Technical Paper

ISSN 1996-6814 Int. J. Pavement Res. Technol. 6(4):319-326

Using M-E PDG to Study the Effectiveness of Electronic Waste Materials Modification on Asphalt Pavements Design Thickness

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Abstract: The objective of this study was to use the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to investigate the effectiveness of electronic waste (e-waste) modification on the minimum design thickness of asphalt pavements. Common e-waste plastic powders, acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS), were used to modify Hot Mix Asphalt (HMA) mixtures in this study. The HMA modifiers include e-waste plastics intended for end user applications along with chemically treated e-waste plastics. Chemical treatment of e-waste plastics involved using free radical initiators on e-waste plastics in an attempt to improve asphalt binder and plastic bonding capabilities within the mixture. The percentage of ABS and HIPS blended with asphalt mixtures was 2.5% and 5% by weight of binder. In this study, multiple design trial runs of nine different mixtures (including the control mixture) were conducted using the M-E PDG software version 1.1. From the M-E PDG results analysis, it was concluded that in general using e-waste materials as modifiers for asphalt mixtures would decrease the design thickness of the asphalt pavements. The design thickness of treated acrylonitrile butadiene styrene (T-ABS) with percentage of 2.5 by weight of asphalt binder resulted in the smallest pavement thickness among all studied mixtures. This methodology would help evaluate various sustainable materials within asphalt mixtures from the perspective of the pavement designer improving the decision making process constructing more economical pavement sections.

DOI:10.6135/ijprt.org.tw/2013.6(4).319

***Key words**: Electronic Waste Materials; M-E PDG; Pavement Thickness.*

Introduction

E-waste materials are materials which contain electronic components and have reached the end of their usable life. Examples of products which are considered to be e-waste include: cell phones, computers, fax machines, and printers. E-waste is becoming increasingly difficult to manage within plastic and recycling industries. Due to increasing legislation [1, 2], e-waste disposal options have diminished and there has been an increasing focus on the impact that e-waste will place upon the environment. The researchers have previously investigated the impact and performance of e-waste plastic modified asphalt pavement materials [3, 4]. E-waste plastics were previously used to modify asphalt pavement materials includes common e-waste plastics such as: acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS).

Plastics are used as modifiers within asphalt binder in an attempt to improve the high and low temperature properties for asphalt mixtures. Previously, Colbert and You [4] investigated the performance of ABS and HIPS powders blended into virgin asphalt binders. ABS and HIPS plastics were reduced to powders to obtain homogeneity of the modified asphalt binder for quality assurance of asphalt binder performance. The result of this investigation showed a reduction in rutting susceptibility and increase in viscosity of the ABS and HIPS-modified binders compared with the control binder

The primary objective of this study is to extend the authors previous work on e-waste modified asphalt pavement materials and investigate the effect which e-waste has on asphalt pavement performance the using mechanistic empirical design. That would be an effective way to evaluate the asphalt mixtures since the pavement designers may have concerns about newly used modifiers. However, the recently introduced M-E PDG and associated computer software provided a state-of-practice pavement design methodology. M-E PDG methodology is based on pavement responses computed using detailed traffic loading, material properties, and environmental data. The responses are used to predict incremental damage over time.

Objective

The main objective of this investigation is to determine the improvement in performance for e-waste modified asphalt pavement mixtures from design standpoint of view. These mixtures include e-waste plastics intended for end use applications and chemically treated e-waste plastics. Chemical treatment of e-waste plastics involves using free radical initiators on e-waste plastic to modify asphalt mixture, referred hereafter as treated e-waste modified asphalt mixtures, versus conventional HMA mixtures.

Materials

Common bulk e-waste plastics, ABS and HIPS were acquired by the authors. These waste plastics were reduced in size with 100 percent of the material passing the #50 (300 μm) sieve for ABS plastics and 100 percent of HIPS plastics passing the #16 (600 μm). After the bulk e-waste plastics were reduced, the e-waste plastics were coated and mixed with cumene hydroperoxide (0.02% by weight of e-waste plastic powder). Fig. 1 shows the various sizes of ABS e-waste

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Note: Submitted January 21, 2013; Revised June 24, 2013; Accepted June 25, 2013.

A B C

Fig. 1. ABS Electronic Waste Particle Sizes Used for Asphalt Binders and Mixtures A) ABS Particles B) Bulk ABS Particles and Chips C) ABS Powder for Binders and Mixtures.

Table 1. Properties of Control Binder (PG 58-28)

Binder	Property	Value
Original Binder	Viscosity, Pa-s (135℃)	0.308
	G*/sin(δ), kPa (58°C)	1.86
Short Term Aged Binder	G*/sin(δ), kPa (58°C)	3.08
Long Term Aged Binder	G*.sin(δ), kPa (19°C)	1956
	Stiffness (60), MPa (-18℃)	226
	m-value (60) (-18℃)	0.323

Note: G*, complex modulus; δ, phase angle; m-value, rate of change of stiffness with time at 60 sec. of loading.

particles used for asphalt mixture and binders.

The percentage of ABS and HIPS blended within the asphalt mixtures was 2.5% and 5% by weight of binder. The coated e-waste plastics powders were blended and melted into the control asphalt binder (PG 58-28). The properties of the control binder are shown in Table 1.

Cumene hydroperoxide was used as the free radical initiator to treat the e-waste plastics before using them as modifier to the control PG 58-28 binder. The hydro peroxide was designed to modify the molecular structure of the ABS and HIPS plastics to allow for facilitated bonding with asphalt binders [5]. For this investigation, a high shear mixer was used to mix the asphalt and powder together for one hour at a speed of 5000 rpm. The treated e-waste asphalt binders were then mixed for approximately one hour at 3000 rpm. Detailed description of all materials and preparation of modified binders can be found elsewhere [6]. The control and modified e-waste asphalt binders used for this investigation included: 2.5% ABS modified asphalt binder (ABS (2.5%)), 5% ABS modified asphalt binder(ABS (5%)), treated 2.5% ABS modified asphalt binder (T-ABS (2.5%)), treated 5% ABS modified asphalt binder (T-ABS (5%)), 2.5% HIPS modified asphalt binder (HIPS (2.5%)), 5% HIPS modified asphalt binder (HIPS (5%)), treated 2.5% HIPS modified asphalt binder (T-HIPS (2.5%)), treated 5% HIPS modified asphalt binder (T-HIPS (5%)), and a control asphalt binder.

Mixture Preparation

Aggregates with a nominal maximum aggregate size of ½" (12.5 mm) sieve were obtained from Hancock, MI. The designed traffic level for this gradation is an E3 mixture which is designed to withstand traffic levels greater than 1 million ESAL (Equivalent Single Axel Loads) and lower than 3 million according to Michigan Department of Transportation Specifications. The optimal design asphalt binder content for the asphalt mixtures is 5.7% by weight of mixture. Asphalt mixture performance was tested on the asphalt mixtures containing the control asphalt binder along with mixtures containing 2.5 and 5% ABS and HIPS treated and untreated modified asphalt binders. The asphalt mixtures were compacted to 86 gyrations with a targeted 4% air voids.

Experimental Testing

Dynamic Shear Rheometer (DSR) and dynamic modulus (E*) tests are used to obtain the material properties for the M-E PDG design procedures.

Dynamic Shear Rheometer (DSR) Test

The DSR measures rheological properties of asphalt binder rather than empirical properties such as penetration values or softening point. Measurements can be performed at various temperatures, strain and stress levels, and frequencies. The DSR test was performed on the Rolling Thin Film Oven (RTFO) aged binders. The RTFO asphalt binders were produced according to AASHTO T240 [7]. Procedures for the DSR followed the AASHTO 315 specification standard [8]. Complex modulus (G*) and phase angle (δ) at a frequency of 1.59 Hz (10 rad/sec) and temperatures of 46, 52 and 58oC were binders input temperatures for M-E PDG trial runs. Complex modulus (G*) and phase angle (δ) are the performance measurements expected to determine viscoelastic behavior for the asphalt binders from the DSR test. G* and δ are used as input parameters for the M-E PDG design procedures to characterize the asphalt binders. The DSR results of RTFO aged control and e-waste modified binders are presented in Figs. 2 through 5. Table 2 below shows the true grade of the modified asphalt binder materials. Due to the limited amount of the free radical initiator, the true grade of 2.5% treated e-waste modified binders has not been studied.

In all cases adding electronic waste powders to the control asphalt binder slightly decreases the low temperature grade from the control binder. All e-waste modified binders except for the treated HIPS 5% binder have a three degree reduction in low temperature PG from -31 to -28 Degree Centigrade. In all cases except for the 2.5% HIPS binder the high temperature is increased by one grade from PG 58 to PG 64 except for the 2.5% HIPS binder which showed no increase in PG grade. The treated HIPS 5% binder increased by four grades to a PG 88.

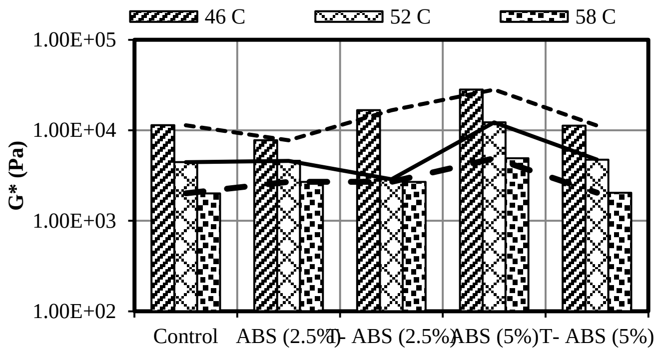

Fig. 2. Logarithmic Plot of Complex Modulus Values for Control and ABS Modified Binders Under Various Temperatures in Degree Centigrade.

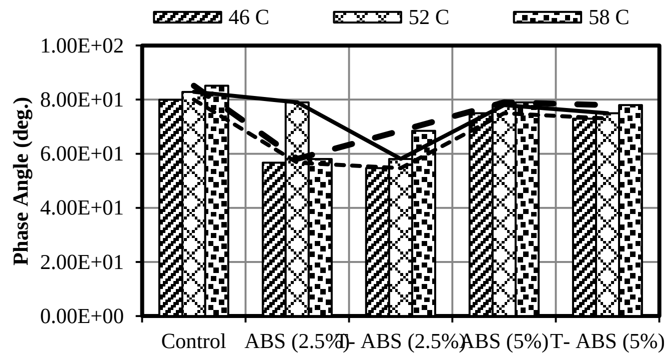

Fig. 3. Phase Angle for Control and ABS Modified Binders under Various Temperatures in Degree Centigrade.

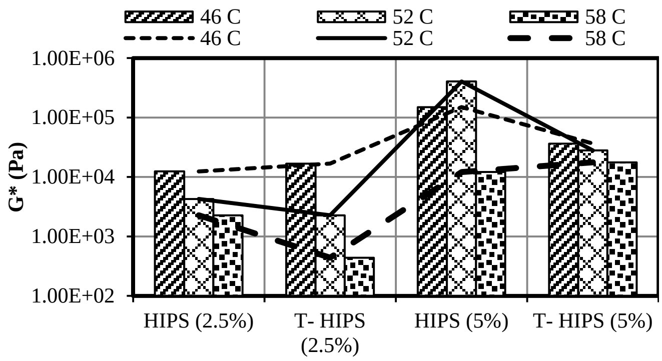

Fig. 4. Logarithmic Plot of Complex Modulus Values for HIPS Modified Binders.

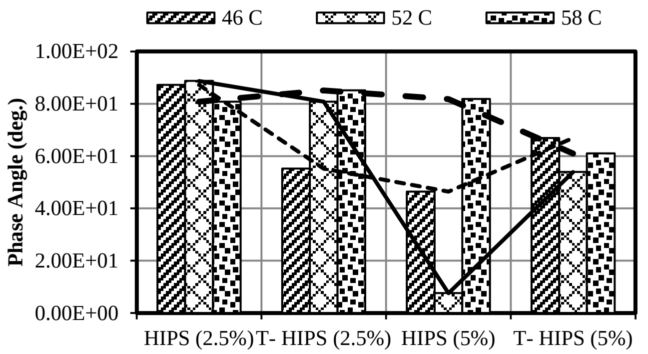

Fig. 5. Phase Angle for HIPS Modified Binders under Various Temperatures in Degree Centigrade.

Table 2. Electronic Waste Modified Binder Continuous or True Performance Grade.

Asphalt Binder Specimen	True Performance Grade
Control	PG 58-31
ABS (2.5%)	PG 64-28
HIPS (2.5%)	PG 58-28
ABS (5%)	PG 64-28
T- ABS (5%)	PG 64-28
HIPS (5%)	PG 64-28
T-HIPS (5%)	PG 88-25

Dynamic Modulus (E*) Test

E* is a crucial parameter for determining the viscoelastic behavior of asphalt pavement materials. It serves as a simple performance test and a key input for the M-E PDG. The E* test is conducted under sinusoidal loading conditions following AASHTO TP 62 specifications [9]. The tests were completed on the control and e-waste modified asphalt mixtures at -10, 4, 21.3 and 39.2^{o}C and at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. In order to have a better comparison between different mixtures throughout all the temperatures and frequencies, sigmoidal master curves were constructed at reference temperature of 21.3˚C. The master curves for control, ABS and HIPS modified mixtures are shown in Figs. 6 and 7. From Fig. 6 it can be seen that T-ABS (2.5%) shows highest E* values at low frequencies or high temperatures. Amongst all ABS modified mixtures, ABS (5%) showed lower E* values. It can also be seen that treating ABS material increases E* of the mixtures. It is quite clear from Fig. 7 that HIPS (5%) showed the highest E* values. Treating HIPS (5%) decreases the E* values of the mixture. T-HIPS (5%) showed lower E* at low frequencies or high temperatures. Control mixture results are very close to HIPS (2.5%) modified mixture.

M-E PDG Methodology

A three layered flexible pavement structure was considered in the M-E PDG procedure to study the effectiveness of different e-waste modified mixtures on asphalt layer thickness. The pavement materials considered in this study are divided into three major groups: asphalt layer, unbound granular aggregates, and subgrade. A 381 mm (15 in) crushed gravel subbase course separated the asphalt layer and the subgrade. The pavement rested on an A-3 classified subgrade soil. Major material input parameters were fixed throughout all design trial runs. The fixed input parameters were assigned constant values and were not changed at any time during these analyses (see Table 3). Only G*, δ and E* input values were varied according to the mixture type to study their particular effect on the performance. A nominal 90% design reliability was suggested throughout the entire study. A new climate data file for Houghton, Michigan, was generated to determine the standard input values for conducting the analysis. The sensitivity analysis technique was employed to investigate the effect of different material inputs on the asphalt layer design thickness. International Roughness Index (IRI), longitudinal cracking, alligator cracking,

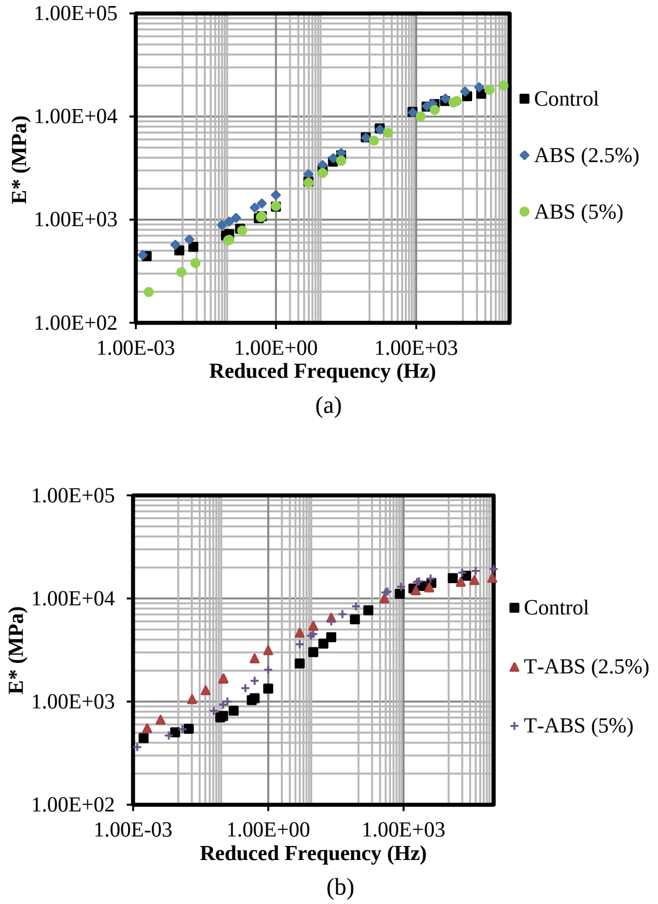

Fig. 6. Master Curves for Control and ABS Modified Mixtures

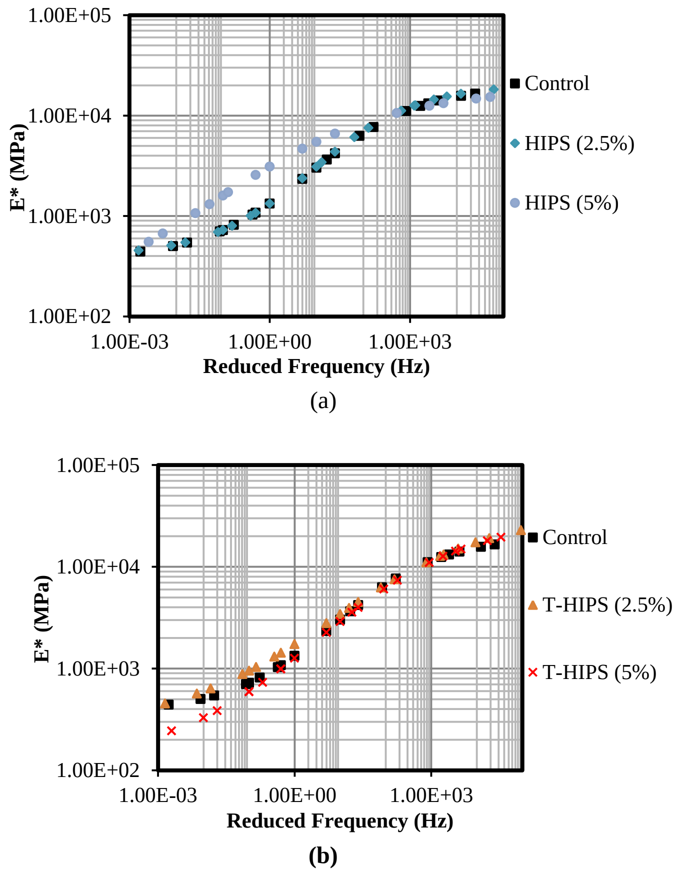

Fig. 7. Master Curves for Control and HIPS Modified Mixtures.

Table 3. Fixed Inputs for M-E PDG Analysis.

Input	Value
Design Life in (years)	20
Initial IRI in (m/km)	1
Terminal IRI in (m/km)	2.72
AC Longitudinal Cracking in (m/km)	378
AC Alligator Cracking in (%)	25
AC Thermal Fracture in (m/km)	190
Chemically Stabilized Layer (Fatigue Fracture %)	25
Permanent Deformation – total in (mm)	19
Permanent Deformation – AC Only in (mm)	6
Average Annual Daily Truck Traffic (AADTT) in (vpd)	1500
Number of Lanes in Design Direction	2
% of Trucks in Design Lane	50
% Trucks in Design Direction	50
Mean Wheel Location in (cm)	47
Operational Speed in (km/h)	100
Traffic Wander Standard Deviation in (cm)	25
Design Lane Width in (m)	3.65
Average Axle Width in (m)	2.6
Tire Pressure – single and Dual Tire in (kPa)	827/827
Dual tire spacing in (cm)	30
Axle Spacing – tandem, Tridem, Quad Axle in (cm)	131/125/125
Average Axle Spacing in (m)	3.65/4.57/5.49
% of Trucks-short, Medium, Long	33/33/34

Subbase Thickness in (mm)	381
Initial Volumetric Properties: Vbe/ Va/ VMA in (%)	11.6/4/18.6
Poisson's Ratio : Parameter a, Parameter b	-1.63/3.84e-006
Thermal Conductivity in (Calories/s×cm×℃)	0.00277
Heat Capacity in (Calorie/gram×℃)	0.23
Type of Subgrade Material	A-3
Type of Subbase Material	A-1-a
Subbase Material Resilient Modulus in (kPa)	275790.29
Subgrade Material Resilient Modulus in (kPa)	241316.5
Aggregate Coefficient of Thermal Contraction (per ℃)	0.162 e–6

HMA layer rutting and total pavement rutting were the distress' (criteria) models used to select the HMA layer thickness.

Sensitivity Analysis

The sensitivity study of the mechanistic-empirical NCHRP 1-37A methodology provided useful and relevant insights into performance prediction sensitivity to input parameters. Multiple design trial runs were performed in the M-E PDG to study the sensitivity of asphalt layer thickness to each material input. The philosophy of choosing asphalt layer thickness in this parametric study comes from the evidence that asphalt concrete thickness has a much more significant impact on performance prediction. Therefore, in the M-E PDG, the design process is dominated by the asphalt concrete layer [10]. Baus and Stires [11] performed a sensitivity analysis to implement the M-E PDG and indicated that layer thickness and |E*| properties were the most significant properties. Using a mechanistic-empirical design method, the large granular base layer thickness did not allow for much reduction in the asphalt layer thickness to meet the same performance criterion. The structural contribution of asphalt layer thickness analysis in the M-E PDG is a major contributing factor of the multilayer linear elastic theory analysis [12]. Evidently, when the base layer thickness is increased it is expected that the overall strength of the pavement will increase and performance will improve. Different trend with increasing base layer thickness may be a consequence of the simplifications implicit in linear elastic modeling of pavement materials [10]. It is well known that the M-E PDG does not yield a design thickness as output for designers. Asphalt layer thickness was obtained through the iterative processes in which predicted performance is compared against the design criteria for the multiple predicted distresses until all design criteria are satisfied to the specified reliability level. If any of the criteria have not been met, this deficiency can be remedied either by altering the materials used, the layering of materials, layer thickness, or other design features. However, for this sensitivity study only HMA layer thickness was investigated. A 12.7 mm (0.5 in) was considered as the maximum difference in HMA layer thickness between two consequential iterative processes (m and n) (i.e K_n - $K_m \leq 0.50$ (in), where K, layer's thickness) to select the minimum design thickness (K_n) (see Fig. 8).

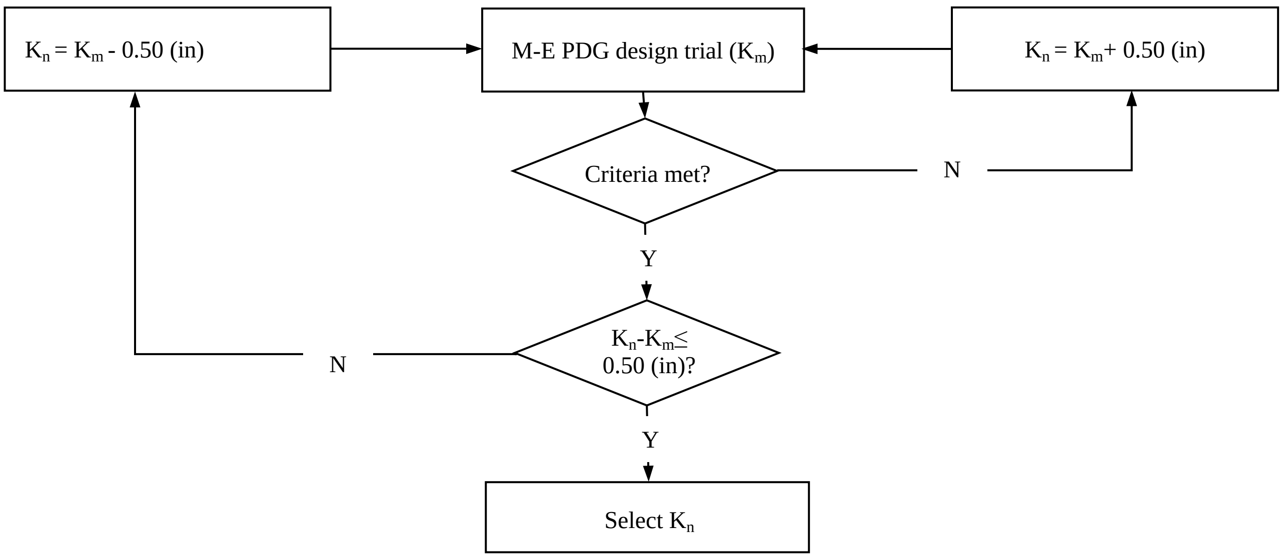

Fig. 8. Flowchart Explains the Iterative Process to Select Minimum Design Thickness of HMA Layer.

Discussion of Design Results

To characterize pavement behavior, each material type has a specific list of inputs to the M-E PDG. The effectiveness of each material type on decreasing the design thickness is a good indicator to the economic benefits. Multiple M-E PDG design trial runs with varying the asphalt layer thickness for each mix were performed to select the Kn based on the methodology shown in Fig. 8.

Alligator cracking, longitudinal cracking, HMA layer and total pavement rutting, and IRI, were the distress' (criteria) models studied to select the K_n for each mix. Each of the aforementioned distresses is assigned a specific value as seen in Table 3 that is not to be exceeded at the end of the pavement design life. If any of the predicted distresses exceed the limit value at the end of the design life (at the reliability level assigned), then the design has failed and a different input strategy has to be followed in next trial run. Thus, the asphalt layer thickness is used as the main variable so that a passing design can be achieved. Figs. 9 through 13 show the sensitivity of different distresses to HMA layer thickness during a 20 year period design for a selected mix.

From Fig. 9 it can be seen that the decrease of asphalt layer to 63.5 mm sharply decreased the percent alligator cracking. The alligator cracking is more sensitive to HMA layer thickness and subgrade support than HMA layer properties. While from Figs. 10 through 13, it can be seen that the longitudinal cracking, rutting, and IRI increased with the decrease of the asphalt layer thickness. Based on the design criteria, the K_n for each mix was calculated and plotted in Fig. 14. From this figure it can be seen that generally the modification of asphalt mixtures with e-waste materials could be an effective way to reduce the design thickness of asphalt pavements. It can also be seen that the minimum design thickness of asphalt mixtures modified with treated acrylonitrile butadiene styrene (T-ABS) with percentage of 2.5 by weight of asphalt binder was the smallest thickness (economic thickness) amongst all the studied mixtures. It can also be seen that treating the e-waste materials helped with constructing the asphalt layer with smaller thickness. The increase of the e-waste material percentage increases the asphalt layer thickness. Generally, it can also be seen that the ABS modified mixtures performed better than HIPS modified mixtures.

Conclusions

The objective of this study was to use the M-E PDG to investigate the effectiveness of e-waste modification on the HMA layer's design thickness. Based on the analysis of the results obtained in this study, following are the concluding remarks:

1. Generally, the e-waste materials can be used to decrease the HMA layer's design thickness.
2. The design thickness of T-ABS modified mixtures with percentage of 2.5 by weight of asphalt binder resulted in the smallest design thickness among the all studied mixtures.
3. As the e-waste material percentage increases, the HMA layer thickness increases.
4. Generally, ABS modified pavements perform better than HIPS modified pavements.
5. Treating the e-waste materials help with constructing the asphalt layer with smaller thickness.
6. The proposed procedure can be used as an effective way to evaluate different asphalt mixtures from the design point of view.

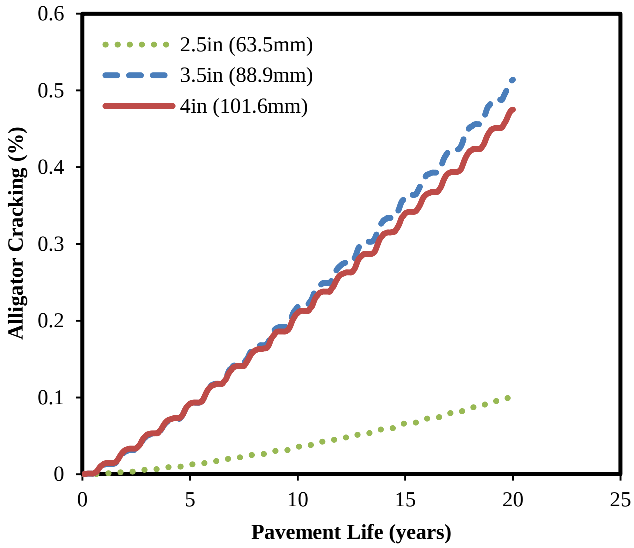

Fig. 9. Effect of HMA Layer Thickness on Alligator Cracking.

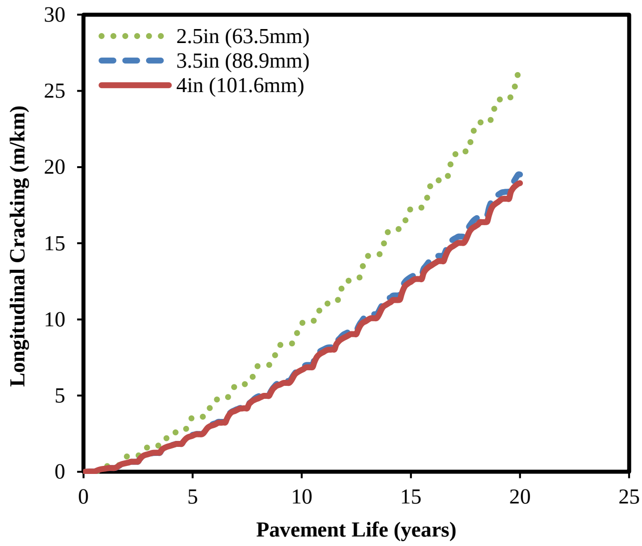

Fig. 10. Effect of HMA Layer Thickness on Longitudinal Cracking.

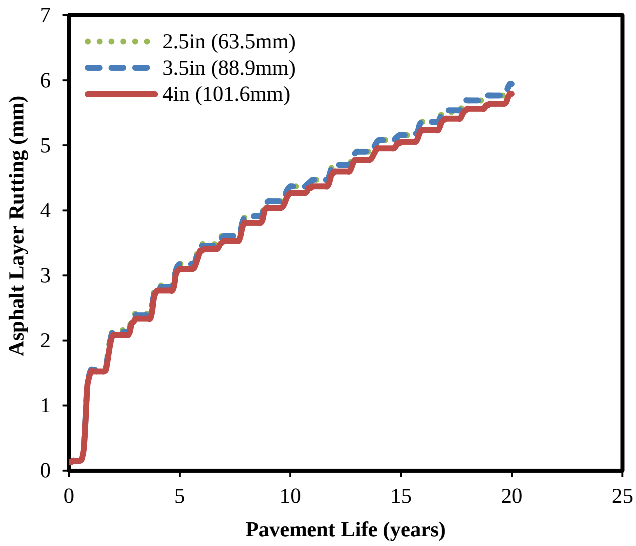

Fig. 11. Effect of HMA Layer Thickness on Rutting of HMA Layer.

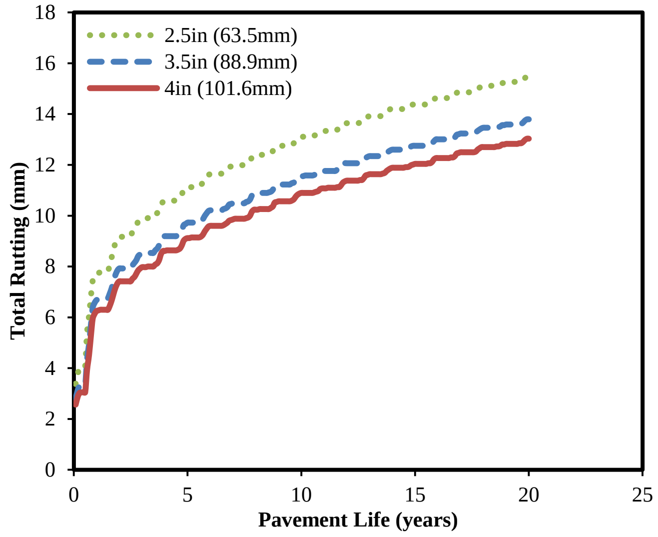

Fig. 12. Effect of HMA Layer Thickness on Total Rutting.

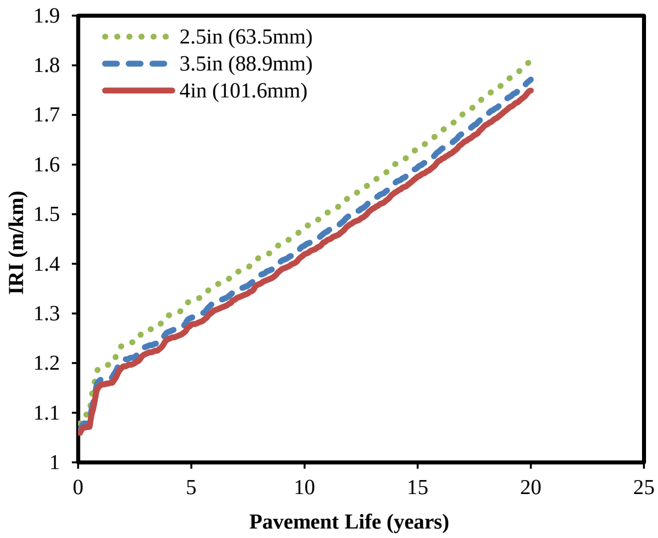

Fig. 13. Effect of HMA Layer Thickness on IRI.

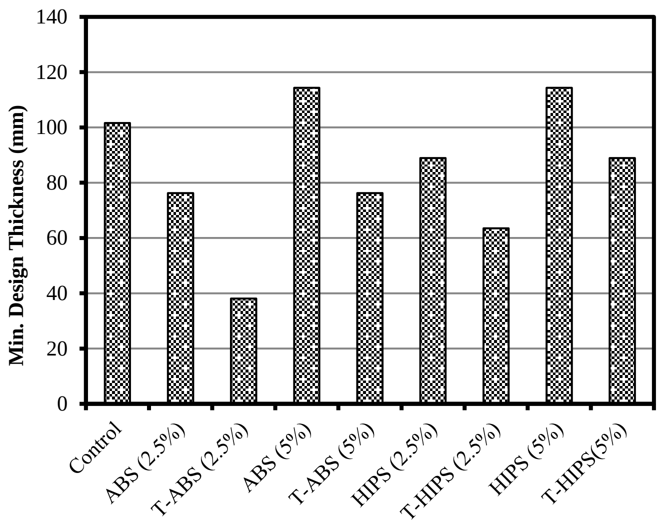

Fig. 14. Minimum HMA Layer's Design Thickness for Different Mixtures.

Future Work

The current work addressed the effectiveness of e-waste materials modification on asphalt pavements' design thickness in cold regions only (Houghton, MI). This methodology is applicable to hot regions such as Arizona and a study of the applicability of e-waste modification for different climates is underway.

Acknowledgements

This material is based in part upon work supported by U.S. National Science Foundation under grant 0936726 and the Michigan Space Grant Consortium. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author's and do not necessarily reflect the views of the National Science Foundation nor the Michigan Space Grant Consortium. The first and second researchers also acknowledge the financial support as research assistantship from the two sponsors and supporting industries.

Reference

1. The State of Conneticut (2007). Chapter 446n (Including Public Act 07-189 and 08-35) Covered Electronic Devices. in Public Act 08-35, The State of Conneticut, Editor 2007: Hartford, Conneticut. p. 9.
2. The State of Illinois (2008). Electronic Products Recycling and Reuse Act, in Public Act 095-0959, The State of Illinois, Editor 2008, The State of Illinois,: Springfield, Il. p. 50.
3. Colbert, B., Mills-Beale, J., and You, Z. (2011). Low Temperature Cracking Potential of Aged Asphalts Using Simulated Aging Techniques. in ICCTP 2011: Towards Sustainable Transportation Systems - Proceedings of the 11th International Conference of Chinese Transportation Professionals, ASCE.
4. Colbert, B. and You, Z. (2012). Properties of Modified Asphalt Binders Blended with Electronic Waste Powders. *Journal of Materials in Civil Engineering*, 24(10), p. 1261-1267.
5. Scorah, M.J., Zhu, S., Psarreas, A., McManus, N.T., Dhib, R., Tzoganakis, C., and Penlidis, A. (2009). Peroxide-Controlled Degradation of Polypropylene Using a Tetra-Functional Initiator. *Polymer Engineering and Science*, 49, pp. 1760-1766.
6. Colbert, B. (2012). The Performance and Modification of Recycled Electronic Waste Plastics For The Improvement of Asphalt Pavement Materials. in Civil and Environmental Engineering 2012, Michigan Technological University: Houghton, MI, USA, p. 120.
7. AASHTO T 240-09 (2011). Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test),in AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing. American Association of State Highway and Transportation Officials: Washington DC, USA.
8. AASHTO T 315-10 (2011). Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR),in AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and

Testing. American Association of State Highway and Transportation Officials: Washington DC, USA.
9. AASHTO TP 62-03 (2004). Standard Method of Test For Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures. American Association of State Highway and Transportation Officials, Washington DC, USA.
10. Schwartz, C.W and Carvalho, R.L. (2007). Implementation of the NCHRP 1-37A Design Guide. Final Report, Volume 2:Evaluation of Mechanistic-Empirical Design Procedure, Department of Civil and Environmental Engineering, University of Maryland, USA.
11. Baus, R.L. and Stires, N.R. (2010). Mechanistic-Empirical Pavement Design Guide Implementation. Report No. GT006-10, submitted to The South Carolina Department of Transportation and The Federal Highway Administration.
12. Das, A. and Pandey, B. B. (1999). Mechanistic-empirical design of bituminous roads: an Indian perspective. *Journal of Transportation Engineering*, 125(5), pp. 463–471.