Evaluating the Potential for Hot Mix Asphalt Rutting Performance Using Laboratory and Digital Imaging Technique

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Paper prepared for presentation at the
"Characterization of soils and pavement materials for mechanistic empirical pavement design" session of the 2013 Conference of the
Transportation Association of Canada
Montreal,

ABSTRACT

The objective of this study is to evaluate the non-structural rutting resistance of six typical Superpave™ mixes used in Ontario for surface course using conventional and advanced methods. Hamburg Wheel Rut Tester (HWRT), Dynamic modulus test, and Digital Imaging Processing (DIP) technique were used in the evaluation. These mixes include two Superpave SP12.5 and four SP12.5 FC2 mixes. Six Superpave Performance Grading (PG) binders and three traffic levels were used in the design of these mixes. The effect of aggregate type and binder type in improving the rutting resistance was investigated.

Manual method was used to quantify the shear upheave for all mixes. The common devices in measuring Hot Mix Asphalt (HMA) rutting ignore the effect of shear flow and only measure the effect of densification which might affect the ranking of mixes according to rutting susceptibility.

DIP was used for further analysis of aggregate effect on HMA rutting resistance. This included estimating aggregate contacts, segregation and orientation of two dimensional cross section images after loading. This method provides internal structural analysis of HMA in order to understand the failure mechanism in rutting and its relationship with each individual component characteristics.

Dynamic modulus test was also conducted to investigate the correlation between the HMA stiffness and rutting. It was found that Dynamic modulus |E*| is very effective for evaluating the resistance of HMA mixtures against rutting due to the strong correlation. The results of this study also showed that DIP provides an indication of HMA rutting potential. Aggregate contacts showed a good correlation with mixture rutting resistance measured manually and by using HWRT. Overall, imaging analysis would assist in the design of long lasting pavement.

INTRODUCTION

Hot Mix Asphalt (HMA) has been intensively studied with conventional laboratory methods in previous studies. However, advanced methods such as Digital Imaging Processing (DIP) technique could provide more benefits. Microstructure components effects can be studied to better understand the failure mechanism of HMA.

Rutting is often described as a permanent surface depression, which occurs in the wheel path of the pavement caused by traffic loads and is observed as a vertical depression with shear upheavals. There are two types of rutting, namely structural and non-structural rutting. Structural rutting is often caused by poor pavement design and deformation of underlying layers. Non-structural rutting occurs within the asphaltic layers caused by HMA densification or flow when the surface of the lower layers remains unaffected.

The rutting is generally caused by insufficient compaction during pavement construction, surface wear by chains and studded tires, overweight traffic, inadequate stability of asphalt, and deficient structural capacity of pavement. The vertical compression rutting occurs in the form of a depression without any accompanying hump due to the one-dimensional densification of HMA including excessive air voids or lacking adequate compaction. On the contrary, the rutting in the form of a depression with accompanying shear upheavals occurs because of the lateral flow of HMA; the lateral flow is usually observed in the top 100 mm of the pavement surface (1). In most cases, the rutting in HMA pavement is caused by a combination of densification and shear-related deformation (2).

A standardized accelerated laboratory test is very useful for predicting the rutting resistance of HMA. At present, a loaded wheel tester is commonly used in the United States to determine the rutting potential of HMA. In Canada, three types of loaded wheel rut testers, namely the Asphalt Pavement Analyzer (APA), the Hamburg Wheel Rut Tester (HWRT), and the French Laboratory Rutting Tester (FLRT) are used for testing HMA (3). These devices can only measure the densification of HMA under repetitive load without evaluating the shear upheaves on the sides of the wheel pass. Also, it is important to note that only macroscopic performances are obtained and no microstructural effect can be studied by these devices.

Aggregate interlock plays a significant role in HMA rutting resistance. An FC2 mix is a friction Course in which both fine and coarse aggregate are obtained from crushed bedrock as stated in the Ministry of Transportation of Ontario (MTO) Designated Sources for Materials (DSM) manual. This aggregate provides better skid resistance and carries heavy traffic loads.

DIP is the process of using digital computers to analyze images (4). This process refers to a specific technique to identify the internal structure of asphalt mixes (5). Successful application of the 2D digital image processing procedure on the investigation of the orientation of coarse aggregates in asphalt mixes was carried out by Yue and Morin (6). Contrast improvement, thresholding, and edge identification are the three main steps involved in the DIP (7). Different methods are used to convert the image to greyscale in which each pixel takes a number that varies from 0 (black) to 255 (white). Thresholding is one of the most important approaches to image segmentation. This process is applied to split out the image composition by selecting greyscale levels. Zelelew et al. (7) used image pre-processing and gray scale as the two essential stages to calculate the HMA volumetric properties, percentage of aggregate, mastic and air voids in the mix.

A number of softwares such as Matlab and ImageJ have been used for image processing. Recently, Ipas2 was developed at the University of Wisconsin to analyze the asphalt images. This software can be used to estimate several microstructure properties such as aggregate orientation, contacts, and segregation.

RESEARCH OBJECTIVE

This investigation evaluates the rutting resistance of six HMA mixes with traditional and advanced methods. The goal is to understand the HMA rutting susceptibility with respect to each internal structure characterization. A two dimensional (2D) digital image for the Superpave

Gyratory Compactor (SGC) sample was obtained from vertical cut of the tested samples under wheel pass. The failure mechanism in the sample model was analyzed.

EXPERIMENTAL WORK

Test Materials

Six Superpave surface layer HMA mixes were tested at the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo. These mixes include two Superpave SP 12.5 and four Superpave 12.5 FC2 mixes. Table 1 shows a description of all mixes tested by the HWRT. This includes the aggregate gradations used in these mixes and the optimum asphalt content. The mixes were designed for three traffic levels B, D and E. Mixes 1 to 4 are plant mixes while Mixes 5 and 6 are laboratory prepared.

Hamburg Wheel Rut Test

The rutting test was performed in the CPATT lab to evaluate the rutting resistance of different HMA mixtures. The test was carried out according to AASHTO T 324-04, HWRT of Compacted HMA (8). The test setup for the rutting test is shown in Figure 1. Four laboratory compacted Ø150×63H mm cylinder specimens were used for each run. The samples were compacted by Superpave Gyratory compactor (SGC). The specimens were tested in wet condition by using solid steel wheels. The tests were carried out at a temperature of 50 ^{0}C. Linear Variable Differential Transducers (LVDTs) were used to measure the depth of the impression under the wheel to determine the rutting depth. The permanent deformation was measured at least every 25 passes at the beginning of the test and at every 250 passes at the end of the test using a data acquisition system.

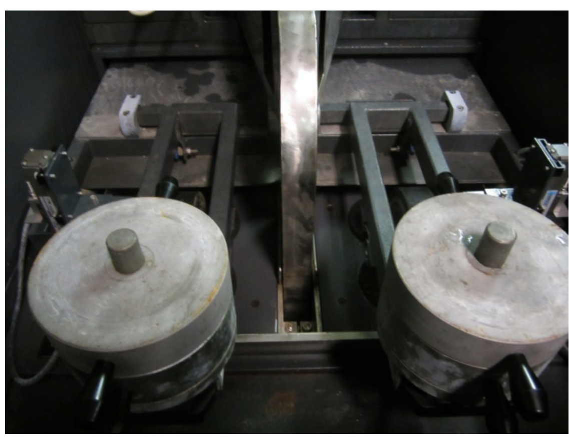

FIGURE 1. CPATT HWRT used for determining rutting resistance of HMA

DIGITAL IMAGING TECHNIQUE METHODOLOGY

Conventional analysis methods for rutting cannot be used to investigate the effect of microstructure components on the rutting performance. Only rut depth and tested mixes ranking are obtained. Imaging analysis is a beneficial tool to determine aggregate characterizations. Two samples for each mix were cut at the centre under the wheel pass. Samples were scanned and the scanner resolution was 600 dots per inch (dpi). Images were analyzed using IPas2 software. This software calculates the number of aggregate contacts and contact length based on preselected distance between aggregate particle and other surrounding particles (9),(10). The following properties were calculated for each image:

- Aggregate segregation in top 20 mm of the tested sample.
- Number of contact zones between aggregate
- Length of contact between aggregate
- Aggregate orientation

A framework for the scanning and analysis process can be seen in Figure 2

TABLE 1. Gradation and Binder Properties for the HMA Mixes used in Model Validation

Sieves Sizes(mm)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
19	100	100	100	100	100	100
12.5	97.8	95.3	91.4	97.5	98.3	98.3
9.5	83	79.9	79.3	79.7	85.1	85.1
4.75	56	51.8	58.4	55	54.7	54.7
2.36	42.1	42.1	43	49.3	40.5	40.5
1.18	27.5	27.9	32.5	40.1	31.4	31.4
0.6	16.6	18.4	23.7	32.9	24.3	24.3
0.3	9.6	11.5	13.9	12.3	14.8	14.8
0.15	6.1	6.8	5.7	5.3	6.9	6.9
0.075	4.3	4.1	3.9	3.7	3.3	3.3
Binder percentage, (%AC)	5.2	5.2	5.1	5.2	5	5.05
SP[1]	12.5	12.5FC2	12.5	12.5FC2	12.5FC2	12.5FC2
Superpave performance grading	PG 52-34	PG 70-28	PG 58-28	PG 64-34	PG 64-28	PG 64-28D
Traffic Level	B	D	B	D	E	E
VMA	16	15.5	14.4	16.2	15.43	15.1
VFA	75.2	74.3	72.3	74.9	71.33	74.83
T1, ^{o}C	-24	-18	-18	-24	-18	-18
Stiffness S(t)[2], MPa	227	95	258	171	163	96
m(t)	0.312	0.352	0.307	0.34	0.308	0.361
T2, ^{o}C	13	25	19	19	22	22
G"[3], KPa	2256	859	4123	1460	3010	1393

[1]Superpave mix gradation [2] measured @temperature T1 [3] G* Sin (δ)@temperature T2

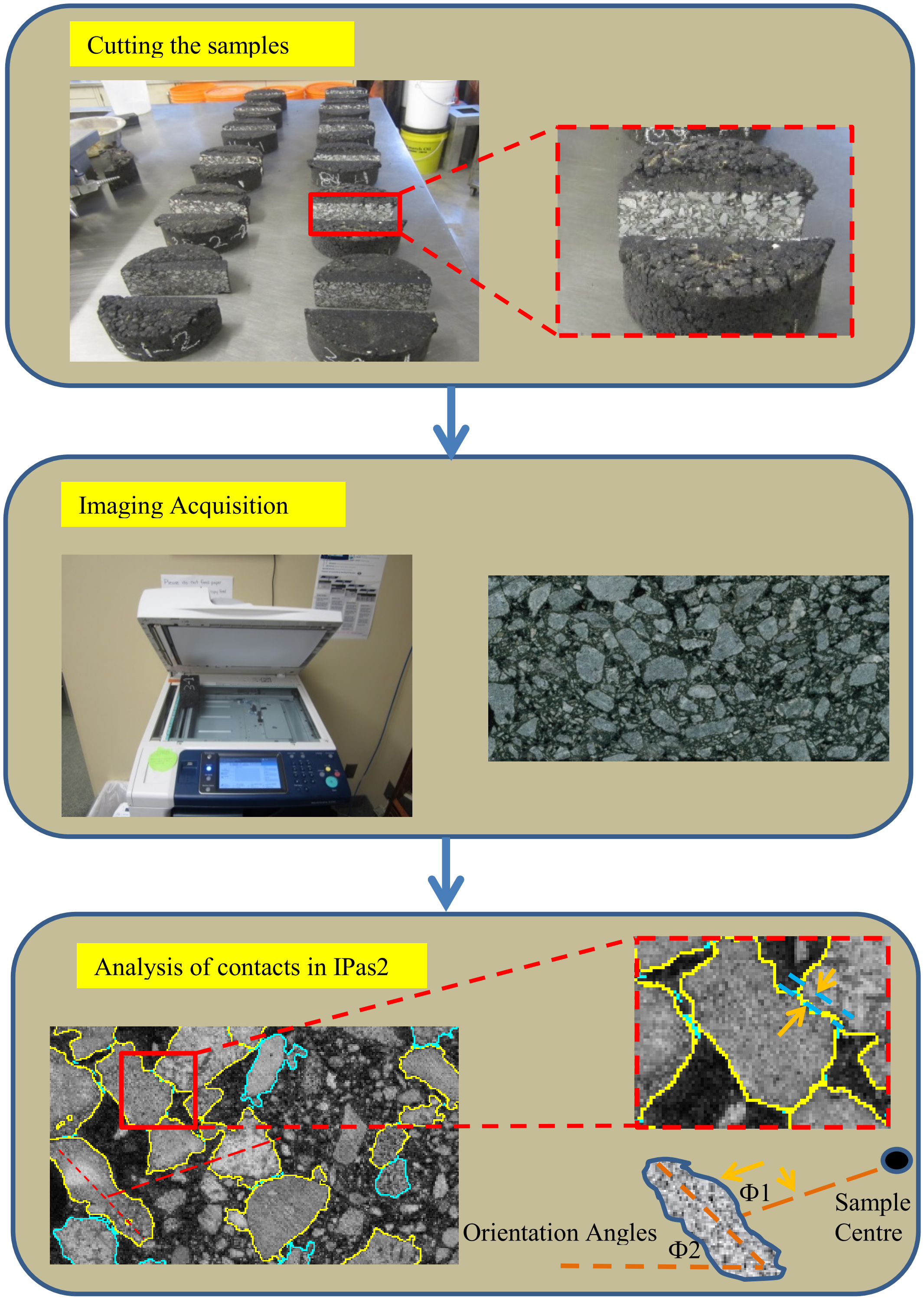

Figure 2. Images acquisition and and anlysis method

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RESULTS AND ANALYSIS

Experimental Work Results and Discussion

Comparison of HMA Laboratory Rutting susceptibility

The purpose of this section is to assess the rutting resistance of six surface layer Superpave mixes that are typically used in Ontario, as shown in Figure 3. Mixes 1 and 3 were SP12.5 while others were SP12.5FC2 mixes. The rutting performance of the different mixes was statistically significant with respect to the Analysis of Variance (ANOVA ($\alpha = 0.05$)) as shown in Table 2. It is clear from the chart that Mix 2 provides the highest rut resistance while Mix 1 has less potential to resist permanent deformation. It has been observed that the aggregate is controlling the mixes rutting resistance. The SP12.5 mixes have higher susceptibility to rut as compared to the SP 12.5 FC2 mixes. Mixes 5 and 6 were designed from the same aggregate gradation but had two Superpave binder grades of PG64-28, regular and modified, respectively. The modified PG 64-28 has no statistically significant impact on the HMA rutting performance. However, both mixes show improvements in rutting resistance as compared to other mixes, with the exception of Mix 2.

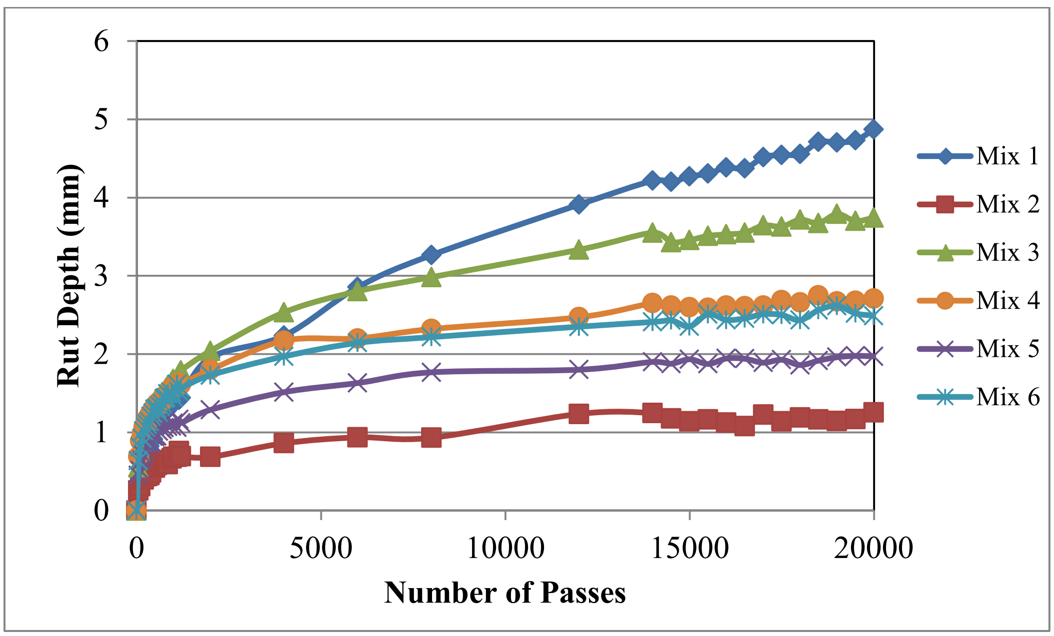

Figure 3. Rutting of six asphalt mixes

Table 2. ANOVA Statistical Analysis

Source of Variation	Sum of Square (SS)	Degree of freedom (df)	MS	F	P-value	F crit
Type of Mix	17.93	5.00	3.59	16.09	0.0001	3.20
Error	2.45	11.00	0.22			
Total	20.39	16.00				

Simulating Filed Measuring Rutting method

The difference between the method of measuring rut depth in both the laboratory HWRT and field was observed. The laboratory rut depth represented by the depression from the original sample surface before running the test is measured using a LVDT. The field measured rut depth is measured using a rut bar or straight edge. However, it should be noted that although the magnitude of the rutting is different, the ranking provided by the HWRT is typically consistent with field observation. This research involves investigating HMA rut depth by considering the shear upheave on the rut sides. The goal is to check whether the modified rut depth has significant effect on the output. Figure 4.a and b show the commonly used method for measuring field rut depth and the suggested method for HWRT rut measurement, respectively. Table 3 summarizes the average rut depth measured by the HWRT LVDT and the manual method in Figure 4.b. A significant difference ranging from 47 % to 165% has been observed on the final rut depth after 20,000 passes. As a result, it is recommended to modify the method of measuring the rut depth in laboratory devices.

(a) (b)

FIGURE 4. Field and laboratory measuring of HMA rutting depth

TABLE 3. Average of Measured Rut Depth using Two Method

Mix	HWRT rut depth, mm	Modified HWRT rut depth, mm	Shear Upheave, mm	Percentage change [1]
Mix 1	4.9	11.7	6.8	141
Mix 2	1.3	1.9	0.6	49
Mix 3	3.7	9.9	6.2	165
Mix 4	2.37	4.9	2.5	106
Mix 5	2.0	4.8	2.8	140
Mix 6	2.5	3.7	1.2	47

[1]((LVDT Rut - Manual Rut) /LVDT Rut) x100

Correlation between Dynamic Modulus and HWRT rut depth

The dynamic modulus (|E*|) of HMA is a measure of its stiffness response under repetitive sinusoidal (haversine) loading. It is the key input parameter of choice for the AASHTOWare Pavement ME Design (AASHTOWare) and an essential parameter for Level 1 design of HMA (11, 12). The dynamic moduli of four asphalt mixtures were also tested in the

CPATT laboratory. The test was carried out on Ø100×150H mm cylinder specimens. Each test specimen was tested for five temperatures (-10 ^{0}C, 4 ^{0}C, 21 ^{0}C, 37 ^{0}C, and 54 ^{0}C) and six loading frequencies (0.1 Hz, 0.5 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz and 25 Hz).

In Figure 5, the master curve was constructed by shifting the dynamic modulus data to 21 ^{0}C reference temperature. In general, Mix 1 has the lowest stiffness while Mix 2 has the highest stiffness at very low frequencies. This also matches these mixes ranking in the rutting resistance. Figure 6 also confirms the sample conclusion by a high correlation between the rut depth and the |E*| at 54 ^{0}C for both 0.5 Hz and1.0 Hz loading frequencies. The results provide good evidence on the importance of measured dynamic modulus values for the accuracy of pavement design in MEPDG which will be completed for the second stage of this research for typical Ontario HMA mixes.

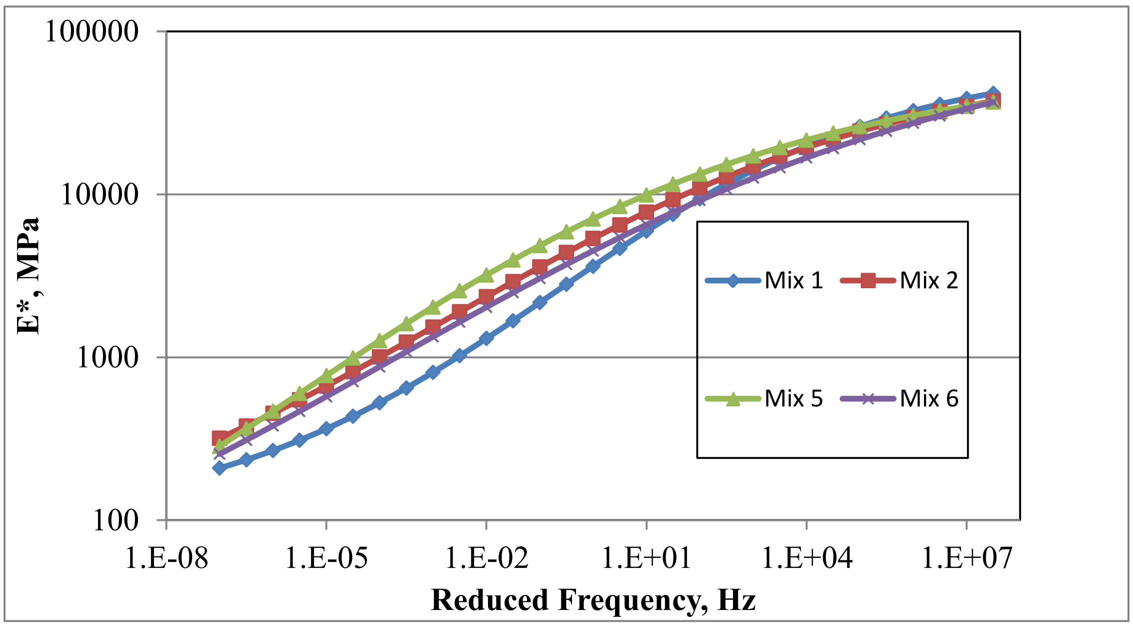

FIGURE 5. Dynamic modulus master curve of HMA mixes

Internal Structure Analysis of HMA Mixes

The internal structure of HMA analysis includes binder stiffness and aggregate characterization. Each individual aggregate particle can be numbered and the shape characterization can be calculated. Figure 7 shows an example of processed images with aggregate borderlines and numbers. The minimum aggregate size was 1.18mm for accuracy of the imaging analysis (13). The results of aggregate characterization from imaging analysis and its' correlation with the measured rutting potential were estimated for all mixes.

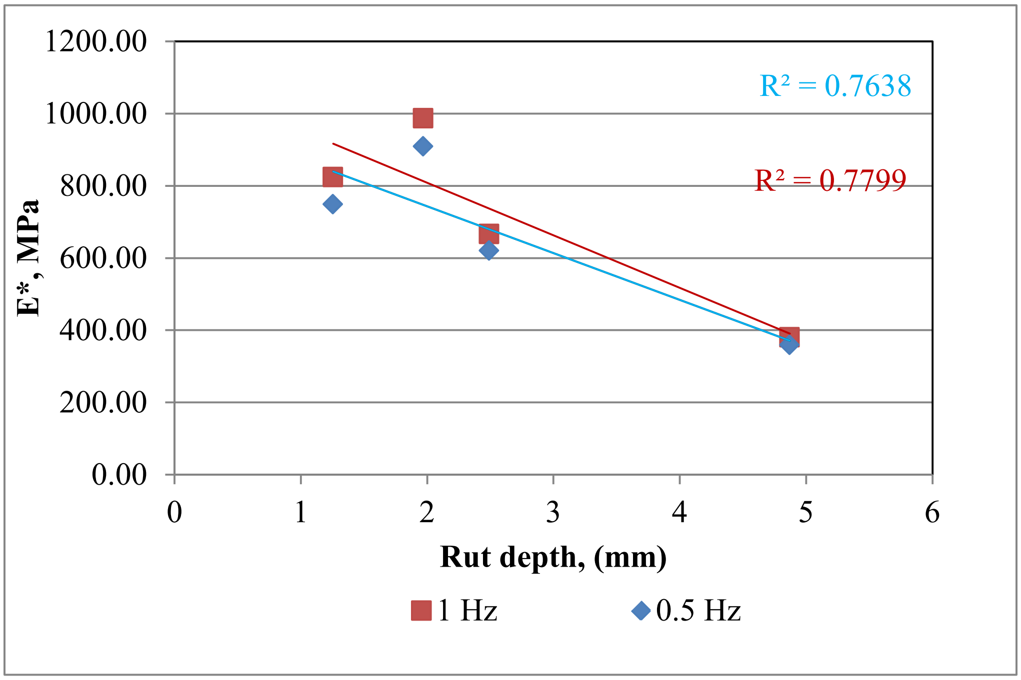

FIGURE 6. Relationship between dynamic modulus and HMA rut depth

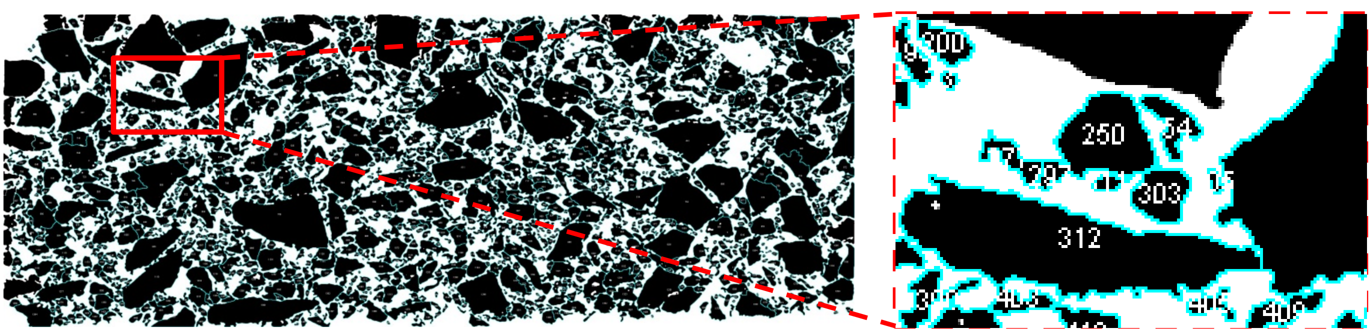

FIGURE 7. Example of processed images

Effect of Binder Stiffness

The binder properties were obtained from the binder analysis sheets given in each mix design. The relation between G*/ Sin (δ) and rutting depth of six binder types for original and Rolling Thin-Film Oven (RTFO) aged binder are given in Figure 8. As can be seen in this figure, the increase in G*/ Sin (δ) of original binder in decrease the rut depth. No trend was observed between the stiffness of aged binder and the measured rut depth. This highlights that the binder testing was considered for mixtures with same aggregate type, characterization, and volumetric (14). Therefore, introducing new parameters in evaluating HMA rutting will help to understand its' occurrence and mitigation.

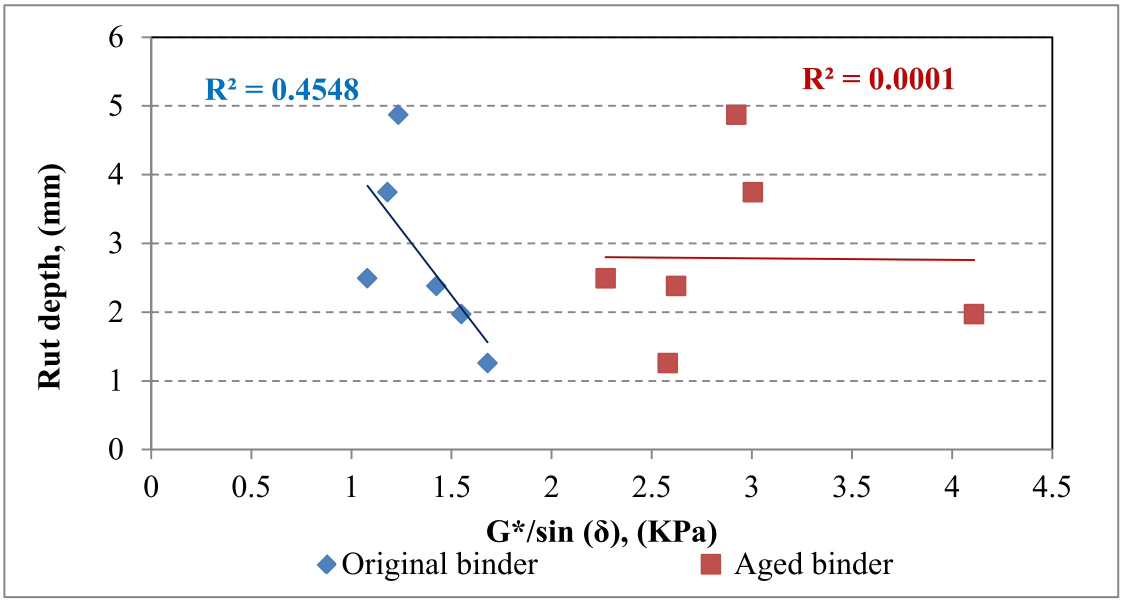

FIGURE 8. Relationship between binder properties and HMA rutting

Effect of Aggregate Segregation

Figure 9 shows the percentage of each aggregate size in the top third of the tested samples in rutting. These aggregate particles transfer loads to underneath particles. 12.5 mm aggregate sizes were not detected for Mixes 4, 5, and 6 in the top 20 mm. This also presents a method to determine the effect of aggregate packing on rutting failure mechanism. Segregation should be quantified for each tested sample to determine the shifted gradation from the design gradation. The top 20 mm can be used as a recommended location to measure the segregation to rutting correlation.

Effect of Aggregate Orientation

Figure 10 shows the average of orientation angle from horizontal axis with both HWRT rut depth and modified HWRT. Poor correlation was observed between the rut depth and the orientation angle. The angle ranged from 73 to 78 degrees and slight change was noticed from one mix to another. However, aggregate orientation angle in three dimensional (3D) analyses could provide a better correlation with HMA performance.

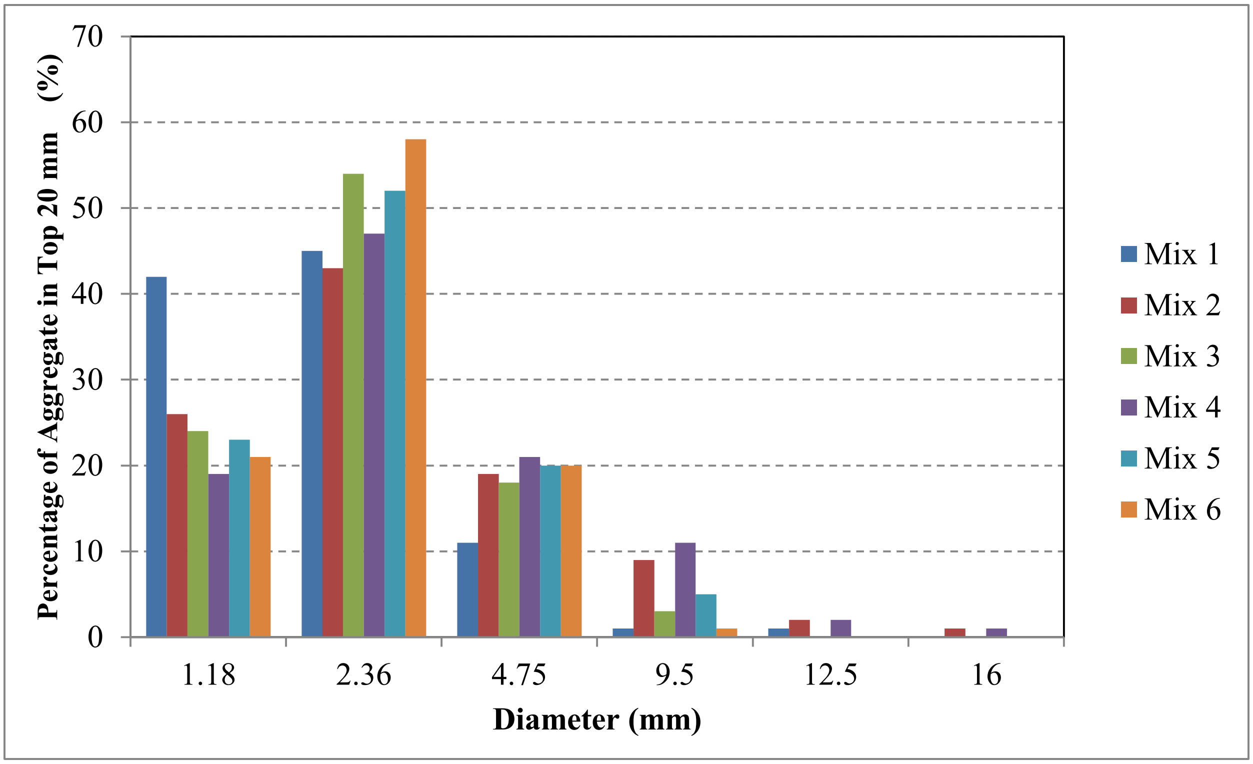

FIGURE 9. Aggregate segrgation of HMA mixes

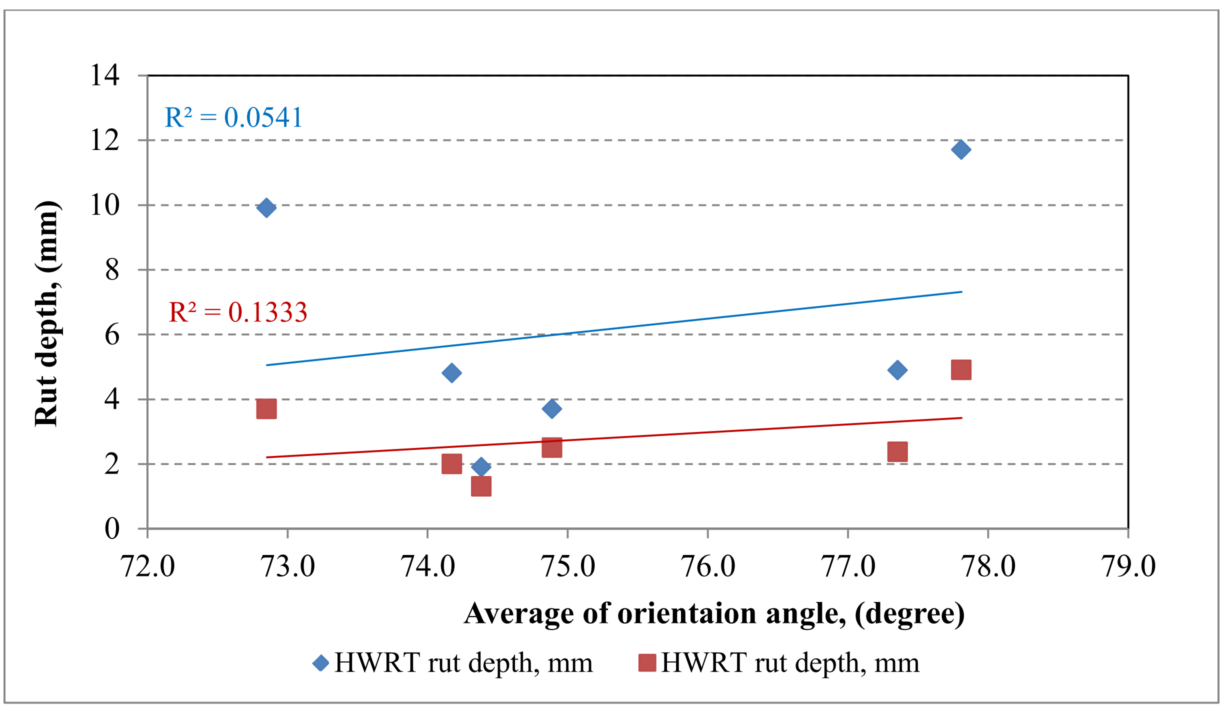

FIGURE 10. Average of orientation angles of aggregate

Effect of Aggregate Particle Contacts

Among the factors affecting permanent deformation is the aggregate to aggregate contacts in the compacted mixes. This factor impacts the stress distribution in HMA. As a result the rutting resistances were correlated with aggregate contact length. The numbers of contact zones between two aggregate particles in each mix are shown in Figure 11.a. It is observed that the number of zones in contact decrease with the increase of rutting depth. Figure 11.b illustrates the same trend for contact length as rutting depth increases. The results confirm the important role of aggregate to aggregate contacts on the load transfer. These HMA microstructure parameters should be considered in the design of HMA and selection of compaction methodology.

Similar trends were observed for both HWRT rut depth and modified HWRT which include the shear upheave on the rut sides. A higher coefficient of determination (R^2) was obtained with modified HWRT. These correlations highlight the significance of quantifying shear failure of HMA in improving the analysis of the HWRT rutting results.

Based on the results, good aggregate and binder combination in HMA should be selected to increase the contact length and number of contact zones. This can be measured by saw cutting and scanning the compacted samples after loading.

CONCLUSIONS

This paper provides insight on microstructure analysis of HMA mixes. The results of this study reveal that image analysis is a good method to study HMA rutting potential. Several Aggregate characterizations can be calculated by DIP method and correlated with the HMA rutting performance. Based on the results of this study, the following conclusions are drawn:

- Experimental results indicated that the SP12.5FC2 for traffic levels D and E mixes has a significantly higher rutting resistance than the SP 12.5 for traffic level B for all the binder types used in the study.

- Mix 2 provided the best rutting resistance in compared with other mixes used in this investigation.
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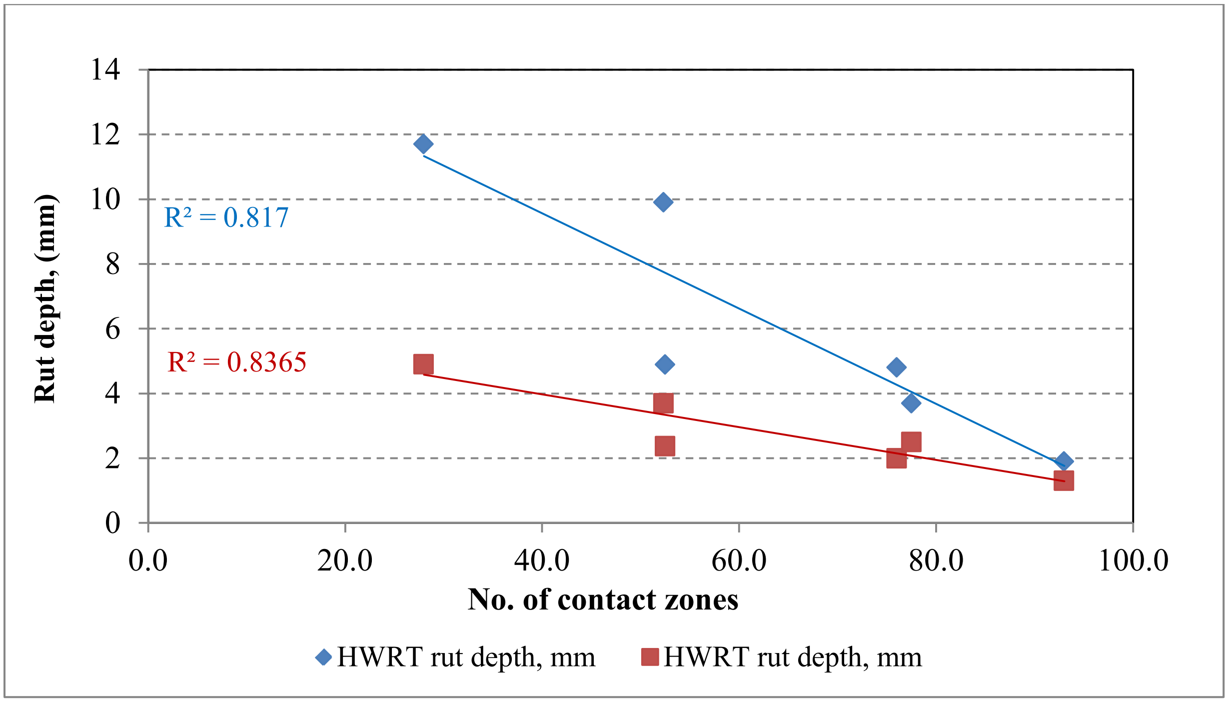
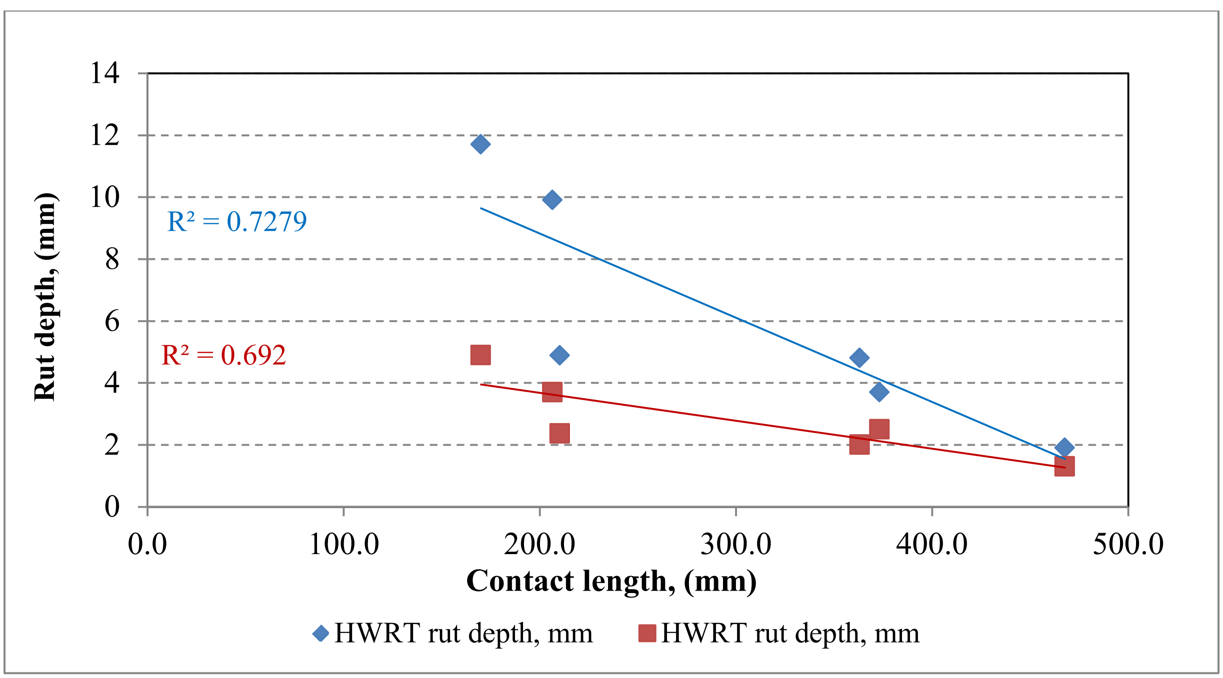
- Quantifying the shear upheave on the rut sides is important. This simulates the field measuring method and affects the ranking of the mixes with respect to rutting resistance.



(a) Number of Contact zones of aggregate



(b) Conatct length

FIGURE 11. Relation between aggregate contacts and HMA rutting

- Since the binder characterization is not the only factor affecting HMA rutting, aggregate contribution in rutting potential needs to be quantified. Aggregate orientation and contact were important factors in HMA rutting resistance. A 2D image analysis under the wheel pass can provide a good estimate of these two parameters.

- Correlations of HWRT rut depth with aggregate contact length and number of contact zones were better than aggregate orientation.

- High correlation was observed between the HWRT rut depth and the measured dynamic modulus stiffness at 54 ^{o}C.

- Aggregate microstructure characterization can be combined with binder properties to better understand the HMA rutting mechanism and mitigation

FUTURE WORK

The next step in this research will focus on the correlations between the predicted rut depth by Finite Element Method (FEM), the measured rutting depth, and the aggregate properties obtained from DIP method. Also, more aggregate source and sizes will be used. Furthermore, using X-ray Computed Tomography as a nondestructive technique in three dimensional (3D) characterization of HMA mixes.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Ministry of Transportation of Ontario in particular Warren Y. Lee and Imran Basher for funding this study through the Highway Infrastructure Innovation Funding Program. We also want thank Haolin Zhang and Jingwen Cao, two co-op students who have assisted in the laboratory work for this study. We also gratefully acknowledge the support of various partners at the Centre for Pavement and Transportation Technology and the Norman W. McLeod Chair.

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