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Plastic Waste Utilization as Asphalt Binder Modifier in Asphalt Concrete Pavement

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Abstract—The main objective of this paper is to evaluate the use of plastic waste as a low cost asphalt binder modifier. For this purpose Marshall mix design procedure was used. Marshall mix design procedure seeks to select the Optimum Binder Content (OBC) to be added to a specific aggregate blend resulting in a mixture that satisfies the desired properties of strength and durability. In order to evaluate the plastic waste modified (PWM) asphalt mixtures, the OBC for the conventional asphalt mix was first identified, and then different percentages of crushed plastic waste by weight of the identified OBC were tested. Marshall test results for the modified asphalt mixtures were analyzed to find the optimum PWM content. Finally, the static indirect tensile strength (IDT) was determined for all mixtures using the splitting tensile test. It was found that PWM content of 7.43% by weight of OBC is recommended as the optimum PWM content needed for enhancing the performance of asphalt mixtures. It enhanced stability by 42.56%, flow by 89.91% and strength by 13.54%. This would lead to a more durable pavement by improving the pavement resistance to fatigue cracking and rutting.

***Keywords*—**Binder content modifier, Marshall test, plastic waste, polyethylene terephthalate.

I. Introduction

GOOD road infrastructure is a vital requirement for the social and economic development of any country. The goal of roads is to provide durable and long lasting pavements to improve riding comfort and safety, as well as to reduce maintenance costs. This can be achieved by providing good structural pavement design as well as good asphalt mixture design. Throughout the years, numerous studies have been conducted to improve asphalt mixture design for better performing pavements [1]-[3]. Significant improvement on asphalt mixture quality has been made by the addition of modifiers. These modifiers can enhance asphalt binder's stiffness at normal service temperatures which will reduce rutting and shoving, while decreasing its stiffness at low temperatures to improve its resistance to fatigue cracking [1], [2]. Also, modifiers can increase adhesion between asphalt binder and aggregates in the presence of moisture, this will reduce the probability of aggregate stripping [3], [4]. The most common asphalt mixture modifiers are filer, extender, fiber, oxidant, antioxidant, hydrocarbon, crumb rubber and polymers [5], [6]. Crumb rubber can be obtained from tiers while polymers can be obtained from waste disposal plastic such as plastic bags and bottles. Disposal of plastic waste materials has become a serious environmental problem [7]. The steady increase in the use of plastic products has resulted in proportionate rise in plastic waste. It is produced in a massive scale worldwide with an estimated production of 12 billion metric tons of plastics in 2050, representing 90% increase over 2017, and confirming an increasing trend over the past years [8]. This can have serious downsides on the environment and health. Therefore, the utilization of plastic waste in asphalt mixtures would not only enhance pavement performance, but would also manage plastic waste and solve disposal problems [9], [10].

The main objective of this paper is to study the ability of using recycled plastic waste as a low cost asphalt binder modifier to improve performance of asphalt roads as well as to extend their service life. For the purpose of this study Organic Polyethylene Terephthalate (PET) materials in the form of plastic cups and plastic bottles were used as an asphalt binder modifier. The PWM asphalt mixture was tested and compared to a conventional asphalt mixture using Marshall mix design procedure. Also, the IDT was determined for all mixtures using the splitting tensile test. It was found that the PWM asphalt mixture outperformed the conventional asphalt mixture.

II. Literature Review

Asphalt pavement is composed of bituminous surface course and underlying granular base and subbase courses. The bituminous surface or the asphalt mix is composed of three elements: mineral aggregates, asphalt binder and air voids. Asphalt pavement performance is affected by the properties and proportions of the asphalt mixture components. It can be enhanced with the utilization of various types of modifiers such as polymers in the form of plastic waste [11]. The concept of plastic waste utilization as asphalt binder modifier to enhance asphalt concrete mix performance has been studied by many researchers. Chen [12] evaluated the use of polymer as a binder modifier. It was found that the modified asphalt provided better resistance against permanent deformation, more durability and lower rut depth compared to the conventional asphalt mixture. Sasane et al. [13] utilized plastic waste in the construction of pavement. The study revealed that plastic waste pavement showed better resistance to water which reduced the stripping of bitumen from aggregates. Kalantar et al. [14] studied the possibility of utilizing waste PET materials as polymer asphalt binder modifier. It was found that the modified asphalt binder mix resulted in

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decreasing consistency and increasing resistance to flow and temperature changes when compared to the conventional asphalt mix. Swami et al. [15] concluded that the modified asphalt binder mix reduced not only bitumen bleeding in hot temperature and noise pollution under heavy traffic loading, but also the overall project cost by almost 8%.

III. Methodology

For the purpose of this study, Marshall mix design procedure was used to evaluate the use of plastic waste as asphalt mix binder modifier. Marshall mix design procedure seeks to select the OBC to be added to a specific aggregate blend resulting in a mixture that satisfies the desired properties of strength and durability, so in order to evaluate the modified asphalt mixtures, the OBC for the conventional asphalt mix was identified, then different percentages of crushed plastic waste by weight of OBC were tested on the PWM asphalt mixtures. Marshall test results for the modified asphalt mixtures were analyzed to find the optimum PWM content by weight of OBC. Finally, the IDT was determined for all mixtures using the splitting tensile test.

A. Selection of OBC for the Conventional Asphalt Mix

The selection of OBC in asphalt concrete (AC) pavement is important as it relates to performance. It affects stiffness, strength, and durability of AC pavements; also it is responsible for different types of distresses in the AC pavement such as fatigue cracking, raveling and permanent deformation.

Marshall mix design procedure was used according to ASTM D 1559 [16], five percentages of asphalt contents have been examined to determine the best asphalt content in the conventional asphalt mix, including 4.5%, 5%, 5.5%, 6% and 6.5% by weight of aggregate particles. 85/100 penetration-grade asphalt cement was used. Table I shows the standard test methods for the consistency properties of the asphalt binder and their tests results. Well graded aggregates were used with the gradation shown in Table II. 15 Marshall cylindrical samples, three samples for each asphalt content were prepared to get an average value of Marshall stability, bulk density and flow. The weight of each sample was 1100 gm (without bitumen weight). The samples were prepared at a temperature of 160-165 °C, 75 blows were given for each side of the sample reflecting heavy traffic volume. Marshall stability and flow tests were conducted according to ASTM D 1559 [16]. Bulk specific gravity was determined according to ASTM D 70-97 [17].

TABLE I
85/100 Asphalt Consistency Properties

Properties	Standard Test Method	Test Result
Penetration @ 25°	ASTM D5-86 [18]	AC (85-100)
Ductility @ 25°	ASTM D113-86 [19]	+100
Specific Gravity @ 25°	ASTM D70-97 [17]	1.01
Softening Point C°	ASTM D36-70 [20]	49
Flash Point C°	ASTM D92-12 [21]	300
Fire Point C°	ASTM D92-12 [21]	315
Solubility in Trichloethylene %	-	99%

TABLE II
Aggregate Gradation

Sieves size (in)	Retained percent (%)	Weight (gm)
¾” (19.5 mm)	0	0
½” (12.5mm)	20	220
3/8” (9.51mm)	12	132
No. 4 (4.76mm)	23	253
No. 8(2.38mm)	15	165
No. 40(0.42mm)	21	231
No. 200 (0.075mm)	5	55
Pan	4	44
Σ	100	1100

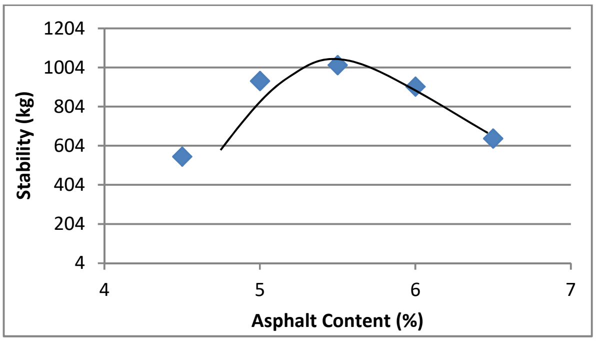

Fig. 1 (a) Stability vs. Asphalt Content

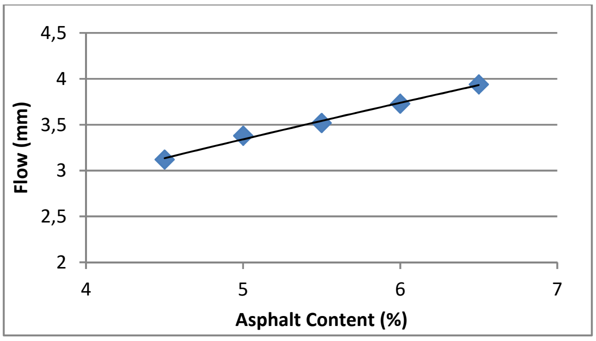

Fig. 1 (b) Flow vs. Asphalt Content

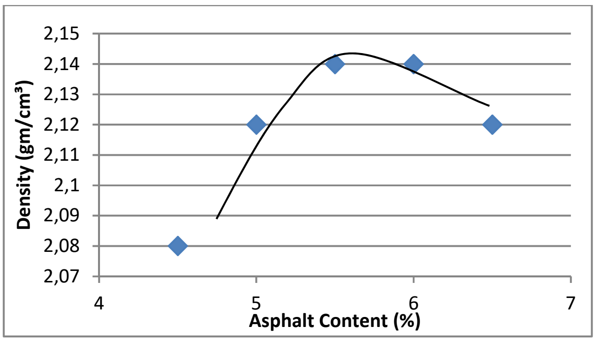

Fig. 1 (c) Bulk Density vs. Asphalt Content

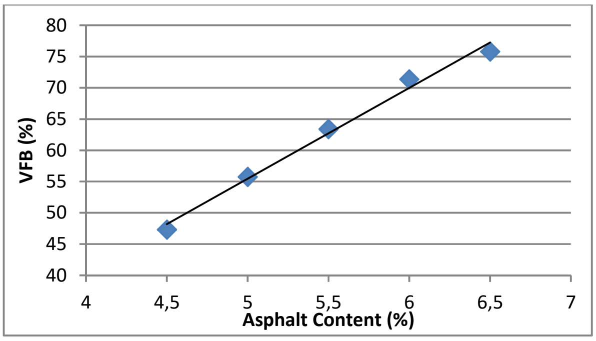

Fig. 1 (d) AV vs. Asphalt Content

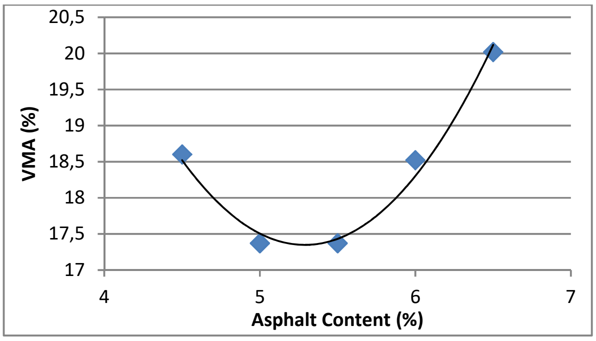

Fig. 1 (e) VMA vs. Asphalt Content

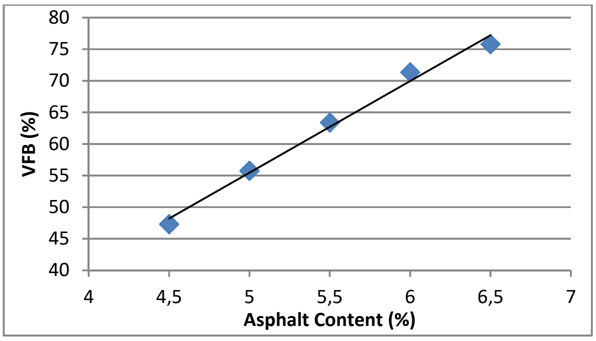

Fig. 1 (f) VFB vs. Asphalt Content

Fig. 1 Marshall Test Results for the Conventional Asphalt Mix

Marshall properties of the conventional asphalt mix including the average value of stability, flow, density, air voids (AV) in total mix, voids filled with bitumen (VFB) and voids in mineral aggregates (VMA) were obtained and plotted for each asphalt content, as shown in Fig. 1. Fig. 1 was utilized to obtain the OBC. Note that according to ASTM D 1559 [16], corrected stability should be used because it is possible that while preparing Marshall samples, the thickness may vary from the standard specification of 63.5 mm.

Fig. 1 (a) shows that Marshall stability increases with the increase in the binder content up to an optimum value then it decreases. Also, it can be seen that the maximum stability value, almost 1016 kg, corresponds to 5.42% binder content. Fig. 1 (b) shows that flow values increase with the increase in the binder content values. Fig. 1 (c) shows that that the bulk density increases with the increase in binder content up to an optimum value then it decreases. The maximum bulk density value of 2.14 gm/cm³ corresponds to 5.49% binder content. Fig. 2 (d) shows that the percent of AV decreases as the binder content increases. The median of the allowed percentage of air voids (AV = 3-5%) was found to be 6.1%. Fig. 2 (e) shows that VMA decreases then it increases at a sharp rate as the binder content increases. Fig. 2 (f) shows that the VFB values increase at a sharp rate as the binder content increases.

According to Jendia [22], the OBC can be found as the average of three values of asphalt content including asphalt content at the optimum stability, optimum bulk density and the asphalt content at the median of allowed percentage of air voids (AV = 3-5 %). The OBC for the conventional asphalt mix was found to be 5.66 %.

B. Preparation of Asphalt Mix Modified with Recycled Plastic Waste

Plastic waste such as plastic bottles and plastic cups are mostly made of PET polymer. Polymers get softened at 130-140 °C without releasing gas and when mixed with hot bitumen, PET melts to form an oily coat over the aggregate and the mixture is laid on the road surface like a normal tar road. Plastic bottles and cups were collected from houses and schools. To facilitate mixing these PET materials with asphalt at the laboratory under its softening point, which is about 160 °C to 170 °C, the collected PET materials were chosen with maximum thickness of 60 micron. To provide appropriate plastic particles the plastic bottles and cups were cleaned then slashed into small pieces then crushed and sieved such that it passes through 3-5 mm sieve using shredding machine.

To test the performance of the modified asphalt mixture, another 15 Marshall cylindrical samples were prepared at 5.66% OBC and by considering different percentages of PWM including 0%, 5%, 10%, 15% and 20% by weight of OBC. The 5.66% asphalt content corresponds to 66 gm resulting in 1166 gm total weight of the sample. Table III summaries PWM percentages and weights used in the modified asphalt mixtures.

TABLE III
PLASTIC WASTE PERCENTAGES WEIGHTS

		OBC (%)		OBC Weight (gm)	
Sample No	PWM (%)	Asphalt	PWM	Asphalt	PWM
1, 2, 3	0	5.66	0	66.00	0
4, 5, 6	5	5.38	0.28	62.70	3.30
7, 8, 9	10	5.09	0.57	59.40	6.60
10, 11, 12	15	4.81	0.85	56.10	9.90
13, 14, 15	20	4.53	1.13	52.80	13.20

Fig. 2 shows the average value of the corrected stability, flow, density, AV in total mix, VFB and VMA obtained for the PWM asphalt mix.

Fig. 2 (a) shows that Marshall stability value increases with the increase in PWM content up to an optimum value then it decreases. Also, it shows that the maximum stability value of almost 1250 kg corresponds to 12.5% PWM content. This stability value in the PWM asphalt mix is 42.56% higher than that of the conventional asphalt mix. Fig. 2 (b) shows that the flow in the PWM asphalt mix was generally higher than that of the conventional asphalt mix. The highest flow value of 5.53 mm corresponds to a 20% PWM content. Fig. 2 (c) shows that the bulk density decreases with the increase in PWM content; this can be explained by the low density of the added plastic material. Also, it can be seen that the bulk density of the PWM is lower than that of the conventional asphalt mix. The maximum bulk density value of 2.121 corresponds to 5% PWM content. Fig. 2 (d) shows that the percent of AV in the PWM asphalt mix is generally lower than that of the conventional asphalt mix. Also, Fig. 2 (d) shows that the percent of AV increases as the plastic waste content increases. It reaches the highest value of 5.7% at 20% PWM content. The AV within the allowed range of specifications was found to be 4.8%. Fig. 2 (e) shows that VMA of the modified asphalt mixes are higher than that in the conventional asphalt mix. It can be seen that the VMA % of the modified asphalt mix increases as the PWM content increases, it reaches its highest value of 17.57% at PWM content of 20%. Fig. 2 (f) shows that VFB values increase as the PWM content increases.

Again, according to Jendia [22] the OBC for the PWM asphalt mix was found as the average of three values of PWM content including PWM content at the maximum stability, maximum bulk density and the PWM content of AV at the median of allowed range of specifications, in this case the PWM content that corresponds to the lowest value AV was taken since the allowed range was not included in the tested samples. The optimum PWM content by weight of OBC was found to be 7.43%.

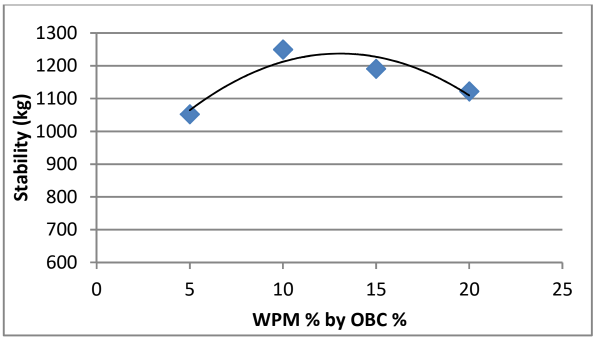

Fig. 2 (a) Stability vs. PWM Content

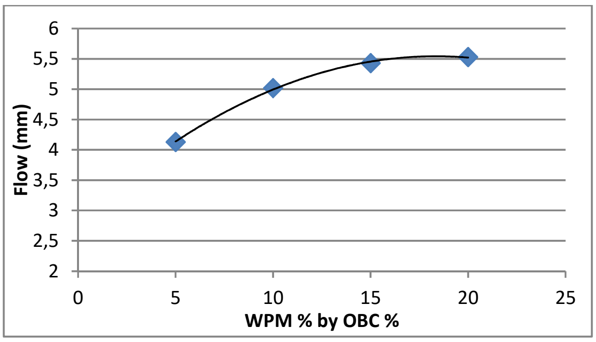

Fig. 2 (b) Flow vs. PWM Content

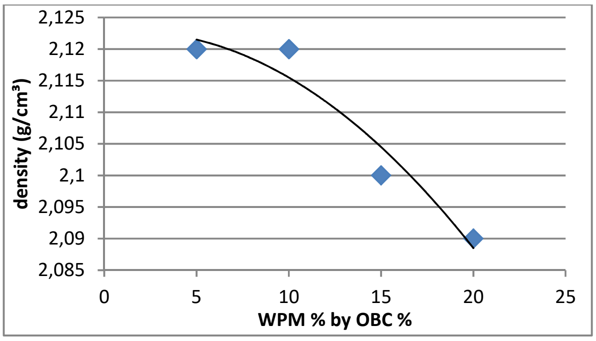

Fig. 2 (c) Asphalt Mix Bulk Density vs. PWM Content

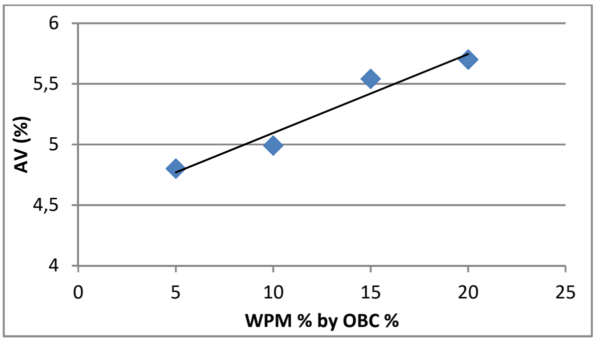

Fig. 2 (d) AV vs. PWM Content

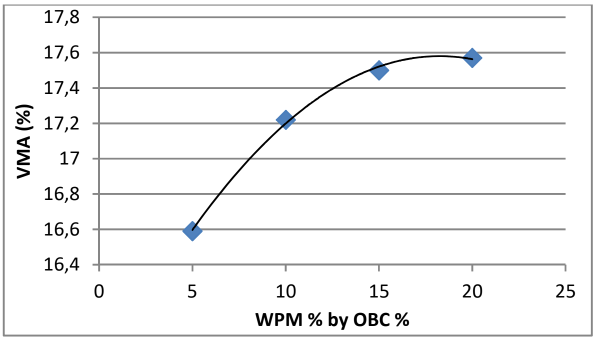

Fig. 2 (e) VMA vs. PWM Content

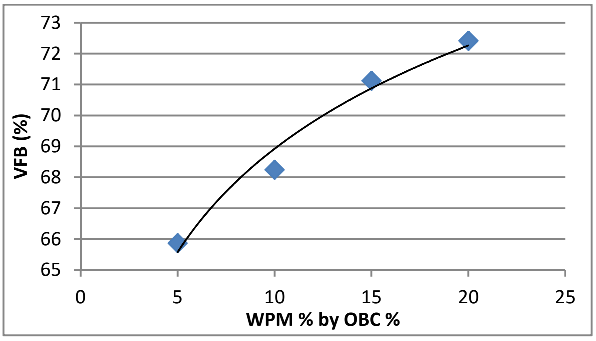

Fig. 2 (f) VFB vs. PWM Content

Fig. 2 Marshall Test Results for the PWM Asphalt Mix

C. *Effect of Plastic Waste on the Asphalt Mix IDT*

The IDT test was used to identify the tensile properties of asphalt mixtures. It is an indicator of the strength against fatigue cracking and permanent deformation of the AC pavements. It was carried out according to the procedure outlined in ASTM D 6931 [23]. 18 Marshall samples were prepared considering different percentages of PWM content including 0%, 5%, 7.43%, 10%, 15% and 20% by weight of OBC. A compressive load of 51 mm/minute was applied. The samples were kept in the Perspex water bath at the required temperature for a minimum time of half an hour before testing, and the same temperature was maintained during the test. This loading configuration developed fairly uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametric plane. This eventually caused the specimen to fail by splitting vertically. The IDT was calculated using (1) [23]:

$$\mathrm{IDT} = \frac{2*p}{\pi D t} \quad (1)$$

where IDT: Indirect Tensile Strength, KPa; P: Maximum Load, KN; D: specimen diameter, mm; t: Specimen height before testing, mm.

Table IV shows the average IDT results corresponding to different percentages of PWM content.

TABLE IV
IDT TEST RESULTS

Polymer (%)	0	5	7.43	10	15	20
Average IDT (kpa)	286.18	292.58	324.92	306.53	293.62	292.29
Percent Increased (%)		2.24	13.54	3.82	2.60	2.14

Table IV shows that by the addition of PWM, the IDT of asphalt mixtures increased significantly, it can be seen that by adding the optimum PWM content value of 7.43%, the IDT increased by 13.54% as compared to the conventional asphalt mixture. This will enhance the pavement resistance to fatigue cracking as well as to permanent deformation.

D. Comparison of the Conventional Asphalt Mix with the PWM Asphalt Mix

A comparison of the mechanical properties of the conventional asphalt mix and the PWM asphalt mix at the optimum PWM content of 7.43% by weight of OBC is shown in Table V.

TABLE V
COMPARISON OF CONVENTIONAL ASPHALT MIX WITH PWM ASPHALT MIX PROPERTIES

Property	Conventional 5.66 %OBC	7.43 % PWM by weight of OBC	Percent Change (%)
OBC	5.66 %	5.66 %	-
Stability (kg)	876.42	1249.41	+42.56
Flow (mm)	3.17	6.02	+89.91
Bulk Density (gm/cm³)	2.08	2.12	+1.92
AV %	4.53	4.99	+10.15
VMA %	17.66	16.84	-4.64
VFB %	67.38	71.12	+5.55
IDT (kpa)	286.18	324.92	+13.54

Table V shows that asphalt mix modified with 7.43% plastic waste by OBC % would significantly enhance stability by 42.56%, flow by 89.91%, and strength by 13.54%. This improvement can be explained by the enhanced adhesion developed between asphalt and plastic waste coated aggregates caused by the intermolecular bonding which improve asphalt mix strength. This would be reflected in the enhanced durability and stability of the asphalt mix which would lead to enhancing pavement resistance to fatigue cracking and permanent deformation. Also, Table V shows that the bulk density values for the two asphalt mixtures are approximately equal, the AV % and VFB % slightly increased in the PWM asphalt mix, and the VMA % decreased.

IV. SUMMARY

The main objective of this paper is to evaluate the use of plastic waste as a low cost asphalt binder modifier. PET materials such as plastic bottles and plastic cups were used. Plastic waste was collected from houses and schools. The collected PET materials were chosen with a maximum thickness of 60 micron. This would facilitate mixing them with asphalt at the laboratory under its softening point. Also, in order to provide appropriate plastic particles, the bottles and cups were cleaned then slashed into small pieces then crushed and sieved such that it passes through 3-5 mm sieve using shredding machine.

Marshall mix design method was used to compare the modified asphalt mix with the conventional asphalt mix. Marshall mix design procedure seeks to select the OBC to be added to a specific aggregate blend resulting in a mixture that satisfies the desired properties of strength and durability, so in order to evaluate the modified asphalt mixtures, the OBC for the conventional asphalt mix was identified, then different percentages of crushed plastic waste by weight of OBC were tested on the PWM asphalt mixtures. Marshall test results for the modified asphalt mixtures were analyzed to find the optimum PWM content. Finally, the static IDT was determined for all mixtures using the splitting test. It was found that PWM content of 7.43% by weight of OBC is recommended as the optimum PWM content needed for enhancing the performance of asphalt mixtures. Asphalt mix modified with 7.43% PWM by OBC % would significantly enhance stability by 42.56%, flow by 89.91% and strength by 13.54%. This improvement can be explained by the enhanced adhesion developed between asphalt and plastic waste coated aggregates caused by the intermolecular bonding which improves asphalt mix strength. This would be reflected in the enhanced durability and stability of the asphalt mix which would lead to enhancing pavement resistance to fatigue cracking and rutting or permanent deformation.

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