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Performance of Asphalt Concrete Pavement Reinforced with High-Density Polyethylene Plastic Waste

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Abstract: This research investigates the possibility of using high-density polyethylene (HDPE) plastic waste to improve the properties of asphalt concrete pavement. HDPE plastic waste contents of 1, 3, 5, and 7% by aggregate weight were used. HDPE plastic waste=stabilized asphalt concrete pavement (HDPE-ACP) was evaluated by performance testing for stability, indirect tensile strength, resilient modulus (MR), and indirect tensile fatigue (ITF). In addition, microstructure, pavement age, and CO_2 emissions savings analyses were conducted. The performance test results of the HDPE-ACP were better than those without HDPE plastic waste. The optimum HDPE plastic waste content was 5%, offering the maximum MR, ITF, and pavement age. Scanning electron microscope images showed that the excessive HDPE plastic waste content of 7% caused a surface rupture of the sample. Improvements in the pavement age of the HDPE-ACP samples were observed compared with the samples with no HDPE plastic waste. The highest pavement age of the HDPE-ACP sample was found at an HDPE plastic waste content of 5% by aggregate weight. The CO_2 emissions savings of the sample was 67.85 kg CO_2-e/m^3 at the optimum HDPE plastic waste content.

Keywords: HDPE plastic waste; asphalt concrete pavement; performance test; microstructure analysis; CO_2 emission

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1. Introduction

Transportation infrastructure, including roads, railways, ports, and airports, have played a significant role in economic growth and development [1]. The structure of roadways consists of four layers: surface layer, base, subbase, and subgrade. The surface layer can be classified as flexible or rigid pavement. Flexible pavement (e.g., asphalt concrete pavement) is widely used in many countries [2–4] because of its inexpensive materials, fast construction, and easy maintenance. Asphalt concrete pavement (ACP) is composed of aggregates and asphalt cement. The increase in traffic volume and truckloads has caused pavement failures, such as rutting [5] and fatigue cracking [6,7]. Therefore, the improvement of asphalt cement in terms of performance and carbon dioxide (CO_2) emissions is of interest to researchers.

Several researchers have investigated the improvement of asphalt cement properties with additives such as fly ash [8], polymer [9–14], and crumb rubber [15,16]. Al-Cardone et al. [17] investigated a plastomeric compound containing recycled plastic (polyethylene, PE and polypropylene, PP) modified asphalt concrete mixtures. The fatigue and rutting resistance of asphalt concrete mixtures were improved with the addition of recycled plastic. Diab et al. [18] studied the effects of different polymeric products on the performance of polymer-modified asphalt with 2% and 5% additives by the weight of asphalt binder. The 5% high-density polyethylene (HDPE) addition in the polymer-modified asphalt sample exhibited the maximum resilient modulus. Furthermore, the physical, mechanical, and structural properties of modified asphalt cement were reported by Sharma et al. [19]. The optimal HDPE and low-density polyethylene (LDPE) contents of asphalt cement were determined to be 3% and 5% by weight of asphalt cement, respectively. Excessive HDPE and LDPE contents used in their research resulted in less workability and stability in the modified asphalt cement.

Industry in Thailand produces 2.33 million tons of plastic per year, and plastic usage increases by 7–8% every year [20]. The extensive use of plastic has resulted in challenges with waste disposal management. Plastic waste can be recycled, combusted, and landfilled [21–24]. However, incineration emits large amounts of CO_2 into the atmosphere. Similarly, plastics in landfills contribute to environmental pollution because plastic waste does not decay, corrode, or dissolve [25]. Several researchers have evaluated the use of various plastic wastes in the field of asphalt concrete pavement, such as LDPE [26,27], HDPE [13,28], and PP [29]. The main chemical composition of plastic waste is similar to that of asphalt cement in which hydrocarbons (C–H) are prominent [13]. However, the properties of asphalt cement–plastic waste blend depend on the plastic waste concentrations and type [29]. Karmakar et al. [15] reported that HDPE plastic waste could be used to modify asphalt cement. However, an HDPE waste plastic content of more than 1 wt.% resulted in less compatibility in asphalt cement.

Although research on the use of HDPE plastic waste in asphalt concrete pavement applications is available, the performance, microstructure, pavement age, and CO_2 emissions savings of asphalt concrete pavement reinforced with HDPE plastic waste have yet to be analyzed. This research investigated the use of HDPE plastic waste to enhance the performance of asphalt concrete pavement. The performance of HDPE plastic waste stabilized pavement was tested for stability, indirect tensile strength (ITS), resilient modulus, and indirect tensile fatigue (ITF). The microstructural analysis via scanning electron microscopy (SEM), pavement age, and CO_2 emissions were also studied. This research shows that using HDPE plastic waste as an additive enhances the properties of asphalt concrete pavement, reducing environmental pollution and waste materials.

2. Materials and Methods

2.1. Materials

The aggregate materials of limestone were collected from the stone mill factory, Phu Pha Man District, Khon Kaen Province, Thailand. The particle size distribution of the aggregate materials is shown in Figure 1. The aggregate material samples were prepared according to the Department of Highways (DOH) specifications. The coarse aggregate had an average grain size D_{50} of 3.5 mm. Table 1 shows the aggregate properties. A bulk specific gravity of aggregate of 2.661 according to ASTM C127-15 [30] was used in this study.

Table 1. Properties of aggregate.

Properties	Aggregate
Bulk specific gravity	2.661
Apparent specific gravity	2.707
Effective specific gravity	2.643
Flakiness index (%)	42
Elongation index (%)	28
Asphalt Absorption (%)	0.26
Los Angeles Abrasion (%) Aggregate 3/4″	23.4
Soundness (% WT loss) Aggregate 3/4″	1.1
Soundness (% WT loss) Fine Aggregate	3.2

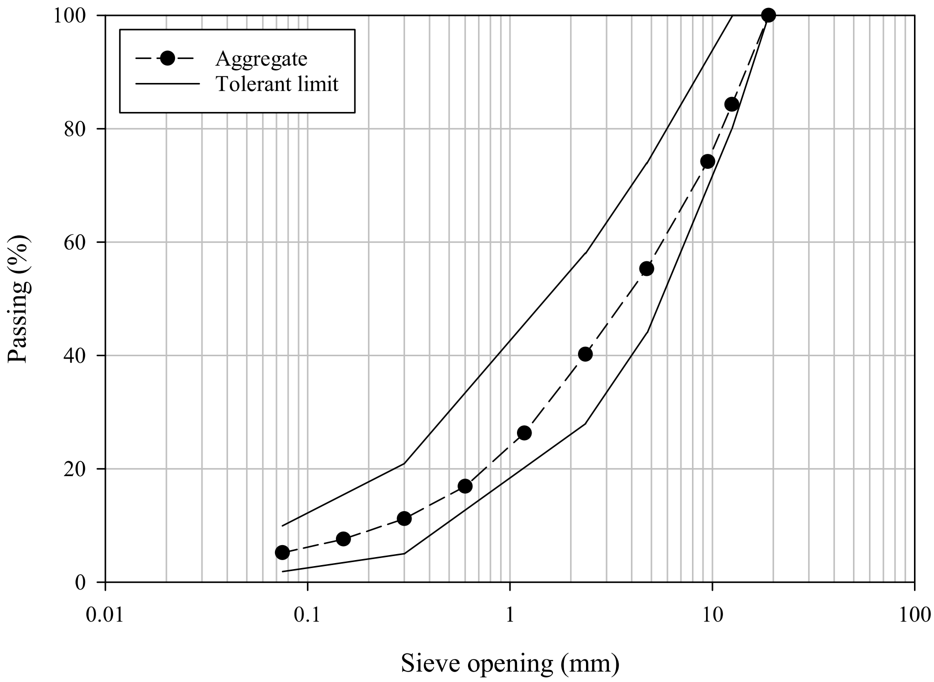

Figure 1. Grain size distribution curves of aggregate.

The asphalt cement (AC) used in this study was AC 60/70. The physical properties of AC followed Thai Industrial Standards (TIS 851/2561) and the DOH [31] and are indicated in Table 2.

Table 2. Physical properties of AC60/70.

Properties	Result	TIS 851/2561
Penetration at 25 °C	67	60–70
Softening point (°C)	48	45–55
Ductility	110	>100

The HDPE plastic waste in this study comprised waste plastic bottles obtained from the Rajamangala University of Technology Isan, Nakhon Ratchasima campus. HDPE plastic waste has a density of 0.91–0.94 g/cm^3 [12] and a melting point of 149 °C. This heating temperature was required so that the HDPE plastic waste could dissolve entirely in AC. The HDPE waste plastic bottles were first washed and dried, then crushed by a plastic crusher machine and passed through a No. 4 sieve. The HDPE plastic waste content was prepared for 1, 3, 5, and 7% by aggregate weight.

2.2. Sample Preparation and Testing

The Marshall mix design method following DOH specifications [31] was used to verify satisfactory voids in the asphalt concrete mixtures. The asphalt contents used in the design of the asphalt concrete mixtures were 4.0, 4.5, 5.0, 5.5, and 6.0% by aggregate weight. After obtaining the optimum aggregate and asphalt binder, the specimens were prepared with HDPE plastic waste contents of 0, 1, 3, 5, and 7% by aggregate weight.

First, the aggregates were heated to 160–170 °C, and the prescribed amount of HDPE plastic waste was mixed for 0.5–1 min. This is the so-called dry modification method (plastic is mixed directly with aggregates). The asphalt binder was then heated to 160 °C and added into the aggregate-HDPE plastic waste mixtures and mixed to achieve homogeneity. The aggregate-HDPE-asphalt binder mixtures were transferred to a steel mold with a diameter of 101.6 mm and height of 63.5 mm and compacted under 75 Marshall blows for each face. The specimens were then removed from the mold and cured at room temperature (27–30 °C) for 24 h.

The HDPE-ACP samples were evaluated by the stability test ASTM D1559-89 [32], ITS test according to ASTM D6931-17 [33], and the resilient modulus (MR) according to ASTM D4123-82 [34] and ASSHTO [35]. ITF test per BS-EN-12697-24 [36] of the HDPE-ACP samples were investigated by using a repeated controlled stress pulse to damage the specimen. The target test stress of 300 kPa and a temperature of 25°C were used. To ensure consistency, three specimens were created for a stability test, an ITS test, and an MR test at room temperature, 20 °C, and 35 °C, respectively, whereas the four samples were used for the ITF test [6].

Microstructural analyses via SEM of the specimens at 0, 5, and 7 wt.% HDPE plastic waste percentages were also performed. The SEM could also photograph chosen areas ranging in width from 1 cm to 5 microns for analysis in the scanning mode (magnification ranging from 20× to approximately 30,000×). Before the SEM examinations, small samples from the middle of each specimen were taken and coated with gold [37–39].

3. Results and Discussions

3.1. Performance Test Results

The physical properties of the asphalt concrete sample without HDPE plastic waste and the recommended properties for asphalt concrete mixtures by the DOH [31] are indicated in Table 3. Based on the Marshall mix design method, the asphalt binder was 5.0%, which resulted in a Marshall air void of 4.1%. This optimum aggregate and asphalt binder were used to prepare the HDPE-ACP samples with HDPE plastic waste contents of 0, 1, 3, 5, and 7% by aggregate weight.

Table 3. Physical properties of asphalt concrete.

Properties	Mixture	DH-S408/2532
Asphaltic content (%)	5.0	3–7
Marshall air void (%)	4.1	3–5
Marshall density (gm/mL)	2.385	-
Void in mineral aggregate (VMA) (%)	14.6	>14
Void filled with asphalt cement (%)	71.9	-
Marshall stability (kN)	9.21	8
Marshall flow (0.25 mm)	11	8–16
Stability/Flow ratio (kN/0.25 mm)	189	>160
Strength Index (%)	89.8	>75

Figure 2 shows the stability and flow values of the HDPE-ACP samples at the various HDPE plastic waste contents. The stability values increased as the HDPE plastic waste content increased. For example, the stability values of the samples were 9.21, 9.34, 9.91, 10.18, and 10.20 kN for HDPE plastic waste contents of 0, 1, 3, 5, and 7%, respectively. This was because the increase in a molecule of AC results from polymers in HDPE plastic [29]. On the other hand, the flow values of the samples decreased with the increase in HDPE plastic waste content up to 5% and then leveled. The increase in HDPE plastic waste contents caused the increase in viscosity and hardness [29]. Köfteci et al. [40] also showed that the level of hardening of modified asphalt binders was higher than that of pure bitumen because of the use of the high molecular weight polymer of HDPE [29].

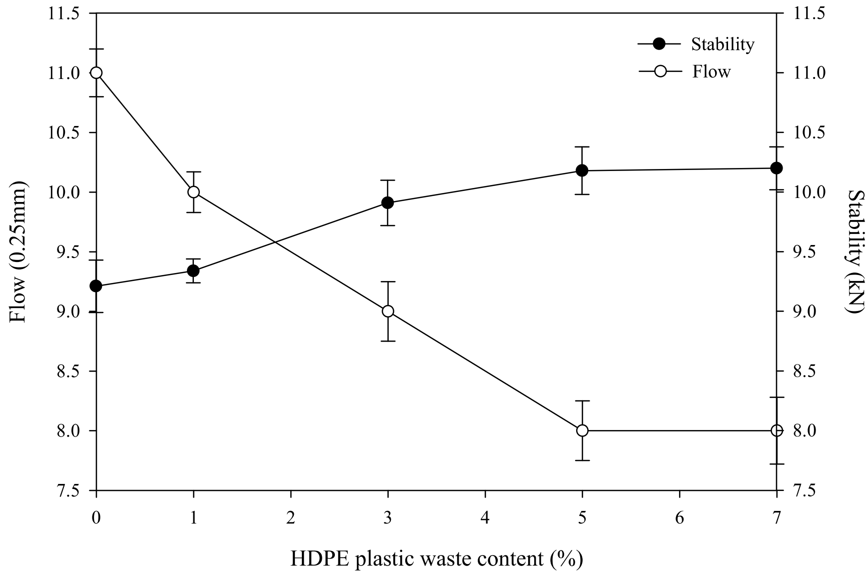

Figure 2. Stability and flow values of HDPE-ACP.

Figure 3 indicates the ITSs of the HDPE-ACP specimens. The HDPE plastic waste content affected the ITS significantly. The ITS of the samples increased with the HDPE plastic waste content. These values were 514, 725, 811, 1050, and 1100 kPa for HDPE plastic waste contents of 0, 1, 3, 5, and 7% by aggregate weight, respectively. The results were expected because HDPE plastic waste has been found to improve the properties of AC [11,12], which results in a polymer network in AC [8]. The ITSs of all exceeded the requirement for flexible pavement by the South Carolina Department of Transportation (SC DOT) (ITS > 448 kPa) by 15, 62, 81, 134, and 145% for HDPE plastic waste contents of 0, 1, 3, 5, and 7% by aggregate weight, respectively.

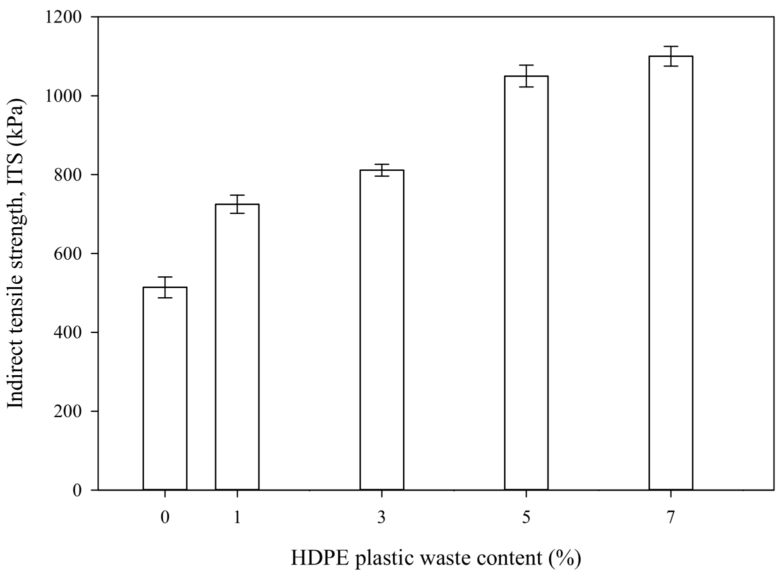

Figure 3. Indirect tensile strength of HDPE-ACP.

Figure 4 shows the MR of the HDPE-ACP specimens tested. The maximum MR of 3011 MPa was found in the HDPE-ACP specimen with an HDPE plastic waste content of 5% by aggregate weight, which was roughly 1.5 times more than asphalt concrete without HDPE plastic waste. The HDPE-ACP samples had higher elastic moduli. However, for the HDPE plastic waste content of 7% by aggregate weight, the MR of the sample was less because the excessive HDPE plastic waste content caused an increase of the polymer network in AC [19], resulting in less compatibility (phase separation) [28].

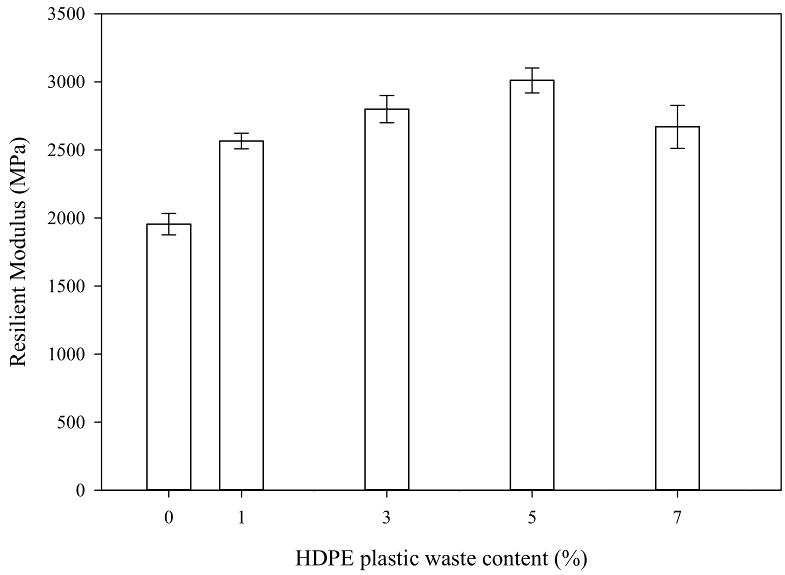

Figure 4. Resilient modulus of HDPE-ACP.

Figure 5 presents the fatigue life of the HDPE-ACP samples. To determine the number of pulses, an indirect tensile fatigue test was done in which the load was applied repeatedly until failure. The HDPE-ACP sample exhibited longer fatigue life (ITF) than the asphalt concrete without HDPE plastic waste. The longest fatigue life increased with HDPE plastic waste content up to 5% by aggregate weight and then dropped. Similar trends were also reported by Takaikaew [6], who concluded that fiber-reinforced asphalt mixtures exhibited a 36.9% higher fatigue life than the conventional mixtures. The pulse numbers indicating fatigue life were 987, 1268, 1329, 1462, and 931 for HDPE plastic waste content of 0, 1, 3, 5, and 7% by aggregate weight, respectively.

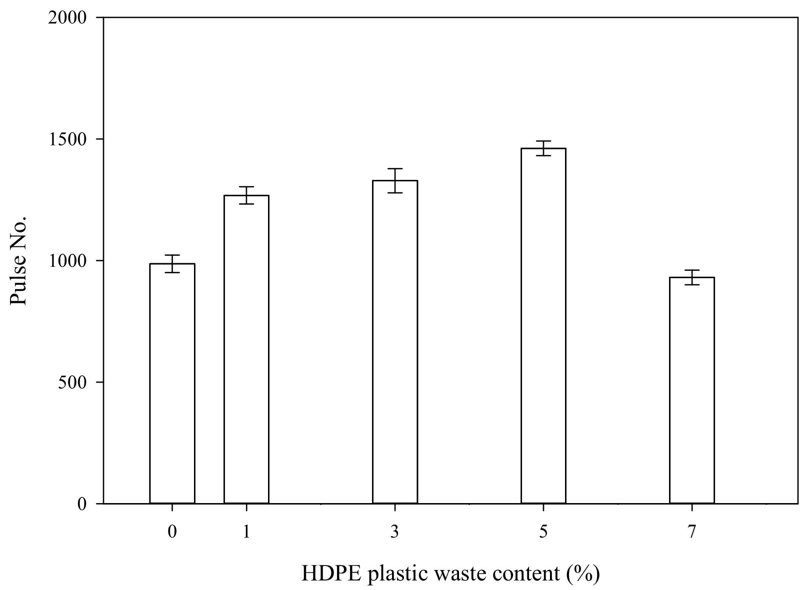

Figure 5. The fatigue life of HDPE-ACP.

3.2. Microstructure analysis

Figure 6 shows 1000×-magnified SEM images of HDPE-ACP samples with HDPE plastic waste contents of 0, 5, and 7%. The aggregates were filled and covered by the AC and HDPE plastic waste. For asphalt concrete without HDPE plastic waste (Figure 6a), uniform distribution and better compatibility were detected. At the optimum amount of HDPE plastic waste content of 5% by weight of aggregate (Figure 6b), a microcrack was detected on the concrete surface. The coexistence of aliphatic C–H of HDPE plastic waste and asphaltene of AC might have increased the elastic property significantly [15]. For the excessive HDPE plastic waste content of 7% by aggregate weight, a surface rupture was detected (Figure 6c). A similar result was reported by Sharma et al. [19], who concluded that the excessive HDPE content resulted in a ruptured surface and decrease in ductility of AC. Furthermore, the addition of high HDPE plastic waste content in the sample resulted in higher dosages of polymers, which led to a less compatible AC matrix [13].

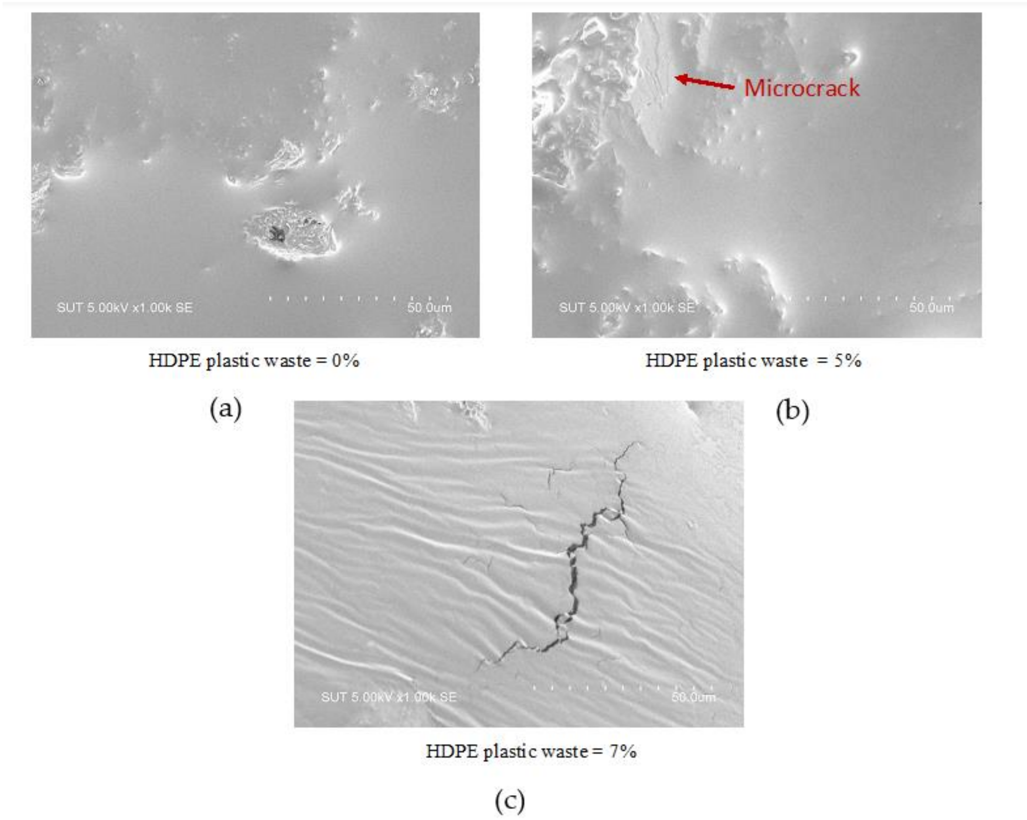

Figure 6. 1000×-magnified SEM images of HDPE-ACP at HDPE plastic waste: (**a**) 0%; (**b**) 5%; and (**c**) 7%.

3.3. Pavement Age

The international roughness index (IRI) is widely used for evaluation of pavement serviceability such as riding quality. Generally, IRI value increased as pavement age increased [41]. Previous research [42,43] reported that an IRI less than or equal to 2.7 m/km was acceptable to ride quality, and an IRI higher than 2.7 m/km was considered unacceptable. The pavement age was calculated by using Paterson's [4], Indian pavement deterioration [2], and Albuquerque and Núñez's models [3], which are presented by the following equations:

$$\mathrm{IRI} = [\mathrm{IRI}_0 + 725(1+\mathrm{SNC})^{-4.99} \times \mathrm{ESAL}] \times \mathrm{e}^{0.0153\mathrm{AGE}} \quad (1)$$

$$\mathrm{IRI} = [34856(\mathrm{CSAL}/\mathrm{SNCK}^5)]*\mathrm{EXP}(\mathrm{m}*\mathrm{PAGE}) + [7.43\mathrm{CR}] + [190.57\mathrm{PH}] + [22.34\mathrm{PT}] + [\mathrm{m}*\mathrm{RG}*\mathrm{t}] \quad (2)$$

$$\mathrm{IRI} = -173.4 + e^{(5.177+0.001*\mathrm{C}-0.002*\mathrm{S}+0.005*\mathrm{N})} \quad (3)$$

where IRI_0 is initial international roughness index, SNC is pavement modified structural number, ESAL is cumulative number of equivalent single-axle loads, AGE is age of the pavement since construction, rehabilitation, or reconstruction, CSAL is change in cumulative standard axles over time in years, SNCK is modified pavement strength, m is environmental factor, PAGE is pavement age, CR is percent change in cracked area, PH is percent change in pothole area, PT is percent change in patched area, RG is change in roughness over time in years, t is time interval, C is climate type, S is pavement SNC, and N is cumulative ESAL.

Equations (1)–(3) were used to predict pavement age of HDPE-ACP at the different HDPE plastic waste contents, as presented in Figure 7. All parameters defined by these were used in this study except the international roughness index (IRI) and modified structural number (SNC). An IRI of 2.7 m/km was used to calculate the pavement age. The SNCs were computed using the stiffness (asphalt concrete, base, and sub-base), thickness, and California bearing ratio (CBR) of the subgrade. Based on Figure 4, the MR values of asphalt concrete and the HDPE-ACP were used to compute SNC. This study applied thicknesses of asphalt concrete, base, and sub-base as 100, 150, and 200 mm, respectively. The CBR of the subgrade was assumed to be 4%.

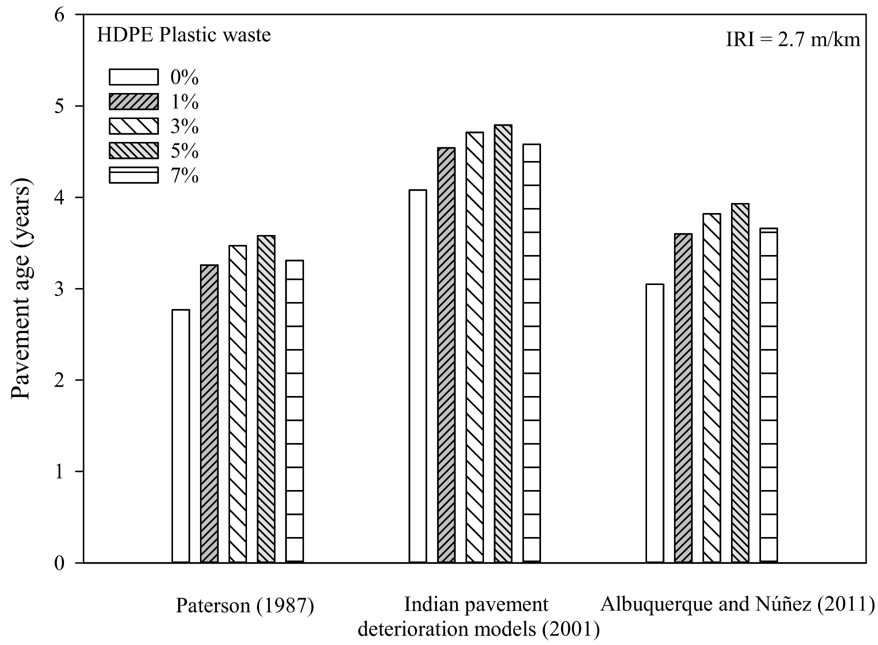

Figure 7. The pavement age of HDPE-ACP at different models.

The highest pavement age of the HDPE-ACP sample was found at an HDPE plastic waste content of 5% by aggregate weigh for all models, which was lower than 5 years. This finding agrees with the results reported by Albuquerque and Núñez [3]. In their study, the pavement age at IRI of 3.5 m/km was 10 years. Paterson's model yielded a lower pavement age than the Indian pavement deterioration and Albuquerque and Núñez's models. The pavement age of the HDPE-ACP sample with an HDPE plastic waste content of 5% by aggregate weight predicted by the Paterson's model was 25 and 9% shorter than those predicted by the Indian pavement deterioration and Albuquerque and Núñez's models, respectively. Based on Paterson's model, the pavement age increased by 18, 25, 29, and 20% for HDPE plastic waste contents of 1, 3, 5, and 7% by aggregate weight, respectively.

3.4. CO_2 Emissions Savings

Figure 8 indicates the CO_2 emissions (kg CO_2-e/m^3) savings of the HDPE-ACP samples with HDPE plastic waste contents of 1, 3, 5, and 7% by aggregate weight. The emission factors of HDPE plastic waste are shown in Table 4 [44,45]. The emission factors of incineration of plastic (0.569 kg CO_2-e/ton) is twice that of the landfill disposal of plastic (0.271 kg CO_2-e/ton). Compared to the incineration of plastic, the CO_2 emission savings of HDPE-ACP were 13.57, 40.71, 67.85, and 94.99 kg CO_2-e/m^3 for HDPE plastic waste contents of 1, 3, 5, and 7% by aggregate weight, respectively.

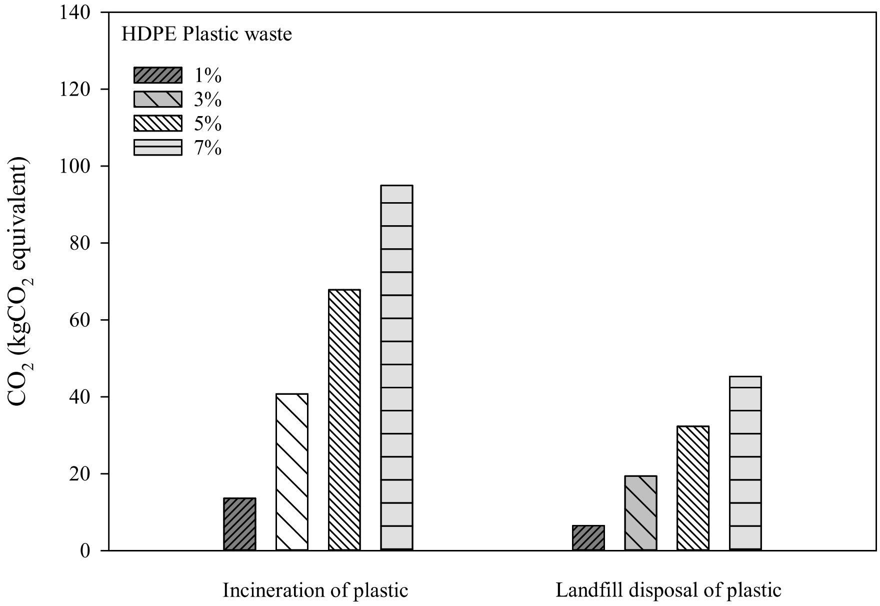

Figure 8. The emission CO_2-e (kg CO_2-e/m^3) savings of HDPE-ACP.

Table 4. The emission factor of HDPE plastic waste [44,45].

Methods	Emission Factor (kg CO_2-e/kg)
Incineration of plastic	0.569
Landfill disposal of plastic	0.271

4. Conclusions

This research studies the use of HDPE plastic waste to improve asphalt concrete pavement performance. The following conclusions can be drawn:

1. The stability and ITS of the HDPE-ACP samples increased with HDPE plastic waste content because of the increase of the molecular and polymer network in the AC. On the other hand, the flow values of the sample decreased with the increase in HDPE plastic waste content up to 5 wt.% and then leveled. The reduction of flow values resulted from the increasing strength of the samples.
2. The maximum MR and fatigue life values of the HDPE-ACP samples were with an HDPE plastic waste content of 5% by aggregate weight because of the higher modulus. However, for the HDPE plastic waste content of 7 wt.%, the MR and fatigue life values of the HDPE-ACP sample decreased because the excessive HDPE plastic waste content increased the polymer network, resulting in less compatibility in the AC.
3. SEM images show that the aggregates were filled and covered by the AC and HDPE plastic waste. The excessive HDPE plastic waste content of 7 wt.% cause a surface rupture of the sample. The higher dosages of polymers in the sample led to a less compatible AC matrix.
4. Improvements in the pavement age of the HDPE-ACP samples were observed compared with the samples with no HDPE plastic waste. The highest pavement age of the HDPE-ACP sample was found at an HDPE plastic waste content of 5% by aggregate weigh.
5. Based on the emission factor of incineration of plastic, the CO_2 emissions savings of the HDPE-ACP were 13.57, 40.71, 67.85, and 94.99 kg CO_2-e/m^3 for HDPE plastic waste contents of 1, 3, 5, and 7% by aggregate weight, respectively. Future research

should focus on the impact of potential drainage and discharge of microplastics on the built environment of asphalt concrete reinforced with HDPE plastic waste.

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