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A novel foaming additive derived from waste polyethylene terephthalate (PET) for low-carbon warm mix asphalt

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Abstract

Plastic pollution is growing relentlessly due to the careless disposal of waste plastic products. This study focuses on converting waste plastic bottles into a foaming additive for the production of eco-friendly warm mix asphalt (WMA). The additive, namely PET-TETA, was synthesized from waste PET via an ammonolysis process. Its chemical and physical properties were characterized by X-ray diffractometer (XRD), scanning electron microscope (SEM), and thermogravimetry-differential thermal analyzer (TG-DTA) tests. The WMA mixture was prepared using PET-TETA and compared to a conventional hot mix asphalt mixture and another WMA mixture prepared with a commercial foaming additive. The performance of the asphalt mixtures was characterized using the indirect tensile stiffness modulus test, moisture susceptibility test, and immersion Hamburg wheel-tracking test. Results showed that PET-TETA was a semicrystalline material containing approximately 26% hydration water, which could be released gradually during the preparation of asphalt pavements. The overall performance of the WMA mixture with PET-TETA was comparable to the other two asphalt mixtures, and it exhibited higher strengths and better resistance to stripping. Therefore, PET-TETA can be considered a sustainable and effective WMA additive, providing a solution to the issue of waste plastic disposal.

Keywords: Asphalt Pavement, Warm Mix Additive, Waste Plastic, Physical and Chemical Properties

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1. Introduction

The ubiquitous presence of waste plastic has become one of the most pressing environmental issues due to the increasing production of disposable plastic products over the last century. In Hong Kong, waste plastic is the third largest constituent of municipal solid waste (MSW), with 945.9 thousand tons (21% of MSW) generated in 2020 alone (HK EPD, 2021). Although measures such as the Plastic Recycling Pilot Scheme has been implemented by the local government to promote plastic recycling, the capacity of the local recycling industry remains limited, and import policies by other economies have become more stringent. As a result, only a small portion of waste plastic is being recycled in Hong Kong. The amount of waste plastic recycled in Hong Kong was recorded at 102 thousand tons in 2020, accounting for only 10.8% of the generated waste plastics. The vast majority of waste plastics is disposed of at landfill sites. However, waste plastics are non-degradable, posing significant environmental and economic challenges in a densely populated urban city like Hong Kong.

Utilizing waste plastic in asphalt pavement as additives through chemical treatment is considered a potential approach to address this problem. Previous studies have investigated the feasibility of synthesizing beneficial additives from various waste plastics, including polyethylene (PE) (Awwad and Shbeeb, 2007; Hınıslıoğlu and Ağar, 2004; Liang et al., 2021; Punith and Veeraragavan, 2007), polyethylene terephthalate (PET) (Leng et al., 2018; Li et al., 2021; Sreeram et al., 2018; Xu et al., 2022a; Xu et al., 2021), and polypropylene (PP) (Al-Hadidy and Tan, 2009; Xu et al., 2022b; Yeh et al., 2005). Among them, PET derived additives have been thoroughly studied and were thought to obtain the best potential for use in asphalt pavement. Li et al. developed a method of using triethylenetetramine (TETA) and waste PET to synthesize a polymer additive (i.e., PET-TETA) that improved the resistances to stripping and deformation of the

produced asphalt pavement (Li et al., 2021; Xu et al., 2021). It is interesting to note that PET-TETA absorbed a certain amount of water through the hydration process during washing at the final step for cleaning the product. **Fig. 1** illustrates the thermal property of PET-TETA. It can be observed that the water of hydration is unstable and can be easily expelled by heating. Approximately 20% of water was released in a temperature range of 100 – 200 ºC, showing the potential of PET-TETA to be used as a foaming additive in warm mix asphalt (WMA). This green paving material-WMA allows conventional hot mix asphalt (HMA) to be mixed and paved at lower temperatures without compromising on maintaining good engineering performance.

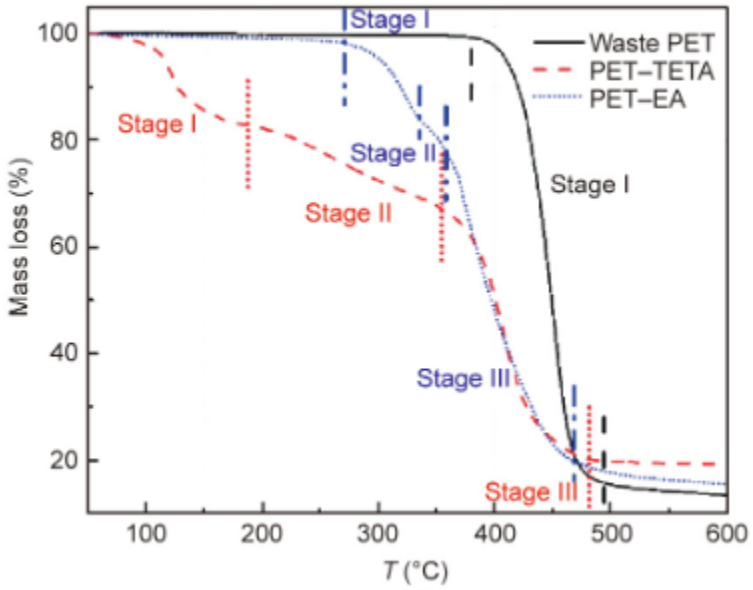


Fig. 1. Thermogravimetric analysis of waste PET and PET derived additives (Retrieved from Xu. et al., 2021).

Foaming technologies have been widely used to prepare WMA due to their simple operation and low construction cost, and the construction temperature can be reduced by 20-40 ºC (Capitão et al., 2012; Middleton and Forfylow, 2009; Rubio et al., 2012; Zhang et al., 2018; Zou et al., 2022).

The foaming effect can be achieved by adding water-bearing agents or using water injection techniques. A commercial product, aspha-min, has been commonly applied to prepare WMA in practice. It is a synthetic zeolite that contains crystal water in its structure. When a water-bearing agent is added to hot asphalt mixtures at construction temperatures of 140 -180 ^{o}C, the unstable hydration water is detached and vaporized, which creates a rapid volume expansion of the asphalt binder. This foaming effect improves the coating between asphalt binder and aggregate and allows asphalt mixtures to be constructed at lower temperatures. Therefore, PET-TETA is considered an environmental friendly alternative to the conventional commercial foaming additive due to its comparable water-bearing property. However, the chemical and physical characteristics of PET-TETA as a foaming additive have not been investigated yet. In addition, the performance of WMA containing PET-TETA is needed to be studied. To fill this research gap, the objective of this study is to investigate the performance of the WMA mixture prepared using PET-TETA through comprehensive laboratory tests. The chemical and physical properties of the synthetic PET-TETA were characterized by X-ray diffractometer (XRD), scanning electron microscope (SEM), and thermogravimetry-differential thermal analyzer (TG-DTA) tests. The performance of the prepared WMA mixture using PET-TETA was investigated through the indirect tensile stiffness modulus test, moisture susceptibility test, and immersion Hamburg wheel-tracking test. The results were compared to the conventional HMA mixture and another WMA mixture prepared with a commercial foaming additive to validate the effectiveness of PET-TETA as a foaming agent in asphalt pavement.

2. Methodology

2.1. Synthesis and characterization of PET-TETA additive

In this study, waste PET water bottles were collected from local plastic recycling bins. A pretreatment process was conducted to eliminate impurities by removing product labels and washing the bottles using normal detergent solutions and water. Waste PET bottles were then cut into rod-like pieces with an approximate length of 5 mm, and dried at 80 °C for 4 hours. Afterward, the PET waste was added to a round bottom flask with TETA, and the mass ratio of PET and TETA was adjusted to 1:2. The ammonolysis process of PET was performed under reflux at 140 °C for 2 hours. Synthetic products were collected at the end of the reaction using vacuum filtration. The PET-TETA additive, a white powder, was obtained through water cleaning, drying, and grinding processes. **Fig. 2** illustrates the synthesis process of PET-TETA.

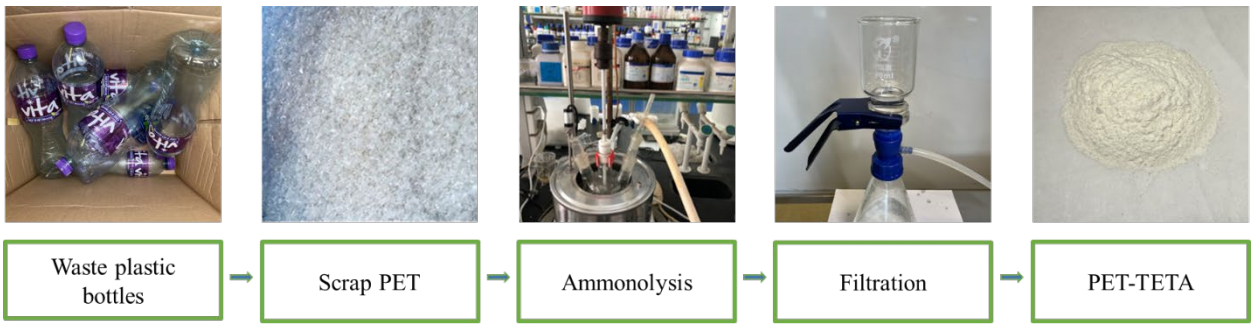


Fig. 2. Synthesis process of PET-TETA from waste plastic bottles

The properties of the two WMA additives (i.e., PET-TETA and aspha-min) were characterized by XRD, SEM, and TG-DTA tests. The XRD test was conducted using a Rigaku SmartLab X-ray diffractometer with a 9-kW rotating anode X-ray source and a high-energy resolution semiconductor detector. The scanning was operated using a step width of 0.02 °, a speed of 4 °/min, and an X-ray wavelength (λ) of 1.54 Å. The detected XRD patterns were compared with the powder diffraction file (PDF) database for identification. The SEM test was conducted using a Tescan VEGA3 SEM system with a high spatial resolution (up to 100,000X) with a secondary

electron and backscatter detector. The TG-DTA test was conducted using a Rigaka Thermo plus EVO2 thermal analyzer. The measured temperature range was set from 25 ºC to 600 ºC with a heating rate of 10 ºC/ min.

2.2. Raw materials and sample preparation

Three asphalt mixtures were prepared in this study, including conventional hot mix asphalt (HMA), WMA with PET-TETA (PET), and WMA with aspha-min (APM). The dosage of PET-TETA was 2% by the mass of the asphalt binder according to previous studies. The dosage of aspha-min was 5% by the mass of the asphalt binder based on supplier recommendations. A frequently used surface course material for local carriageway pavements, namely polymer-modified stone mastic asphalt with a nominal maximum aggregate size of 10 mm (PMSMA10), served as the mixture design for all three types of mixtures (Highways Department, 2016). The coarse aggregates, fine aggregates, and mineral fillers used in this study were local granite rocks. The asphalt binder used in this study was styrene-butadiene-styrene (SBS) polymer-modified bitumen with a Superpave performance grade of PG76-16 (AASHTO, 2013a). The binder content was set at 6.0% by the total mass of the asphalt mixture (the same hereinafter, if not specified). Hydrated lime and cellulose fiber were also used in this study, and their contents were 0.3% and 2%, respectively. **Fig. 3** illustrates the gradation curve of the PMSMA10 mixture.

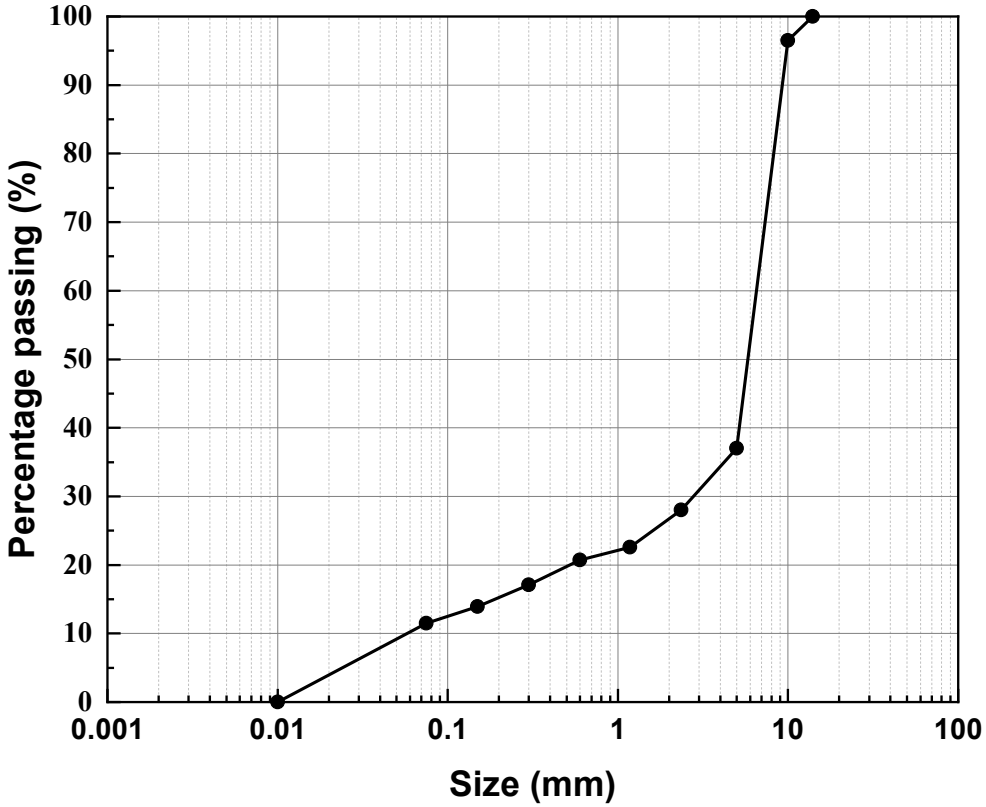


Fig. 3. Aggregate gradation of the PMSMA10 mixture.

Superpave gyratory compactor (SGC) was adopted in this study to prepare test specimens. The mixing temperatures of HMA mixtures and WMA mixtures were controlled at 180 ºC and 155 ºC, and their compaction temperatures were controlled at 160 ºC and 135 ºC to achieve a construction temperature reduction of 25 ºC. In the preparation of WMA mixtures, the foaming of asphalt binder was achieved by shear-mixing the foaming additive into the hot asphalt binder at 155 ºC for 3 minutes. The foamed asphalt binder was subsequently mixed with the aggregates and the mixture was compacted at the designed temperature. The mixtures were compacted to a designed air void

content of 4% ± 0.5% and tested for indirect tensile stiffness modulus (ITSM). Specimens with a higher air void content of 7% ± 0.5% were also produced for the moisture susceptibility test and Hamburg wheel-tracking test according to test specifications. Specimens were made in two replicates for Hamburg wheel-tracking test, while four replicates were tested for the other tests. **Table 1** presents the general information on the prepared specimens and engineering tests.

2.3. Laboratory tests for asphalt pavement performances

Surface distresses, such as rutting, moisture damage, fatigue cracking, and thermal cracking are often generated after repetitive traffic loading (Jiang et al., 2022; Li et al., 2020; Tan et al., 2022). The high temperature performance and intermediate temperature durability of the produced asphalt mixtures were investigated in this study regarding the relatively hot climate of Hong Kong. In addition, the moisture susceptibility of the prepared WMA mixtures was evaluated concerning the water introduction during the foaming process (Hasan et al., 2015; Xu et al., 2017). The cracking resistance of HMA, PET, and APM at intermediate temperatures was evaluated by the ITSM test. The rutting resistance of HMA, PET, and APM at high temperatures was investigated by immersion Hamburg wheel-tracking test. The moisture damage resistance of HMA, PET, and APM was determined by the moisture susceptibility test with freeze-thaw cycle conditioning.

The dimensions of the test specimens produced for the ITSM test were 100 mm (diameter) × 40 mm (height) (BSI, 1993). To investigate the cracking performance of the prepared mixtures right after the construction and after a long service time, the produced specimens were subjected to a short-term and long-term aging process. The laboratory aging process was conducted in the following ways: before compaction, loose mixtures were conditioned at 135 ^{o}C for 4 hours in a force-draft oven; after compaction, compacted mixtures were further aged at 85 ^{o}C for 5 days in

the oven (AASHTO, 2010). A PAVETEST dynamic testing system (DTS-30) was used to measure the modulus of HMA, PET, and APM.

The dimensions of the test specimens produced for the moisture susceptibility test were 100 mm (d) × 62.5 mm (h) (ASTM, 2014). The moisture susceptibility was evaluated by the Tensile strength ratio (TSR) between freeze-thaw cycle conditioned mixtures and unconditioned mixtures. The conditioning process was conducted by saturating the prepared specimens with water. Then, the partially saturated specimens (i.e., 70% to 80%) were conditioned at -18 ºC for 16 h in a freezer and 60 ºC for 24 h in a water bath. The indirect tensile (IDT) strength of the produced asphalt mixtures was measured by DTS-30.

The dimensions of the test specimens produced for the Hamburg wheel-tracking test were 150 mm (d) × 60 mm (h) (AASHTO, 2013b). A CRT-WTIM wheel tracker (Cooper Research Technology) with linear variable differential transformers (LVDTs), a water bath with a temperature control system, and two moving steel wheels was used to record the rut depth in this study. The immersion Hamburg wheel-tracking test was conducted using a wheel load of 705 N and a rolling speed of 52 passes/ min. The test specimens were conditioned and tested in the water bath at 50 ºC, the most common temperature used for the test. Rut depth was recorded every 200 passes, and the test was completed after 20,000 passes or a maximum LVDT displacement of 1.6 in. (40.9 mm).

Table 1 Details of the prepared specimens and engineering tests.

Label	**HMA**	**APM**	**PET**
Mixture	Conventional hot mix asphalt	Warm mix asphalt with aspha-min	Warm mix asphalt with PET-TETA
Mixing/ compaction temperature (ºC)	180/ 160	155/ 135	155/ 135

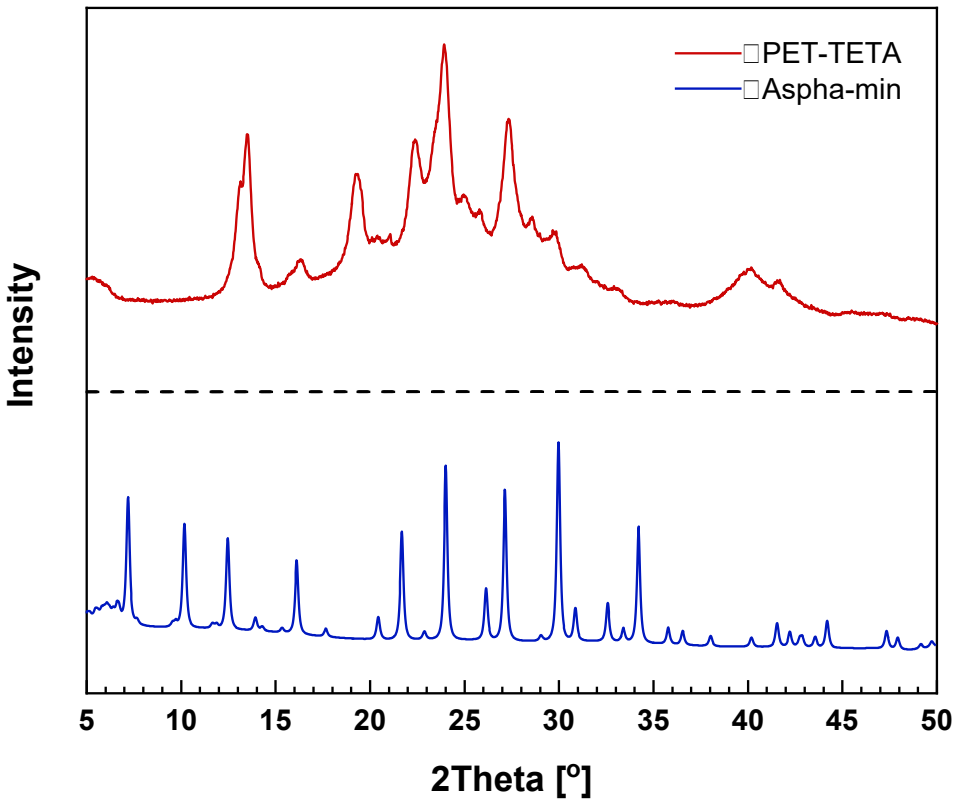
Test	Indirect tensile stiffness modulus test
Specimen diameter/ thickness (mm)	100/ 40
Air void content (%)	3.5 - 4.5
Test temperature (°C)	20 ± 0.2
Test	Moisture susceptibility test
Specimen diameter/ thickness (mm)	100/ 62.5
Air void content (%)	6.5 - 7.5
Test temperature (°C)	25 ± 0.5
Test	Hamburg wheel-tracking test
Specimen diameter/ thickness (mm)	150/ 60
Air void content (%)	6.5 - 7.5
Test temperature (°C)	50 ± 1.0

3. Results and Discussion

3.1. Characterization of PET-TETA

Fig. 4 illustrates the XRD patterns of PET-TETA and aspha-min. A clear crystalline structure can be observed for aspha-min. However, PET-TETA behaved more like an amorphous polymer but also contained a few crystalline regions. The crystalline phase of zeolite A was identified in aspha-min based on the PDF database. Aspha-min captures hydration water in its tight polyhedral cage crystalline structure, where the water molecules are linked by coordinate covalent bonds or hydrogen bonds. However, it was unable to match PET-TETA to any specific crystals as it exhibits no apparent crystalline structure, indicating that the mechanisms of absorbing and releasing water are quite different for PET-TETA and aspha-min. The results of XRD patterns show that PET-TETA has both crystalline regions and amorphous regions. Unlike aspha-min that stores hydration water in its crystalline structure, the crystalline region in PET-TETA genuinely has an adverse

effect on water absorption. The crystalline region is the area of molecules where polymer chains are more aligned and closer to each other. The amorphous region is the area of molecules where polymer chains are loosely distributed, and there is no orderly manner. PET-TETA absorbs water through hydrogen bonding with water molecules, each hydrophilic amide group in PET-TETA has a slightly positive hydrogen atom and two lone pairs on the oxygen atom, which both can engage in hydrogen bonding with water molecules, and both hydrogen bonding networks extend in all directions. The molecules in crystalline regions are stacked together and held by the van der Waals force, making it difficult for water molecules to attach within these regions. However, the amorphous regions in PET-TETA grant it the ability to bond with water molecules as there is more space for water molecules to be absorbed instead of the crystalline regions. **Fig. 5** shows a schematic diagram of the crystalline and amorphous regions of PET-TETA. Most chains in PET-TETA are randomly coiled and entangled in a disordered pattern, while some chains are aligned together and form an ordered structure.



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201 **Fig. 4.** XRD patterns of PET-TETA and aspha-min.

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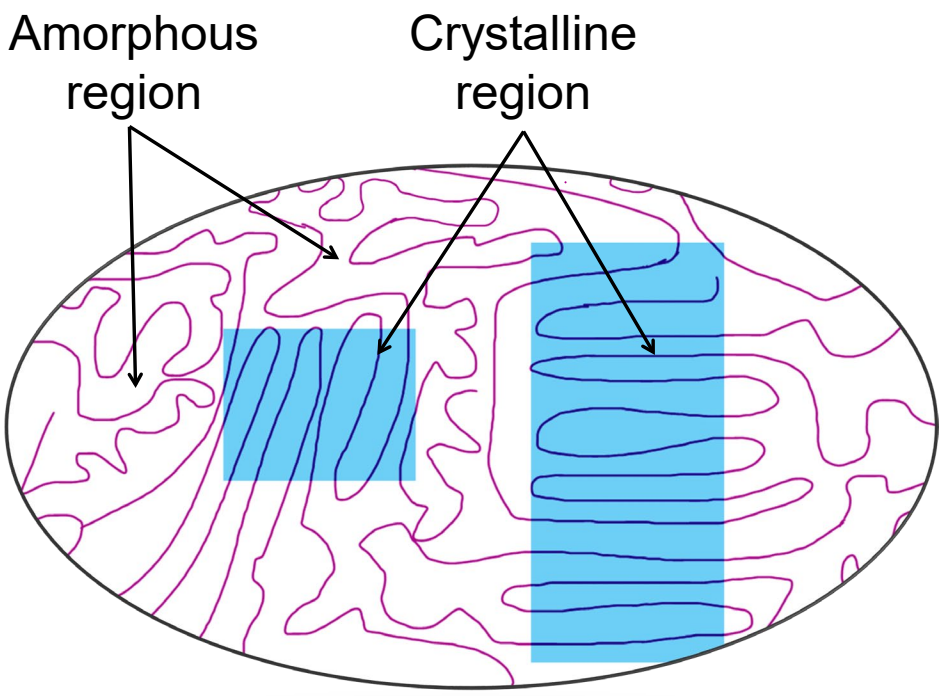
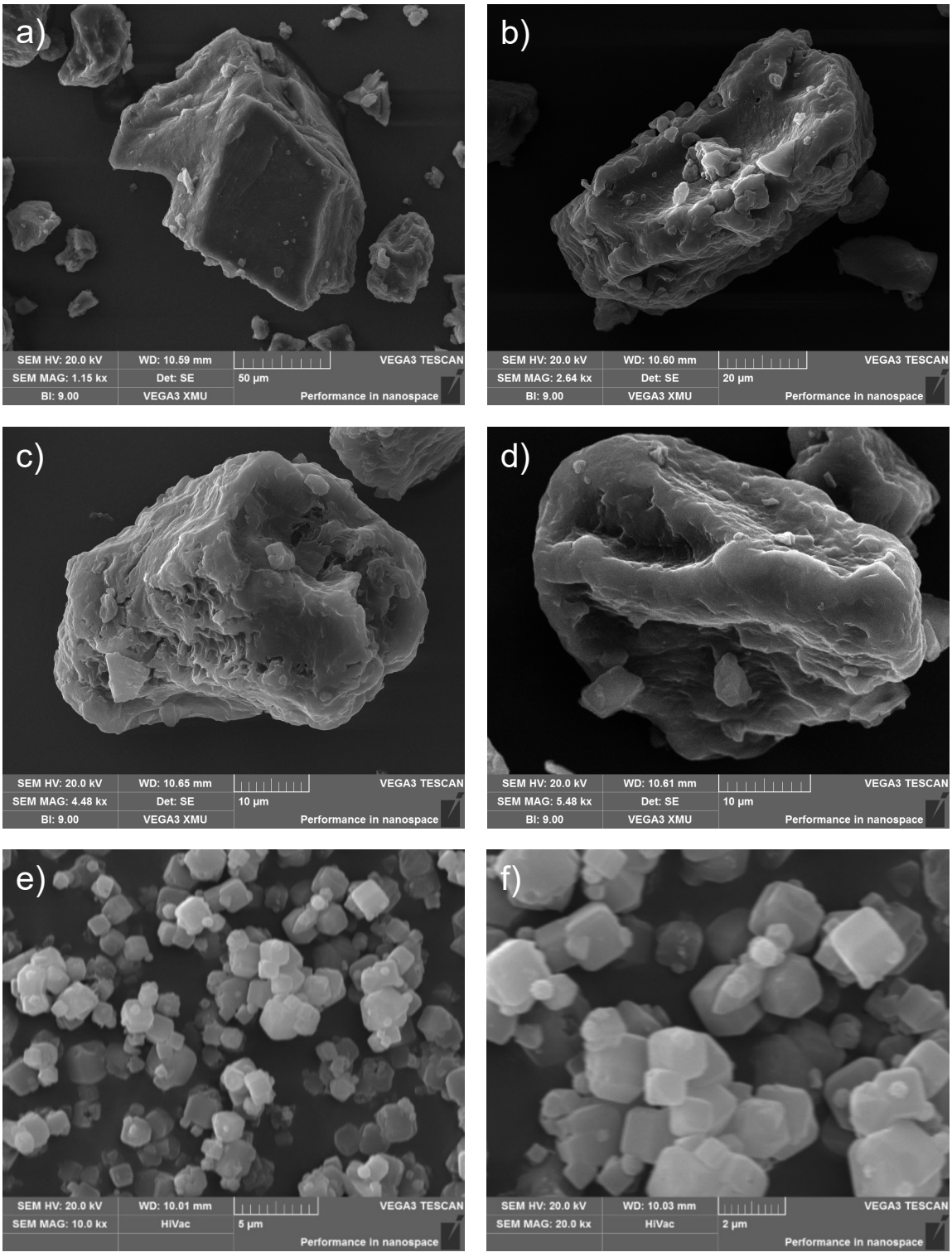


Fig. 5. Schematic diagram of PET-TETA that contains both amorphous and crystalline regions.

Fig. 6 shows the SEM images of PET-TETA and aspha-min. It is clear to observe the cubic crystalline structure of aspha-min from **Fig. 6 (e) and (f)**, and the crystalline size is about 2μm in diameter. However, PET-TETA presents random morphologies and poses no specific grain sizes. The crystalline regions of PET-TETA can be observed in **Fig. 6 (a)**, which form a trapezoidal prism-like structure. The molecules in crystalline regions sit together in a more ordered pattern, and the chains are stacked together so that the structure displays flat surfaces and sharp edges.

In contrast, **Fig. 6 (b), (c), and (d)** present poorly defined patterns of amorphous regions since their components are in irregular arrangement, showing rough surfaces and round edges. In addition, a lot of pores are observed in the structures from the SEM images. The disordered arrangement of molecule chains in amorphous regions creates voids in their structures, which helps PET-TETA to absorb water by allowing water molecules to fit in these spaces. The particle sizes

of PET-TETA ranged from several micrometers to hundreds of micrometers, and bigger particles had more crystalline patterns, while finer particles presented more amorphous structures. Unlike the ordered molecules in crystalline regions, amorphous regions contain no plane of atoms that can slip past each other, and the stress is not relieved during the grinding process. Therefore, excessive stress formed cracks at amorphous regions, and the molecule chains were broken up into small pieces, while the molecules in crystalline regions could generally maintain their structures, resulting in their size differences.



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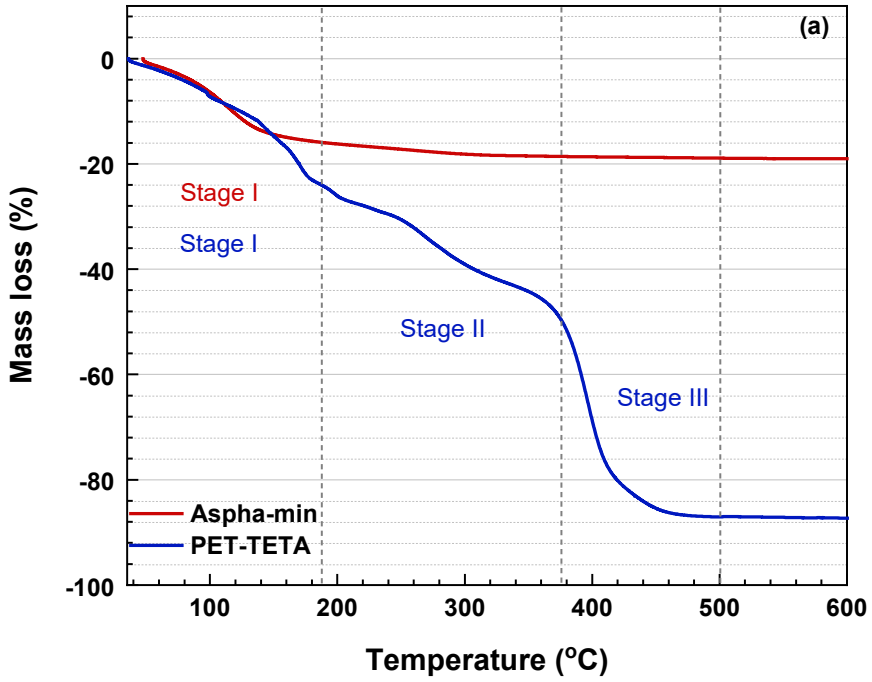
224 **Fig. 6.** SEM images of PET-TETA ((a) 1k×, (b) 3k×, (c) 4k×, (d) 5k×) and aspha-min ((e) 10k×

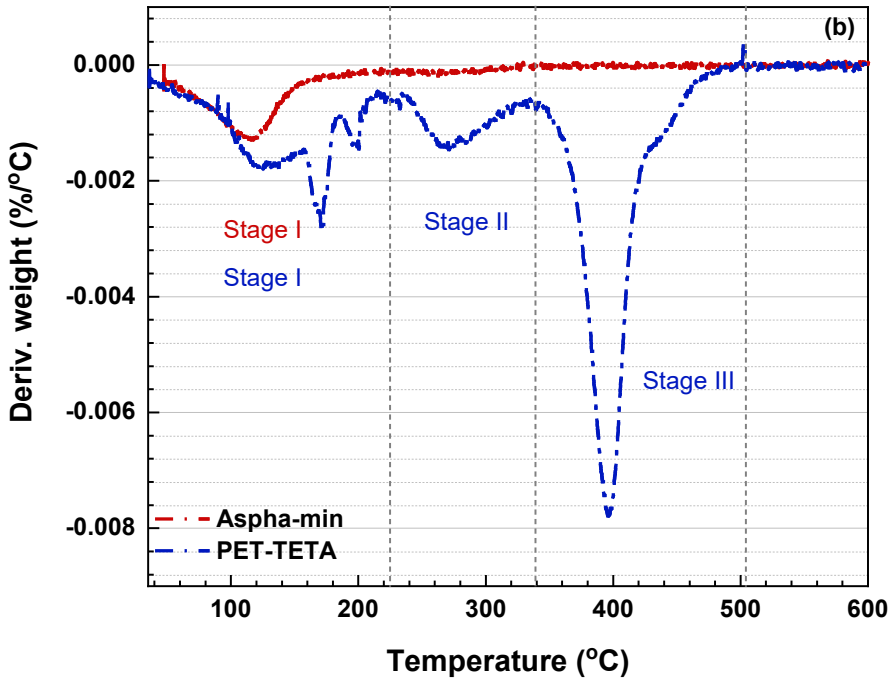
225 and (f) 20k×)

Fig. 7 shows the thermal properties of PET-TETA and aspha-min. The mass loss before 200 ºC indicates the release of water, and the mass loss over the range of 200-600 ºC implies the release of pyrolysis products by thermal decomposition (Duan et al., 2008; Saldo et al., 2002). It can be observed that both materials released hydration water when the temperature started to increase, but aspha-min had only one stage of mass loss while PET-TETA presented multiple stages of mass loss. The total mass losses of aspha-min and PET-TETA at 600 ºC were 18.7% and 87.9%. The results suggest that aspha-min has no thermal decomposition except for the release of crystal water, while PET-TETA has components that can be decomposed at high temperatures. Aspha-min, a hydrated aluminosilicate zeolite, released crystal water when heating began and continued up to approximately 200 ºC. Then, it decomposed very slowly when the temperature kept rising from 200 ºC to 600 ºC since aluminosilicate is relatively stable and hardly decomposes under such temperatures. However, PET-TETA, the ammonolysis product of PET, also released hydration water when the temperature increased, but it further degraded at about 250 ºC and 400 ºC. The observed percentage mass losses of hydration water from aspha-min and PET-TETA were 16.3% and 26.0%, which implies that PET-TETA has better water bonding abilities than aspha-min.

Moreover, the earlier heat absorption peak of aspha-min (i.e., about 110 ºC) indicates that aspha-min is more sensitive to temperature changes than PET-TETA, which had a heat absorption peak at approximately 150 to 170 ºC. Based on the thermal properties of the two materials, PET-TETA is expected to have a better foaming effect and asphalt coating by releasing more hydration water and preserving steadier water evaporations at high construction temperatures. **Fig. 8** shows the foaming effect of aspha-min and PET-TETA in asphalt binder at 150 ºC. It can be clearly observed that PET-TETA performed better foaming. PET-TETA generated large bubbles, while aspha-min produced small dense foams. The differences in their water bonding characteristics might be the

major reason for it. PET-TETA contains larger amounts of hydration water that is mostly bonded to the molecules in the loose amorphous region, which is preferred to be released when there is sufficient heat. However, aspha-min encloses less hydration water, and it is caged in the tight polyhedral crystalline structure. Therefore, it released less water in the foaming process, and the escape of water was slower, resulting in inferior foaming compared to PET-TETA.





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256 **Fig. 7.** (a) weight loss and (b) heat flow of aspha-min and PET-TETA.

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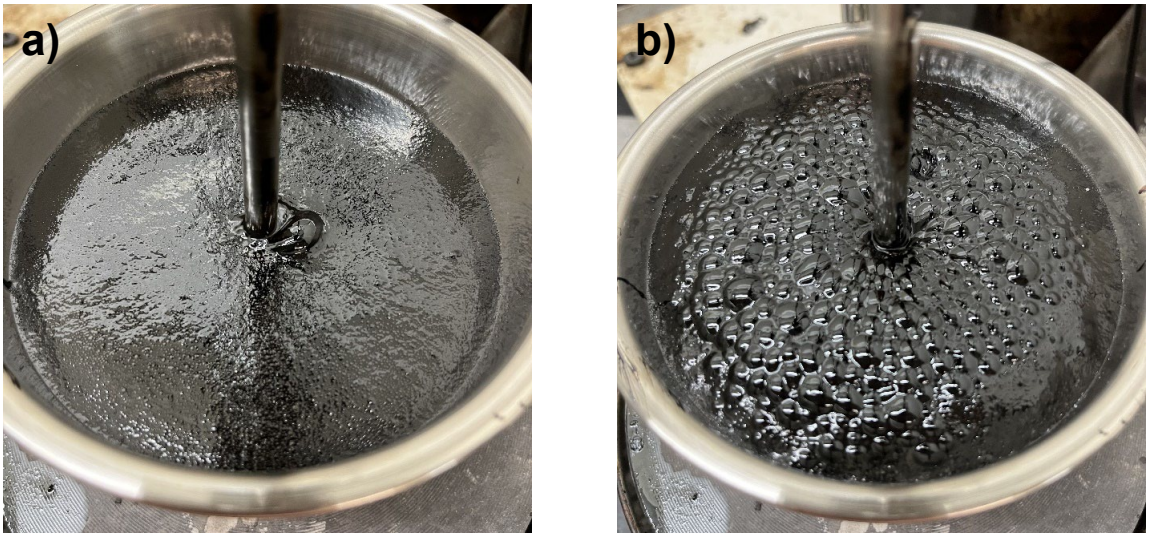

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Fig. 8. Foaming effect of (a) aspha-min and (b) PET-TETA.

3.2. Indirect tensile stiffness modulus of the produced asphalt mixtures

Fig. 9 presents the ITSM test results of HMA, PET, and APM. The indirect stiffness modulus was measured at 2,371 MPa, 2,707 MPa, and 2,148 MPa for unaged HMA, PET, and APM, respectively. WMA mixtures generally have lower stiffness moduli than HMA mixtures because they suffered lower aging during the manufacturing process with reduced production temperatures, as observed in the case of APM. However, PET showed the highest stiffness modulus that was 14% higher than HMA and 26% higher than APM. It was due to the increased bonding strength between PET modified asphalt binder and mineral aggregate. PET-TETA composes amino groups that can form hydrogen bonds with the surface hydroxyl groups of aggregate. Besides, the alkaline amino groups of PET-TETA can interact with aggregate granite, which is a typical acidic rock. Therefore, PET has a higher resistance to elastic deformation because of its stronger molecular bonding, resulting in an increased stiffness modulus.

The indirect stiffness modulus was measured at 3398 MPa, 3904 MPa, and 3367 MPa for long-term aged HMA, PET, and APM, respectively. The differences in the values of the indirect stiffness moduli before and after the long-term aging process were 1026 MPa for HMA, 1197 MPa for PET, and 1218 MPa for APM, indicating that the three asphalt mixtures have similar resistances to aging. After long-term aging, PET still presented the highest stiffness modulus, which was approximately 15% higher than that of HMA and APM. The findings of the ITSM test suggest that the use of aspha-min, a zeolite based foaming additive, had little influence on the stiffness modulus of the material, and it could hardly affect the long-term cracking resistance of the produced asphalt mixture. The zeolite based foaming additive could only create a foaming effect by releasing crystal water, but the material itself can not react with asphalt binder so that it presents insignificant effects

on the stiffness modulus of the produced asphalt mixture. However, the application of PET-TETA could influence the stiffness modulus of the produced asphalt material through the modification of asphalt binder and improve its interaction with aggregate. As a result, PET performs better resistance to elastic deformation. However, it may also have a higher sensitivity to cracking caused by plastic deformation at intermediate temperatures.

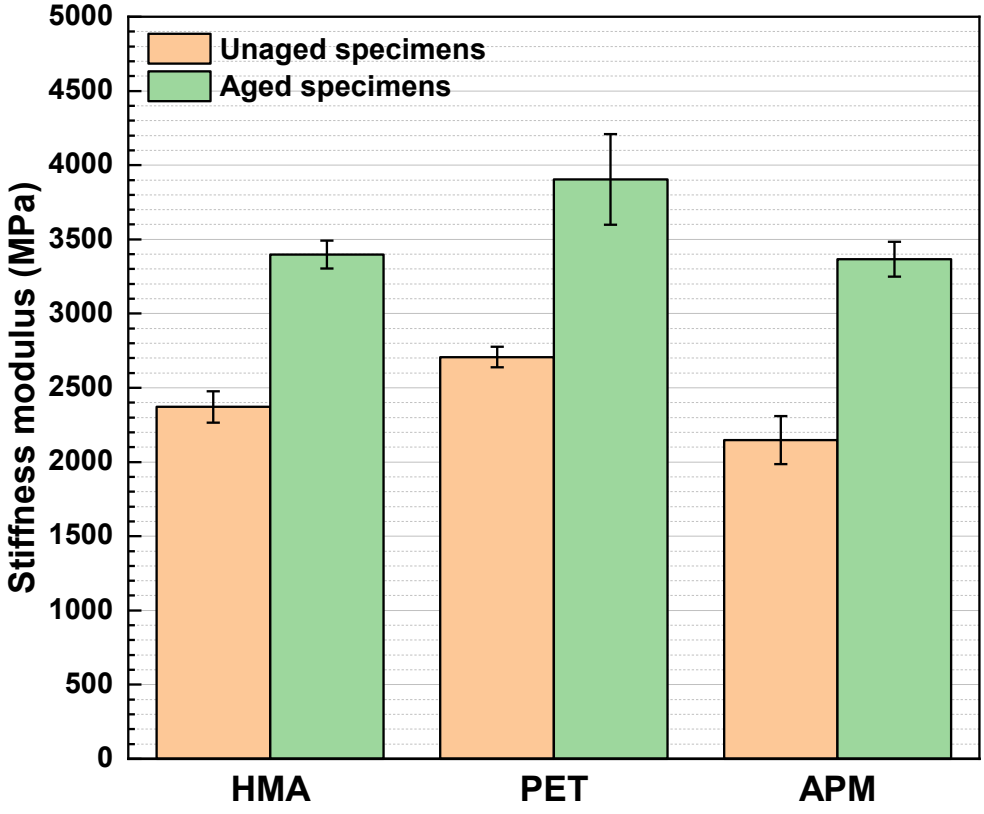


Fig. 9. ITSM test results of the produced asphalt mixtures before and after aging

3.3. Susceptibility to moisture damage of the produced asphalt mixtures

The moisture susceptibility of asphalt mixtures was investigated by measuring the indirect tensile (IDT) strengths of samples before and after the freeze-thaw cycle conditioning. The results of the

IDT strengths of HMA, PET, and APM are illustrated in **Fig. 10**. It can be observed that PET had the highest IDT strength among the three mixtures regardless of the water conditioning. Before conditioning, HMA, PET, and APM showed IDT strengths of 9.6 kN, 10.9 kN, and 9.7 kN, respectively. After conditioning, the IDT strengths of all three mixtures were decreased due to moisture damage, with values recorded at 7.8 kN, 9.7 kN, and 8.0 kN for HMA, PET, and APM, respectively. The IDT strength of HMA and APM was comparable to each other, which suggests that the application of aspha-min had insignificant influences on moisture susceptibility.

However, the use of PET-TETA improved the IDT strength of the produced asphalt mixture. PET displayed IDT strengths of about 13% and 23% higher than the other two asphalt mixtures in dry and wet conditions. Moreover, PET had the highest tensile strength ratio (TSR) of 89.2%, while the TSR values for HMA and APM were 80.9% and 82.1%, respectively. The results suggested that the produced WMA mixtures had no moisture damage concerns compared to the conventional HMA. Moreover, the application of PET-TETA could significantly reduce the susceptibility to moisture damage of the produced asphalt mixture. The increase in the bonding strength and the resistance to water damage by using PET-TETA was mainly due to the following reasons: 1) The higher polarity of PET-TETA made the modified bitumen more affiliated to the polar aggregate surface, resulting in a better coating; 2) PET-TETA composes amino groups that could form strong hydrogen bonds with the surface hydroxyl groups of aggregate; 3) The alkaline amino groups of PET-TETA could interact with the acidic aggregate granite that was used in this study; 4) Water is more likely to attack the aggregate surface due to the hydrophilic nature of the mineral aggregate, the increased adhesion between PET-TETA modified bitumen and aggregate prevents the adhesive failure caused by water damage.

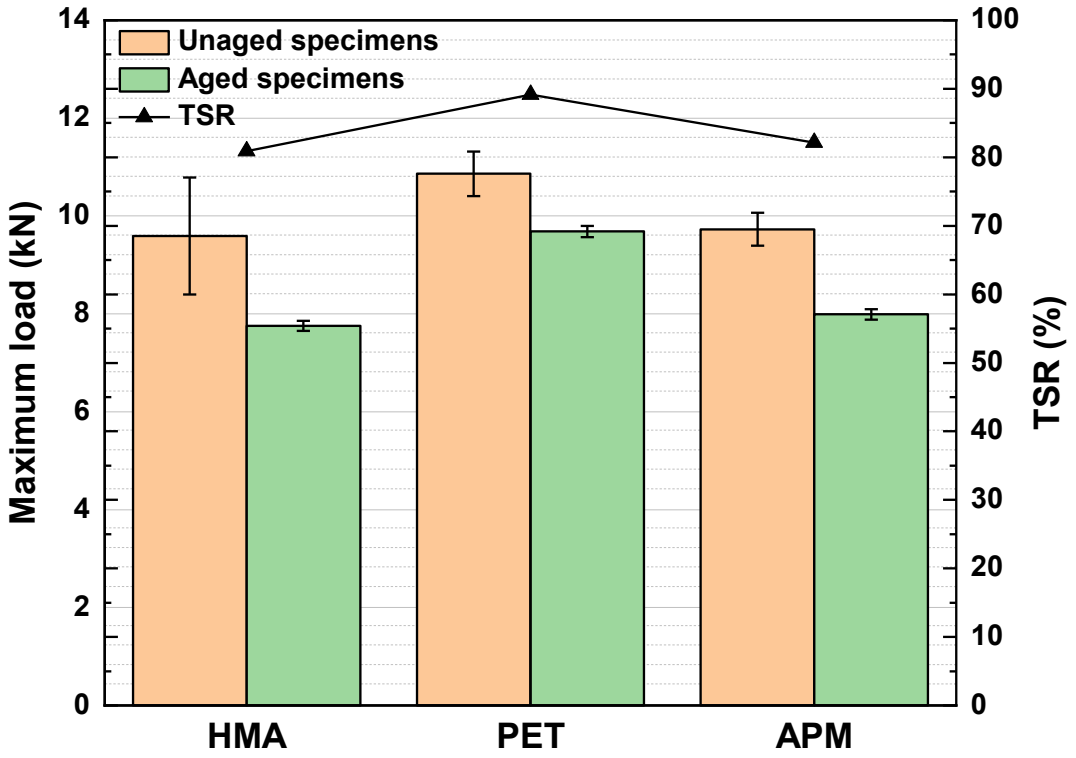


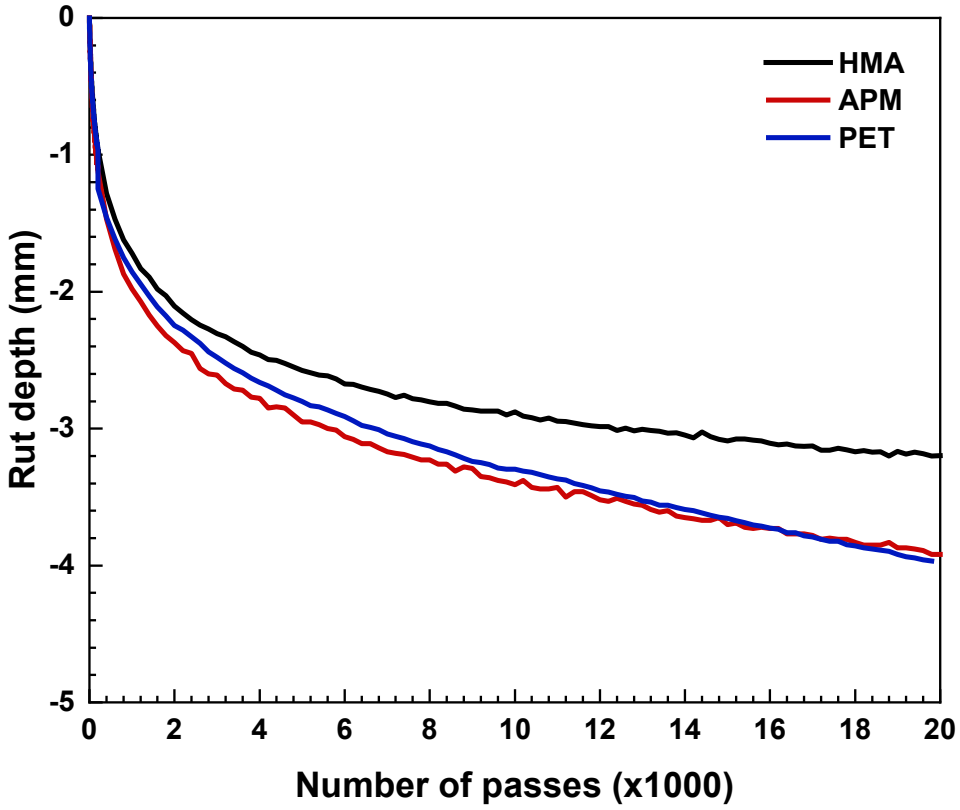
Fig. 10. IDT strengths of the produced asphalt mixtures

3.4. Rutting resistance of the produced asphalt mixtures

The following performance parameters are generally derived from the Hamburg wheel-tracking test, including creep slope, stripping slope, and stripping inflection point (SIP). The creep slope indicates the rutting resistance by the depth of rutting per loading pass in the creep stage. The stripping slope demonstrates the resistance to moisture damage by the rutting depth per loading pass in the stripping stage. SIP specifies the beginning of moisture damage, which is the number of passes that the regression lines of the creep stage and the stripping stage intersect.

Fig. 11 shows Hamburg wheel-tracking results of HMA, PET, and APM at 50 ºC. It is noticed that the obtained curves only involved the creep stage throughout the 20,000 cycles of loading, suggesting there was no distinct stripping developed during the test. The results indicated satisfactory moisture damage resistances of the produced asphalt mixtures, which are consistent with the findings of the moisture damage test. **Table 2** presents the measured values of creep slopes and maximum rut depths of HMA, PET, and APM. After 20,000 cycles of loading, HMA showed the lowest rut depth of 3.20 mm, while APM and PET had higher values of rut depths of 3.92 mm and 3.97 mm. It is noted that the rutting resistance of asphalt mixtures decreases with the reduction of production temperatures due to the deficient aging of the asphalt binder (Bennert et al., 2011). Therefore, HMA mixtures are expected to perform better rutting resistances than WMA mixtures, as the production temperatures of WMA mixtures were significantly lower than HMA mixtures. The measured creep slopes and maximum rut depths of APM and PET were very close to each other, which suggested that the use of aspha-min and PET-TETA had similar influences on the rutting resistances of the produced asphalt mixtures. Although PET had strengthened molecular bonding and stronger adhesive forces due to the asphalt binder modification, it seems that this modification did not increase the rutting resistance of the produced asphalt mixture. A possible reason is that PET-TETA is a soft polymer degraded from PET through the ammonolysis process, it could improve the adhesion between asphalt binder and aggregate, but it might not be as effective as in enhancing the cohesion of the modified asphalt binder. However, cohesion property is a significant parameter in controlling the rutting performance of asphalt mixtures, especially in the creep stage (Anderson et al., 1982; Kanitpong and Bahia, 2005). The findings suggest that the application of PET-TETA had minimal influence on rutting resistance. A maximum rut depth of 0.5 in. (12.7mm) at 50 ºC after 20,000 passes is allowed for asphalt mixtures prepared with a PG-

346 76 binder (Yildirim et al., 2007). It is clear that all three asphalt mixtures had sufficient rutting
347 resistances, although APM and PET showed marginally higher maximum rut depths than HMA.



348

349 **Fig. 11.** Hamburg wheel-tracking curves of the produced asphalt mixtures

350 **Table 2** Creep slope and the maximum rut depth of the produced asphalt mixtures

Mixture	Creep slope (mm/ 1000 passes)	Maximum rut depth (mm)
HMA	0.06	3.20
APM	0.09	3.92
PET	0.10	3.97

4. Conclusions

In this study, PET-TETA was synthesized using waste plastic bottles. Its chemical and physical properties were characterized and compared with a commercial foaming additive. Then, three asphalt mixtures (HMA, PET, and APM) were prepared, and their engineering performance was investigated through comprehensive laboratory tests. The findings revealed that PET displayed comparable performance to HMA and APM, with enhanced strength and resistance to elastic deformation and stripping. This was attributed to the effective asphalt modification by PET-TETA. In light of the above, the primary conclusions can be drawn as follows:

- The PET-TETA additive was characterized as a degraded polymer that consisted of both amorphous and crystalline regions. The presence of hydration water was observed, which was formed through hydrogen bonding between hydrophilic amide groups and water molecules. Furthermore, it was found that the water molecules were predominantly attached to the molecular chains in the amorphous regions due to space restrictions in the crystalline regions.
- PET-TETA generated superior asphalt foaming compared to the commercial foaming additive. This was attributed to the higher content of hydration water present in PET-TETA, which was approximately 60% greater than that of the commercial foaming additive.
- PET exhibited enhanced resistance to elastic deformation, as evidenced by its stiffness modulus, which was approximately 15% higher than that of HMA and APM. However, further investigation is required to evaluate its resistance to plastic deformation and fatigue cracking after an extended period of service
- The use of PET-TETA as a foaming additive enhanced the coating between the asphalt binder and the aggregate, resulting in an asphalt mixture that was more resistant to water stripping.

Additionally, PET exhibited improved strength properties than HMA and APM, with an increase of approximately 13% and 23% observed prior to and after water conditioning, respectively. PET also demonstrated the highest tensile strength ratio of 89.2% among the three mixtures.

- All three asphalt mixtures exhibited satisfactory resistance to both rutting and moisture damage. Nonetheless, PET and APM displayed slightly greater maximum rut depths than HMA due to reduced aging of the asphalt binder at lower production temperatures.

The present study validated the effectiveness of applying PET-TETA as a foaming additive in warm mix asphalt, offering a sustainable solution to the issue of waste plastic disposal by producing a green paving material that utilizes waste plastic. In the future, a broader range of asphalt mixtures will be prepared, and field investigations will be conducted to further validate the performance of PET-TETA as a foaming additive. In addition, a life-cycle cost analysis of incorporating PET-TETA in asphalt pavement will be included in future studies to provide a more comprehensive understanding of the economic and environmental implications of this approach.

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