An Evaluation of Waste Plastic in Asphalt Pavement

Towards a Circular Economy

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By

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

An Evaluation of Waste Plastic in Asphalt Pavement Towards a Circular Economy

presented by Shishi Chen,

a candidate for the degree of Masters of Science in Civil and Environmental Engineering

and hereby certify that, in their opinion, it is worthy of acceptance.

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GLOSSARY

AASHTO: American Association of State Highway and Transportation Officials

DCT: Disk- Shaped Compact Tension Test

DOT: Department of Transportation

HDPE: High-Density Polyethylene

HMA: Hot mix asphalt

HWTT: Hamburg Wheel Tracking Test

LDPE: Low-Density Polyethylene

LLDPE: Linear Low-Density Polyethylene

MAPIL: Missouri Asphalt Pavement and Innovation Laboratory

PETE or PET: (Polyethylene Terephthalate)

PP: Polypropylene

PS: Polystyrene

V or PVC: Polyvinyl Chloride

ABSTRACT

Incorporating waste plastic into asphalt pavement is an evolving recycling strategy based on a circular economy approach. Dow has cooperated with MU to use optimal recycle plastic to target better pavement performance with less plastic leaking pollution. The goal is to find the optimal method to cooperate waste plastic with asphalt mixture, that is, an economical and environment-friendly way to target better mixture performance.

Linear low-density polyethylene (LLDPE) and waste Polyethylene Terephthalate (PET) is the main plastic used in this project. Other additives (GTR, ElvaloyTM, and PPA) are also added to the mixture by dry process or wet process with the goal to improve the compatibility of plastic in the asphalt mixture.

Various binder tests were conducted to evaluate the effect of LLDPE and PET modified binder by a wet process. AASHTO Superpave binder performance grading (PG) tests (Viscosity, DSR, BBR) test was utilized to characterize the workability, high-temperature (rutting) performance, and low temperature (cracking) performance. AASHTO Superpave method was performed to explore the LLDPE modified mixture performance with MoDOT criteria. Rutting resistance, cracking resistance at different temperatures were studied with a suite of laboratory tests, such as the Hamburg Wheel Tracking test (HWT), DC(T) test, IDEAL-CT test. Water samples from the rutting test and the permeability test were also further tested for microplastic detection.

In terms of performance grade (PG) of chemically treated waste PET modification by wet process, this study is analogous to Leng's study (2018). Waste PET modification, up to 15% by weight of the binder, slightly increases the workability, high temperature, and low-temperature performance. Appreciate range for the amount of waste plastic was determined to be 2-3% by weight of the bitumen regard to PG performance. Elvaloy (PPA)-only or LLDPE pellet-only modified binder increases binder viscosity, which indicates a harder binder at the same temperature. Thus, the fail temperature from the DSR test at high temperature and intermediate temperature also improve. The increase in viscosity from the additives has a negative effect on the m value and stiffness of BBR test results. The combination of both LLDPE pellets and Elvaloy (PPA) made the binder

even stiffer with viscosity increasing from 0.421 pa*s to 1.319 pa*s, which is more than three times.

The addition of plastic by dry process affected specimens in mixture volumetric properties and performance test results. Melted plastic remains very viscous and dense and was not coated on the dense-graded aggregates used in this study. Plastic modified asphalt mixtures decreased the theoretical maximum gravity of the mixture for the volumetric property. Performance tests results show that plastic modified mixture greatly improve rutting resistance with rut depth from 17.1mm to 0.9 mm, which satisfied the MODOT criteria of 12.5 mm rut depth and enhance low-temperature cracking resistance to some degree. Even the CT index of LLDPE modified mixtures fails to meet the recommended threshold of MODOT, the CT index improves with the increase of LLDPE amount and the decrease of LLDPE size. It’s also worth mentioning that the smaller size of LLDPE also helps to disperse itself in asphalt mixture, which produces a more stable and reliable asphalt mixture in the long term. Even stiffer with viscosity increasing from 0.421 pa*s to 1.319 pa*s, which is more than three times.

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Chapter 1. INTRODUCTION

1.1 Statement of Problem

Plastic is predominantly used in today's life and growing environmental challenges due to its non-biodegradable properties. There are continuing policies and research involved to find the method to dispose of waste plastic due to the environmental concern of waste plastic(Haider, 2020; Chowdhury, 2020). Using waste plastic in infrastructure construction is gaining more popularity with the potential to reduce raw material, protect the environment, and increase economic benefit (Wang, 2016). Waste plastic cooperates with asphalt mixture mainly as a binder or aggregate substitute, a binder modifier, or extender (Nouali,2020; Wu, 2020) by the dry or wet method. Due to increasing demand for traffic volume, traffic load, and climate change, rutting and cracking resistance become more predominant. However, leverage the waste plastic content and asphalt mixture performance is still urgently needed based on the paving technology and standard. Therefore, it's worth conducting a study to investigate the effect of waste plastic in asphalt pavement.

Figure 1. Waste plastic issue

1.2 Objective

a. Reconducted some current research findings on waste plastic modified binder and asphalt mixture by wet and dry process.
b. Evaluated the effect of waste plastic additive on binder performance by the wet process within Viscosity and Superpave Performance Grading tests.
c. Investigated the mixture performance of waste plastic modified asphalt mixture by the dry process by conducting the Hamburg Wheel Tracking test, DCT, and IDEAL-CT test.
d. Examined the potential environmental pollution of asphalt mixture containing waste plastic.

1.3 Scope of Research

This study evaluation includes both binder and mixture tests to quantify the effect of waste plastic in asphalt pavement towards a circular economy. Which mainly includes:

a. Investigation on waste LLDPE plastic coating aggregates.
b. Evaluation of Binder performance of waste plastic modification, mainly LLDPE and PET, by the wet process within viscosity and PG grading tests.
c. Study of asphalt mixture performance containing waste LLDPE by the dry process by conducting the Hamburg Wheel Tracking test, DCT, IDEAL-CT tests.
d. Exploration of a potential way to detect microplastic detection from laboratory water samples of the Hamburg Wheel Tracking Test.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The circular economy approach in the pavement industry is gaining spectacular worldwide growth to achieve significant environmental and economic benefits through recycling and reusing waste materials in the construction of infrastructure(Geissdoerfer, Savaget, Bocken, & Hultink, 2017). In recent times, waste plastic, a major culprit of environmental pollution, has been looked at as a potential resource to be utilized, rather than re-utilized, in the building of asphalt roads. Precedence of re-purposing waste materials into construction materials already exists, e.g. use of end-of-life waste tires in terms of Ground Tire Rubber (GTR) or reusing old asphalt pavements as Recycled Asphalt Pavements (RAP) or shingles as Recycled Asphalt Shingles (RAS), in construction of a new asphalt road(William G. Buttlar & Rath, 2017; Federal Highway Administration, 2011). Research has shown that proper usage of GTR, RAP, or RAS, could improve pavement performance in addition to aiding the sustainable measure of the paving agency (Al-Qadi, Qazi, & Carpenter, 2012; Colbert & You, 2012). Similarly, the use of waste plastic, such as Polyethylene Terephthalate (PET) (Ahmadinia, Zargar, Karim, Abdelaziz, & Ahmadinia, 2012a; Leng, Padhan, & Sreeram, 2018), Polyethylene (PE) (Costa, Silva, Oliveira, & Fernandes, 2013), and polystyrene (PS) (Rajasekaran, Vasudevan, & Paulraj, 2013), etc., have also been researched to be potential binder additive or aggregate replacement of asphalt pavement while eliminating the disposal of waste in landfill.

2.1.1. Waste Plastic

Plastic is a predominant product in daily life. There are mainly seven types of plastic according to ASTM D7611 as presented in Table 1. PETE or PET (Polyethylene Terephthalate) are commonly found in beverage bottles and perishable food containers. HDPE (High-Density Polyethylene is the most commonly recycled plastic and always used for milk jugs and cleaning product containers. V or PVC (Polyvinyl Chloride) is often used in credit cards and plumbing pipes. LDPE (Low-Density Polyethylene) can be found in plastic wrap and frozen food containers while PP (Polypropylene) is commonly found in tupperware, car parts, thermal vests, yogurt containers, and even disposable diapers. Beverage cups and packing materials are usually made up of PS (Polystyrene).

Resin Identification Number	Resin	Resin Identification Code –Option A	Resin Identification Code –Option B
1	Poly (ethylene terephthalate)	1 PETE	01 PET
2	High density polyethylene	2 HDPE	02 PE-HD
3	Poly (vinyl chloride)	3 V	03 PVC
4	Low density polyethylene	4 LDPE	04 PE-LD
5	Polypropylene	5 PP	05 PP
6	Polystyrene	6 PS	06 PS
7	Other resins	7 OTHER	07 O

Figure 2. Waste plastic types

2.1.2. Waste Plastic Modified Binder

There are mainly two methods to cooperate additives to asphalt mixture, dry process, and wet process. The dry process is adding additives to base binder and aggregates during asphalt mixture production whereas the wet process is blending additive with a base binder with a set time before mixing with aggregates (Rath, Love, Buttlar, & Reis, 2019). Research on modified binder shows different performance with different processes (Hassan, Airey, Jaya, Mashros, & Aziz, 2014; Zhu, Birgisson, & Kringos, 2014). Some research on modified binders by dry process shows inconsistent field performance, especially in the long term(Rahman, Airey, & Collop, 2010). Mixtures prepared by the wet process represent similar or better performance properties than the controlled one(Fang et al., 2013; Kök, Yilmaz, & Geçkil, 2013). The wet process is through high shear blending, agitation, or others. However, a wet process which applied with high shear with a period of blending time is the main disadvantage for currently paving technology and environmental benefit (Ranieri, Costa, Oliveira, Silva, & Celauro, 2017). Therefore, finding a potential way to blending additive with a base binder in the wet process while requiring less effort is significant and beneficial.

According to National Association for PET Container Resources, thermoplastic, such as PET and LLDPE, are the most common types of plastic, which constitutes 80 percent of total plastic products (Dewil et al,2006). Therefore, it's worth conducting a study to investigate the effect of waste PET and LLDPE in asphalt pavement. In this study, since the melting point of the PET additive (noted as PET) is around 80 °C, high shear blending (4000 rpm shear rate with 1 hour) was utilized by the wet process to evaluate chemically-treated waste PET additive modified binder. Viscosity and PG Grading (DSR and BBR) tests were performed to evaluate the effect of waste PET additive with various dosages by weight of the binder in a bid to develop an economical method in the wet process.

2.1.3. Waste Plastic Modified Mixture

Previous experimental studies on the waste plastic application on asphalt pavement mainly focused on PE, PET, PS, and HDPE with both dry process and wet process (Polacco, Filippi, Merusi, & Stastna, 2015; Zhu et al., 2014) on the binder and mixture performance. Some of the areas researched were: (a) moisture resistance of PET in stone mastic asphalt (SMA) (Ahmadinia, Zargar, Karim, Abdelaziz, & Ahmadinia, 2012b) and durability study of PET as partial and complete substitutes for sand in concrete composites (Marzouk, Dheilly, & Queneudec, 2007); (b) flexural strength in asphalt mixture containing PP and PS, as a partial replacement for sand (Ismail & AL-Hashmi, 2008); (c) Marshall stability of PE and LLDPE modified binder (AASHTO et al., 2008; Swami & Jirge, 2012); (d) performance grade and viscosity properties of waste plastic modified binder (Costa et al., 2013)(Costa et al., 2013); (e)fatigue performance of PET modified asphalt mixes (Modarres & Hamedi, 2014).

It's worthy to mention that most research studies on waste plastic modified asphalt mixture is using stone mastic asphalt (SMA) (Wu et al, 2020). SMA is a gap-graded and densely compacted mixture, which is often used on major highways with heavy traffic loads (Wang et al, 2016). I addition, rutting, and cracking are becoming more crucial distresses due to high traffic demand and environmental factors (William G Buttlar & Harrell, 2000; Shu, Huang, & Vukosavljevic, 2008). However, very limited scientific investigations haven't been investigating the common HMA mixes directly towards the rutting and cracking performance. This study utilized common aggregates for the HMA mixture to evaluate the volumetric properties, cracking resistance, and rutting resistance of asphalt mixture containing waste LLDPE with the Superpave method.

CHAPTER 3. MATERIALS

3.1. Binder

A PG 64-22 is used as a base binder through binder and mixture test only for waste LLDPE modification in this project. The unmodified binder for waste PET additive was obtained from the refineries of Philips66 located in Kansas City, MO, and was graded by the manufacturer as PG 58-28. The viscosity and PG grading properties are tested for both base binders according to AASHTO 320 standard as shown in Table 1.

Table 1. Base binder properties

Parameters	Viscosity @135°C, Pa*s	Unaged binder, G*/sinδ, Kpa	RTFO-aged binder, G*/sinδ, Kpa	PAV-aged binder, G*sinδ, Kpa	Stiffness, Mpa	m-value
PG 64-22	0.46	1.28 @ 64°C	3.68 @ 64°C	4259 @ 25°C	113 @ -12°C	0.35 @ -12°C
PG 58-28	0.303	1.32 @ 58°C	3.47 @ 58°C	4055 @ 22°C	206 @-18°C	0.29 @ -18°C

3.2. Aggregate

A dense graded aggregate blend is designed from the American Public Works Administration (APWA) Type 3 specification, which is for low volume roads. A 35-gyration design is used for a Superpave gyratory compactor for volumetric testing. This aggregate blend includes five individual stockpiles, four of which are crushed limestones (3/4", 3/8", manufactured sand, and screenings stockpiles) along with one natural sand stockpile. Individual stockpile gradations are shown in Table 2.

Table 2. Aggregate gradation for the mixes

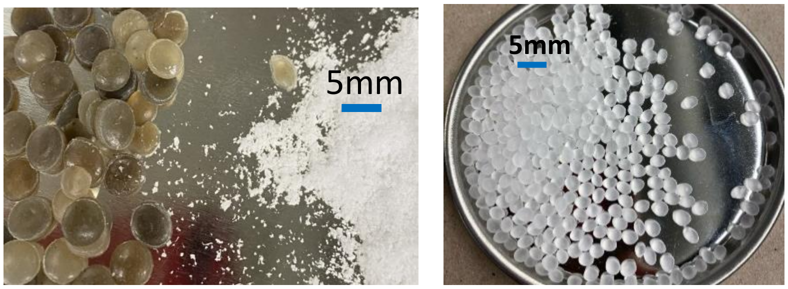
Sieve Size	Greenwood 3/4" (#754)	Greenwood Washed 3/8" (#925)	Greenwood MS (#952)	Greenwood Screens (#965)	Holliday Nat Sand	Blend
	27.0	8.0	28.0	17.0	20.0	100.0
37.5 mm (1-1/2")	100.0	100.0	100.0	100.0	100.0	100.0
25.0 mm (1")	100.0	100.0	100.0	100.0	100.0	100.0
19.0 mm (3/4")	100.0	100.0	100.0	100.0	100.0	100.0
12.5 mm (1/2")	70.8	100.0	100.0	100.0	100.0	92.1
9.5 mm (3/8")	42.4	100.0	100.0	100.0	100.0	84.4
4.75 mm (#4)	7.1	54.7	86.0	99.1	98.9	67.0
2.36 mm (#8)	4.1	11.9	30.2	85.8	95.2	44.1
1.18 mm (#16)	3.4	5.1	13.8	57.9	84.8	32.0
600 mm (#30)	3.0	3.9	8.4	41.2	63.5	23.2
300 mm (#50)	2.7	3.7	6.3	30.9	22.6	12.6
150 mm (#100)	2.5	3.4	5.1	25.4	2.3	7.2
75 um (#200)	2.3	3.3	4.8	22.4	1.2	6.3
Gsb	2.603	2.594	2.586	2.557	2.622	2.593
Gsa	2.702	2.700	2.693	2.675	2.669	2.688
Pb						

3.3. Modifiers

The effect of different waste plastic and different size is evaluated. Waste LLDPE and PET plastic are mainly evaluated. The third modifier, Elvaloy, is also added into LLDPE by the wet process in an attempt to mitigate the phase separation.

3.3.1 Waste LLDPE

Dow provided Recycled LLDPE pellets (Figure 3-a left) with more than 95% purity and pure LLDPE power (Figure 3-a right). LLDPE pellet has an average diameter of 5mm and less than 1 mm for LLDPE power LLDPE is made with significant numbers of short branches and a substantially linear polymer. Elvaloy (Figure 3-b) is a terpolymer, which consists of ethylene, butyl acrylate, and glycidyl methacrylate (GMA). The existence of an epoxy ring in the GMA group allows Elvaloy to react chemically with asphalt binder.



(a) (b)

Figure 3. (a) LLDPE pellets/power; (b) ElvaloyTM at room temperature

3.3.2. Waste PET

Waste PET was obtained from waste PET bottles collected from a local recycling center. The waste plastic was cut into 5cm*5cm flakes and dried at 80 °C for 2 hours at room temperature. The flakes were then treated with Ethanolamine at 130-140°C for 8 hours resulting in a homogenous mixture (Figure 4). Spectroscopy analysis from Leng et al. has also shown that the PET additive with a melting point of 80°C has an acceptable level of compatibility with bitumen (2018).

Figure 4. Waste PET additive

CHAPTER 4. METHODOLOGY AND RESULTS

4.1 Binder Test

A suite of laboratory tests was conducted at Missouri Asphalt Pavement and Innovation Laboratory (MAPIL) on asphalt binders to grade their performance according to AASHTO M320. The tests included the Rotational Viscometer, Dynamic Shear Rheometer (DSR), and Bending

Beam Rheometer (BBR) test to obtain parameters comprising of complex shear modulus (G*), creep stiffness (S), etc. Various dosages of PET additive modified binder were tested to investigate the optimum dosage of PET additive while LLDPE modified binder is tested at specific proportion with comparison to waste LLDPE modified asphalt mixture by dry process.

As Table 3 shows, Elvaloy (PPA)-only or LLDPE pellet-only modified binder increases binder viscosity, which indicates a harder binder at the same temperature. Thus, the fail temperature from the DSR test at high temperature and intermediate temperature also improve. The increase in viscosity from the additives has a negative effect on the m value and stiffness of BBR test results. The combination of both LLDPE pellets and Elvaloy (PPA) made the binder even stiffer with viscosity increasing from 0.421 pa*s to 1.319 pa*s, which is more than three times. More test results can be found below.

Table 3. Binder testing suite and summary of test results of LLDPE modified binder

Trial	Viscosity, Pa*s	Fail Temperature, °C			BBR @-22°C	
		Original	RTFO	PAV	m	s, Mpa
Control	0.421	65.1	67.6	22.1	0.304	152
0.9%Elvaloy(PPA)	0.810	70.7	72.9	22.7	0.295	174
1.5%PE pellets	0.619	68.6	69.0	23.9	0.295	164
0.9%Elvaloy(PPA)+1.5%PE pellets	1.319	76.6	78.5	22.3	0.264	209

4.1.1. Wet Process with Plastic

For binder testing, additives (LLDPE, PET ElvaloyTM, and PPA) are added into the binder with high shear mixing as a proportion of the binder mass through the wet process. The wet process to cooperate with waste LLDPE and PET into a binder is different. Various dosages of PET additive modified binder were tested and LLDPE modified binder.

For LLDPE per Dow instruction, a representative procedure for blending RPE (recycled polyethylene) with ELVALOY™ RET and PPA would be:

a. Preheat the unmodified binder to 325°F (165°C) in a quart can – approximately 500 grams of the unmodified binder.

b. Transferred the quart can to a heating mantle at 365°F (185°C). Typically, the binder would cool in the mantle to about 300°F. Suggest stirring at low speed until the binder equilibrates at the reaction temperature.

c. Adjust the speed as high (5000 rpm) as possible, once at temperature has stabilized, so no air incorporation occurs to avoid oxidizing the asphalt. Add the recycled plastic in one shot. Adjust the speed as needed during digestion. The goal is to have complete dissolution at this stage so completely smooth blend with the recycled plastic only. This may take up to 30 minutes but likely less time.

d. Once the RPE is completely incorporated you can move the blend to low shear mixing (200 to 400 rpm) set up. Temperature can also be reduced to 325°F (165°C). RPM should be adjusted to be sufficient to maintain a mild vortex to draw down the pellets when added in one shot.

e. Add the ELVALOY™ RET and allow to digest for 2 hours.

f. PPA (typically 20 weight% vs the LOY) can be added and stirred an additional hour. 0.18% PPA is used in this study.

g. To mimic short-term storage, place the sample in a 325°F oven overnight before testing the next day. Typically, before testing, we will hand stir the blend with a tongue depressor or popsicle stick including the bottom and walls to check for undissolved RPE.

It's also worth mentioning that the LOY resin can be milled since the above process was performed as it gives our lab team time to test samples from the previous day of blending. The plastic and LOY can likely be added at the same time to reduce the time but we have not confirmed that in the lab. It’s significant that everything is completely mixed thoroughly before adding PPA as it completes the LOY reaction with asphalt. Also, 365°F is at the high end for digesting the LOY (melting point about 70°C) and used to more easily incorporate the recycled plastic (melting point about 115°C).

For Waste PET, the samples that used the homogenized PET mixture (melting point 80°C) were prepared by mixing the PET with a continuously heated binder by a high shear blending. High shear blending was conducted at 4000 rpm shear rate for an hour at 150 °C. This homogenized plastic mixture was used to modify a pre-heated can of asphalt binder at the rate of 1%, 2%, 4%, 6%, 10%, and 15% by weight of the base binder. Standard PG tests, such as viscosity, DSR, and BBR tests were performed on the wide-range of modified binders to determine the best-suited percentage of PET in asphalt binders. Figure 5b shows the reaction of PET and asphalt binder while in a shear mixer. With the addition of the PET additive, the swelling was observed in the binder indicating some degree of reaction between the binder and the PET additive.

(a) (b)

Figure 5. (a) Shear mixer of LLDPE and Elvaloy; (b) Swelling observed in a shear mixer with PET additive at 150°C

4.1.2. Rotational Viscometer Test

A rotational Viscosity test (ASTM-D4402) was conducted to measure the apparent viscosity of an unaged binder at 135 °C to verify the workability performance of the liquid binder. Two 10g replicated binder samples in a Brookfield Viscometer with a temperature-controlled thermal chamber (Figure 8a) were used to determine the resistance of flow (viscosity) with a constant rotation speed of 50 rpm at 135°C. A #27 spindle was utilized to evaluate viscosity with a maximum threshold of 3 Pa*s at 135°C.

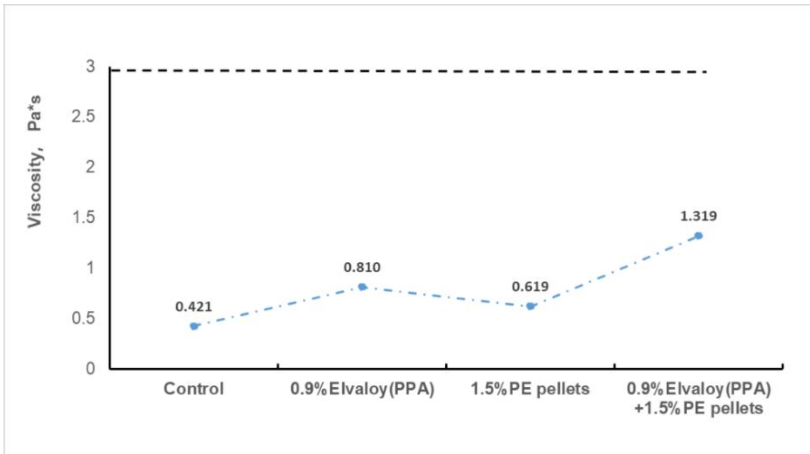


Figure 6. The viscosity of binder at 135°C

Figure 6 presents the viscosity results of different modified binder at 135°C, and they all passed the 3 pa*s criteria. The addition of Elvaloy or LLDPE pellets by wet process increases binder viscosity, which indicates this addition makes binder stiffer at the same temperature. The combination of Elvaloy and LLDPE pellets makes the binder even stiffer, whose viscosity is more than three times larger than the base binder.

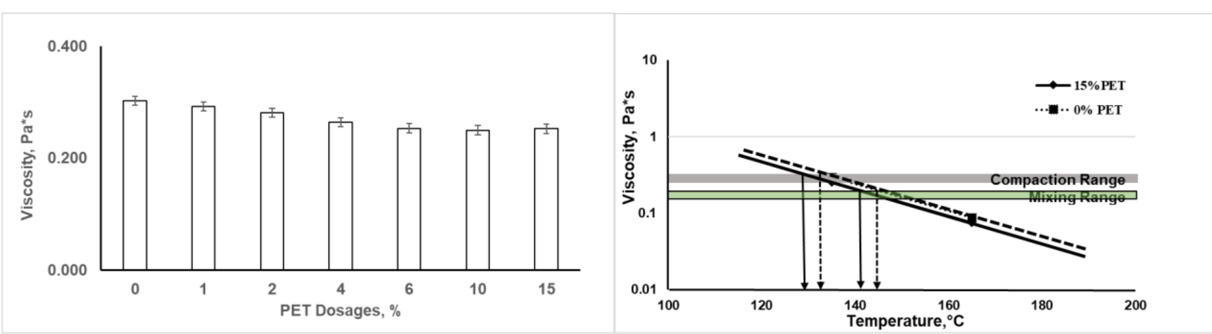


Figure 7. (a) Viscosity with different dosages of waste PET additives at 135 ˚C; (b) Viscosity – Temperature Chart

Figure 7a shows the viscosity of waste PET modified binders at 135°C. It was observed that the viscosity of the PET modified binder marginally decreased with an increase in the PET content. Figure 7b shows the Viscosity-Temperature chart for 0% and 15% PET modified binder. The mixing and compaction temperatures for both the binders were within 5°C of each other, indicating that this chemically modified PET has minimal effect on the flowing property of the base binder used in this study. Thus, unlike other binder modifiers such as rubber or SBS, high percentages of chemically modified PET can be used as binder modifiers without worrying about the pump-ability or workability of the asphalt binder.

4.1.3. Dynamic Shear Rheometer Test

Rheological properties (Figure 8b) were determined by a Dynamic Shear Rheometer (AASHTO T315) for PG grading. Rolling Thin-Film Oven (RTFO) (ASTM-D2872) and Pressure Aging Vessel (PAV) (ASTM-D7175) were utilized to simulate short-term aged and long-term aged binders, respectively. Standardized binder samples (25 mm diameter by 1 mm thick for unaged and RTFO-aged binder) were used to obtain dynamic shear modulus (G*) and phase angle (δ) at 58, 64, and 70°C to compute the high-temperature grade, and intermediated temperature performance were tested from PAV-aged samples (8 mm diameter by 2 mm thick) at 22, 25, and 28°C according to the AASHTO M320 criteria.

(a) (b) (c)

Figure 8. (a) Brookfield Viscometer; (b) Dynamic Shear Rheometer (DSR); (c) Bending Beam Rheometer (BBR) at MAPIL

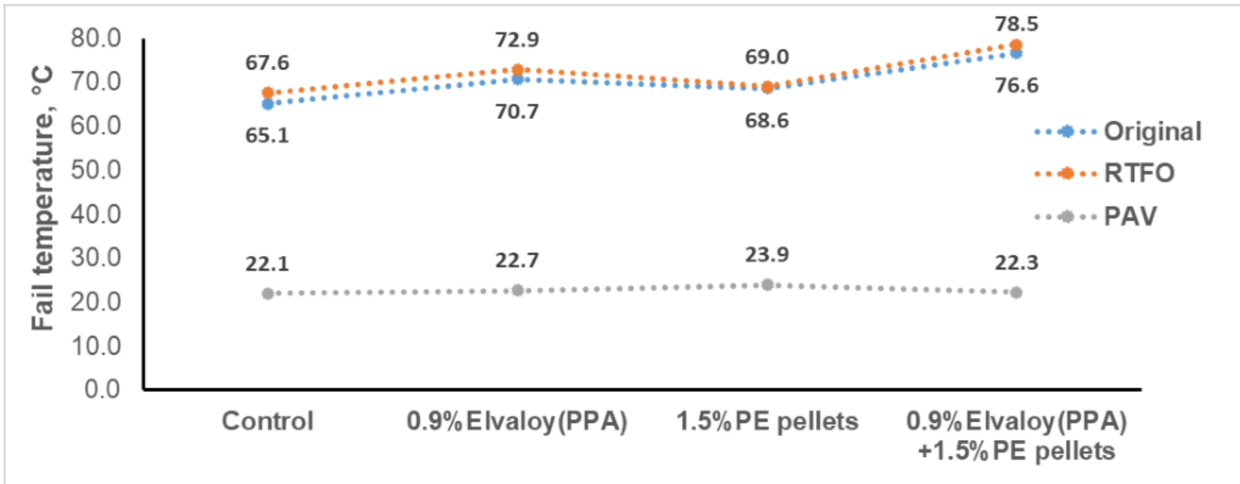


Figure 9. Failing temperature from DSR test

Figure 9 represents the Original, RTFO, and PAV failing temperature of blends contain LLDPE Pellet, Elvaloy, and PPA. The addition of 1.5% LLDPE was able to bump the failing temperature by approximately 3.0°C on both original and RTFO grade. However, the addition of 1.5% LLDPE was not enough to create one grade bump.

The addition of 0.9% Elvaloy and 0.18% PPA was able to create one grade bump. When 1.5% LLDPE combined with 0.9 Elvaloy and 0.18% PPA, two grade bumps observed. When blends contain Elvaloy only, LLDPE Pellet only, and a combination of LLDPE Pellet and Elvaloy were compared, a non-linear effect was found when LLDPE Pellet was combined with Elvaloy and PPA. This indicated that a chemical reaction was present between LLDPE Pellet, Elvaloy, and binder.

There were no significant changes found on PAV failing temperature after Elvaloy and LLDPE Pellet addition. This indicated that the addition of Elvaloy and LLDPE Pellet at low amounts did not affect intermediate temperature performance.

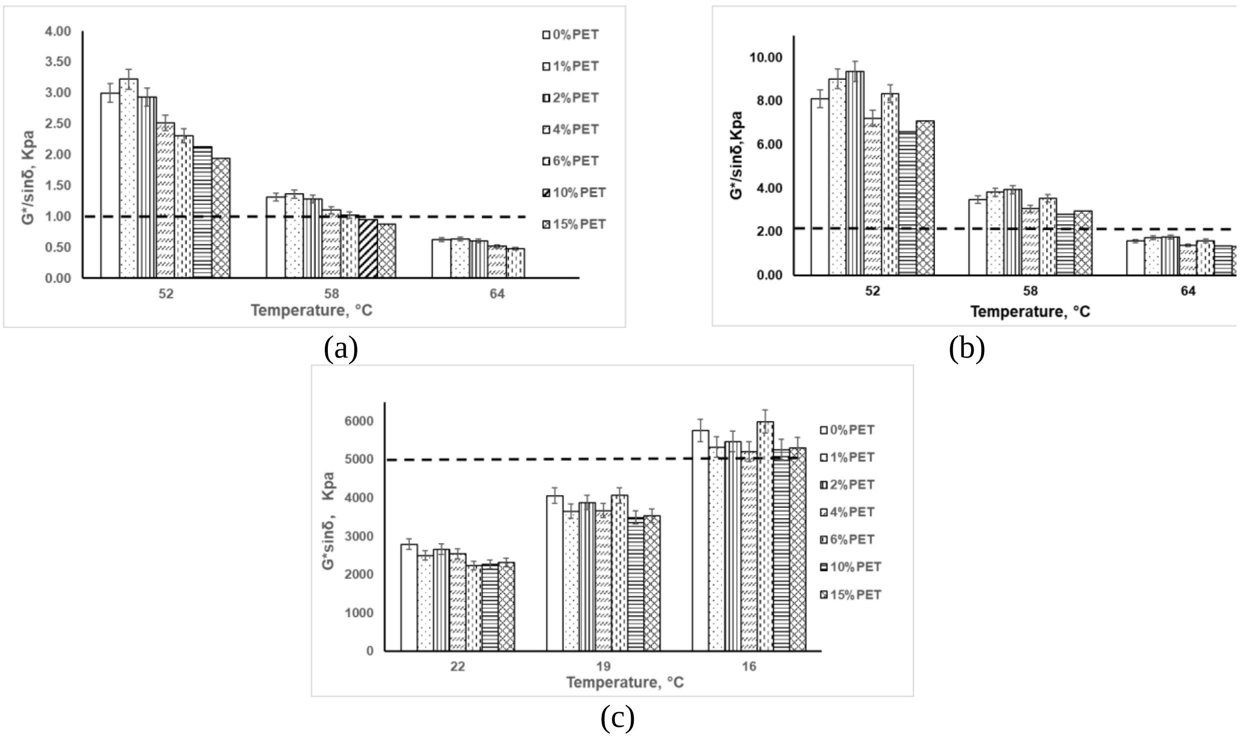


Figure 10. (a) G*/sin δ of the unaged binder; (b) G*/sin δ of the short-term aged binder; (c) G*sin δ of long-term aged binder

As shown in Fig. 10a and b, these preliminary tests with homogenized PET mixture showed that the addition of waste PET additive progressively decreased the value of the rutting parameter with the unaged and RTFO-aged binder, with the best performing dosage being between 1-4%. The fatigue parameter at 19°C showed all dosages would have adequate fatigue performance with a 4% dosage achieving the best G*sinδ value.

4.1.4. Bending Beam Rheometer Test

Flexural Creep Stiffness (S) and relaxation (m-value) of the PAV-aged binders at low PG temperature were evaluated by the bending beam rheometer (Figure 8c) (AASHTO-T316). The test consists of a constant load of 980+50 mN applied for 240 seconds to the mid-point of an asphalt binder beam with dimensions 6.25 x 12.5 x 127 mm, supported at two ends spanning 102 mm. The test was carried out within an alcohol bath for adequate temperature control. Creep stiffness and m-value at 60 seconds for different binders were reported and compared. The BBR test was conducted at -12 ˚C and -18 °C, respectively. , which was 10˚C warmer than the low-temperature grade of the base binder.

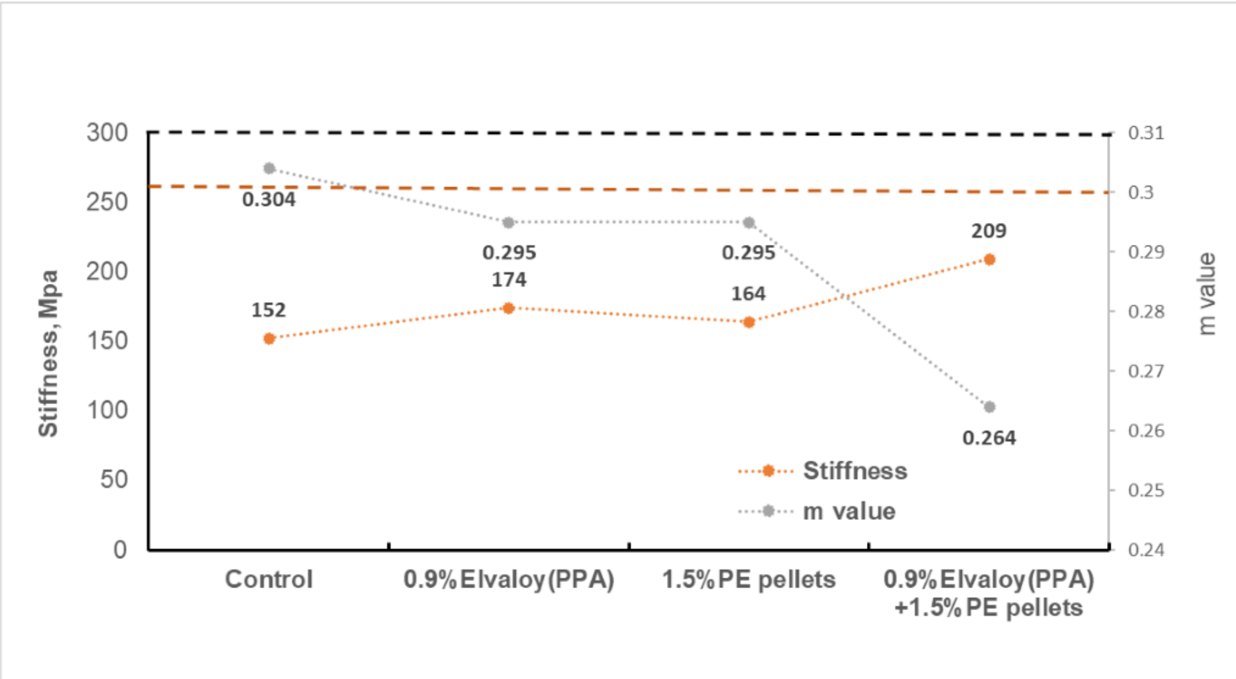


Figure 11. Stiffness and m-value from BBR test

Figure 11 represents the m-value and stiffness of blends containing Elvaloy and LLDPE Pellet. The BBR test is intended to determine whether a binder would experience thermal distress below -22°C in the field, which is indicated by an m-value greater than 0.300 and a stiffness less than 300 MPa. Compared to the control binder, the m-value decrease when Elvaloy, PPA, and LLDPE Pellet were added. This indicates that the addition of LLDPE and Elvaloy (PPA) has a negative effect on the low-temperature performance of the binder.

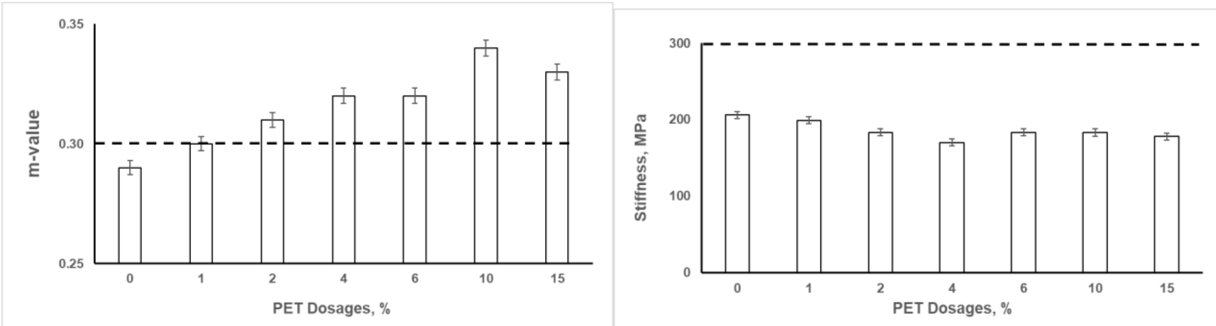


Figure 12. (a) m-value of waste PET additive modified binder at -18°C; (b) Stiffness of waste PET additive modified binder at -18°C

BBR test was conducted at -18 °C to determine the low-temperature performance of the modified binder as shown in Fig. 12a and b. The results showed that increasing PET percentage improved the stiffness as well as m-value up to about 4% of PET incorporation.

4.2 Mixture Tests and Results

This study employed a variety of laboratory tests on selected asphalt mixtures after consultation with Dow scientists. The tests included volumetric test, performance test, and microplastic detection with the mixture samples containing LLDPE. Volumetric testing was conducted for each additive or combination of additives to determine their impact on the air voids/compatibility of the modified mixes. The Disk-shaped Compact Tension (DC(T)) test, the IDEAL-CT test was conducted to determine cracking potential at low and mid-range temperatures. Hamburg Wheel Track (HWT) testing was conducted to characterize the rutting performance, and water samples from the HWT water bath were analyzed for microplastic. Additionally, to detect microplastic release a permeability device was used on specimens cracked in the IDEAL-CT test. Table 4 presents the matrix of mixture tests on the selected mixtures with different additives. With the addition of plastic, the optimal binder content decrease in different degrees with 4% air voids.

Table 4. Matrix of mixtures with different additives combination

Trial	% by wt. of mix			
	Binder	LLDPE	GTR	Elvaloy(+PPA)
1	5.0	0	0	0
2	4.6	1	0	0
3	4.3	2.5	0	0
4	4.6	1	0.23	0
5	5.0	0	0	0.008
6	4.3	1	0	0.008
7	4.4	1	0	0

Note: Trial 1-6 use LLDPE pellets; Trial 7 uses pure LLDPE powder;
Binder content is determined from AASHTO volumetric test with 4% airvoids.

4.2.1. Dry Process with Plastic

Adding LLDPE to asphalt mixture by the dry process is as follow:

a. Preheated binder @ 150 °C for 4 hours and aggregates @ 185°C for 4 hrs.

b. LLDPE power/pellets are mixed into the dry aggregates for 1 minute;

c. Reheated for 15 minutes and mix binder into LLDPE-mixed aggregates @170°C for 2 minutes.

Recent research indicated plastic can be coating on aggregate on the surface as a binder extender or fines substitute (Raja et al,2020; Rajasekaran et al,2013). India study shows Polyethylene polymer tends to form a film-like structure over the aggregate when it is sprayed over the hot aggregate over 160°C (2013). In this study, the same dense-grade aggregate is used to evaluate the coating effect of waste LLDPE pellets. 1.5 % LLDPE by weight of binder (0.07% by weight of mix) is added and mixed in a bucket at 185°C and 200°C for a minute.

As shown in Figure 13, LLDPE pellets with a diameter of 5mm and a thickness of around 2mm are not coating at aggregates even at a higher temperature of 200°C. Melted plastic remains very viscous and dense, and hard to spread. Possible reasons might be the melting point of LLDPE is larger than 230C, which makes it difficult to melt and coat on the surface of aggregates while the size of LLDPE pellets and the properties of aggregates might affect the heat transfer, which is insufficient for a polymer to form a film-like structure over the aggregate.

Figure 13. Plastic is not coating on aggregates @200°C

Table 5 presents a summary of the performance test results of different asphalt mixtures. Comparing the control specimen of trial 1, the addition of additive improves the fracture energy and decreases the rutting depth. Therefore, LLDPE/GTR/Elvaloy or combined additive modified asphalt mixture (trial 2-trial7) have a positive impact on low-temperature cracking and rutting resistance. However, the CT index of modified asphalt mixtures from the IDEAL CT test shown negative trends of cracking resistance at room temperature. There is not much difference among different types of additives with an average CT index of 25 compared to 104 of control specimen. More detailed results analysis and discussion can be found below.

Table 5. Performance test results of asphalt mixture

	% by wt. of mix				Performance Test Results		
	Binder	LLDPE	GTR	Elvaloy	DCT, G_f, J/m^2	Rut depth, mm	CT index
1	5.0	0	0	0	431	17.9	104
2	4.6	1	0	0	464	1.5	20
3	4.3	2.5	0	0	689	1.2	32
4	4.6	1	0.23	0	537	1.4	21
5	TBD	0	0	0.008	TBD	TBD	TBD
6	4.3	1	0	0.008	384	0.9	19
7	4.4	1	0	0	462	1.3	27

Note: Trial 1-6 use LLDPE pellets; Trial 7 uses pure LLDPE powder;
Binder dosage is determined from AASHTO volumetric test with 4% airvoids.

4.2.2 Volumetric Design

Volumetric properties were characterized by AASHTO standard procedures R30, T312, T209, and T166. The volumetric properties were evaluated at an in-design of 35 gyrations in a Superpave gyratory compactor (Figure 14). Trial binder contents were performed for each additive or combination of additives to determine the optimal binder content for each mixture. Optimal binder content is the percent binder in the mix at which the Gmb puck has 4% air voids at n-design gyrations. As presented in Table 6, the theoretical maximum specific gravity, Gmm, decreases with the addition of different additives since the density of the additive is less than the binder and aggregates.

Figure 14. Superpave gyratory compactor at MAPIL

Table 6. Gmm of different asphalt mixtures with 4% air voids

Trial	% by wt. of mix				GMM
	Binder	LLDPE	GTR	Elvaloy(+PPA)	
1	5.0	0	0	0	2.456
2	4.6	1	0	0	2.425
3	4.3	2.5	0	0	2.388
4	4.6	1	0.23	0	2.416
5	5.0	0	0	0.008	TBD
6	4.3	1	0	0.008	2.447
7	4.4	1	0	0	2.428

Note: Trial 1-6 use LLDPE pellets; Trial 7 uses pure LLDPE powder;
Binder content is determined from AASHTO volumetric test with 4% airvoids.

4.2.3. Disk-shaped Compact Tension Test (DC(T))

One of the main targets of this study, the cracking resistance of asphalt mixture is evaluated by The Disk-Shaped Compact Tension Test (DC(T)) as shown in Figure 15 according to ASTM D7313(07). This test is conducted to characterize the fracture behavior of asphalt mixtures in low temperatures, from which fracture energy is obtained at 10°C warmer than the PG low-temperature grade. In this low-volume design, fracture energy should pass 400 J/m^2.

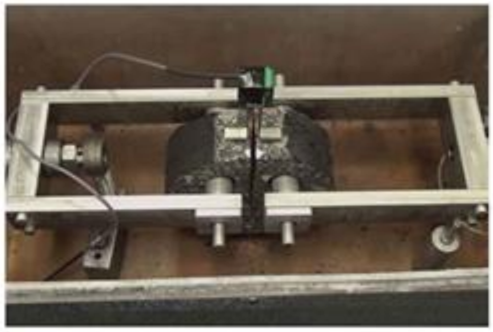


Figure 15. DC(T) devise at MAPIL

As Figure 16 shows, the addition of LLDPE/Elvaloy™/GTR contributes to the improvement of fracture energy. For this low-volume traffic design, all samples passed the 400 J/m2 criteria (Table 7). Compared to trial 2 and trial 3, the increase of LLDPE from 1.0 % LLDPE to 2.5% LLDPE by weight of mix greatly improves the fracture energy, which indicates the enhancement of the low-temperature cracking resistance. Compared to trial 2 and trial 4, the addition of 5% GTR by weight of binder with 1% LLDPE by weight of mix improves fracture energy to some degree. However, with the increase of LLDPE pellet addition, discontinuity is observed as shown in Figure 17. Therefore, LLDPE power was studied with the hope to help plastic disperse better in the asphalt mixture. Trial 7 shows that a smaller size of LLDPE results in similar fracture energy but decrease the binder content with 1.0% LLDPE by weight of mix comparing to trial 2. This might indicate a smaller size saves more binder and cost during the HMA manufacturing process. The coefficient of variance of sample results (Table 8) shows all specimens pass the 20% CV standard. However, comparing to trial 2, LLDPE power presents a larger CV, which might not help to disperse the plastic into the asphalt mixture given that binder content also decreases from 4.6% to 4.4%.

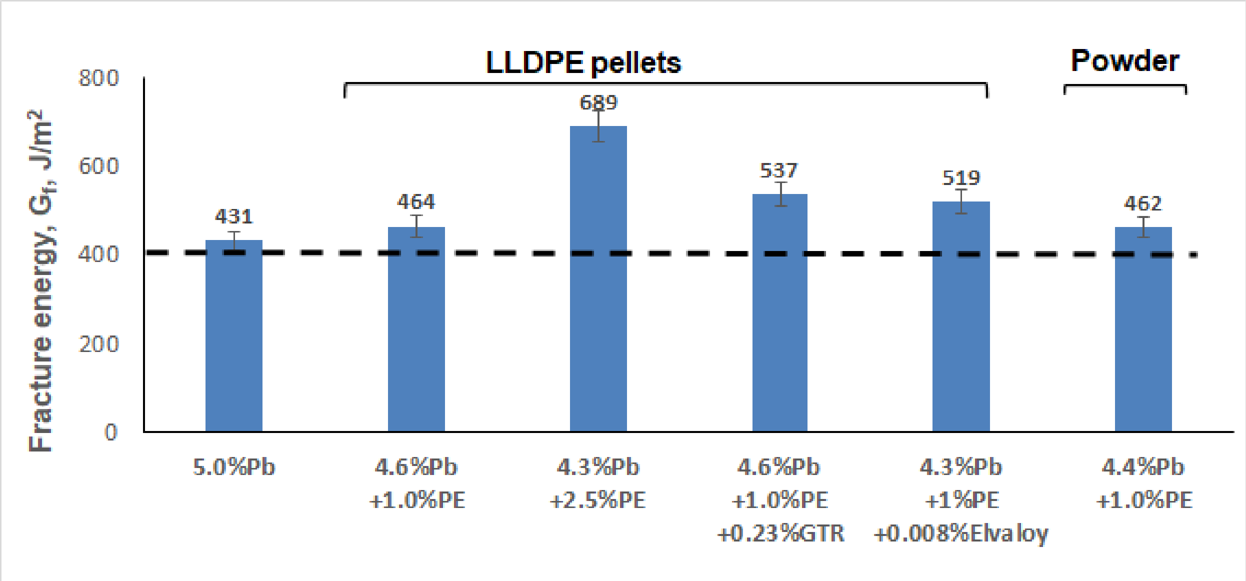


Figure 16. DC(T) Fracture energy results of asphalt mixtures

Table 7. DC(T) fracture energy criteria with traffic level

Traffic Level (ESALS)	Low <10M	Moderate 10M-30M	High >30M
Fracture energy, min (J/m^2)	**400**	**460**	**690**

Figure 17. Discontinuity on the mixture for 2.5 %LLDPE pellets with 4.3% binder

Trial	Sample 1	Sample 2	Sample 3	Sample 4	Average Fracture energy, J/m2	CV(coeff. of variance, %) <20%
1	380	440	448	457	431	7.0
2	430	452	463	510	464	6.3
3	587	627	758	782	689	12.1
4	510	458	664	515	537	14.3
5	TBD	TBD	TBD	TBD	TBD	TBD
6	543	433	473	628	519	14.3
7	536	396	440	488	465	11.3

Figure 18. CV of fracture energy results

4.2.4. Hamburg-Wheel Tracking Test

Laboratory wheel-tracking devices (Figure 19) are performed to run simulative tests that measure the rutting resistance and moisture-susceptibility of asphalt mixtures. The mixture sample is evaluated by rolling a repeated small load wheel device with 20,000 passes according to AASHTO T324-16., and the rut depth is measured. The bathwater after the test is collected to detect hazardous leachate of microplastic. The smaller the rutting depth is, the better the rutting resistance is with a threshold of 12.5mm for low volume road design from MODOT.

Figure 19. Laboratory wheel-tracking devices

(a) (b)

Figure 20. Rut profile example: (a) 0%LLDPE pellets with 5.0% binder;

(b)1.0%LLDPE with 4.6% binder

As shown in Figure 21, LLDPE modified asphalt mixture greatly reduces the rut depth from 17.9 mm to 1.2 mm, which is an indication of the enhancement of rutting resistance. From trial 2 to trial 7, different dosages of LLDPE and other additives have very litter difference on rut depth with a range of 1.2 to 1.5 mm. Therefore, determining the optimal LLDPE dosage might be more dependent on DCT results.

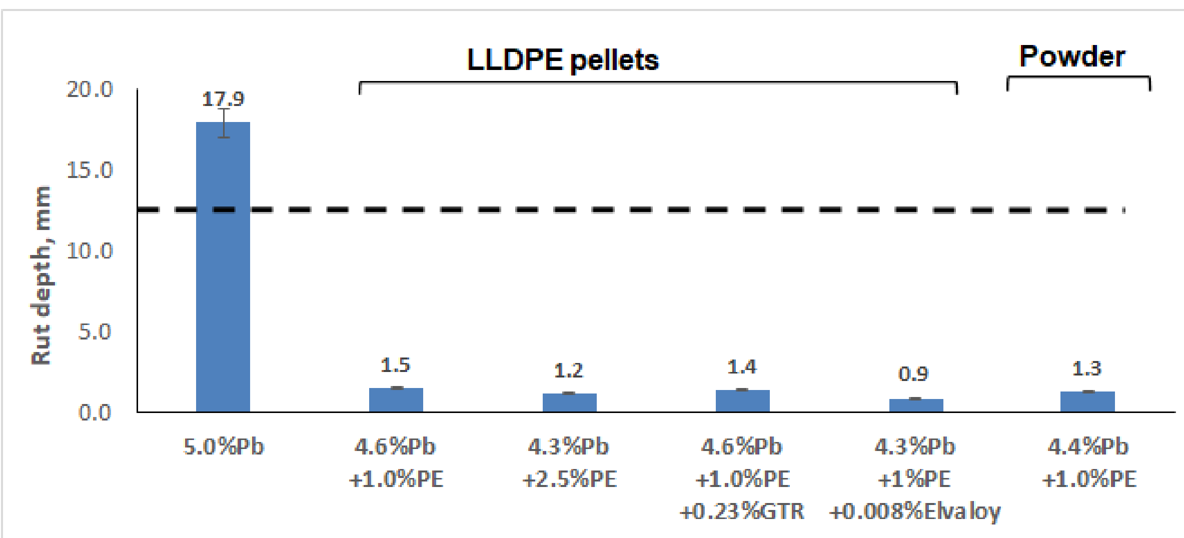


Figure 21. Rut depth of asphalt mixtures

4.2.5. Indirect Tension Asphalt Cracking Test (IDEAL-CT)

The IDEAL CT test (ASTM D8825) uses a cylindrical specimen 62mm tall by 150mm diameter (Figure 22) to determine the cracking performance of asphalt mixtures at intermediate temperatures of 25°C. A constant load-line-displacement rate, 50.0 ± 2.0 mm/min, is applied on mixture samples until deformation tolerance is at 75 % of the peak load. Therefore, fracture energy can be determined from the load-displacement curve, from which the CT index is calculated. Four replicates were fabricated for each trial and the final CT index is the average of Four test results. the error bars in Figure 22 shows the range of the calculated CTs for each mix. Generally, the higher the CT index value, the better the cracking resistance.

Figure 22. IDEAL CT devices at MAPIL and IDEAL CT specimen

In this study, the cylindrical specimen was compacted to 95mm for the IDEAL-CT test. As shown in Figure 23, all the plastic modified asphalt mixtures are far below the threshold of 55, which is recommended by MODOT. It's possible given the fact that most of the mixtures produced relatively high DC(T) fracture energy. However, even these types of dense-graded mixtures had a difficult time meeting the MODOT criteria. It's worthy to mention that with the increase of LLDPE content or the decrease of LLDPE size, the CT index improves comparing trial 3, trial 7, and trial 2.

Given that LLDPE, Elvaloy, GTR or combined additive modified did not effectively affect the CT index of asphalt mixture, change the base binder to softer binder is highly recommended.

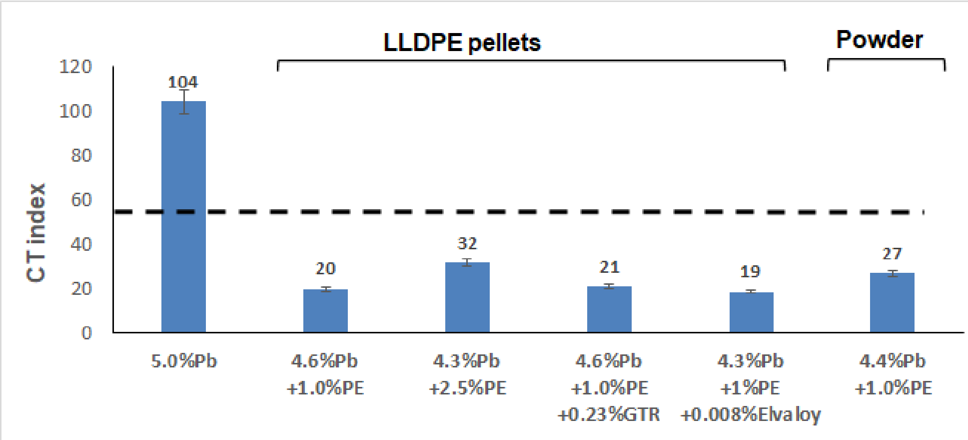


Figure 23. CT index of asphalt mixtures

CHAPTER 5. SUMMARY AND RECOMMENDATION

The addition of LLDPE and PET in asphalt binder and mixture generally presents positive and acceptable trends. In terms of performance grade (PG) of modified binder, waste PET modification, up to 15% by weight of the binder, slightly increases the workability, high temperature, and low-temperature performance. Appreciate range for the amount of waste plastic was determined to be 2-3% by weight of the bitumen regard to PG performance, which provides economic and environmental benefits. LLDPE modified binder by wet process improve PG grading results to some degree. Extra additive (Elvaloy^{TM}, etc.) at a proper amount also improve rutting and cracking performance.

LLDPE modified mixtures by dry process indicate a significant enhancement in rutting and low-temperature cracking performance. While the addition of LLDPE in the asphalt mixture had a difficult time passing MODOT recommended criteria for CT index, the CT index improve with the increased amount of LLDPE and the decrease of LLDPE size.

Considering the binder and asphalt mixture performance on the limited findings of this laboratory study, the addition of waste PET and LLDPE shows acceptable and promising trends to a regenerative industry system on asphalt pavement at the optimum dosage and scientific method. Appropriate use of waste of plastic contributes to extend pavement service life and reduction of raw material towards circular economy strategy. It's recommended that both wet process and dry process with different additives (Elvaloy^{TM}, GTR, etc.) or combination of these additive, different size or combination of different types of waste plastic are recommended in future study. The interaction principle between waste PET additive and asphalt components on their polarity and reciprocal compacity is required to decide the role of this additive if this additive is a binder replacement, filler replacement, or can be potentially utilized toward a dry process for more omnipresent economic and environmental benefit. The field test is highly recommended to determine the environmental practices concern (hazardous leachate) and the applicability of regulatory limitations before use in addition to construction availability and cost.

APPENDICES

	TRƯỜNG ĐẠI HỌC HÀNG HẢI VIỆT NAM VIETNAM MARITIME UNIVERSITY TRUNG TÂM TVPT CÔNG NGHỆ XÂY DỰNG HÀNG HẢI MARITIME CONSTRUCTION CONSULTANT AND TECHNOLOGY DEVELOPMENT CENTRE PHÒNG THÍ NGHIỆM KIỂM ĐỊNH CHẤT LƯỢNG XDCT LAS-XD 1292 CONSTRUCTION QUALITY INSPECTION LABORATORY LAS-XD 1292 Đ/c:484 Lạch Tray-Ngô Quyền-Hải Phòng Email: lasxd1292@gmail.com ĐT/Fax: 0225.3855679	

KẾT QUẢ THIẾT KẾ BÊ TÔNG NHỰA

Results of mixture design for asphalt concrete

Cơ quan yêu cầu *(Client)* :	
Công trình *(Project)* :	
Hạng mục (*Work item*) :	Thiết kế cấp phối bê tông nhựa / Mix design asphalt concrete
Phương pháp thử (*Method of testing*):	TCVN 8860-2011
Loại bê tông nhựa (*Type of AC*) :	BTNC 19 (Bê tông nhựa có rác thải nhựa / *Asphalt concrete with Plastic waste*)
% nhựa đường + rác thải nhựa (Theo hỗn hợp) % of Bitume & Plastic waste (*Follow sample*)	**4.20 (%)**
Ngày thí nghiệm (*Date of testing*) :	

TỶ LỆ THIẾT KẾ THEO TCVN 8819:2011 *(RATIO OF DESIGN FOLLOW TCVN 8819:2011)*

Vật liệu *Materials*	*Bin 4* *(19 - 25)*	*Bin 3* *(12.5 - 19)*	*Bin 2* *(4.75 - 12.5)*	*Bin 1* *(0 - 4.75)*	*Bột đá* *Filler*	Nhựa đường *Bitumen*	Rác thải nhựa *Plastic waste*	GHI CHÚ *Notice*
Phần trăm *Ratio (%)*	**8.3**	**19.8**	**33.3**	**39.6**	**3.1**	**4.03**	**0.35**	Theo cốt liệu *Follow agg.*
Phần trăm *Ratio (%)*	**8.0**	**19.0**	**32.0**	**38.0**	**3.0**	**3.86**	**0.34**	Theo hỗn hợp *Follow sample*

THIẾT KẾ CHO MẺ TRỘN

CHO MẺ TRỘN / *DESIGN FOR:* **400 KG**

Vật liệu *Materials*	*Bin 4* *(19 - 25)*	*Bin 3* *(12.5 - 19)*	*Bin 2* *(4.75 - 12.5)*	*Bin 1* *(0 - 4.75)*	*Bột đá* *Filler*	Nhựa đường *Bitumen*	Rác thải nhựa *Plastic waste*	GHI CHÚ *Notice*
Trọng lượng *Weight* *(Kg)*	**32.0**	**76.0**	**128.0**	**152.0**	**12.0**	**15.5**	**1.3**	Theo hỗn hợp *Follow sample*

CHỦ ĐẦU TƯ *(The Employer)*	THÍ NGHIỆM *(Tested by)*	PHÒNG TN LAS-XD 1292 *(Check by)*	CƠ QUAN THÍ NGHIỆM *(Organ of testing)*
	Vũ Thế Lượng	*Phạm Tiến Thành*	*TS. Phạm Văn Trung*

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