Laboratory investigation on the moisture susceptibility and fatigue resistance of hot mix asphalt modified with high- and low-density polyethylene plastic wastes

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ABSTRACT

The demand for better management of plastic wastes all over the world is increasing. Polymers such as high-density polyethylene (HDPE) and low-density polyethylene (LDPE) are examples of these wastes. Studies showed that these could be used as polymer modifiers that could improve asphalt pavement performance. Although several studies had been conducted to evaluate the performance of asphalt mixtures with HDPE and LDPE, conflicting results had been seen. Additional research is still needed to find out the true effect of plastic on the performance of asphalt mixtures. Hence, this study assessed the performance of hot mix asphalt (HMA) modified with HDPE and LDPE pellets. The Marshall mix design was used to prepare, evaluate HMA mixtures and determine the optimum percentage of HDPE and LDPE that can be added to HMA. Moreover, wheel-tracking, and immersion-compression tests were used to evaluate rutting resistance and compressive strength of HMA mixtures, respectively. Results showed that the addition of 8% HDPE and 8% LDPE by weight of bitumen are the optimum contents. The performance of the HMA mixtures with HDPE and LDPE in terms of fatigue resistance and moisture susceptibility shows improved results. This proves the potential use of the materials as polymer modifiers in HMA. Moreover, HMA with HDPE when compared to the HMA with LDPE shows better results in reducing the moisture susceptibility and improving the fatigue resistance of HMA.

Keywords: Marshall stability, optimum binder content, plastic wastes, polymer modified HMA

INTRODUCTION

The production of waste such as plastics is increasing with the growing population. Countries have been facing solid waste management problems. Recycling plastic wastes as modifiers of materials for the construction of roads and infrastructure is gaining acceptance worldwide (e.g. Akinpelu et al. 2013; Arabani et al. 2017; Brasileiro et al. 2019). This is not only due to economic reasons, but also a way to put wastes into something useful. In the Philippines, the Department of Environment and Natural Resources (DENR) recorded those residential wastes which include plastic wastes constitutes 56.7% of the municipal solid waste (MSW) generation in the Philippines. Recyclable wastes account for almost a third of MSW with plastics comprising around 38% of these (DENR 2018). Hence, there is a need to make use of these wastes so that disposal to landfill sites are minimized if not abolished.

Flexible pavements are often used for the construction of roads in various countries like the Philippines. They need to improve their quality and performance considering the increasing traffic volume on roads. One way to improve the properties and quality of asphalt pavement is the addition of polymers such as plastic wastes. Polymers help improve binder properties resulting in safer roads and reduction of maintenance (e.g. Costa et al. 2013; Abdullah et al. 2017; Deshmukh et al. 2017). The addition of plastic wastes to asphalt mixture likely increases its stiffness, viscosity, strength, rutting resistance and fatigue resistance (e.g. Sutradhar et al. 2015; Manju et al. 2017; Sarkar 2019; Wu and Montalvo 2021). However, some results show negative effects to other performance parameters of asphalt mixtures (Wu and Montalvo 2021).

Various studies that investigated the effects of the modification of hot mix asphalt (HMA) with plastic wastes such as high-density polyethylene (HDPE) or low-density polyethylene (LDPE) also vary in the results of optimum plastic content. For example, Nejad et al. (2014) after investigating the performance of HMA with HDPE found out that mixtures with HDPE exhibited higher fatigue life compared to the control. Additionally, results also showed better rutting resistance for HDPE-modified mixtures. In other studies, the percentages of plastic wastes added in the modified asphalt mix range from 2% to 20% (e.g. Kofteci 2016; Abdullah et al. 2017; Dalen et al. 2017; Chegenizadeh et al. 2021) and the most common concentration of plastic waste for the modified asphalt mix was 10% by weight of the binder (e.g. Rahman et al. 2013; Chandrawal et al. 2016; Asare et al. 2019).

Studies indicate that the number of plastic wastes to be added to the HMA mixture depends on the area where the materials must be applied, its size, type of plastic wastes, type of mineral filler, among other factors (Dalhat and Wahhab 2017; Abu Abdo and Khater 2018; Khurshid et al. 2019). The aggregates and bitumen used in each study were available locally in their countries. In previous studies, different types of bitumen were used such as AC 35/50, 40/50, 60/70, and 70/80, 80/100 (e.g. Attaelmanan et al. 2011; Jain et al. 2011; Nasir et al. 2014; Sojobi et al. 2016). In some of the studies, performance of the mix has shown conflicting results. For example, HDPE improve and worsen rutting resistance (Wu and Montalvo 2021). Also, polyethylene terephthalate (PET) led to a worsened moisture resistance and thermal cracking resistance. These conflicting results indicate that additional research is necessary to further investigate the true effect of the addition of plastics on the performance of the asphalt binder and asphalt mixtures (Wu and Montalvo 2021).

With the demand for utilization of plastic wastes to road construction in the Philippines, this study aimed to identify the optimum content of HDPE and LDPE that could be applied in this context. Specifically, this study evaluated the volumetric properties and the effect of the concentration of HDPE and LDPE on the properties of HMA such as fatigue resistance and moisture damage resistance.

METHODS

Materials

Asphalt cement (AC) penetration grade 60/70 was used (Table 1). Aggregates of Grading D according to the DPWH (2017) standards (Table 2) were utilized. Cement was used as a mineral filler for HMA. Pelletized recycled HDPE and LDPE was used with a diameter of not more than 4.75 mm. The percentage of recycled HDPE and LDPE plastic served as an additive to the bitumen of the asphalt mixture with 8%, 10%, and 12% by weight of bitumen.

Table 1. Table 1. Properties of asphalt cement 60/70 asphalt binder utilized for control and polymer modified hot mix asphalt.

Property	Standard
Penetration, 25°C; 100 g, 5 s, 0.1 min	60–77
Softening point, °C	48–53
Flash point	Min 200
Ductility, cm	Min 100
Mass	Min 0.1
Decreasing Mass, %	Max 1.0

Table 2. Table 2. Details of grading D aggregates used in producing hot asphalt mixtures based on Department of Public Works and Highways (2017).

Sieve Size (mm)	% Passing	Grading	% Retained	Weight of Aggregate (g)	Cumulative (g)
9	100	100	-	-	-
12.5	95–100	97	3	36	36
9.5	74–92	83	14	168	204
#4 (4.75)	48–70	59	24	288	492
#8 (2.36)	33–53	43	16	192	684
#16 (1.18)	22–40	31	12	144	828
#30 (0.60)	15–30	23	8	96	924
#50 (0.30)	10–20	15	8	96	1020
#200 (0.075)	4–9	7	8	96	1116
Mineral Filler	7	-	-	84	1200

Mix Design, Stability, and Flow

The Marshall Mix Design method according to the American Society for Testing and Materials (ASTM) D1559 (ASTM 2020) was used in designing the HMA mix and analyzing the optimum content of bitumen and plastic wastes. First, samples were prepared to determine the optimum binder content. With air voids designed between 3–4%, the determined optimum binder content is 5.5%. Then for testing the volumetric properties of HMA, three samples each were prepared for the control mix, and samples with 8%, 10%, and 12% HDPE and LDPE, separately.

The HDPE and LDPE modified HMA consists of recycled HDPE and LDPE plastic, bitumen, aggregate, and filler. Aggregates were batched, then heated in the oven at 200ºC for 24 h. Then bitumen was heated in an oven at a temperature of 180ºC for 1 h, then mixed with the aggregates at a temperature of 170ºC–180ºC. The mixture was poured and compacted at 75 blows on each side in a standard specimen mold. After compaction was completed, the sample specimen was removed from the mold and undergone a cooling process for at least 24 h. Specimens were placed in a water bath at 60ºC for 30 min before testing.

The Marshall stability and flow test indicate the performance measure for the Marshall mix design method. Marshall stability is the maximum load that a compacted specimen may carry at 60ºC. Stability is equal to the maximum load in kilogram. Flow value is the total deformation the Marshall test specimen undergoes at the maximum load. The criterion for the test is heavy traffic with property standards (Table 3).

Table 3. Marshall mix design criteria used for evaluating hot mix asphalt performance test results.

Experiment	Min	Max
Bulk Specific Gravity (G_{mb})	2.20	2.50
Maximum Theoretical Density (G_{mm})	2.40	2.70
Air Voids (%)	3.00	5.00
Marshall Stability Adjusted (N)	8,006	-
Marshall Flow Adjusted (0.25 mm)	8	14

The formulas indicated below were used to calculate the G_{mm}, G_{mb}, and air voids. Equation 1 shows the formula for determining the G_{mm}, where G_{mm} is the maximum theoretical density, A is the mass of the dry sample, D is the calibrated mass of the container and water, and E is the mass of the vacuum.

$$G_{mm} = \frac{A}{A + D - E} \qquad \text{Eq. 1}$$

Equation 2 shows the formula for determining the G_{mb}, where A is the mass of the dry sample, W is the mass of the sample on immersion, and SSD is the mass of the sample after immersion.

$$G_{mb} = \frac{A}{SSD - W} \qquad \text{Eq. 2}$$

The percent air voids are presented in equation 3, where both the G_{mm}, G_{mb} calculated using the results from equations 1 and 2.

$$\%\ air\ voids = \frac{G_{mm} - G_{mb}}{G_{mm}}\ x\ 100 \qquad \text{Eq. 3}$$

The Marshall Stability is calculated using equation 4, where R is the reading on martial test equipment, CR is the calibration factor on the equipment which is 30.34 pounds/division in this case. R should be in the range of 3.0 - 4.5 mm to pass.

$$Stability = (R\ x\ CR) \qquad \text{Eq. 4}$$

After these tests, the modified bituminous mixtures were prepared for testing the fatigue and moisture damage resistance of the HMA control mix and the modified ones.

Fatigue Resistance Test

The HMA resistance to fatigue is one of the crucial parameters of an asphalt pavement. The Hamburg wheel track test according to the American Association of State Highway and Transportation Officials (AASHTO) T324 (AASHTO 2020) was used to test properties of HMA through a wheel that gives repeated loads to the asphalt specimen. The performance of the asphalt mix samples is related to actual performance in the field. Fifteen samples were prepared for testing the fatigue resistance of HMA with and without the plastic wastes. The test was run for approximately 2 h. After the test, the deformation of the samples was measured. The deformation is obtained by getting the height difference of the original height and middle part of the specimen which was subjected to repeated loading.

Moisture Damage Resistance Test

Moisture induced damage is a complicated mode of distress leading to the loss of stiffness and structural strength in asphalt pavement mixture. This will also cause a financial burden in maintaining the pavement structure. The immersion-compression test was conducted to measure the loss of asphalt strength due to water on compacted bituminous mixtures. In conducting this test, samples were grouped into wet and dry conditions. Eighteen samples were prepared for testing the moisture damage resistance. The standard specimen in this test has a diameter and height of 101.6 mm. This test aims to obtain the first appearance of IRS, including full meaning as index of retained strength calculated as shown in equation 5, where S_1 is the compressive strength of unconditioned specimens, and S_2 is the compressive strength of conditioned specimens. The value of the IRS should be greater than 70% to be able to pass this test.

$$IRS, \% = \frac{S_2}{S_1}\ x\ 100\% \qquad \text{Eq. 5}$$

Statistical Analysis

The analysis of variance (ANOVA) was utilized in this study to identify if there is a statistical significance between the means of the HMA without HDPE and LDPE and the ones with the percentage of these waste plastics. The principle is that the total variation in the dependent variable is broken into one, and is related to some specific causes, known as the variation between the samples (Molugaram and Rao 2017). Variations within the samples are attributed to chance. The null hypothesis states that there is no significant difference between the groups. The alternative hypothesis states that there is a significant difference between the means and groups. This further shows that at least one of the means differ from the others.

RESULTS

HMA Volumetric Properties

Bulk specific gravity *(G_{mb})* and maximum theoretical density (G_{mm}) were obtained and were used in calculating the percent air voids in the mix. G_{mm} is always greater than G_{mb}. The values of G_{mm} for all samples tested (Table 4) are all within the range according to DPWH standards of 2.4–2.7. While the values of G_{mb} were all within the range of 2.2–2.5 according to DPWH standards (Table 3). HMA with HDPE had lower G_{mb} and G_{mm} compared to those with LDPE. Statistical analysis showed that there is no significant difference between these values compared to the control HMA. This result means that the HMA with plastic wastes can be used as a substitute for conventional HMA.

The values obtained for air voids (Figure 1) were within the parameters of the standard test values given by the DPWH as seen in Table 3 (within 3–5%). In general, HMA with LDPE and HDPE has lower air voids compared to the control mix (4.03%). With increasing HDPE and LDPE content, the percentage of air voids increases as well. HMA with 8% HDPE has the lowest value of air voids (3.21%) compared to the control mix and HMA with 8%, 10%, and 12% HDPE and LDPE. HMA with 12% LDPE plastic showed no difference compared to the controlled mix, which means the addition of 12% LDPE plastic in HMA did not lessen the small airspaces that occurred in the HMA.

Table 4. Average bulk specific gravity and maximum theoretical density of hot mix asphalt samples prepared for performance testing. HMA – hot mix asphalt; HDPE – high-density polyethylene; LDPE – low-density polyethylene.

Property	HMA control	HMA with 8%		HMA with 10%		HMA with 12%	
		HDPE	LDPE	HDPE	LDPE	HDPE	LDPE
Maximum G_{mm}	2.606	2.579	2.606	2.582	2.586	2.59	2.599
G_{mb}	2.501	2.494	2.503	2.493	2.497	2.487	2.487

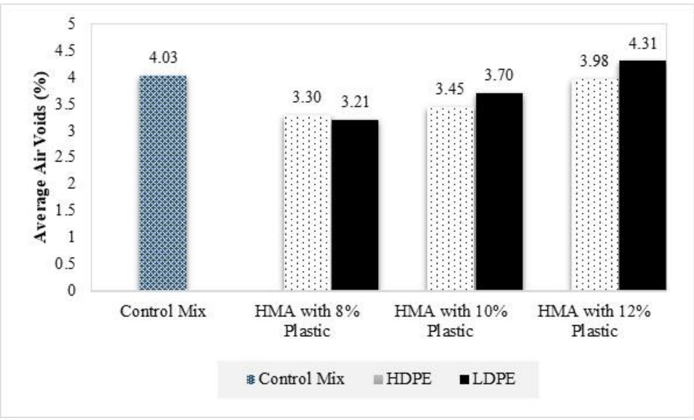

Figure 1. Average values of percent air voids for hot mix asphalt mixtures with and without plastic content.

Marshall Stability and Flow

The results for Marshall stability (Figure 2) passed the minimum stability required of 8,006 N. This is according to the DPWH standards (Table 4). The stability of samples with 8% and 10% HDPE and LDPE plastic wastes surpasses the performance of the controlled mix by 358–1660 N. While HMA with 12% HDPE and LDPE had stability value lower than the control mix by 417–254 N. HMA with 8% LDPE plastic wastes gave the highest stability value. This means that it can resist more horizontal deformation when subjected to severe traffic loads.

The addition of 8%, 10%, and 12% of HDPE plastic wastes in HMA (Figure 3) have passed the standard maximum value for Marshall flow in Table 4. HMA with 8% and 10% HDPE showed the same flow value which is lower than the control. However, a higher flow value compared to the control was exhibited by HMA with 12% HDPE. While the addition of 8% LDPE had the same flow value as that of the control mix. While HMA with 10% HDPE had a lower flow value than the control. A higher value of flow was also exhibited by samples with 12% LDPE plastic wastes. Improvement of flow value compared to the control was observed within 8% and 10% contents. However, a further increase in the plastic content increased the flow value.

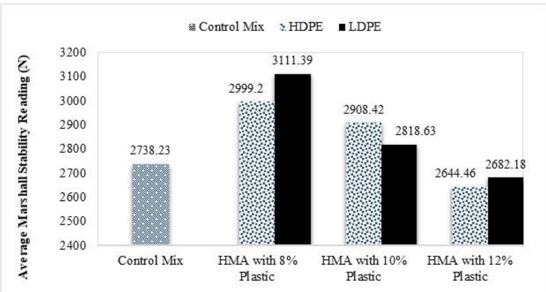

Figure 2. Average Marshall stability of hot mix asphalt control and modified mix.

Based on the statistical analysis results for stability and flow, there was no significant difference between the control mix and the mixtures modified with HDPE and LDPE. This means that the addition of plastic is at par with the results of the mix without plastic waste. However, there was no significant improvement in the stability and flow results.

HMA Fatigue Resistance

Results of the fatigue resistance test (Figure 4) showed that the samples with HDPE and LDPE deformed were lesser than the control HMA by 2.67 mm, 0.67 mm, and 1 mm. Having high concentration percentages of HDPE and LDPE gives lesser deformation which indicates that these helps increase the useful service life of the pavement. However, statistical analysis showed that adding LDPE plastic waste had no significant effect on improving the deformation of HMA. While adding HDPE plastic waste on HMA had a significant effect as the *P*-value is lower than the significance level.

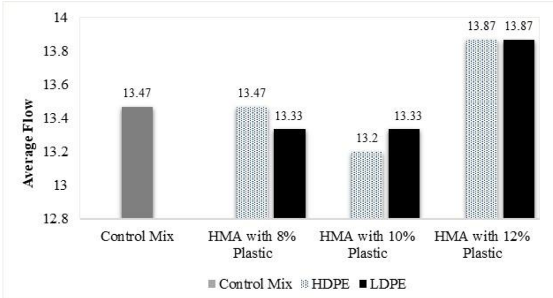

Figure 3. Average values of Marshall flow of hot mix asphalt control and modified mix.

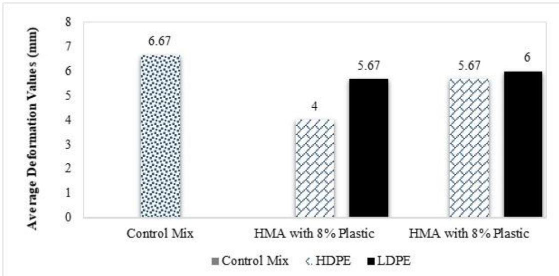

Figure 4. Deformation of hot mix asphalt with and without plastic wastes.

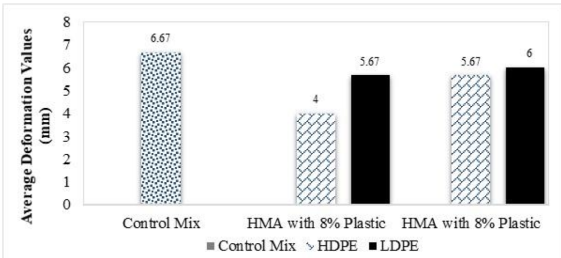

Figure 4. Deformation of hot mix asphalt with and without plastic wastes.

The relationship between the deformation and the additional percentages of HDPE and LDPE plastic wastes is shown in Figure 5. As the additive percentages of HDPE and LDPE in HMA increases, the deformation also increases. Thus, an additional 8% and 10% of HDPE and LDPE plastic wastes in HMA did not surpass the deformation of conventional HMA.

Statistical analysis showed that the addition of HDPE and LDPE might not improve the fatigue resistance but could be used instead of the conventional HMA. This implies the potential use of the plastics instead of being put to waste.

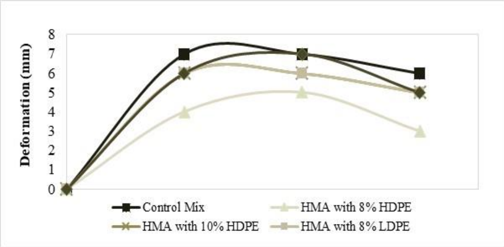

Figure 5. Trends of deformation in hot mix asphalt with and without high-density polyethylene and low-density polyethylene.

HMA Moisture Damage Resistance

Both the average dry HMA sample specimen containing 8% HDPE and LDPE did not perform well compared to the control mix when it comes to the compressive strength (Figure 6). While both averages of wet HMA sample specimen containing 8% HDPE and LDPE performed well as it showed higher compressive strength than the control mix. Statistical analysis indicated a significant effect on both the addition of HDPE and LDPE on the compressive strength of a dry HMA, while wet HMA containing HDPE and LDPE showed no significant effect on the compressive strength of HMA.

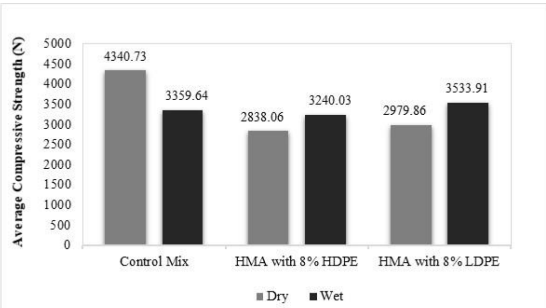

Figure 6. Average compressive strength of hot mix asphalt mixtures with and without plastic content.

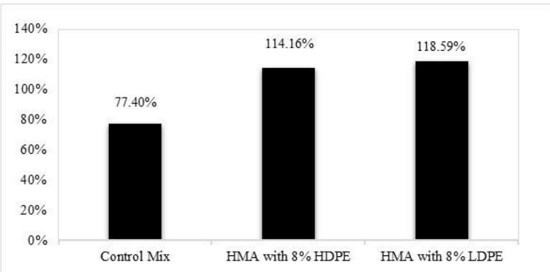

Figure 7. Percent index of retained strength of hot mix asphalt samples with and without high-density polyethylene and low-density polyethylene.

The values obtained have passed the minimum IRS value which is 70% (Figure 7). Both the addition of HDPE and LDPE to HMA helped improve moisture damage resistance of HMA with higher IRS compared to the control mix. IRS of the HMA sample specimen with 8% HDPE plastic wastes had a greater resistance to moisture damage compared to the control mix by 36.76%. While the IRS of the HMA sample specimen with 8% LDPE has a higher resistance to moisture damage compared to the control mix by 41.19%.

DISCUSSION

The volumetric properties of HMA first investigated include the bulk specific gravity, maximum theoretical density, percentage of air voids, Marshall stability, and flow. Using AC 60/70 and aggregates of grading D, tests were done to determine the optimum concentration of HDPE and LDPE that could be added to HMA. Also, fatigue resistance and moisture damage resistance of HMA mixture were evaluated.

Volumetric Properties, Stability and Flow

Results of tests performed showed that volumetric properties of HMA with HDPE and LDPE have passed all the DPWH standards in terms of Marshall stability, flow, and air voids. These results were compared to the HMA control mix. Further, HMA with recycled HDPE plastic has lower percentages of air voids compared to HMA with recycled LDPE plastic. Higher percentages of air voids mean that the sample absorbed more water and air that may result in cracking and stripping of the asphalt.

HMA Fatigue Resistance

HMA with 8% LDPE can resist more horizontal deformation and can increase the fatigue resistance by 13.63%. In HMA, having a high and good Marshall stability means resistance to horizontal deformation and an increase in fatigue resistance. HMA with 10% HDPE reduces permanent deformation by 1.98%. Low vertical deformation as indicated by the flow value, showed that the sample can resist more permanent deformation. HMA with the addition of 8% HDPE reduces permanent deformation by 40.03%. Low vertical deformation indicates that the sample can resist more permanent deformation and can increase the fatigue resistance of HMA. This is supported by Chegenizadeh et al. (2021) that the mixtures containing 8% HDPE is best in rutting resistance performance. Although stone mastic asphalt (SMA) mixtures with 4% HDPE was in this study, it shows the best fatigue resistance.

HMA Moisture Damage Resistance

HMA with 8% HDPE and LDPE plastic wastes both exceeded the standard IRS value of 70% and that of the control mix. Having a high IRS value indicates that a sample is less susceptible to moisture. HMA with 8% LDPE plastic waste can resist more stripping damage by 53.22%. This result is quite like results in the previous study (e.g. Haider et al. 2020a,b) where compacted asphalt mixtures with various types of aggregates was used and was found that mixtures with waste plastic modifiers of 9% HDPE and LDPE have better moisture resistance than normal asphalt mixture without modifiers.

Test results in this study show that HMA with a concentration of 8% HDPE and LDPE plastic waste is the recommended optimum plastic content that can potentially improve the performance of HMA. These results support past studies where researchers found the optimum contents of plastic wastes to be between 5–10% (e.g. Jain et al. 2016; Al-Hadidy 2019; Asare et al. 2019; Haider et al. 2020a,b; Chegenizadeh et al. 2021). However, results here are different from that of other studies such as that of Jain et al. (2011) who recommended 15% of plastic wastes to be added. The difference may be due to the method of adding the plastic particles to the aggregates as contrary to addition to the binder as utilized in this study. Also, Kofteci (2016) found that 2–4% of HDPE by weight of bitumen in HMA leads to best resistance to moisture damage. Moreover, findings in this study also show that HMA with HDPE is more effective than the HMA with LDPE in terms of reducing the moisture susceptibility and improving the fatigue resistance of HMA.

These results can be helpful to local authorities in the Philippines. HDPE and LDPE plastic wastes with the proposed percentage of 8% can be used for the improvement of road performance in the country. Constructing field test road sections based on the findings in this study can help further evaluate HMA performance in the field. However, this study is not free from limitations and imperfections. Additional research can be done to assess the effect of HDPE addition to the resistance of HMA to cracking, rutting, and fatigue at different mix temperatures. Further investigation is also recommended incorporating a combination of HDPE and LDPE percentage in HMA using various aggregate grading and AC contents. This may lead to determining the lowest mix temperature possible for HMA which can potentially reduce operating costs in producing asphalt mixtures. Additional additives may also be needed for lowering mix temperatures.

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