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Evaluation of conventional behavior of bitumen containing PET plastic and HMA pavement response utilizing 3D-Move analysis software

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Abstract

A well-developed road network provides good services for road consumers. Most roads in the world are flexible types of pavement. Bitumen has viscous-elastic properties and is very sensitive to temperature it plays a vital role in producing hot mix asphalt and influences the performance of HMA pavement. Flexible pavements are linked to extreme temperatures, causing rutting and fatigue cracking. Pavement distress shortens service life and increases maintenance costs. This research focused on improving pavement resistance to distress by modifying the conventional properties of bitumen using alternative materials such as shredded PET plastic. In this study, two stages were applied. The first stage was collecting samples, and the second stage determined the conventional properties of bitumen by adding 3%, 6%, and 9% of shredded PET plastic to the bitumen. Penetration, ductility, and softening point tests were performed to analyze the conventional behavior of bitumen. Finally, top-down and bottom-up cracks are used to evaluate rutting damage, with 3D-Move analysis software that accounts for moving vehicles under various loads and speeds. From the conventional bitumen test, at 3% PET plastic added to the bitumen has no significant effect on the penetration grade, Ductility, and softening point. However, when 6% and 9% PET by weight of bitumen mixed, the penetration grade, ductility, and softening result become 49.3mm, 45.5mm, 97mm, 85mm, and 57mm and 62^{o}C, respectively compared with the penetration grade, ductility, and softening point value of unmodified bitumen (66.5mm, 142cm, and 48.9^{o}C). Besides, the 3D-Move Analysis software results show that asphalt binders with higher PET plastic content best resist the rutting damage, top-down, and bottom cracks.

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1. Introduction

Transport has become a significant economic sector globally, and most roads worldwide are flexible types of pavement (Obeta and Njoku, 2016). A well-developed road network facilitates the transportation and marketing of farm products, while bad roads delay the movement of goods and services from producers to consumers and farm products from the rural areas to urban centers, which leads to vehicle damage and affects the socio-economic activity of the society (Gbam, 2017). Most roads in Ethiopia also have flexible pavement types (Road sector development program, 2015).

Bitumen is the raw material in the construction of HMA pavement. It is a visco-elastic material at a moderate temperature. It is susceptible to temperature, which stiffens when it is cold and softens when it becomes warm. It fails by rutting at high temperatures because it is soft, and at low temperatures, it fails by thermal cracking (Fazaeli et al, 2012). These failures are the most predominant distress types in the hot mix asphalt pavements (Ahmad et al, 2017). This distress reduces the pavement's service life, develops higher surface roughness, leads to vehicle damage and reduced passenger comfort, and increases maintenance costs (Habib et al, 2010 & Mashaan et al, 2014). There are different solutions to minimize pavement distress. The method to improve the quality of bitumen by modification, such as Polymers, crumb rubber, and fiber modification, helped enhance the performance of asphalt pavements by increasing the fatigue life and maximizing the resistance to cracking and permanent deformation (Prasad and Sowmya, 2015). The Properties of asphalt can be improved by controlling the refining process, which is very difficult to achieve. Therefore, the most favored method to enhance the quality of asphalt by modification with Polymer is to improve the hot mix asphalt pavement performance (Habib et al, 2010 & Mashaan et al, 2021). Nowadays, many types of research have been conducted on using Polymer in road construction, such as Plastic roads, because it has two benefits and is more available. One is used as a modifier in the hot mix asphalt pavement, and the other is better to protect the environment from pollution (Chandu et al, 2016).

Improvement of road performance is necessary because there are several traffic factors, such as heavier loads, higher traffic volume, and higher tire pressure. Ahmad et al. (2017); Chukka & Carr (2016); Manju (2017) explained that the shredded PET plastic added to hot aggregates forms a fine plastic coat over

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the aggregate. The coated aggregates mix with asphalt is found to have higher strength and resistance to Rutting and satisfactory performance over the life of the pavement.

The current procedures used to compute pavement responses are much simpler; the stress distributions at the tire-pavement interface are modeled as static, dynamic, uniform, and non-uniform, and stationary circular loads (Ghadimi, 2015). Moreover, 3D Move Analysis Software enters the asphalt mixes' frequency sweep test data (E* and G* test data) into the analysis. The properties of the viscoelastic material were taken into account in the investigation. Furthermore, 3D Move Analysis software is utilized to predict stresses and strains due to loading to predict rutting depths, top-down and bottom-up cracking due to loading of asphalt pavement (Abdo, 2017; Abdo & Khater, 2018).

2. Materials and methods

2.1. Study Area

The study was conducted at the AAiT and AAST Universities' highway laboratory in Addis Ababa, Ethiopia, because of the availability of laboratory equipment for the laboratory tests. Addis Ababa is the capital city of Ethiopia and the largest city in the country by population.

2.2. Materials

The raw materials utilized for the laboratory study include Bitumen 60/70 penetration grade and shredded PET plastic. The equipment was also used to evaluate penetration, ductility, and softening point tests and mechanical mixers to produce the modified bitumen to create homogenous mixtures.

2.3. Research Design

The study used an experimental research method to answer the research question and meet the objectives. The study follows two phases: The first phase was sample collection. Bitumen 60/70 penetration grade and shredded PET plastic were collected at this phase. The second phase was a laboratory test following the ASTM, AASHTO, and ERA procedures. This phase is further classified into two steps. Step I Quality testing- The quality of the bitumen was tested and compared with the ERA specification, and it was checked to fulfill the ERA specification. Step-II conventional and Dynamic shear modulus test (DSR)- to determine Penetration, Ductility, and Softening point test values and frequency sweep test data (E*, G*, and phase angle test data) respectively by adding 3, 6, and 9% of shredded PET plastic in the bitumen. The asphalt quality tests are shown in *Table 1*. In addition, the performance of PET plastic pavement with the normal pavement condition should be compared by considering the effects of loading a moving tire on the pavement, single dual tires, single dual tire tandems, and single single single tire tandem-axle vehicle loading conditions. The research design process is shown below in *Figure 1*.

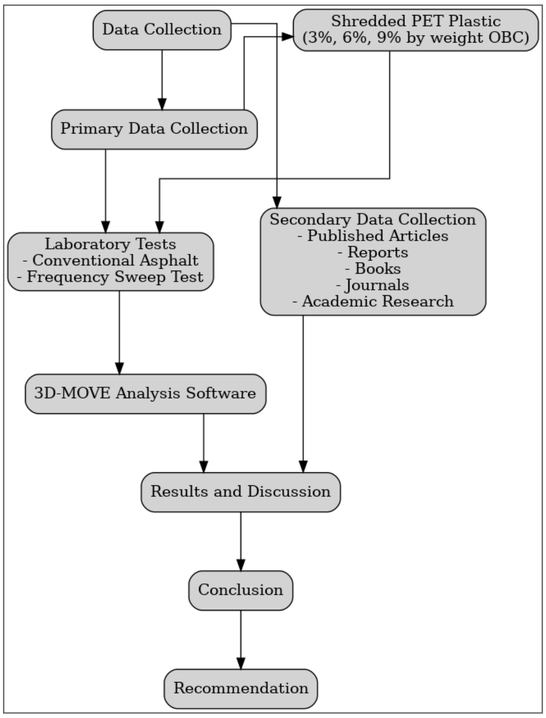

Fig.1 Research design process

Table 1: Asphalt quality tests

Conventional Asphalt Physical Test	Test Method
Penetration Grade test	AASHTO T 49
Ductility test	AASHTO T 51-94
Softening point test	AASHTO T 53-06

2.4. Mixing of PET plastic with bitumen

The shredded PET plastic that remains after passing through the 4.75mm sieve is used. The wet process is used in the melt-blending technique. Bitumen is heated in the oven till fluid condition, and shredded plastic is slowly added at a temperature of 150-160^{0}C. The mix continued for 45 - 60 minutes to produce homogeneous mixtures. The polymer-modified asphalt was sealed in containers and stored for further testing. Finally, performance tests were used as Conventional physical tests and DSR (Frequency Sweep test) (Appiah et al, 2016; Movilla-Quesada et al, 2019; and Farhana et al, 2017).

2.4.1. Conventional Asphalt Binder Physical Tests

Different tests were performed according to AASHTO test Standards to characterize the properties of bitumen, which was mixed with shredded PET plastic at a range of 3-9% by the increment of 3% by the weight of the bitumen. The different percentages of shredded plastic were added to the bitumen and mixed for 45- 60 minutes at a temperature of 150-160°C to ensure good homogeneity; then, various tests were performed. First, the asphalt binder was heated at a temperature of 150°C.

I. Penetration test

According to AASHTO T 49, a 100g sample of asphalt binder with 3%, 6%, and 9% by weight of sample shredded plastic was heated in an oven for enough time to soften entirely and was then uniformly mixed. Then it was transferred into a penetration test cup and allowed to cool to room temperature for 1 hour. The sample was then placed in water with a temperature controller set to 25°C and allowed to condition for about 1 hour. It was then removed, dried quickly, and placed under the needle of the penetrometer. Then, three readings were taken for a single penetration cup after placing the tip of the penetrometer needle precisely at the surface of the cup before the instrument was started. The average of the three sample values was recorded (Ahmad and Mahdi, 2015; Mahrez and Karim, 2010).

II. Ductility test

According to AASHTO T 51, the asphalt binder mixed with 3%, 6%, and 9% by weight of sample shredded plastic was heated and poured into the mold assembly placed on a plate. The samples were cooled in the air at room temperature for about 30 minutes and then put in a water bath at 27°C. The mold was removed on both sides and hooked on the machine; then, the assembly-contained sample was kept in a water bath of the ductility machine for 80-90 minutes, and the machine was operated. Finally, ductility value and the distance from the point up to break off the thread were measured and recorded in centimer (Tunde et al, 2020).

III. Softening Point test

AASTO T 53 stated that asphalt binder mixed with 0, 3, 6, and 9% PET shredded plastic by weight of binder should be heated and poured into two small brass rings and allowed to cool. A heated knife blade was used to trim the surface of the samples to the level of the brass rings. The prepared samples were then conditioned in a temperature controller at 4°C for at least 30 minutes before the test. A steel 3.55g ball-bearing was centered on each specimen and placed in a glass jar. An electric heater and thermometer were fitted into the beaker filled with clean, distilled water. The temperature when each ball and sample touches the bottom plate of the support was recorded as the softening point value. The average of the two read values was taken and rounded to the nearest whole degree (Ahmad and Mahdi, 2015; Abdullah et al, 2017).

IV. Rolling Thin-film Oven test (RTFO)

According to AASHTO T 240, a rolling thin film oven test (RTFO) follows the basic steps for aging asphalt binders. The RTFO simulates the asphalt binder aging (hardening) during the production and construction of HMA pavement (Arabani and Shabani, 2019). It exposes the fresh binder to heat and airflow during rolling. It takes only 85 minutes to perform the test, then provides an aged asphalt binder for further testing by the DSR and conventional asphalt test. The amount of volatile loss indicates the total aging that may occur during HMA production and construction (Yan et al, 2017).

V. Dynamic Shear Modulus test

Frequency sweep tests:- were also performed to determine the dynamic shear modulus G* and phase angle δ at temperatures of 21.1, 37.8, and 54.4^{0}C with 0, 3, 6, and 9% shredded PET plastic mixed with bitumen. The shear strain was applied for all the samples, and the frequency range used was 0.1 Hz to 25 Hz (Hafeez et al, 2013; Saboo and Kumar, 2016).

2.5. 3D-Move Analysis Software

3D-Move analysis software is a continuum-based finite-layer approach to analyze asphalt pavement responses under various moving traffic loads, traffic velocities, axle configurations, and tire contact areas to a pavement structure. The Asphalt Research Consortium developed the software. Which is a group of five organizations: Texas A&M University, Western Research Institute, University of Nevada-Reno (UNR), University of Wisconsin-Madison, and Advanced Asphalt Technologies, available at http://www.arc.unr.edu/Index.html. Moreover, 3D Move Analysis Software enters the asphalt mixes' frequency sweep test data (E* and G* test data) in the analysis. The properties of the viscoelastic material were taken into account in the study. Furthermore, 3D Move Analysis software utilized stresses and strains due to loading to predict rutting depths, top-down and bottom-up cracking due to loading of asphalt pavement (Abdo, 2017; Abdo & Khater, 2018). The main screen of the 3D-Move Analysis software version 2.1 is shown in *Figure 2.*

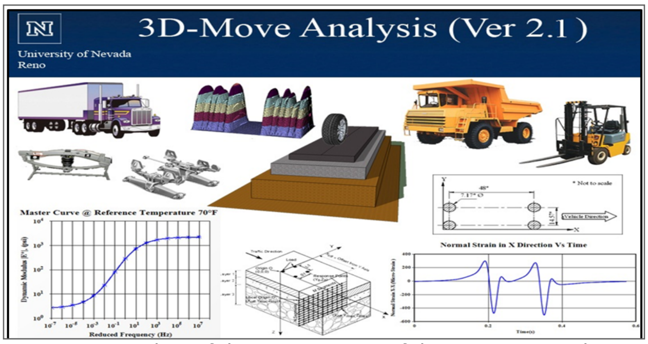

Fig.2 Screenshot of the Main Screen of the 3D Move Analysis software

2.5.1. 3D-Move Analysis of Software Selection Criteria

Most mechanistic procedures used to compute pavement responses are simpler; the tire-pavement interface's stress distributions are modeled as static, uniform, and stationary circular loads. For example, ELSYM5, WESLEA 3.0, BISAR 3.0, CIRCLY 7.0, KENLAYER, ILLI-PAVE, MICH-PAVE (Ghadimi, 2015). Therefore, 3D-Move Analysis software can be compared with others based on different conditions. These are:-

1. Model Approach

The 3D-Move model has been recognized as an efficient tool for simulated moving loads compared to other software because the 3D-Move program uses a finite layer approach and the Fourier Transform Technique for estimating pavement responses. This Fourier series expansion decomposes the loads into harmonic components in space (x and y directions). The total response at a given location is then calculated by adding the individual responses from each harmonic component (Sun et al, 2017; Ahmed and Erlingsson, 2016). It can handle any number of layers with complex loading at the surface and any number of response evaluation points. The 3D-Move model is ideally suited for pavement response evaluations since only a few critical responses are needed for pavement performance evaluations. Therefore, 3D-Move is much more computationally efficient than the moving load models based on the finite element method, such as KENLAYER, ILLI-PAVE, and MICH-PAVE (Nasimifar, 2015).

2. Tire-Pavement Interaction

3D-Move uses tire-pavement interaction-induced loading to model pavement responses. This is a critical factor considering that the noncircular loaded area and non-uniform contact stress induced by the tires can significantly affect pavement response computation. In addition, the tire-induced load varies with the vehicle's speed as it travels through the pavement. To ensure the success of mechanistic modeling, tire-pavement interaction, loading characteristics, and material behavior must be incorporated realistically. However, Conventional multi-layer programs such as BISAR, ELSYM, and WESLEA software are simple to use. Still, they do not accurately consider the mechanisms associated with moving tire-induced loading on the pavement. Most of them are limited to defining static uniform circular loads. Moreover, the software developed based on Burimister's layered theory solves for an elastic multilayered system under stationary single or multiple circular loaded areas with uniform normal contact pressure (Elseifi, 2019).

3. Defining Loading Characteristics

The load applied by a moving vehicle varies with its traveling speed and pavement surface characteristics. Conventional response analysis tools typically ignore this variation in the moving load. However, 3D-Move analysis considers loading characteristics with different traveling speeds because vehicle speed, such as strain and deflection, influences pavement response computation.

4. Axle Configuration and Contact Pressure Distribution

In 3D-Move Analysis, the pavement contact stress distribution is input data and assumes simple contact stress distributions such as circular or elliptical loaded areas with uniform vertical stress. However, the pavement contact stress distributions are non-uniform and more complex. The 3D-Move Analysis considers six loading conditions and is classified into an option; each option has been predefined in different load cases. These are: - Option A: Pre-defined load cases, Option B: User selected Pre-defined Axle/ Tire Configuration (Uniform pressure), Option C: User selected Tire Configuration and Contact Pressure Distribution from Database, Option D: Semi-Trailer Truck Including Vehicle Dynamics, Option E: Special Non-Highway Vehicles, and Options F: User-Input Tire Configuration and Contact Pressure Distribution (3D-Move Analysis Software ver. 2.1 manual, 2013).

5. Characterization of Asphalt Materials

The asphalt layer can be characterized as a linear elastic material or as a viscoelastic material. The dynamic modulus is required for the viscoelastic analysis. Therefore, 3D Move Analysis Software allows the analysis to input the asphalt mixes' frequency sweep test data (E*, G*, and phase angle δ data). The viscoelastic material properties were taken into account in the analysis, and they can be input in three different ways, but the other software is not considered (Abdo, 2017; Abdo & Khater, 2018).

6. Pavement Performance Models

The current version of the 3D-Move analysis software is equipped with two pavement prediction models: NCHRP 137A and VESYS performance models. These models primarily have cracking and rutting distress modes. However, the software listed above is not considered to be in such a condition.

NCHRP 1- 37A performance prediction model consists of six distress modes:

· AC Top-down & Bottom-up cracking

· AC (Asphalt Concrete) Rutting

· Base Rutting

· Subbase Rutting and

· Subgrade Rutting.

VESYS Model:- is a well-documented probabilistic and mechanistic flexible pavement analysis computer program series (Zhou, 2006). This model has also been incorporated into 3D-Move Analysis software to predict flexible pavements' structural responses and integrity. The VESYS model for flexible pavements consists of a primary response and damage models.

The primary response model is the time-dependent state of stress, strain, or deformation in the pavement. The direct response model represents the pavement system by an n-layer semi-infinite continuum such that the upper n-1 layers are finite in thickness.

All layers are infinite in horizontal extent. In contrast, the bottom layer is infinite in extent. The materials in each layer are assumed to be isotropic and homogeneous. The damage model in the VESYS model consists of three independent models that predict the accumulation of pavement cracking, rusting, and roughness within a given design period (3D-Move Analysis Software ver. 2.1 manual, 2013).

Under such circumstances, 3D-Move performs much more efficiently than the other moving load models based on the finite element method.

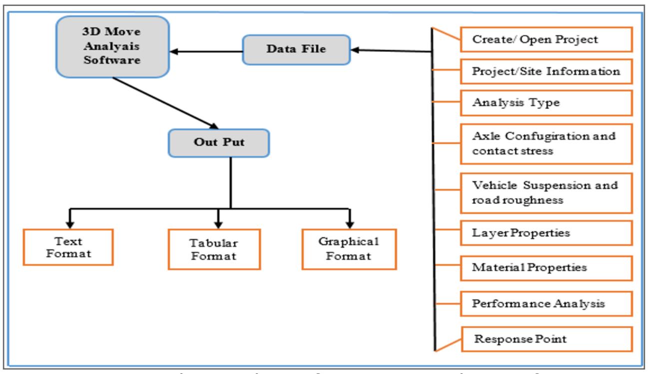

Fig.3 General Procedure of 3D-Move Analysis Software

3. Results and Discussion

3.1. Effect of PET on the Conventional Properties of Unaged Asphalt Binder

3.1.1. Effect of PET plastic on the Penetration Test

The test results of the asphalt binder 60/70 grade prepared at various percentages of PET plastic, 0, 3, 6, and 9% by total weight of asphalt binder. *Figure 4* represents the effect of variable concentrations of PET plastic on the penetration properties of asphalt binder and presented that decreased penetration grade values by 10.2%, 25.8%, and 31.5% with an increase in the concentration of PET plastic by addition of 3%, 6%, and 9% of PET, respectively, as compared to the original bitumen. This shows the increase in stiffness and consistency of bitumen. The stiffness of the bitumen can be advantageous as it increases the material's stiffness and improves the mix's rutting resistance. The 3% PET modified bitumen penetration grade value is not a significant change from the original bitumen grade range. However, when 6% and 9% PET by weight of bitumen are mixed, the penetration results become 49.3mm and 45.5mm, respectively, which is closer to bitumen grade 40/50. This mix can be suitably used in hotter climatic conditions, especially in regions with a substantially higher temperature differential. *Figure 4* shows the linearity equation (PT -2.4488%PET + 66.253), indicating that the addition of one percent of PET plastic decreases the 2.4488 unit value of penetration grade from the original asphalt binder.

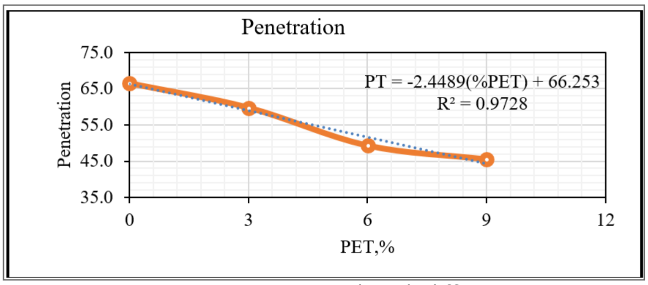

Fig.4 Penetration test result with different PET

3.1.2 Effect of PET plastic on the Ductility Test

Figure 5 shows the effect of various percentages of bitumen-modified PET plastic on the ductility value of bitumen. The Ductility of the original bitumen value was slightly reduced by 5.6% with 3% PET plastic and gradually decreased with the addition of different percentages of PET plastic, reducing by 31.6% with 6%. At 9% PET plastic, the ductility value is highly reduced by 40.1% compared with the original bitumen. But still, now, the value is satisfied with the ERA specification. This shows that the adhesive property of the modified binder decreases with an increase in the concentration of PET due to low interlocking between excessive polymer molecules with bitumen, making bitumen stiffer. Therefore, the optimum percentage of this PET plastic is necessary for the desired value of Ductility of bitumen needed for construction work. *Figure 5* shows the linearity equation (DT= -6.9%PET + 145.63), indicating that one percent of PET plastic added decreased 6.9 unit value of ductility value from the original asphalt binder.

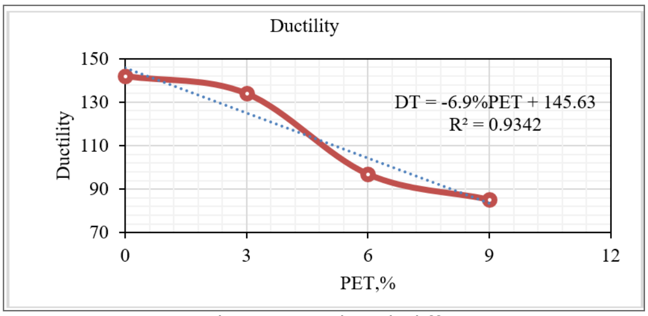

Fig.5 Ductility test result with different PET

3.1.3. Effect of PET plastic on the Softening Point Test

Figure 6 shows that the softening point value increases with increasing PET plastic content. This phenomenon depicts that the resistance of the binder to the effect of heat is increased, and reduces its tendency to soften at high temperatures. Thus, with the addition of PET, the modified binder becomes less susceptible to temperature changes. Consequently, by using PET plastic waste in a bituminous mix, the rate of Rutting decreases due to the increase in softening point. *Figure 6* shows the linearity equation (SF 1.533%PET + 47.65), indicating that the addition of one percent of PET plastic increases the softening value by 1.533 units from the original asphalt binder.

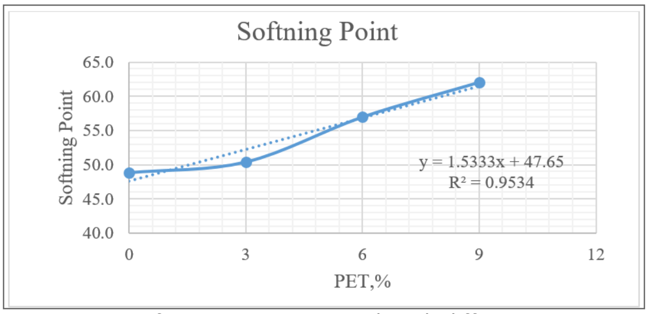

Fig.6 Softening Point test result with different PET

3.1.4. Aging Effect of Bitumen on the conventional tests using RTFO

After aging the modified bitumen, Penetration, Ductility, and softening point tests were conducted for each percentage of mixes for the 0%, 3%, 6%, and 9% PET plastic. After aging, the penetration, ductility, and softening point value decrease because of air oxidation, polymerization (molecules combine and form large molecules), and loss of more volatile components. Figures 7, 8, and 9 show that the gap between the aged and unaged values of penetration, Ductility, and softening point decreased with increased concentration of PET plastic. This shows that the original asphalt binder becomes highly aged when exposed to air and heat, compared with the modified asphalt binder, and decreases the aging character because the plastic concentration reduces the amount of asphalt binder content and decreases the oxidation and loss of volatile components.

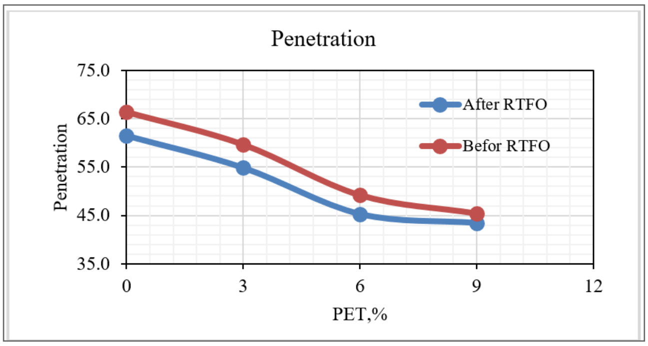

Fig.7 Comparison between penetration for aged and unaged binder

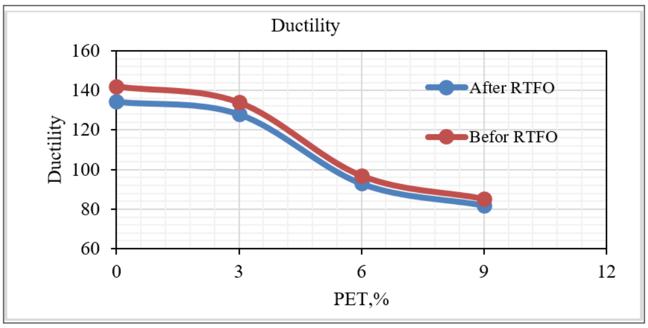

Fig.8 Comparison between Ductility for aged and unaged binder

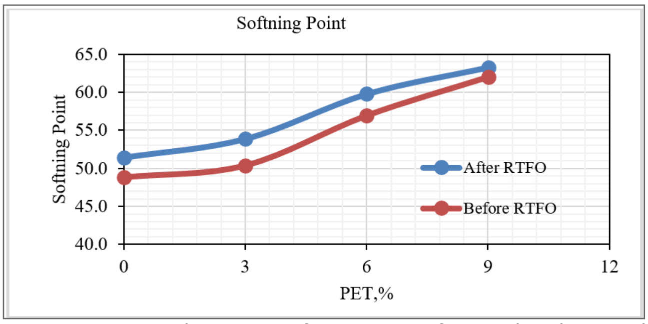

Fig.9 Comparison between Softening Point for aged and unaged binder

3.2. Numerical Results of Pavement Response with and without PET plastic

In this section, to compare the performance of plastic pavement with the normal pavement by considering the effects of loading a moving tire on the pavement by a recreation of dual tire single, dual tire tandem, and Super single tire tandem-axle vehicle loading conditions with 3 million repetitions during the design period of 20 years. A typical 4-layer flexible pavement structure was used in the analysis, consisting of a 5cm AC layer, 25cm base course, 30cm Sub-base, and subgrade.

Results showed that increased PET contents decreased AC Rutting, top-down, and bottom-up cracking. *Figure 10* shows that the rutting depths in the asphalt concrete layer decreased with PET plastic content. At 0 and 3%, plastic content has no significant variation, while at 6 and 9%, the rutting failure decreases with increased PET. Furthermore, dual-tire single-axle load has more significant pavement damage than other load cases because the load is concentrated and has a higher load effect on the pavement. In contrast, super single tire tandem axle load has a lower impact than others because it has more than two axles and a single broader tire base. Due to this, a higher contact surface area leads to the uniform distribution of the load and decreases the pressure. In addition to this, the rutting resistance of a modified binder is better than that of a conventional binder.

Figure 11 also shows that the top-down cracking results followed the same trend as Rutting, at 3%, PET plastic has a slightly higher value than the conventional binder. However, at 6 and 9%, PET plastic content has a lower top-down value and best performance. It indicates that the PET plastic modifier binder has better resistance to top-down cracking at the top of the pavement by decreasing High surface horizontal tensile stresses due to truck tires, age hardening of the asphalt binder resulting in high thermal stresses in the HMA, and modify the stiffness of the upper layer caused by high surface temperatures. *Figure 12* indicates that HMA pavement is more resistant to bottom-up cracking when the PET content increases. It means that the modified binder of HMA pavement has a better resistance to tensile bending stresses at the bottom of the HMA layer and then progresses up to the pavement's surface. Super single tire tandem axle load has a lower value than others. Overall, the results of the analysis showed that asphalt binders with higher PET plastic content perform best since the stiffness of the asphalt mixes increases with the addition of PET plastic. Thus, asphalt mixes perform better and have higher resistance to distress.

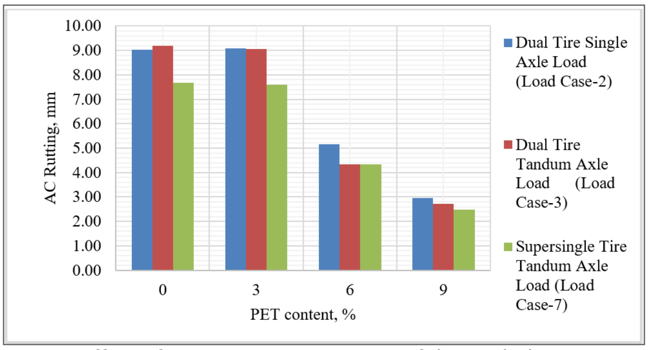

Fig.10 Effect of PET content on Rutting of the asphalt concrete layer

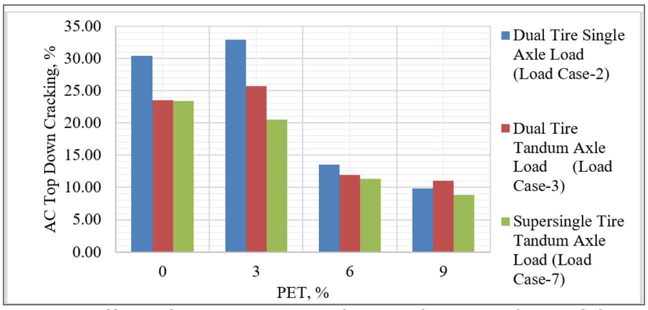

Fig.11 Effect of PET content on the top-down cracking of the asphalt concrete layer

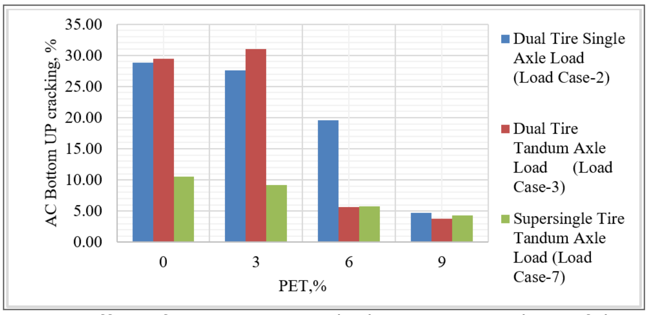

Fig.12 Effect of PET content on the bottom-up cracking of the asphalt concrete layer

4. Conclusion and Recommendation

This study tries to evaluate bitumen-containing PET plastic's conventional behavior and the pavement response using 3D-Move analysis software. Based on the results obtained from this study, adding PET plastic changes the bitumen properties by decreasing the penetration and ductility value with an increased softening point as the PET plastic content increases. At 3%, PET-modified bitumen was not significantly changed from the original bitumen grade range. However, when 6% and 9% PET by weight of bitumen are mixed, the penetration results show 49.3mm and 45.5mm, respectively, which is closer to bitumen grade 40/50. Also, at 3% PET, plastic added to the bitumen has no significant effect on the ductility value of the original bitumen. However, it gradually decreases with the increase in the addition of PET plastic. After aging, penetration, ductility, and softening point values decreased because of air oxidation and loss of more volatile components, making it stiffer for all the mixes. This means that the results showed that asphalt binders with higher PET plastic content can best resist damage and top-down and bottom-up cracks. On the other hand, at 0 and 3%, plastic content has no significant variation, while at 6 and 9%, the rutting failure decreases with an increase in the PET content. For the top-down cracking at 3%, the PET plastic is slightly higher than that of the conventional binder.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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