Evaluation of rutting performance of asphalt mixtures using Extra-Large Wheel Tracking and 2-D imaging technique

Abubeker Worake Ahmed[1, a], Amir Arshadi[2, b], Sigurdur Erlingsson[1, 3, c], Hussain Bahia[4, d]

[1] Pavement Technology, The Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden
[2] College of Engineering, University of Oklahoma, Norman, OK 73071, United States
[3] Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland
[4] Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, United States

[a] abubeker.ahmed@vti.se
[b] arshadi@ou.edu
[c] sigurdur.erlingsson@vti.se
[d] hubahia@facstaff.wisc.edu

Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.102

ABSTRACT

The internal aggregate structure provides the load carrying skeleton of the asphalt mixtures, which plays a leading role in the rutting resistance of pavements. The main objective of this study is to investigate the application of two-dimensional (2-D) imaging and analysis technique to evaluate the role of aggregate packing in rutting performance of three different types of asphalt mixtures. The 2-D images are derived by scanning the cross sections of cylindrical samples taken from asphalt slabs which have been tested using an Extra-large wheel tracking device. Samples from loaded and unloaded areas of the slabs are analyzed to assess any difference in aggregate re-orientation and segregation effects. The mixture rutting performance is evaluated based on the total length of the contact between the aggregate particles which is derived from the image analysis. The software system called IPAS2 (Image Processing and Analysis Software) developed in previous studies is used to process the images of the asphalt mixtures with different gradations and binder contents. The results demonstrate a clear correlation between the internal structure indices and the mixture rutting performance. Such results can explain the significant role of aggregate structure in rutting of pavements.

Keywords: Aggregate, Performance testing, Permanent Deformation

1. INTRODUCTION

Asphalt concrete mixtures are known as multi-phase complex composites of bitumen, air voids, and mineral aggregate particles. Due to the significantly higher stiffness and volume fraction of aggregates in the mixture, the principal mode of load transfer through the mixture is believed to be through the aggregate particles. The load-carrying skeleton of asphalt concrete mixtures is mainly provided by the aggregate to aggregate contact or the internal aggregate structure [1]. It is therefore expected that the characteristics of the internal structure, including packing and interaction between aggregates, indicate the mixture rutting performance. Since it is difficult to directly measure internal structure, various mechanical tests and procedures are employed to evaluate the mix performance to rutting and/or to characterize the mix [2, 3]. Among the different mechanical test methods, the wheel tracking test is commonly employed to characterize the rutting performance of asphalt mixtures. Such tests are very useful for evaluating the bulk properties of mixtures without explaining what the specific components contributions are, including aggregates, bitumen, and air voids.

Other non-mechanical approaches to evaluate the internal structure of asphalt mixes include 2D or 3D image processing techniques. Several studies have attempted to use the image processing technique to characterize the internal structure of asphalt concrete mixtures such as aggregate orientation and segregation [4-6]. The challenging task in the image processing techniques was to properly define the aggregate boundaries within asphalt concrete mix. Some of the image processing methods, therefore, utilised various filtering techniques and relied heavily on personal judgment to define the aggregates boundaries [4]. With the advancement of technology, obtaining the detailed internal structure of asphalt mixtures is no longer a complicated task, however; little effort has been made to improve the precision and accuracy of the analysis phase [1, 7, 8]. Roohi et al. [1] successfully showed that the internal aggregate structure properties of asphalt mixture can be quantified using a newly developed image analysis indices defined for both the total aggregates and for the effective load bearing aggregate structure, namely: number of aggregate-to-aggregate contact zones, aggregate contact (proximity) length, and contact plane orientation.

Both the mechanical and image analysis techniques facilitates the flexible pavement design and/or pavement management processes by providing indicators of the rutting performance of asphalt mixtures because rutting is considered as a load related or structural distress and is included as a failure criterion in most Mechanistic-Empirical (M-E) pavement design procedures.

The main objective of this study is to evaluate the relationship between the rutting performance of asphalt mixtures by means of an extra-large wheel tracking (ELWT) test results and the results of the image processing technique. Three different types of asphalt concrete mixtures were tested. The image analysis software IPAS2 was used to process the images of the asphalt mixtures with different gradations and bitumen contents. The results from the ELWT test and the image processing were analysed to study the influence of the internal aggregate structure on the rutting performance.

2. THE EXTRA-LARGE WHEEL TRACKING DEVICE

Laboratory wheel tracking devices are widely used to evaluate and rank the rutting performance of asphalt mixtures under environmental and loading conditions that simulate the actual field conditions [2, 3]. The ELWT test device is used in this study to evaluate the development of rutting or fatigue cracking of different pavement materials subjected to wheel loading and environmental conditions (temperature and water) that can be adjusted to simulate the desired field conditions. The ELWT device can be used to evaluate rutting performance of a single or layered thin asphalt layers (Figure 1). The test is conducted on slabs that are 50 cm wide and 70 cm long and the thickness of the slab can be varied between 4 and 12 cm. A single wheel load of up to 25 kN can be applied on test slabs through a small inflated tyre (size 6.00R9 with width of 115 mm) with a tyre pressure within the range of 500-1000 kPa. The wheel travels in the longitudinal direction at a speed of 1-5 km/h. Lateral traffic wander an important factor in the analysis and design of flexible pavements [9], therefore, the wheel of the ELWT is allowed to move in the transverse direction within a width of 6 cm at an interval of 1 cm so as to simulate traffic wander. Pavement and air temperatures are continuously measured and can be varied between 5 and 60°C. The permanent deformation (rutting) in the test slab is measured using high precision laser beam equipment.

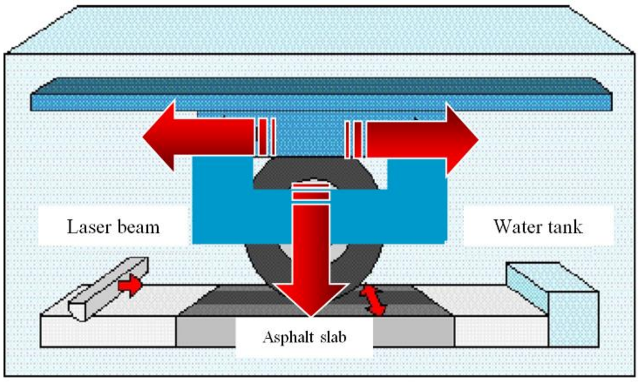
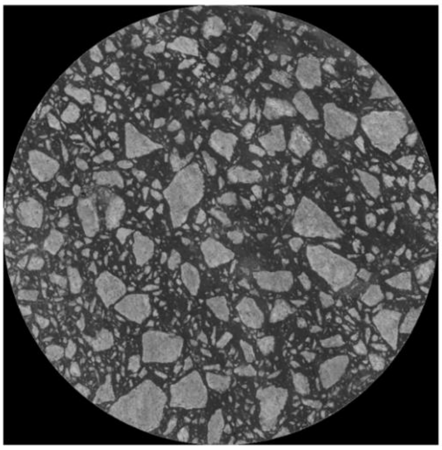


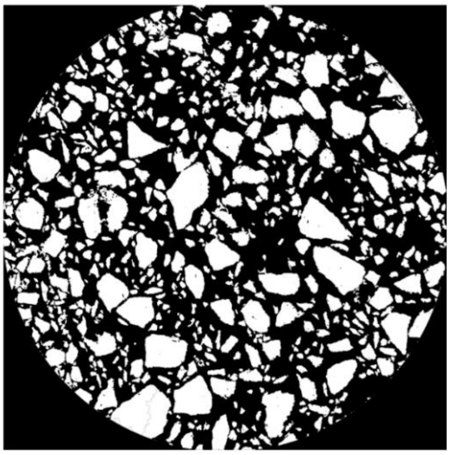
Figure 1: Schematic diagram of ELWT test setup

3. 2D IMAGE ANALYSIS

A flatbed scanner was used to capture digital images at a resolution of 20 μm/pixel of cuts of cylindrical samples taken from asphalt slabs tested using ELWT device. Two dimensional digital image processing techniques were used to convert the images to binary images following filtering procedures described by Coenen et al [7] using the image processing software IPAS2 (Figure 2). The software uses a three step filtering procedures to generate binary images consisting of watershed filtering, thresholding, and hybrid max filtering, details of which can be found elsewhere [1,7] .



(a)



(b)

Figure 2: Images of the mixture. (a) Scanned image of asphalt concrete cross section (b) Scanned image after image filtering processes

Image analysis was performed for aggregate structural characterization on all of the converted black and white scanned images to obtain the packing and segregation level of the mixtures. Aggregate total contact length in 2-Dimensional images is used as an indicator of the mixture packing condition. In the software, contact is assumed when two aggregate particles' perimeter pixels are within a distance specified by the user. These pixels form the contact lines (Figure 3) [1]. A mixture with a higher total contact length shows a higher aggregate connectivity and packing level.

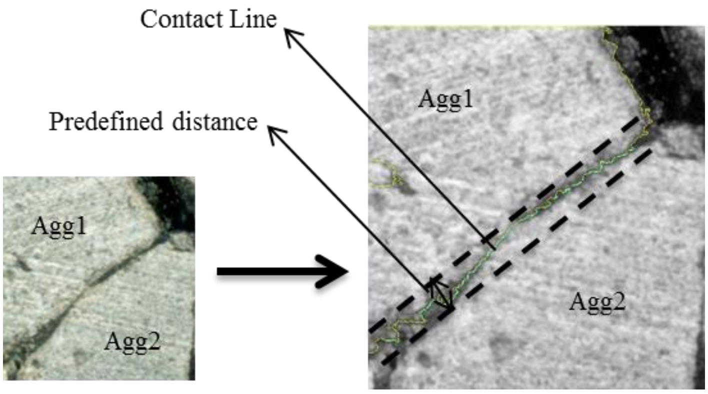


Figure 3: Contact line (Roohi et al. 2012)

4. THE TESTING PROGRAM

4.1 Test Slabs

Three types of standard asphalt mixtures which are commonly used for asphalt surfacing (ABT11), binder layer (ABb22) and bituminous base layer (AG22), respectively, were tested using the ELWT device. Table 1 presents the bitumen types and contents as well as the target air void for the mixes. Table 2 shows the physical properties of aggregates. The mixes were made of crushed granite aggregates. Figure 4 presents the grain size distribution curves for the mixes as well as an example of scanned image for all of the mixes.

Table 1: Mixture properties

Mix	Nominal max aggregate size [mm]	Bitumen grade [Pen] or [PG]	Bitumen content [%]	Target air voids [%]	Number of replicates
ABT11	11	70/100 (PG58-22)	6.6	3.0	3
ABb22	22	70/100 (PG58-22)	5.2	6.0	3
AG22	22	160/220 (PG52-28)	4.7	7.1	3

Table 2: Physical properties of aggregates

	Fractions				
	4/8	8/11	11/16	10/14	11.2/16
Flakiness index [%]	16.7	5.5	2.9		
Elongation index [%]	25.2	5.8	4		
Particle specific gravity	2.63				
Micro Deval [%]				4	
Los Angeles Abrasion [%]				16	
Nordic Ball Mill [%]					5.8

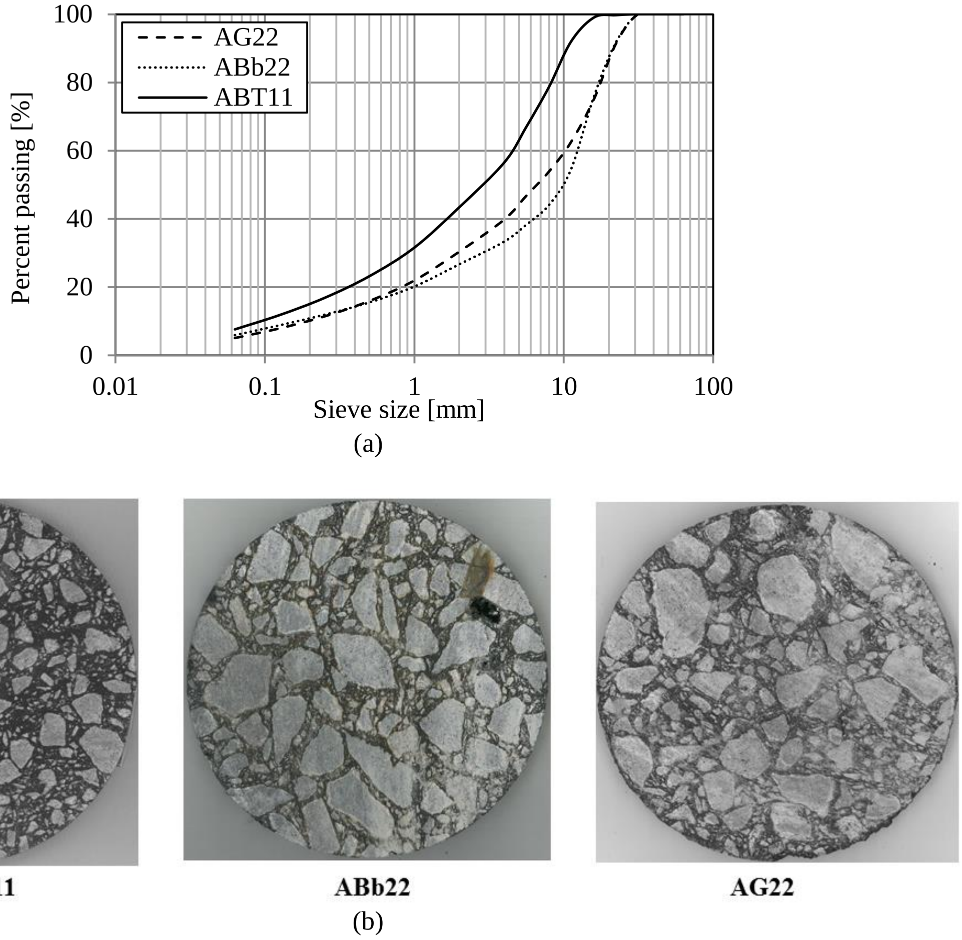


Figure 4: (a) Gradation curves of the different mixtures; (b) Example of scanned images of the mixes

A total of nine asphalt slabs, three replicas for each mix, were prepared. The mixes were prepared according to common European standard practices and the 50 × 70 cm slabs were roller compacted to attain the desired degree of compaction. Table 3 shows properties of the asphalt slabs.

Table 3: Properties of asphalt slabs

Mix	Specimen	Planned Thickness [mm]	Actual Thickness [mm]	Air Void [%]
ABT11	1	40	40.3	4.8
	2	40	40.5	3.9
	3	40	40.6	4.3
ABb22	1	60	59.7	4.7
	2	60	60.1	4.5
	3	60	59.8	4.5
AG22	1	60	59.5	6.5
	2	60	59.9	6.7
	3	60	59.8	6.2

The tests were carried out at different tyre inflation pressures and pavement temperatures. The mixes considered in the study are commonly used as the surface, binder and bituminous base layers. Therefore, in the ELWT tests, the tyre pressure was adjusted to account for their location in an actual construction. A wheel load of 10 kN was selected for the tests in order to safely carry out the test without any significant damage to the samples. For the first two asphalt slabs of each mix, pavement temperatures of 10, 20 and 30°C were used. Load cycles of 14,000 were applied for 10 and 20°C tests and 25,000 cycles were applied for the tests at 30°C. Pavement temperatures of 10, 15, 25 and 35°C, each with 14, 000 load cycles, were used for the 3rd group of slabs of each mix. The tests were carried out in increasing temperature in order to protect the slabs from excessive damage for subsequent tests. The speed of the wheel was kept at 2.5 km/h for all tests. Table 4 presents the test program and summarizes the loading, tyre inflation pressure and test temperatures. Figure 5 shows the test slab preparation and the actual ELWT test setup.

Table 4: ELWT test wheel loads, tyre pressure and test temperatures

Mix	Slab 1		Slab 2		Slab 3	
	Wheel load [kN]	Contact pressure [kPa]	Wheel load [kN]	Contact pressure [kPa]	Wheel load [kN]	Contact pressure [kPa]
ABT11	10	800	10	800	10	800
ABb22	10	700	10	700	10	700
AG22	-	-	10	600	10	600
Temperature [°C]	10, 20, 30		10, 20, 30		10, 15, 25, 35	

Figure 5: Compaction of the slabs and the actual ELWT test setup

4.2 Stiffness of the Mixes

Frequency sweep Cyclic Indirect Tensile Test (ITT) [10] according to the European standard EN12697-26:2012 was conducted to obtain the dynamic modulus of the asphalt mixes. Cylindrical specimens drilled from the ELWT tested slabs were used for the ITT. The frequency sweep tests were carried out at four temperature levels (-7, 0, 10, 20°C) and six frequencies (16, 8, 4, 1, 0.5, 0.1 Hz). Figure 6 presents the master curves for the dynamic modulus of the mixtures at a reference temperature of 20°C. The master curves were constructed using a sigmoidal fitting function.

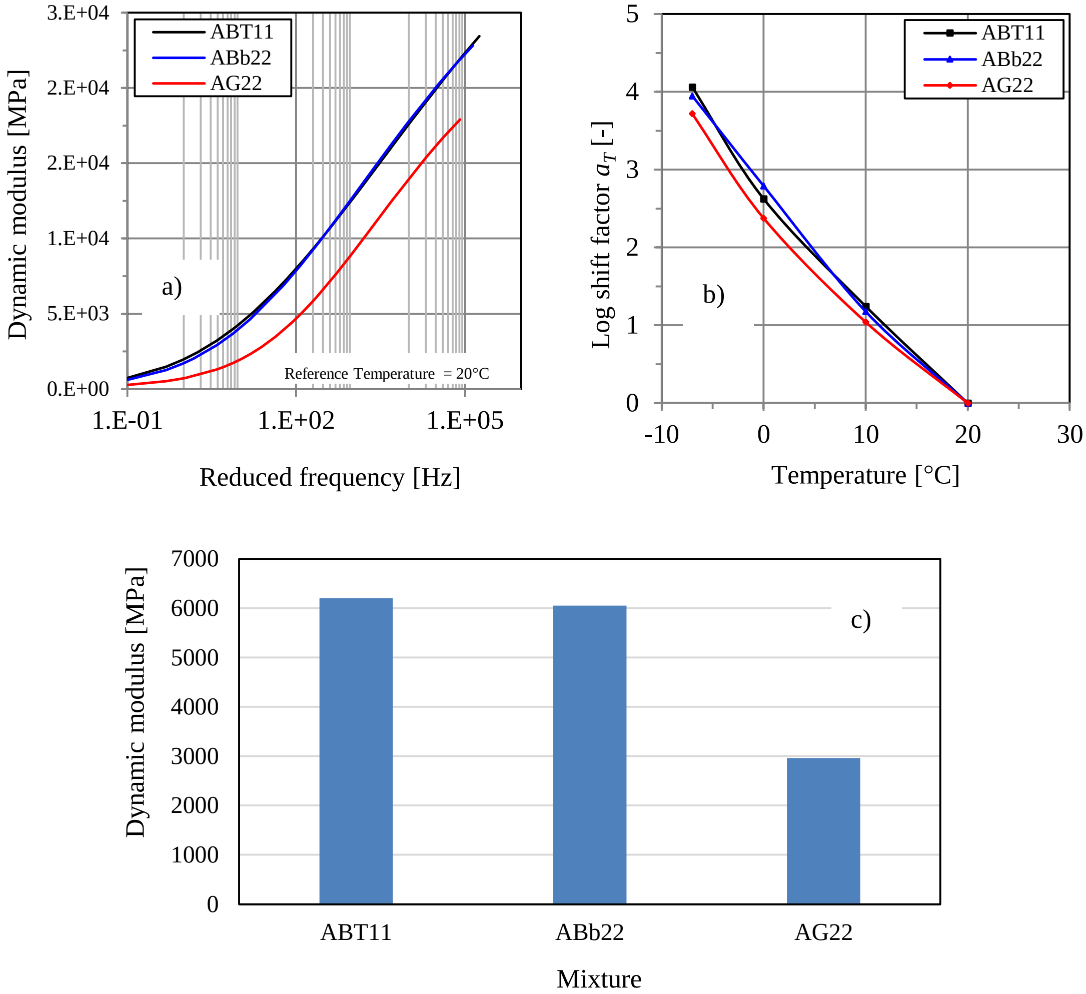


Figure 6: a) Master curves; b) shift factors for dynamic modulus of ABT11, ABb22 and AG22 mixes at a reference temperature of 20°C; c) dynamic modulus of the mixes at 15°C and 10 Hz loading frequency

5. PERMANENT DEFORMATION MODELLING

A simple permanent strain model for asphalt concrete layers was employed to model the development of rutting n the ELWT tested slabs [11, 12]:

$$R_d = \int_0^\infty \varepsilon_p(z)dz = \sum_{i=1}^{n} \varepsilon_{p,i}\Delta z_i \tag{1}$$

where $\varepsilon_{p,i}$ and Δz_i denote permanent vertical strain and the thickness of the i^{th} sub-layer respectively, n is the total number of sub-layers, and R_d is the rut depth. $\varepsilon_{p,i}$ is estimated using a permanent strain model for pavement layer. The permanent strain model used is the simplified MEPDG model for asphalt concrete mixtures given as [11]

$$\varepsilon_p = a_1 T^{a_2} N^{a_3} \varepsilon_r \tag{2}$$

where a_1, a_2 and a_3 are material constants, T is the pavement temperature in °C, N is the number of load cycles and ε_r is the induced vertical strain by the loaded wheel calculated using an multilayer elastic response model [13]. Furthermore, the influence of traffic wander was incorporated for the ELWT test using an incremental damage accumulation procedure, i.e., the elastic strains at different wheel positions were first calculated and then the contributions to permanent deformation were obtained. Finally the total permanent deformation was determined by combining the contributions by means of the time hardening procedure [14].

6. RESULTS AND DISCUSSIONS

Figure 7 presents the modelled and measured permanent deformation of the ELWT test slabs. It can be observed that the M-E permanent deformation model shown in Equation (2), along with the adopted strain hardening procedure, captured the permanent deformation behaviour of the asphalt slabs at all pavement temperatures. The model parameters a_1, a_2 and a_3 in Equation (2) were obtained by minimizing the least square error between the measured and the modelled permanent deformation of the slabs. Table 5 presents the model parameters estimated based on least square fitting of the measured permanent deformations.

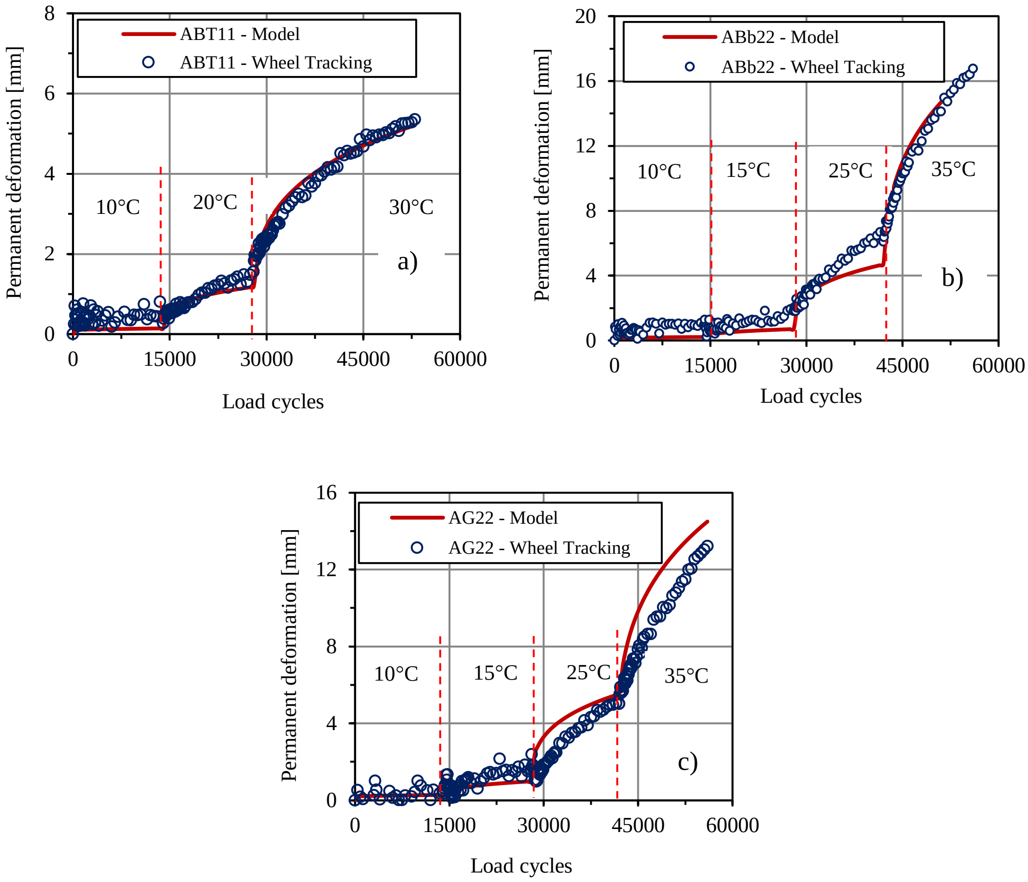


Figure 7: Measured and modelled permanent deformation of asphalt slabs using an ELWT device (a) ABT11, (b) ABb22 and (c) AG22

Table 5: Permanent Deformation Model Parameters Based on ELWT Tests

Layer	a_1	a_2	a_3
ABT11	0.0249	1.85	0.27
ABb22	0.0217	1.85	0.27
AG22	0.0157	1.85	0.27

Note that, as shown in Table 4, the tyre pressure selected for each mixture was different (800 kPa for ABT mix, 700 kPa for ABb mix and 600 kPa for AG mix), however, a 10 kN wheel load was used for all slabs. The tyre pressure was varied to simulate the mixes position in actual construction, i.e. ABT mixture is used as a surface layer, ABb is a binder layer and AG is a road base mix.

Figure 8 shows a comparison between the permanent strains based on Equation (2) after 30,000 load cycles for the three asphalt mixtures. The elastic strains are calculated from a three layer system consisting of the ABT mixture (40 mm) as surface, the ABb mixture (60 mm) as a binder and the AG mixture (60 mm) as a road base layer over a rigid subgrade. A wheel load of 10 kN and tyre pressure of 800 kN was used [15]. The master curves shown in Figure 6 were used to obtain the elastic modulus of the mixes at different temperatures. As shown, among these mixtures, the AG mixture demonstrated the lowest rutting resistance followed by the ABT mixture. Despite having a stiff bitumen, the ABb mixture produced the lowest rutting resistance at higher temperatures (for temperatures greater than 25°C).

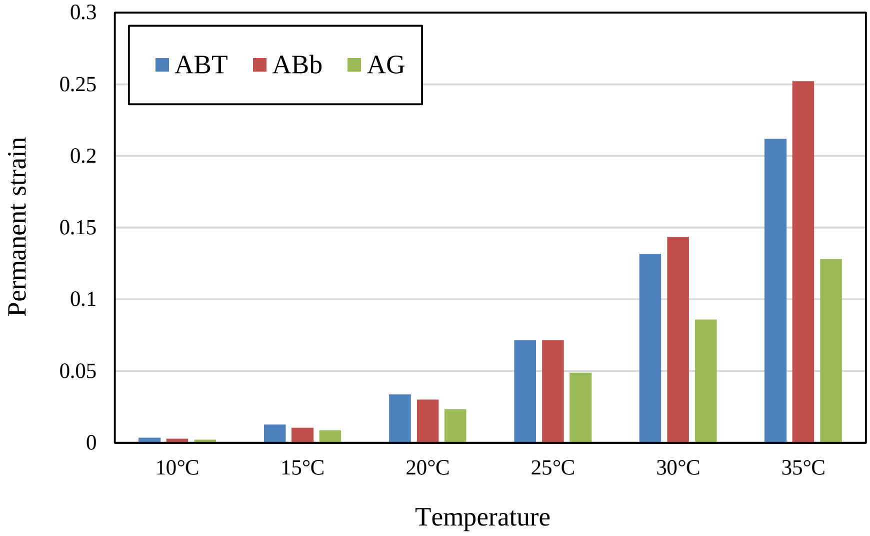


Figure 8: A comparison between rutting resistance of the asphalt mixtures through ELWT device

Figure 9 shows the results of the image analysis as the total contact length per unit area which is the measure of the aggregate to aggregate contact in the mix. The results are shown as average values from thin slices sawed from the unloaded as well as the loaded part of the slabs. From the unloaded values it can be seen that the ABT mixture shows the highest total contact length followed by the AG mix. This is due to the fact that these two mixtures have dense graded aggregate matrix (see Figure 4). The ABb mixture has a slightly gap graded aggregate structure and hence a lower contact length. The total contact length of the aggregate structure from the unloaded sections may be considered as the result of the initial compaction and the corresponding grain size distribution and other mixture properties.

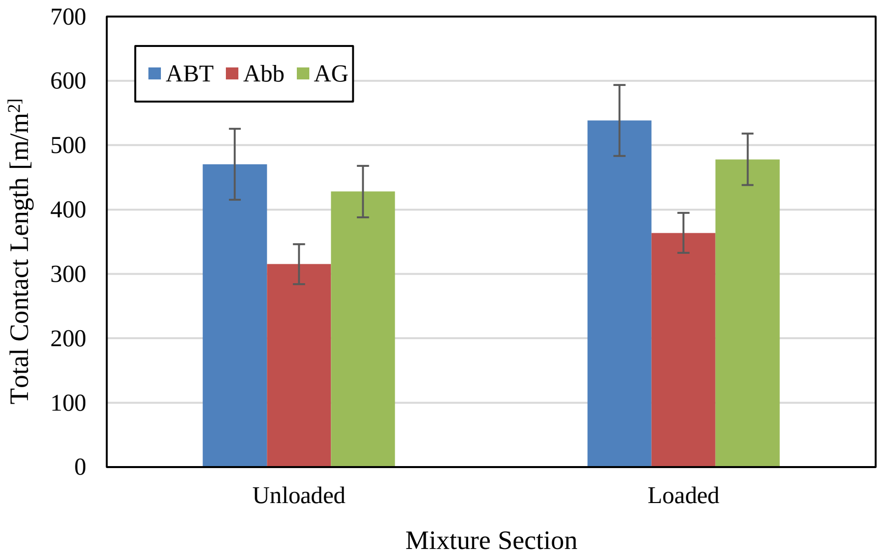


Figure 9: Total contact length of the asphalt mixtures

The effect of packing due to wheel loading is evident from Figure 9 by the difference in contact lengths between the unloaded and the loaded parts, i.e., the contact length from the loaded parts is higher than the unloaded parts for each of the three mixes. The change in contact length between the loaded and unloaded sections may be translated as the measure of the mixtures' susceptibility to rutting due to wheel loading. The observed increase in total contact length due to the loading is 14.5% for the ABT mix, 15.4% for the ABb mix and 11.7% for the AG mix. Accordingly taking into account the different mixes location in the structure the ABb mixture is most prone to rutting, followed by the ABT mixture and finally the AG mixture being the most rut resisting mixture. This ranking agrees well with the predicted performances of the mixtures in Figure 8.

7. CONCLUSIONS

This study investigated the application of a two-dimensional (2-D) image analysis technique to evaluate the role of aggregate packing in rutting performance of three different types of asphalt mixtures. The 2-D images are derived by scanning the cross sections of drilled cylindrical specimens taken from asphalt slabs which have been tested using an Extra-large wheel tracking device.

The mixture rutting performance was evaluated based on the total contact length, which is the measure of aggregate to aggregate connectivity. Furthermore, a higher total contact length of the aggregate structure of the mixtures was observed for specimens drilled from the loaded area than those from unloaded sections of the asphalt slabs indicating the effect of packing due to the induced wheel loading. The change in contact length between the loaded and unloaded sections may be translated as the measure of the mixtures' susceptibility to rutting due to wheel loading. Accordingly, the ranking of the rutting resistance of the three mixtures agreed well with the predicted performances. Therefore the image analysis results may explain the significant role of aggregate structure in rutting of pavements.

REFERENCES

[1]. Internal structure characterization of asphalt mixtures for rutting performance using imaging analysis, Roohi N. S., Laith T. and Bahia H. U., *Road Materials and Pavement Design*, 13:sup1, pp. 21-37, DOI: 10.1080/14680629.2012.657045, 2012.

[2]. NCHRP Report 508: *Accelerated laboratory rutting tests*: *Evaluation of the asphalt pavement analyser*, Kandhal, P.S., and Cooley, L. A., *Transportation Research Board, National Research Council*, Washington, D.C, 2003.

[3]. Mechanical testing of bituminous mixtures. In: Partl, M.N., Bahia, H.U., Canestrari, F., de la Roche, C., Di Benedetto, H., Piber, H., Sybilski, D. (Eds.). *Advances in interlaboratory testing and evaluation of bituminous materials. Report of the RILEM TC 206-ATB,* Di Benedetto, H., Gabet, T., Grenfell, J., Perraton, D., Sauzeat, C., and Bodin, D., pp. 143-256, Springer, ISBN 978-94-007-5104-0 (eBook), 2013.

[4]. Internal structure characterization of asphalt concrete using image analysis, Masad, E., Muhunthan, B., Shashidhar, N., and Harman, T., *ASCE Journal of Computing in Civil Engineering* (Special Issue on Image Processing), 13(2), pp. 88–95, 1999.

[5]. Aggregate orientation and segregation in asphalt concrete, Masad, E., Muhunthan, B., Shashidhar, N., and Harman, T., *ASCE Geotechnical Special Publication, 85*, pp. 69–80, 1998.

[6]. Sensitivity of HMA performance to aggregate shape measured using conventional and image analysis methods Masad, E., Little, D., and Sukhwani, R., *International Journal of Road Materials and Pavement Design, 5*(4), pp. 477–498, 2004.

[7]. Aggregate structure characterization of asphalt mixtures using 2-dimensional image analysis, Coenen, A. R., Kutay, M. E., and Bahia, H. U., *International Journal of Road Materials and Pavement Design*, 13(3), pp. 433-454, 2012.

[8]. Development of an image-based multi-scale finite-element approach to predict mechanical response of asphalt mixtures, Arshadi, A., and Bahia H., *Road Materials and Pavement Design*, pp.1-16, 2015.

[9]. Measurements of the lateral distribution of heavy vehicles and its effects on the design of road pavements, Blab, R., and Litzka, J., *In Proceedings of 4th International Symposium on Heavy Vehicle Weights and Dimensions,* Ann Arbor, MI, USA, 1995.

[10]. Dynamic modulus testing of asphalt concrete in indirect tension mode, Kim, Y. R., Seo, Y., King, M., and Momen, M., *Journal of the Transportation Research Board*, No. 1891, Transport Research Board of the National Academies, Washington, D.C., pp. 163–173, 2004.

[11]. *A Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures,* NCHRP 1-37, Final Report. NCHRP, ARA Inc., and ERES Consultants Division, Washington, D.C., 2004.¨

[12]. Laboratory evaluation of rutting in base course materials, Barksdale, R. D., In *Proceedings of 3rd International Conference on Structural Design of Asphalt Pavements*, London, September, pp.161–174, 1972.

[13]. Fast layered elastic response program for analysis of flexible pavement structures, Erlingsson, S. and Ahmed, A. W., *Road Materials and Pavement Design*, 14(1), pp. 196-210, 2013.

[14]. Development and Validation of Performance Prediction Model and Specifications for Asphalt Binders and Paving Mixes, Lytton, R. L., Uzan, J., Fernando, E. G., Roque, R., Hiltumen, D., and Stoffels, S. M., Report No. SHRP-A-357, Washington, DC: The Strategic Highway Research Program Project, 1993.
[15]. Evaluation of a permanent deformation model for asphalt concrete mixtures using extra-large wheel-tracking and heavy vehicle simulator tests, Abubeker W. Ahmed and Sigurdur Erlingsson, *Road Materials and Pavement Design*, 16(1), pp. 154-171, DOI:10.1080/14680629.2014.987311, 2015.