Limits (kPa^{-1})	Perf. grade (example)
Standard	<10 million ESAL or>72 km/hr	Max. $J_{nr.3.2}$< 4.0	PG 64S-Y
Heavy	10-30 million ESAL or24-72 km/hr	Max. $J_{nr.3.2}$< 2.0	PG 64H-Y
Very heavy	>30 million ESAL or<24 km/hr	Max. $J_{nr.3.2}$< 1.0	PG 64V-Y
Extremely heavy	>30 million ESAL or<24 km/hr	Max. $J_{nr.3.2}$< 0.5	PG 64E-Y

IV. Test Results

A. Conventional Test Results

The physical properties of base and modified asphalt binder were presented in Table II. The trend of results indicates an increase in softening point and decrease in penetration values of TDV modified binders, which indicates that binder has become stiffer after modification.

The increment in softening point and decrement in penetration also affects the penetration index (PI) of binders. Accordingly, A7TDV has highest PI than any other binder in this research. Hence, it can be concluded that binders can be applied in wider range of temperature after modification as they have higher PI than base binder which means that temperature susceptibility of binders has reduced after modification.

B. Loss of Weight after Aging

The loss of weight occurred in asphalt binder after RTFOT which employed for replicating the short-term aging in laboratory condition was calculated and presented in Table III. The amount of loss of weight after RTFOT indicates that TDV modified asphalt samples have better resistance against short term aging as changes in weight are considerably smaller than those of the BA. On the other hand, as can be seen, all the samples used in this work have a less loss of weight than aging criteria of 1%.

TABLE II
PHYSICAL PROPERTIES OF BINDERS

Binder	Penetration (dmm)	Softening point (°C)	PI
BA	52	43	-3.03
A3TDV	40	46	-2.68
A4TDV	35	49	-2.18
A5TDV	33	52	-1.59
A6TDV	30	53	-1.54
A7TDV	30	56	-0.91

TABLE III
LOSS OF WEIGHT OF ASPHALT BINDERS AFTER RTFOT

	Binders			
Property	BA	A3TDV	A5TDV	A7TDV
Initial mass. gr	34.92	35.28	34.95	34.78
Final mass. gr	34.83	35.20	34.89	34.72
Mass loss. %	0.25	0.23	0.18	0.17

C. Dynamic Shear Rheometer Test Results

The rheological parameters such as complex modulus (G*), phase angle (δ), rutting parameter (G*/sinδ) obtained from DSR test were presented in Table IV. The high temperature PG of base and TDV modified asphalt binders are also included in Table IV. Based on the DSR results, the addition of TDV as modifier to asphalt binder leads to increase in G* and decrease in δ. Increase in G* signifies that a better resistance that pavement performs against shear force applied from externally such traffic load. On the other hand, decrease in δ means that the elastic response of asphalt under load is improved. Hence, it can be concluded that TDV modifier has positive effect on the rheological behavior of asphalt binder in terms of stabilization and elasticity.

As observed from Table IV, since TDV modification improves both G* and δ, the rutting parameter (G*/sinδ) also increases which eventually raises high temperature PG of TDV modified binders. Accordingly, high temperature grade of BA rises from PG64-Y to PG70-Y for A3TDV and A4TDV. PG76-Y for (A5TDV and A6TDV) and PG 82-Y for A7TDV respectively. Rheological tests indicate that TDV reduced temperature susceptibility of asphalt since DSR results show that it can be applicable in higher temperature as conventional tests also confirmed.

D. MSCR Test Results

Non-recoverable creep compliance parameter (J_{nr}) of binders which describes the stress dependency of the material obtained from MSCR test was presented in Table V. As shown in Table V, J_{nr} parameters were presented at different testing temperatures of 52, 58, and 64 °C and at the two creep stress levels of 0.1 and 3.2 kPa. TDV modified asphalt binders shows a decrease in J_{nr} value compared to BA. Accordingly, the J_{nr} of A3TDV is 0.96 kPa^{-1} which is lower than J_{nr} value of BA (2.56 kPa^{-1}) at 64 °C testing temperature and 3.2 kPa applied creep stress. The increase in TDV content from 3% to 7% leads to a decrement in J_{nr} value; however, this decrement is not as dramatic as it was in the base and 3% TDV modified binder.

TABLE IV
ASPHALT BINDERS PG GRADING BASED ON MSCR TEST

Binder		Temp	G*	δ	G*/sinδ	Grade
BA	Ori.	58	3.1	86.0	3.15	PG 64-Y
		64	1.4	86.9	1.40	
		70	0.768	88.1	0.769	
	Aged	58	9.7	82.3	9.75	
		64	4.1	84.6	4.07	
		70	1.8	86.4	1.78	
A3TDV	Ori.	58	6.0	85.0	6.04	PG 70-Y
		64	2.6	86.5	2.56	
		70	1.2	87.6	1.17	
		76	0.6	88.5	0.57	
	Aged	58	20.5	78.1	20.94	
		64	8.6	81.3	8.69	
		70	3.8	83.7	3.80	
		76	1.76	85.52	1.76	
A4TDV	Ori.	58	8.8	80.7	8.95	PG 70-Y
		64	3.9	82.7	3.96	
		70	1.9	83.8	1.87	
		76	0.9	84.1	0.94	
	Aged	58	31.2	75.1	32.30	
		64	13.6	77.9	13.86	
		70	6.1	80.0	6.19	
		76	2.9	81.2	2.97	
		82	1.5	81.9	1.52	
A5TDV	Ori.	58	15.1	71.4	15.92	PG 76-Y
		64	7.7	71.4	8.08	
		70	4.1	70.7	4.31	
		76	2.4	68.9	2.57	
		82	1.5	67.5	1.65	
	Aged	58	31.0	75.9	31.99	
		64	13.2	79.7	13.43	
		70	5.8	82.4	5.89	
		76	2.7	84.4	2.73	
		82	1.3	85.8	1.34	
A6TDV	Ori.	58	21.8	62.9	24.52	PG 76-Y
		64	12.0	62.7	13.51	
		70	7.2	61.9	8.19	
		76	4.6	60.9	5.29	
		82	3.2	60.4	3.63	
	Aged	58	43.2	73.0	45.21	
		64	19.0	76.7	19.51	
		70	8.6	79.6	8.75	
		76	4.1	81.6	4.12	
		82	2.0	83.0	2.06	
A7TDV	Ori.	58	27.9	54.9	34.16	PG 82-Y
		64	17.3	53.5	21.51	
		70	11.5	52.7	14.42	
		76	8.2	52.5	10.28	
		82	6.1	53.0	7.62	
	Aged	58	49.4	71.2	52.19	
		64	22.4	74.9	23.24	
		70	10.4	77.9	10.60	
		76	5.0	80.3	5.08	
		82	2.6	82.0	2.58	

TABLE V
J_{NR} VALUES OF BINDERS AT 0.1 AND 3.2 KPA STRESS LEVELS

Binders	MSCR test J_{nr} (kPa^{-1}) values					
	Test temperatures and Creep stress (kPa)					
	64°C		70°C		76°C	
	0.1	3.2	0.1	3.2	0.1	3.2
BA	2.32	2.56	-	-	-	-
A3TDV	0.79	0.96	2.07	2.48	-	-
A4TDV	0.41	0.65	1.24	1.68	2.97	3.85
A5TDV	0.30	0.47	0.79	1.26	1.99	3.01
A6TDV	0.24	0.35	0.63	0.99	1.53	2.47
A7TDV	0.14	0.29	0.42	0.80	1.16	2.02

The MSCR tests are performed in order to provide up to date PG classification taking into consideration the traffic loading level as well. Table VI summarizes the obtained high temperature PG results as described in MSCR criteria. As can be seen, base asphalt BA is classified as PG64S-Y after MSCR test whereas it was PG64-Y for SHRP. This summary means that BA can withstand a total number of traffic up to 10 million ESAL's during service life or it could serve under relatively high average traffic speeds greater than 72 km/h. At the same manner, the A3TDV binder which has a PG76-Y grade based on SHRP classification method is considered to have a PG 64V-Y based on MSCR method. Hence, A3TDV has relatively better rutting performance than BA. Moreover, as TDV content increases binders shows better performance which means that those TDV modified binders can be applied under more high traffic levels compare to BA.

It should be noted that, although both methods indicated the achievement in terms of binder performance after TDV modification, according to MSCR test, A7TDV can be used lower PG. This decrement can be attributed to the nature of MSCR test where the elastic properties of binder are fundamental. On the other hand, in DSR test, stiffness of material plays a key role. Hence, it can be said that although TDV modifier has both affect asphalt's stiffness and elasticity, it is more likely that TDV modification has more influence on the stiffness of asphalt rather than the elasticity which is another essential material property for longer pavement life.

TABLE VI
COMPARISON BETWEEN MSCR AND SHRP CLASSIFICATION METHODS

Binder	PG DSR test	PG plus MSCR test
BA	PG 64-Y	PG 64S-Y
A3TDV	PG 70-Y	PG 70S-Y
A4TDV	PG 76-Y	PG 76S-Y
A5TDV	PG 76-Y	PG 76S-Y
A6TDV	PG 76-Y	PG 76S-Y
A7TDV	PG 82-Y	PG 76S-Y

V. CONCLUSION

The effect of TDV on physical and rheological properties of asphalt has been examined. Based on the test results presented in this work, the following conclusions can be drawn:

After the TDV modification, the asphalt sample has become stiffer which was observed in penetration and softening point test. Moreover, the increase in softening point and decrease in penetration leads to increase in penetration index which means that temperature susceptibility of asphalt binder diminishes which was confirmed following DSR findings where high temperature of PG levels rose after modification.

Better performance has been observed against short term aging after TDV modification by RTFOT, in which loss of weight of asphalt samples between before and after the process reduced.

TDV modification could provide better performance against traffic load applied on pavement as G* and δ parameters enhanced comparing with those of base asphalt.

TDV modified binders have higher rutting parameter (G*/sinδ) both before and after aging processes which promise greater high temperature PG for TDV modified asphalt binders.

While SHRP grading method promotes enhanced PG grades for modified binders as TDV modifier increases, according to MSCR results, in which elastic properties of material is fundamental, this enhancement relatively was confirmed. Accordingly, at higher modification levels (4-7%), asphalt binder has a same high temperature PG of 76 (PG76S-Y). Hence, it be concluded that TDV modifier has positive effect on both stiffness and elasticity of asphalt. However, this effect is much more dramatic on the material's stiffness. Nevertheless, using TDV as modifier in asphalt could limit the permanent deformation which leads to reduce maintenance cost of highway. Furthermore, employing TDV modifier as asphalt modifier might help to reduce the pollution caused by plastics as well since tons of polymer manufactured every year for asphalt modification.

Acknowledgment

Ege University Research Fund is appreciated for their support on the Project 17 MUH 027.

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