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The potential use of recycled polyethylene terephthalate (RPET) plastic waste in asphalt binder

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Abstract

The current study aims to examine the potential use of recycled polyethylene terephthalate (RPET) plastic waste as a modifier for asphalt binder. Plastic bottles were collected, shredded, cleaned, melted, ground, then sieved. An asphalt binder with a penetration grade of 60/70 was used. The RPET plastic waste was blended with 60/70 penetration grade asphalt binder at five percentages (0, 5, 10, 15, and 20 %, by weight of asphalt binder) using a high shear mixer. To study the physical and mechanical properties of RPET-modified asphalt binders, both traditional and Super pave tests were conducted. The test results showed that by incorporating RPET into asphalt binder, the ductility and penetration values decreased, whereas the softening point and viscosity of asphalt binder increased. Furthermore, the rutting performance of RPET-modified asphalt binder, as presented by the rutting parameter (G*/sinδ), was enhanced by increasing the amount of RPET plastic waste at all testing temperatures. The high-temperature performance grade of asphalt binder was raised by one grade (from 64ºC to 70ºC) by adding 15% and 20% of RPET plastic waste. On the other hand, the low-temperature performance of asphalt binder, as presented by creep stiffness and m-value, was negatively affected by adding RPET. The low-temperature performance grade of asphalt binder was dropped by one grade (from -22ºC to -16ºC) by adding RPET plastic waste at percentages of 15 % and 20 %. Moreover, the fatigue cracking performance of asphalt binder, as presented by the fatigue parameter (G*.sinδ), was slightly reduced by adding RPET to the asphalt binder but remained lower than the acceptable Super pave limit (≤ 5000 kPa).

Keywords: Asphalt binder; PET; Plastic waste; Rutting; Fatigue

1. Introduction

1.1. Background

Over the past few years, the use of plastic in multiple industries has expeditiously increased due to the ability to modify it in different forms. Plastic is used for isolating electric wires, construction materials, and food and beverage packaging. However, plastic is a non-biodegradable material and has dire consequences on the environment worldwide [1,2]. To date, traditional plastic recycling methods can only process a fraction of countries' yearly waste [3-6]. This, in turn, has increased the urge to infiltrate plastic waste in multiple industries such as energy [7-10] and construction materials [11-14] in order to manage excessive waste.

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several studies have been carried out to evaluate the potential of using industrial waste products in pavement construction. Kim et al. [15] evaluated the rutting properties of rubberized polymer modified asphalt (PMA) binders by conducting the multiple stress creep recovery (MSCR) test. Two types of ground tire rubber (GTR) were used: normal and treated. According to the test results, the PMA binders with treated GTR showed better rutting performance properties, compared to the PMA binders with normal GTR. Notani et al. [16] investigated the use of waste toner as an anti-rutting enhancement agent for asphalt binder. The test results showed that adding toner to asphalt binder enhanced the asphalt binder's anti-rutting performance and subsequently asphalt mixture. Another study conducted by Chuangmin et al. [17] showed that the addition of waste carbon particles to asphalt binder enhance the high temperature anti-rutting performance of asphalt binder. Ramadan et al. [18] studied the rutting performance of asphalt binder modified with Styrofoam in its waste form. The test results revealed that Styrofoam addition could improve the rutting performance of asphalt binder since both the rotational viscosity and the complex shear modulus (G*) value increased with the increase in the Styrofoam percentage. Al-Khateeb et al. [19] investigated the effect of using waste glass on shear properties of asphalt binder. Complex shear modulus value (|G*|) and phase.

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angle (δ) were measured at several loading frequencies and temperatures. The test results showed an improvement in rutting and fatigue performance by adding glass.

Polyethylene terephthalate (PET) is one of the most commonly used plastics in the world. It is mainly used in beverage bottles for its barrier properties to confine gas and moisture. Despite the fact that PET bottles are recyclable, a single used PET bottle has a short life span, where the recycling industry is unable to match the consumption and waste [20-22]. In addition, PET plastic waste can also be used in asphalt binder or mixture due to its durability and tensile strength [23-25].

PET plastic waste is a widely researched construct in civil engineering. However, most prior research has focused on the addition of PET plastic waste using the dry method as a substance of fine aggregate and filler. Therefore, the use of waste PET was experimented upon in using it as fine particles in asphalt mixture and as an additive in SMA (stone mastic asphalt) [25-31]. The modified RPET mixture showed an increase in the mixture's stiffness level and increased its level of resistance to permeant deformation. This resulted in increasing the mixture's voids in mix (VIM) while decreasing its bulk specific gravity. Other studies have shown that although the stiffness of SMA mixture modified with RPET initially increased by adding a lower amount of RPET into the mixtures, the stiffness decreased with a higher amount of RPET content [32].

Other studies have focused on the fatigue properties of RPET modified asphalt mixture. The results indicate a significant improvement when compared to control mixtures or for mixtures containing a higher amount of RPET in terms of fatigue lives [32-34]. Moreover, other research implies that the elastic property of the asphalt mixture improves by adding RPET. As a result, the mixture will become more flexible and able to prevent crack initiation and propagation due to cyclic load application. Further, the mixture with RPET reached a higher rutting resistance compared to the conventional mixture using the wheel tracking test [35-40] with a reduction in the rut depth by 29% compared to the conventional one.

On the other hand, there are very few studies that have examined the addition of RPET in asphalt binder resulting in an improvement in rutting and fatigue resistance [41-45]. However, the studies only focused on a low percentage of RPET in the binder.

The current study focuses on the behavior effect of using RPET powder in asphalt binder by using a wider range (up to 20%) of RPET by weight of the binder. In addition, this study seeks to determine the benefits of adding RPET to the binder and forming a heterogeneous mixture. More importantly, the mixing was conducted using a high shear mixer to ensure a uniform distribution of RPET powder in the binder. The behavior study of the binder covers both the conventional and Superpave binder tests to assess the viscosity, fatigue, rutting, stiffness, and asphalt binder grading.

1.2. Materials

The materials used in this study include asphalt binder and recycled polyethylene terephthalate (RPET) plastic waste. The following subsections present the material used in detail.

1.2.1. Asphalt binder

In this study, an asphalt binder with a penetration grade of 60/70 was used as a control asphalt binder. The control asphalt binder was received from The Jordan Petroleum Refinery Company located in Zarqa-Jordan. The physical properties of the control asphalt binder are shown in Table 1.

1.2.2. RPET plastic waste

RPET plastic waste was obtained from single-use water bottles. The bottle taps and labels were sieve out and removed to ensure a homogeneous plastic component. Then, the bottles were cleaned up and shredded into smaller sizes. The shredded bottles were melted at 250ºC to form solid pieces (crystallized plastic) and then crushed into a powder using a ball mill. The crushed powder was subjected to sieve analysis to obtain the portion that passes through sieve No.200. Fig. 1 presents the RPET after being shredded, the RPET after milting, and the RPET after crushing and sieving. The chemical structure of RPET is represented in Fig. 2(a). It consists mainly of Carbon, Oxygen, and Hydrogen. Also, Scanning Electron Microscope (SEM) was used to study the morphological characteristics of the surface structure of the RPET, as presented in Fig. 2(b). From the SEM image, the RPET has rough and pore structure.

2. **Laboratory work**

2.1. Specimens preparation

Specimens were prepared by mixing 60/70 penetration grade asphalt binder with RPET plastic waste powder using a high shear

Table 1
Properties of control asphalt binder.

Property	Value	ASTM method
Penetration (0.1mm) at 25°C,100g, 5s	69	D 5
Ductility (cm) at 25°C	100+	D 113
Specific gravity at 25°C	1.02	D 70
Softening point (°C)	47.3	D 36
Flash point (°C)	294	D 92
Fire point (°C)	301	D 92
Rotational viscosity (mPa.s)	437.5	D 4402

Fig.1. RPET plastic waste.

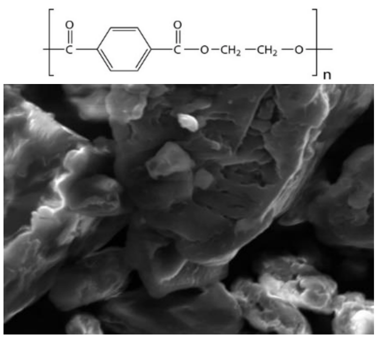

Fig. 2. (a) Chemical structure of polyethylene terephthalate (PET) and (b) SEM Image for RPET.

mixer. The RPET plastic waste powder was added to the asphalt binder at four percentages (5%, 10%, 15%, and 20% by weight of asphalt binder). To ensure consistent distribution of RPET within the asphalt binder, a mixing temperature of 165 ± 5ºC, mixing rate of 4000 rpm, and a mixing time of 60 minutes were adopted using a Silverson L5M-A high shear mixer. For comparative analysis, both the control asphalt binder and the RPET-modified asphalt binders went through the same mixing condition. To examine the quality of the dispersion of the RPET material within the asphalt binder, the Atomic Force Microscopy (AFM) was conducted. Fig. 3 shows the topographical and phase images with a dimension of 60 × 60 µm for asphalt binder modified with RPET. As seen from the figure, the RPET is well distributed within the asphalt binder.

2.2. Testing of asphalt binder properties

In the current study, a structured laboratory testing program was conducted to evaluate the effect of adding RPET plastic waste to asphalt binder properties. Several laboratory tests were carried out to assess the conventional and the rheological properties of asphalt binders. The conventional tests included a penetration test, ductility test, softening point test, and flash and fire point test, whereas the rheological tests include a rotational viscosity (RV) test, a Dynamic Shear Rheometer (DSR) test, and a Bending Beam Rheometer (BBR) test. Short-term aging of asphalt binder was conducted using a Rolling Thin Film Oven (RTFO), then the short-term aged samples were exposed to long-term aging using the Pressure Aging Vessel (PAV).

The rotational viscosity was carried out in compliance with the AASHTO T 316 specification [46]. In this test, a Brookfield viscometer is used to measure the viscosity of the asphalt binder. It measures the torque needed to keep the rotational speed of a standard cylindrical spindle constant (20 RPM) at 135°C and 165°C. Then, the measured torque is used to determine the viscosity of the asphalt binder mathematically. The viscosity is considered an important property that reflects the ability of asphalt binder to flow and is used to decide whether it can be easily pumped or not.

A dynamic shear rheometer (DSR) was carried out in compliance with the AASHTO T 315 specification [47] to evaluate the viscoelastic behavior of asphalt binders at medium and high temperatures. In this test, both a dynamic modulus (G*) and a phase angle (δ) parameter were measured to determine the high-temperature performance grade (PG) of asphalt binders. Furthermore, the dynamic modulus (G*) and the phase angle (δ) were used to evaluate the rutting and fatigue cracking potentials of asphalt mixtures.

A bending beam rheometer (BBR) was carried out in compliance with the AASHTO T 313 specification [48] to assess the ability of asphalt binders to resist low temperature cracking. In this test, both creep stiffness (S) and stress relaxation (m-value) parameters were measured at 60 seconds loading time to determine the low-temperature performance grade (PG) of asphalt binders.

Short-term aging and long-term aging of asphalt binders were conducted in compliance with ASTM D 2872 and AASHTO R 28 specifications, respectively [49,50]. The Rolling Thin-Film Oven (RTFO) device was used to mimic the short-term aging that the asphalt binder shows during the mixing, lay-down, and compaction process. In RTFO, asphalt binder samples were exposed to heating (163°C) and airflow (4000 ml/minute) for 75 minutes.

The Pressure Aging Vessel (PAV) device was used to mimic the long-term aging of asphalt binders. In PAV, asphalt binder samples were exposed to heat (100°C) and pressure (2.1 MPa) for a period of 20 hours to be simulated for a period of 7 to 10 years in-service aging in a pavement (in a matter of hours). The flowchart shown in Fig. 4 represents the experimental design used in the current study.

3. **Results and discussion**

During this study, several tests were carried out to investigate the impact of RPET plastic waste on asphalt binder properties and to analyze its suitability as an asphalt binder modifier in road construction. In the following subsections, the results of the experimental tests are discussed in detail.

3.1. Penetration test results

The effect of adding RPET to asphalt binder penetration is presented in Fig. 5. The figure shows that the penetration of the RPET-modified asphalt binder was decreased by increasing the amount of RPET. The penetration number was decreased from 69 for control asphalt binder to 58 for asphalt binder modified with 20% RPET. This decrease in penetration, as the RPET concentration increases, means that the asphalt binder becomes stiffer. This is because of the solid phase of RPET, which increases the hardness of the modified asphalt binder.

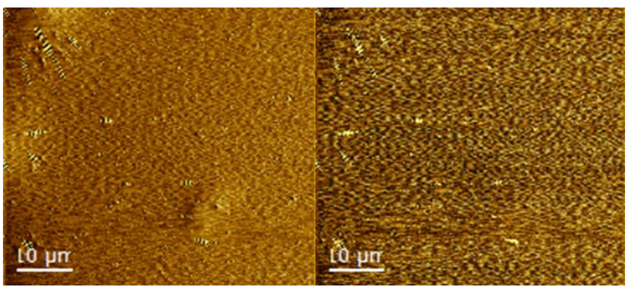

Fig. 3. (a) topographical image of RPET-modified asphalt and (b) phase image of RPET-modified asphalt.

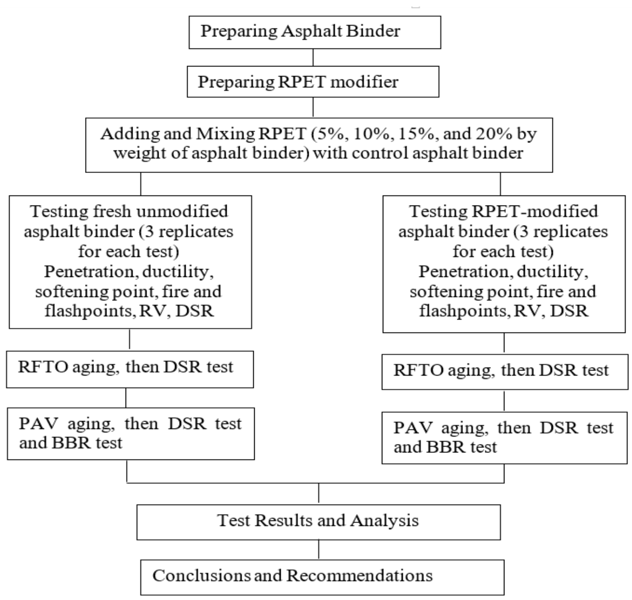

Fig. 4. Experimental test program flowchart.

Increased stiffness of RPET modified asphalt binder can be explained through the semi-crystalline property of RPET [26,37]. Semi-crystalline nature implies that a portion of RPET is amorphous, while the other portion is crystalline. Above its glass transition temperature of about 70°C, the amorphous portion of RPET exists in liquid, while crystalline portion of RPET still exists as solid and rigid form [51].

3.2. Softening point test results

The test results of the softening point tests are presented in Fig. 6. As can be seen from the figure, the softening point values were increased by increasing the amount of RPET. It increased from 47 ºC for control asphalt binder to 51 ºC for asphalt binder modified with 20% RPET. This increase in softening point can be expected since RPET-modified asphalt binders exhibit high resistance to flow by adding more RPET.

3.3. Ductility test results

The tensile strength of RPET-modified asphalt binders, as measured by ductility and presented in Fig. 7, was decreased by increasing the amount of RPET. This could be attributed to the hardening effect of RPET on asphalt binder.

3.4. Rotational viscosity test results

In this research, the effect of adding RPET on asphalt binder viscosity was measured by conducting the rotational viscosity test at two testing temperatures: 135°C and 165°C. The test results were analyzed and plotted in Fig. 8. From the test results, the viscosity of the asphalt binder increased with the addition of RPET at both testing temperatures. This increase in asphalt binder viscosity can be attributed to the consistency increase with the addition of RPET. To enhance the performance of asphalt binder with regard to rutting, it is essential to use asphalt binder with high viscosity. Therefore, asphalt binder with more RPET will perform better in the field with respect to rutting as compared to the control asphalt binders. However, the Superpave system has limited the maximum value of viscosity to the value of 3000 mPa.s at 135°C to ensure proper fluidity of asphalt concert for pumping, delivery, and mixing.

3.5. Dynamic shear rheometer (DSR) test results

The rheological property of asphalt binder plays a crucial role in resisting fatigue cracking and rutting of asphalt pavements. To evaluate the effect of adding RPET on rutting and fatigue performance, the dynamic shear rheometer (DSR) device was used in the current study to evaluate the viscoelastic behavior of control and RPET-modified asphalt binders at both intermediate and high temperatures. For rutting evaluation, the DSR test was carried out at five testing temperatures (52, 58, 64, 70, and 76°C) and at a standard loading frequency recommended by Superpave (1.59 Hz). The main two parameters of the DSR test are the complex shear modulus (G*), which represents the total resistance of asphalt binders to permanent deformation, and the phase angle (δ), which represents the amount of elasticity that the asphalt binder retains. The closer the δ to the zero degrees, the higher the elasticity of the asphalt binder. On the other hand, the closer the δ to the 90 degrees, the more viscous the asphalt binder is. From G* and δ, two

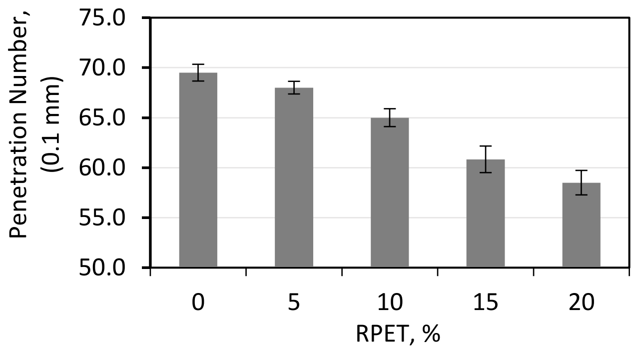

Fig. 5. Penetration versus RPET%.

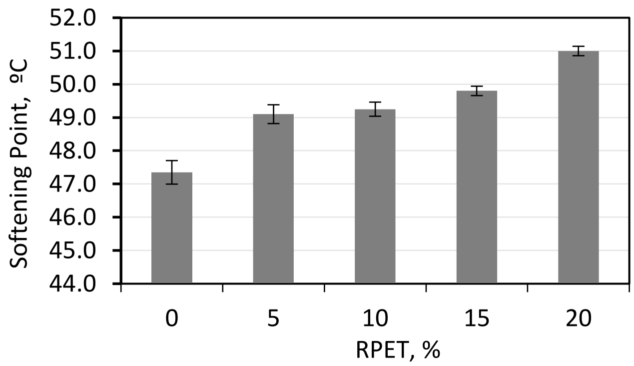

Fig. 6. Softening point versus RPET%.

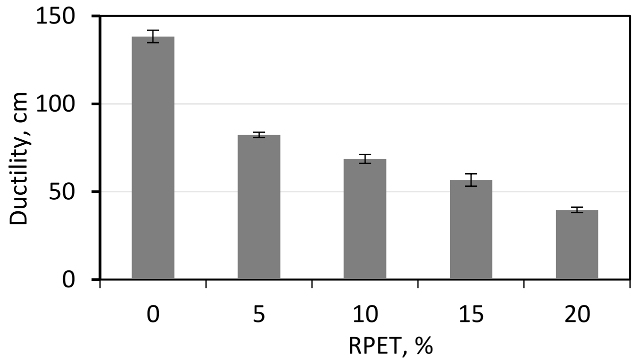

Fig. 7. Ductility versus RPET%

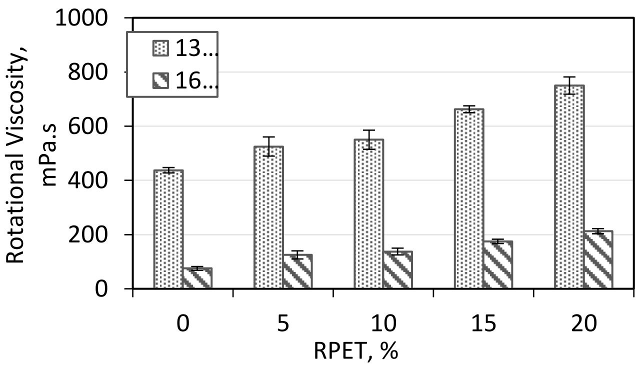

Fig. 8. Rotational viscosity versus RPET%.

important parameters were calculated: the rutting parameter (G*/sin δ) and the fatigue parameter (G*sin δ). According to the Superpave specifications, DSR tests were conducted on unaged, short-term aged (RTFO), and long-term aged (PAV) asphalt binder specimens. For unaged asphalt binders, the G*/ sin δ test results were analyzed and plotted as depicted in Fig. 9. As evident from Fig. 9, the rutting parameter (G*/sinδ) values were increased by increasing the amount of RPET and decreased by increasing the testing temperatures. This means that the rutting performance is enhanced by adding more RPET and degraded at high temperatures. Furthermore, the results showed that the rate of enhancement in the rutting performance of RPET-modified asphalt binder is decreased by increasing the testing temperatures. According to the Superpave specifications (G*/sinδ ≥1.0 kPa), the high-temperature performance grade was raised by one grade from 64°C to 70°C by adding 15% and 20% of RPET to the control asphalt binder. For RTFO aged asphalt binders, the G*/ sinδ test results were analyzed and plotted as shown in Fig. 10. As can be seen from the figure, the rutting parameter (G*/ sinδ) was increased by increasing the amount of RPET. This means that enhancement occurred in the rutting performance by adding more RPET to the control asphalt binder. Based on the Superpave specifications (G*/sinδ ≥2.2 kPa), the high-temperature performance grade was raised by one grade from 64°C to 70°C by adding 15% and 20% of RPET to the control asphalt binder. Hence, asphalt binder modified with 20% RPET will perform better in a hot location, compared to the control asphalt binders.

To evaluate the effect of adding RPET on fatigue performance, the DSR tests were conducted on PAV aged asphalt binder samples at intermediate temperatures and the test results were analyzed and presented as shown in Fig. 11. From the figure, it can be concluded that the fatigue parameter (G*.sinδ) increases as the amount of the RPET increases. This increase in G*.sinδ values negatively affects the fatigue performance of RPET-modified asphalt binders and makes asphalt binders more vulnerable to fatigue cracking. However, G*.sinδ values did not exceed the Superpave specified maximum value of 5000 kPa at all RPET percentages and at all testing temperatures. This conclusion was anticipated since the stiffness of the asphalt binder increased by increasing the amount of RPET.

3.6. *Bending beam rheometer (BBR) tests results*

At low temperatures regions, asphalt binders need to have reasonable resistance to low temperature cracking. To evaluate the performance of control and RPET-modified asphalt binders at low temperatures, the BBR test was carried out on PAV-aged asphalt binder samples. In this test, two parameters were measured; the specimen's creep stiffness (S) and the stress relaxation property (m-value). To avoid low- temperature cracking, Superpave

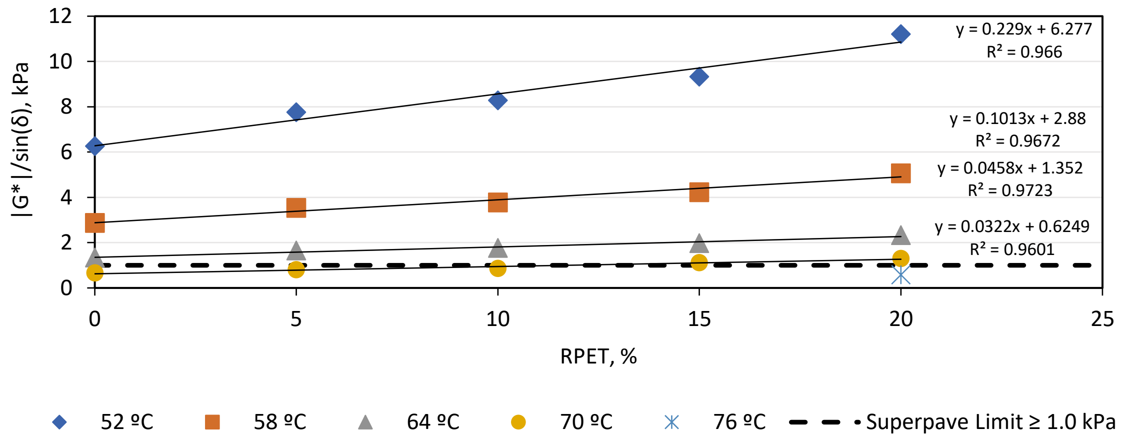

Fig. 9. G*/sin δ versus RPET% (Unaged Asphalt Binders).

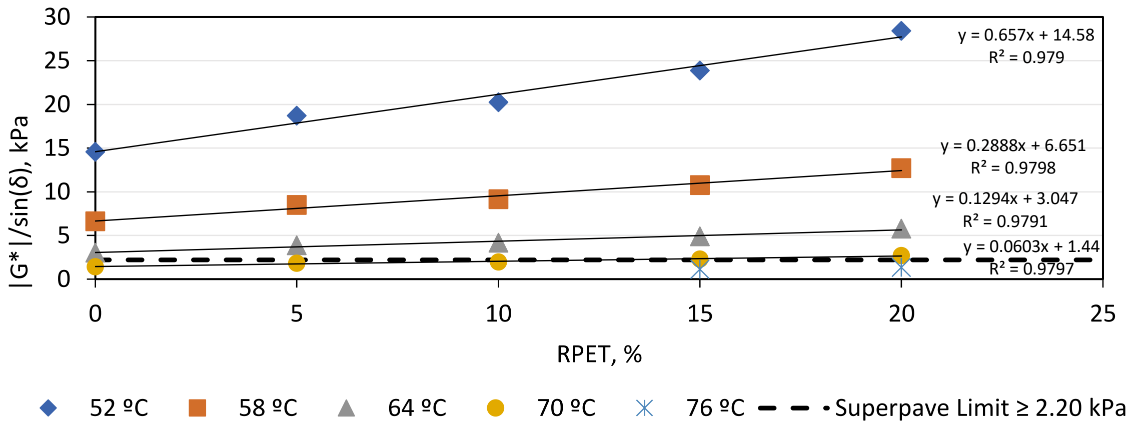

Fig. 10. G*/sin δ versus RPET% (RTFO aged Asphalt Binders).

specified that the asphalt binder should have a creep stiffness (S) ≤ 300 MPa, and stress relaxation (m-value) ≥ 0.3.

To evaluate the effect of adding RPET on the low temperature cracking resistance of asphalt binders, the BBR test results were analyzed and plotted, as shown in Figs. 12 and 13. As illustrated in Fig. 12, the creep stiffness of asphalt binder was increased by increasing the amount of RPET, but still much lower than the Superpave limit of 300 MPa. Also, the stress relaxation as revealed by the m-values, shows a decreasing behavior with increasing the amount of RPET, as depicted in Fig. 13. These results indicate that the addition of RPET to the asphalt binder will negatively affect the low-temperature performance of the asphalt binder by increasing the low temperature stiffness and decreasing the stress relaxation rate (m-value). Therefore, the RPET modified asphalt binder will be more prone to low-temperature cracking as compared to the control asphalt binder. According to the tests' results, the low-temperature performance grade was decreased by one grade from -22ºC to -16ºC by adding 15% and 20% of RPET to the control asphalt binder. The negative effect of RPET on asphalt binder stiffness and stress relaxation can be attributed to the stiffness increase in asphalt binder by adding more RPET.

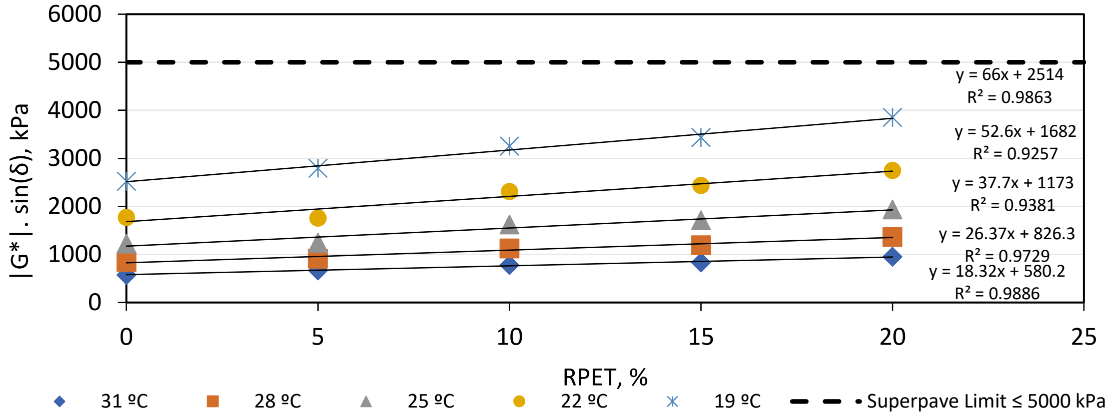

Fig. 11. G*.sin δ versus RPET% (PAV aged Asphalt Binders).

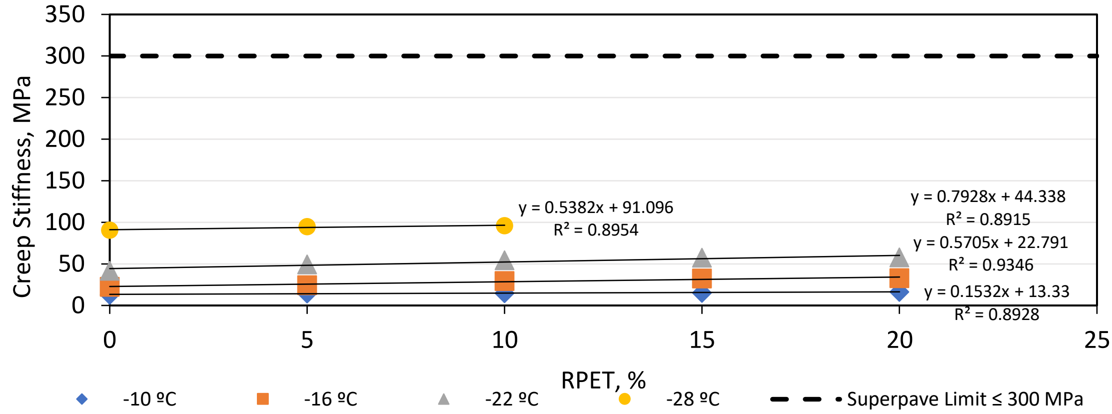

Fig. 12. Creep Stiffness versus RPET content for PAV-Aged Asphalt binder.

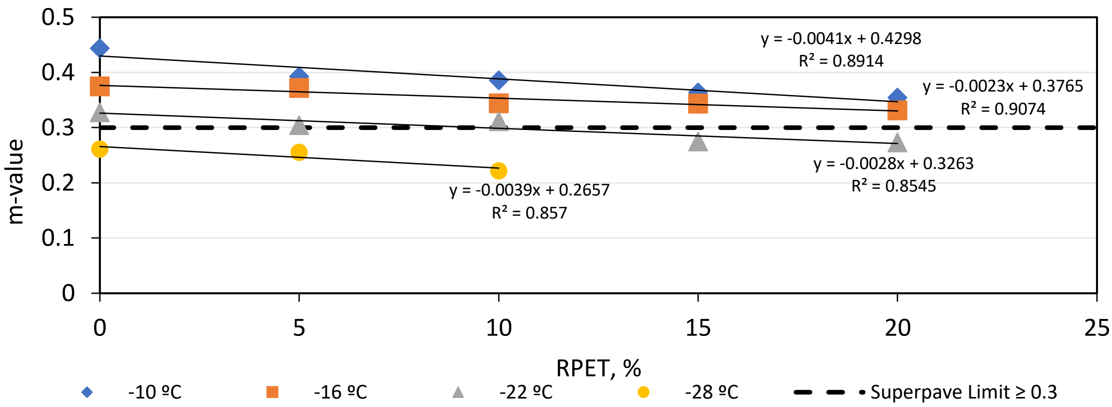

Fig. 13. m-Value versus Temperature for PAV-Aged Asphalt binder.

The effect of using the RPET as a modifier on asphalt binder performance grading (PG) is summarized in Table 2. From the table, it can be concluded that using RPET in asphalt binders will increase the high-temperature PG grade and reduce the low-temperature PG grade as compared to the control asphalt binder. The high-temperature performance grade of asphalt binder was raised by one grade (from 64°C to 70°C) by adding 15% and 20% RPET, whereas the low-temperature performance grade was decreased by one grade (from -22ºC to -16ºC) by adding 15% or 20% of RPET. As a result, it can be concluded that RPET can be used in asphalt binders to enhance the rutting resistance of pavement mixtures. Therefore, it is recommended to use RPET-modified asphalt binders in hot climate regions.

Table 2
Performance Grade (PG) of RPET-modified asphalt binder.

RPET, %	PG grade
0	64-22
5	64-22
10	64-22
15	70-16
20	70-16

4. **Conclusions**

Based on the results and data analysis of the current, the following conclusions and recommendations can be drawn:

1. The addition of RPET to asphalt binder decreased the ductility and the penetration values and increased the softening points and rotational viscosity of the asphalt binder.
2. The high-temperature rutting performance of asphalt binder, as revealed by the DSR rutting parameter ($G^*/\sin\delta$), was improved by adding RPET.
3. The high-temperature performance grade of asphalt binder was raised by one grade from 64ºC (for control asphalt binder) to 70ºC at 15% and 20%RPET.
4. The addition of RPET had a negative effect on asphalt binder fatigue cracking. However, the fatigue parameters ($G^*.\sin\delta$) remained below the Superpave limit of 5000 kPa at all RPET percentages.
5. RPET modifier had a negative effect on the low-temperature performance of asphalt binder. The low-temperature asphalt binder grade was decreased from -22ºC (for control asphalt binder) to -16ºC at 15% and 20%RPET. It can thus be useful to use the RPET modifier in hot climates that are not highly susceptible to very low temperatures.
6. The optimum content of RPET to be added as a modifier to the asphalt binder is thought to be 15%, where the high-temperature performance grade was raised by one grade (from 64ºC to 70ºC) and the low-temperature performance grade was lowered by one grade (from -22ºC to -16ºC).

References

[1] M. N. Siddiqui, Conversion of hazardous plastic wastes into useful chemical products, J. Hazard. Mater. 167 (1-3) (2009) 728-735. https://doi.org/10.1016/j.jhazmat.2009.01.042

[2] B. Prusty, Use of Waste Polyethylene in Bituminous Concrete Mixes, (Bachelor Thesis), National Institute of Technology Rourkela, Rourkela,India, 2012.

[3] Container Recycling Institute, PET bottle sales and wasting in the US. (Container-Recycling.org., 2015), http://www.container-recycling.org/index.php/pet-bottle-sales-and-wasting-in-the-us. Accessed 10 March 2020.

[4] M. K Eriksen, J. D. Christiansen, A. E. Daugaard, T. F. Astrup, Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling, Waste Manage. 96 (2019) 75-85. https://doi.org/10.1016/j.wasman.2019.07.005

[5] G. Lonca, P. Lesage, G. Majeau-Bettez, S. Bernard, M. Margni, Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market. Resources, Conserv. Recycl. 162 (2020) 105013. https://doi.org/10.1016/j.resconrec.2020.105013

[6] D. Gere, T. Czigany, Future trends of plastic bottle recycling: Compatibilization of PET and PLA, Polym. Test. 81 (2020) 106160 https://doi.org/10.1016/j.polymertesting.2019.106160

[7] M. Ubaidullah, A. M. Al-Enizi, S. Shaikh, M. A. Ghanem, R. S. Mane, Waste PET plastic derived ZnO@NMC nanocomposite via MOF-5 construction for hydrogen and oxygen evolution reactions, J. King Saud Univer. Sci. 32 (4) (2020) 2397-2405 https://doi.org/10.1016/j.jksus.2020.03.025

[8] W. Nabgan, B. Nabgan, T. A. T. Abdullah, N. Ngadi, A. A. Jalil, N. A. A. Fatah, H. Alqaraghuli, M. Tahir, Exploration of reaction mechanisms on the plastic waste polyethylene terephthalate (PET) dissolved in phenol steam reforming reaction to produce hydrogen and valuable liquid fuels, J. Analytical Appl. Pyrolysis 150 (2020) 104860 https://doi.org/10.1016/j.jaap.2020.104860

[9] K. Choudhary, K. S. Sangwan, D. Goyal, Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy, Procedia CIRP 80 (2019) 422-427 https://doi.org/10.1016/j.procir.2019.01.096

[10] J. Matsunami, S. Yoshida, O. Yokota, M. Nezuka, M. Tsuji, Y. Tamaura, Gasification of Waste Tyre and Plastic (PET) by Solar Thermochemical Process for Solar Energy Utilization, Solar Energy 65 (1) (1999) 21-23 https://doi.org/10.1016/S0038-092X(98)00085-1

[11] K. Nováková, K. Šeps, H. Achten, Experimental development of a plastic bottle usable as a construction building block created out of polyethylene terephthalate: Testing PET(b) rick 1.0, J. Build. Eng. 12 (2017)239-247 https://doi.org/10.1016/j.jobe.2017.05.015

[12] S. Perera, A. Arulrajah, Y. C. Wong, S. Horpibulsuk, F. Maghool, Utilizing recycled PET blends with demolition wastes as construction materials, Constr. Build. Mater. 221 (2019) 200-209 https://doi.org/10.1016/j.conbuildmat.2019.06.047

[13] N. K. Bui, T. Satomi, H. Takahashi, Recycling woven plastic sack waste and PET bottle waste as fiber in recycled aggregate concrete: An experimental study, Waste Manage. 78 (2018) 79-93 https://doi.org/10.1016/j.wasman.2018.05.035

[14] P. O. Awoyera, A. Adesina, Plastic wastes to construction products: Status, limitations and future perspective, Case Studies Constr. Mater. 12 (2020) e00330 https://doi.org/10.1016/j.cscm.2020.e00330

[15] H. H. Kim, M. S. Lee, S. J. Lee, Performance evaluation of polymer modified asphalt (PMA) binders containing ground tire rubber (GTR), Inter. J. Pavement Res. Technol.12 (2) (2019) 215-222 https://doi.org/10.1007/s42947-019-0027-y

[16] M. A. Notani, P. Hajikarimi, F. M. Nejad, A. Khodaii, Rutting resistance of toner-modified asphalt binder and mixture, Inter. J. Pavement Res. Technol. 13 (1) (2020) 1-9 https://doi.org/10.1007/s42947-019-0131-z

[17] C. Li, J. Zou, W. Ke, G. Wang, T. Li, Y. Li, S. Li, B. Shu, C. Li, Laboratory evaluation of asphalt binder modified by waste carbon particles (WCP) reclaimed from printers, Inter. J. Pavement Res. Technol. (2020) https://doi.org/10.1007/s42947-020-0104-2

[18] K. Z. Ramadan, G. G. Al-Khateeb, M. M. Taamneh Mechanical properties of styrofoam-modified asphalt binders, Inter. J. Pavement Res. Technol. 13 (2) (2020) 205-211 https://doi.org/10.1007/s42947-019-0102-4

[19] G. G. Al-Khateeb, T. S. Khedaywi, M. F. Irfaeya, Shear properties of waste glass-asphalt mastics, Inter. J. Pavement Res. Technol. 12 (3) (2019) 307-314 https://doi.org/10.1007/s42947-019-0037-9

[20] M. Sarker, M. M. Rashid, Thermal degradation of poly (ethylene terephthalate) waste soft drinks bottles and low density polyethylene grocery bags, Inter. J. Sustain. Energy Environ. 1 (3) (2013) 78-86.

[21] L. T. Duarte, E. M. P. e Silva, J. R. Branco, V. F. Lins, Production and characterization of thermally sprayed polyethylene terephthalate coatings, Surface Coatings Technol. 182 (2-3) (2004) 261-267 https://doi.org/10.1016/j.surfcoat.2003.08.062

[22] S. R. Shukla, A. M. Harad, L. S. Jawale, Recycling of waste PET into useful textile auxiliaries. Waste Manage. 28 (1) (2008) 51–56 https://doi.org/10.1016/j.wasman.2006.11.002

[23] R. Navarro, S. Ferrandiz, J. Lopez, V. J. Seguí, The influence of polyethylene in the mechanical recycling of polyethylene terephthalate, J. Mater. Process. Technol. 195 (1-3) (2008) 110-116 https://doi.org/10.1016/j.jmatprotec.2007.04.126

[24] M. Ameri, D. Nasr, Performance properties of devulcanized waste PET modified asphalt mixtures, Petrol. Sci. Technol. 35 (1) (2016) 99-104 https://doi.org/10.1080/10916466.2016.1251457

[25] W. M. N. W. A. Rahman, A. F. A. Wahab, Green pavement using recycled polyethylene terephthalate (PET) as partial fine aggregate replacement in modified asphalt, Proc. Eng. 53 (2013) 124-128 https://doi.org/10.1016/j.proeng.2013.02.018

[26] E. Ahmadinia, M.. Zargar, M. R. Karim, M. Abdelaziz, P. Shafigh, Using waste plastic bottles as additive for stone mastic asphalt, Mater. Des. 32 (10) (2011) 4844-4849 https://doi.org/10.1016/j.matdes.2011.06.016

[27] T. B. Moghaddam, M. Soltani, M. R. Karim, H. Baaj, Optimization of asphalt and modifier contents for polyethylene terephthalate modified asphalt mixtures using response surface methodology, Measure. 74 (2015) 159-169 https://doi.org/10.1016/j.measurement.2015.07.012

[28] T. B. Moghaddam, M. Soltani, M. R. Karim, Stiffness modulus of Polyethylene Terephthalate modified asphalt mixture: a statistical analysis of the laboratory testing results, Mater. Des. 68 (2015) 88-96 https://doi.org/10.1016/j.matdes.2014.11.044

[29] M. Soltani, T. B. Moghaddam, M. R. Karim, H. Baaj, Analysis of fatigue properties of unmodified and polyethylene terephthalate modified asphalt mixtures using response surface methodology, Eng. Failure Anal. 58 (2015) 238-248 https://doi.org/10.1016/j.engfailanal.2015.09.005

[30] L. Widojoko, P. E. Purnamasari, Study the use of cement and plastic bottle waste as ingredient added to the asphaltic concrete wearing course, Proc. Soci. Behav. Sci. 43 (2012) 832-841 https://doi.org/10.1016/j.sbspro.2012.04.158

[31] A. A. Badejo, A. A. Adekunle, O. O. Adekoya, J. M. Ndambuki, K. W. Kupolati, B. S. Bada, D. O. Omole, Plastic waste as strength modifiers in asphalt for a sustainable environment, African J. Sci. Technol. Innov. Develop. 9 (2) (2017) 173-177 https://doi.org/10.1080/20421338.2017.1302681

[32] T. B. Moghaddam, M. R. Karim, T. Syammaun Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles, Constr. Build. Mater. 34 (2012) 236-242 https://doi.org/10.1016/j.conbuildmat.2012.02.054

[33] A. Modarres, H. Hamedi, Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes, Mater. Des. 61 (2014)8-15 https://doi.org/10.1016/j.matdes.2014.04.046

[34] A. Arulrajah, S. Perera, Y. C. Wong, S. Horpibulsuk, F. Maghool, Stiffness and flexural strength evaluation of cement stabilized PET blends with demolition wastes, Constr. Build. Mater. 239 (2019) 117819 https://doi.org/10.1016/j.conbuildmat.2019.117819

[35] E. Ahmadinia, M. Zargar, M. R. Karim, M. Abdelaziz, E. Ahmadinia, Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt, Constr. Build. Mater. 36 (2012) 984-989 https://doi.org/10.1016/j.conbuildmat.2012.06.015

[36] D. Movilla-Quesada, A. C. Raposeiras, L. T. Silva-Klein, P. Lastra-González, D. Castro-Fresno, Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen, Waste Manage. 87 (2019) 751-760 https://doi.org/10.1016/j.wasman.2019.03.018

[37] T. B. Moghaddam, M. Soltani, M. R. Karim, Evaluation of permanent deformation characteristics of unmodified and Polyethylene Terephthalate modified asphalt mixtures using dynamic creep test, Mater. Des. 53 (2014) 317-324 https://doi.org/10.1016/j.matdes.2013.07.015

[38] T. B. Moghaddam, M. Soltani, M. R. Karim, Experimental characterization of rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads, Constr. Build. Mater. 65 (2014) 487-494 https://doi.org/10.1016/j.conbuildmat.2014.05.006

[39] H. Taherkhani, M. R. Arshadi, Investigating the mechanical properties of asphalt concrete containing waste polyethylene terephthalate, Road Mater. Pavement Des. 20 (2) (2017) 381-398 https://doi.org/10.1080/14680629.2017.1395354

[40] J. D. A. A. E. Silva, J. K. G. Rodrigues, M. W. de Carvalho, L. C. D. F. L. Lucena, E. H. Cavalcante, Mechanical performance of asphalt mixtures using polymermicronized PET-modified binder, Road Mater. Pavement Des. 19 (4) (2018) 1001–1009 https://doi.org/10.1080/14680629.2017.1283353

[41] M. Gürü, M. K. Çubuk, D. Arslan, S. A. Farzanian, İ. Bilici, An approach to the usage of polyethylene terephthalate (PET) waste as roadway pavement material, J. Hazard. Mater. 279 (2014) 302-310 https://doi.org/10.1016/j.jhazmat.2014.07.018

[42] R. K. Padhan, A. Sreeram, Enhancement of storage stability and rheological properties of polyethylene (PE) modified asphalt using cross linking and reactive polymer based additives, Constr. Build. Mater. 188 (2018) 772-780 https://doi.org/10.1016/j.conbuildmat.2018.08.155

[43] D. Casey, C. McNally, A. Gibney, M. D. Gilchrist, Development of a recycled polymer modified binder for use in stone mastic asphalt. Resources, Conserv. Recycl. 52 (10) (2008) 1167–1174 https://doi.org/10.1016/j.resconrec.2008.06.002

[44] Z. Leng, A. Sreeram, R. K. Padhan, Z. Tan, Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP), J. Clean. Prod. 196 (2018) 615–625 https://doi.org/10.1016/j.jclepro.2018.06.119

[45] A. Ameli, J. Maher, A. Mosavi, N. Nabipour, R. Babagoli, N. Norouzi, Performance evaluation of binders and Stone Matrix Asphalt (SMA) mixtures modified by Ground Tire Rubber (GTR), waste Polyethylene Terephthalate (PET) and Anti Stripping Agents (ASAs), Constr. Build. Mater. 251 (2020) 118932 https://doi.org/10.1016/j.conbuildmat.2020.118932

[46] American Association of State Highway and Transportation Officials, Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer, AASHTO T316-08, AASHTO, Washington DC, 2008.

[47] American Association of State Highway and Transportation Officials, Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR), AASHTO T315-8, AASHTO, Washington DC, 2008.

[48] American Association of State Highway and Transportation Officials, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), AASHTO T313-8. AASHTO, Washington DC, 2008.

[49] American Society for Testing and Materials, Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test). D 2872. ASTM International, West Conshohocken, PA, USA, 2019.

[50] American Association of State Highway and Transportation Officials, Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV), AASHTO R 28-09, AASHTO, Washington DC, 2009.

[51] R. Choudhary, A. Kumar, K. Murkute, Properties of waste polyethylene terephthalate (PET) modified asphalt mixes: dependence on PET size, PET content, and mixing process, Periodica Polytechnica Civ. Eng. 62 (3) (2018) 685-693 https://doi.org/10.3311/PPci.10797