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Evaluation of significant factors for aggregate retention in chip seals based on mesostructured finite element model

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Abstract

The retention of aggregates or chips on chip seal is critical for the durability of chip seal application in pavement maintenance. Most evaluation on aggregate retention have focused on laboratory experiment regarding asphalt-aggregate bonding, however, there are many other factors that are needed to be investigated as a whole picture. As such, this paper presents a mechanistic point view of understanding the effects on the aggregate retention based on a two-dimensional finite element model of aggregate-asphalt interface. The horizontal strain and shear strain in the interface are evaluated in terms of six factors including asphalt type, temperature, loading level, horizontal loading, aggregate shape, and interface bonding conditions. The analysis of variance (ANOVA) of influencing factors for critical response is further conducted. The results show that shear strain is more significant than the horizontal strain, which should be taken as an evaluation index for aggregate retention in chip seal. The influence of six factors on the shear strain of aggregate-asphalt interface is highly significant. The greatest significant influence is temperature, followed by horizontal loading, asphalt type, loads, aggregate shape, and interface bonding conditions. The results of this study provides a mechanistic viewpoint for chip seal designer to consider varying conditions for ensuring aggregate retention in chip seal.

Keywords: Chip seals; Aggregate retention; Analysis of variance; Aggregate-asphalt interface; Finite element

1. Introduction

Chip seal is widely used in asphalt pavement as a cost-effective preventive maintenance technique, which is proven to seal and protect underlying pavements [1], provide additional friction [2], and even reduce aging in existing pavement [3]. However, with regard to chip seal itself, many distresses would occur, and aggregate (chip) loss is one of the primary early distresses in chip seal that significantly reduces durability of chip seal [4]. The insufficient aggregate retention is mainly because of the poor cohesion between aggregate and asphalt under a combined effect of temperature fluctuation and traffic loading. To understand the mechanism of aggregate retention and the associated factors is helpful for local agency to select appropriate chip seal and extend its service life.

Many researchers have focused on the experiment testing on the performance evaluation of aggregate retention in the chip seal. Aggregate loss is a common parameter in laboratory experiment to characterize aggregate retention. For example, Lee and Kim [5] used flip-over test and Vialit test to assess the aggregate retention. Miller et al. [4] developed bitumen bond strength (BBS) test to evaluate emulsion setting behavior that links to aggregate retention. Aktas and Karasahin [6] studied the effect of

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polymer-modified asphalt on aggregate retention performance of chip seal in cold climate. Based on the aggregate loss conducted by Accelerated Chip Seal Simulation Device, they found that modified asphalt binder exhibited better aggregate retention due to improved adhesion between binder and aggregate. Wasiuddin et al. [7] evaluated the sensitivity of sweep test which is a standard test in ASTM to aggregate and asphalt types, and application rate. Surface free energy has also been used to characterize the adhesion between aggregate and asphalt in chip seal [8].

Huurman [9] used three-dimensional (3D) model to link the mechanistic response in the chip seal to the chip seal distresses, such as permanent deformation, fatigue cracking, low-temperature, and moisture damage. For example, strain in the mastic was used to characterize fatigue cracking, and stress in the adhesive layer was linking to moisture damage. Gerber and Jenkins [10] used two-dimensional (2D) finite element to construct chip seal model and demonstrated its power to determine surface deterioration. Either 3D or 2D model provides analyzed critical response in the interface between aggregate and asphalt.

From the mechanistic point of view, a few studies have been attempted to evaluate the factors that affect chip seal performance, and some of them have pointed out the particular factors affecting the aggregate retention in chip seal [9,11–13]. Milne [14] used FEM to find out two types of factors: the binder type, aggregate and chip seal design as controllable factors, and moisture as non-controllable factor. A mechanistic analysis of stress strain on a single chip seal demonstrated that traffic loading, base binder type (polymer vs. non-polymer), and temperature contributed for the chip seal service life [15].

The performance of a chip seal depends on many factors, including the condition of the pavement to which the chip seal is to be applied, pavement geometry, traffic volume and type, materials, and construction practices [2]. There are many factors that link to the aggregate retention, such as asphalt binder type [6,11], aggregate surface property [12,13]. Based on literature review, there exists a gap in understanding factors that affect aggregate retention in chip seal from a mechanistic point of view. As such, this study gives insight into understanding the mechanism of aggregate retention based on finite element model. Factors associated with aggregate retention were also evaluated to see how they significantly affect, based on statistical analysis results.

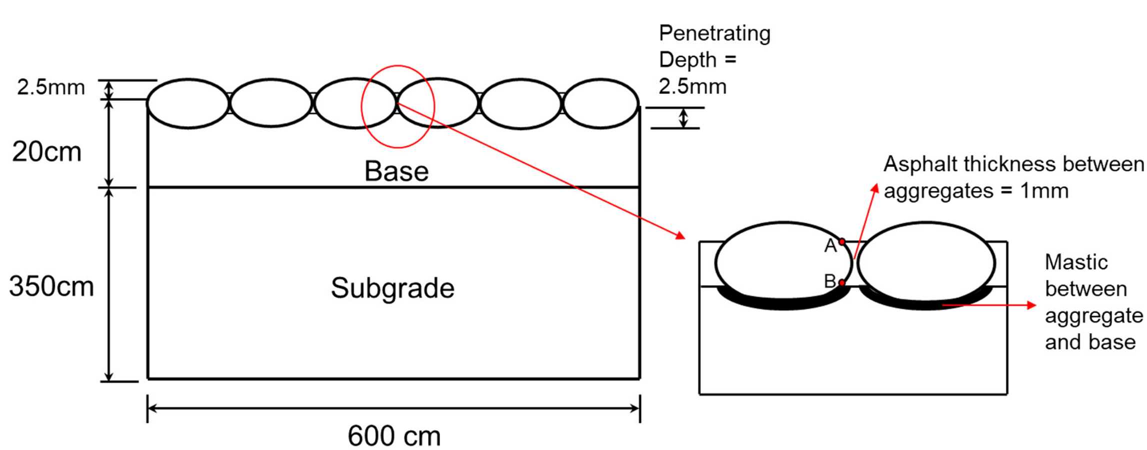
2. Research objectives

The objective of this research is to determine the significant factors that are associated with aggregate retention on chip seal. Both 2D model of chip seal mesostructure and pavement with chip seal were constructed, and the critical horizontal and shear strain were computed. Six significant factors were analyzed including asphalt binder type, temperature, loading, horizontal load, aggregate shape, and contact condition.

3. Macrostructure and mesostructure model

3.1. Model description

Chip seal is constructed by spreading chips (aggregates) over the asphalt that is directly distributed on the existing asphalt concrete layer or pavement base. In this study, the model is focused on the chip seal on the base, as shown in Fig. 1(a). This study focuses on aggregate retention in the chip seal, which is highly related to the critical response in the bonding layer (interface) between asphalt and aggregate, as shown from point A to point B in Fig. 1(b) where a two-dimension finite element model of chip seal mesostructure is established. The model consists of five components: aggregate, asphalt, mastic at the contact layer of aggregate and base, base, and subgrade. The aggregate length and height are 14 mm and 9 mm, respectively. The distance between each aggregate is 1 mm, which is also the asphalt thickness between aggregates. The mastic thickness is 1 mm. The penetration depth of aggregate into base layer



(a) (b)

Fig. 1. Sketch of finite element model for (a) pavement and (b) chip seal.

Table 1
Material properties.

Material	Elastic Modulus (MPa)	Poisson's ratio (μ)
Aggregate	40,000	0.25
Base	1300	0.35
Subgrade	40	0.40

is 2.5 mm. The material property for aggregate, base, and base are characterized by Young's modulus (E) and Poisson's ratio (μ), as shown in Table 1.

3.2. Burger's model for asphalt and mastic

Due to the viscoelasticity of asphalt and mastic, Burger's model with spring and dashpot as shown in Fig. 2 is used to characterize their material property [15]. The spring and dashpot in Burger's model are to characterize the elastic and viscous component, respectively. Table 2 presents the material parameters (E and ŋ) tested using the date obtained from dynamic shear rheometer (DSR) for unmodified and SBS-polymer modified asphalt binder and mastic at 20 °C. The elastic modulus and viscosity parameters in terms of time from DSR are used to construct Burger's model via regression to define Prony series coefficients, which are simply as inputs in ABAQUS to realize viscoelastic properties of binder and mastic. As seen, the SBS-polymer modified binder and mastic showed higher elasticity as well as viscosity than unmodified ones. The mastic has higher elasticity and viscosity than pure asphalt, due to the reinforcing effect of fines in the mastic.

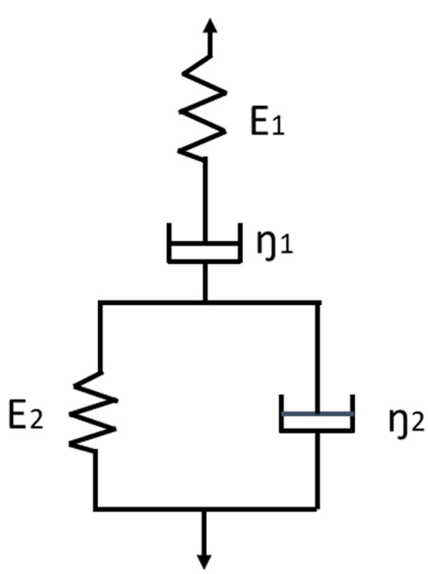


Fig. 2. Burger's model for characterizing asphalt and mastic.

Table 2
Parameters in Burger's Model.

Material	E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)
Unmodified Asphalt	0.625	0.543	0.175	0.011
SBS Modified Asphalt	0.875	1.030	0.190	0.360
Unmodified Mastic	1.59	0.23	0.92	0.86
SBS Modified Mastic	2.19	2.08	0.34	1.4

3.3. Loading and meshing

A single axle load of 100 KN is commonly used to represent standard traffic loading. According to static equivalent principle, the load is converted into circular-distributed loading area with diameter of 12.65 cm. Both inside and outside wheel track are characterized by a loading area of 12.65 cm, and the distance between inside and outside wheel track is 12.65 cm measured from inside edge to edge. To acquire a better accuracy of computation, a finer meshing is used for aggregate, asphalt and mastic in FE model via ABAQUS software, as shown in Fig. 3.

4. Analysis results

The bonding between asphalt and aggregate in chip seal is critical for the aggregate retention and durability of chip seal. This study evaluates the horizontal strain and shear strain at the interface between asphalt and aggregate. The maximum horizontal strain occurs on the edge of inside wheel track, and the maximum shear strain occurs at the edge of outside wheel track, which are the critical strain response investigated in this study. Below are discussed the effect of asphalt type, temperature, loading level, horizontal loading, aggregate shape, and contact condition, on the critical response in the interface, respectively.

4.1. Effect of asphalt type

Two different asphalt binders (SBS modified and unmodified) are used in this study to evaluate the effect of asphalt binder type on the aggregate retention of chip seal. The material properties for the asphalt binders are shown in Table 2. The horizontal strain and shear strain are shown in Fig. 4(a) and (b), respectively. As seen, the horizontal strain of the interface at the depth of less than 1 mm for modified asphalt is 15–20% lower than that for unmodified asphalt. The most significant effect is shown at the depth of close to 2.5 mm where the horizontal strain

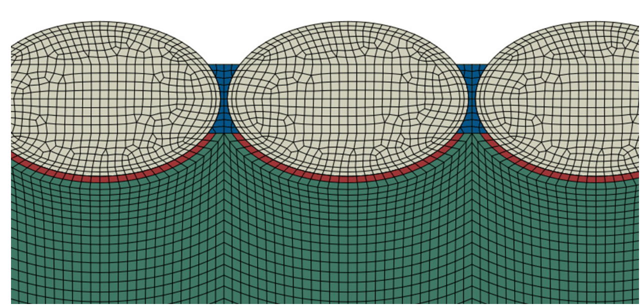


Fig. 3. Meshing of chip seal in mesostructured FE model.

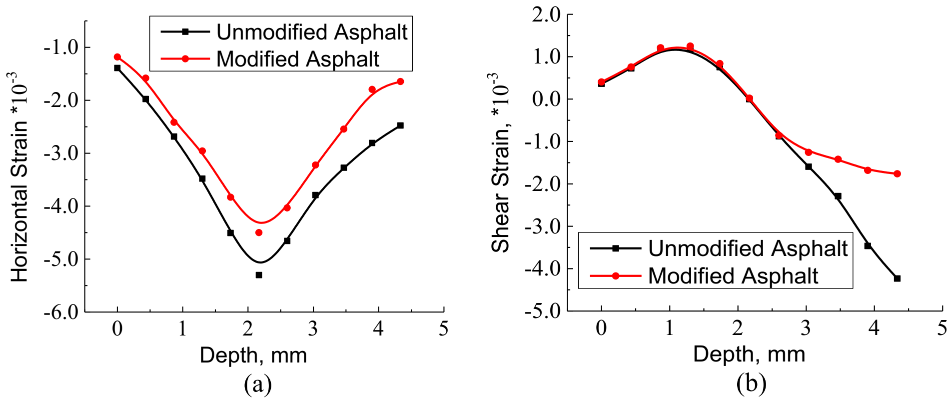


Fig. 4. Critical response in the aggregate-asphalt interface: (a) horizontal strain and (b) shear strain.

in the case of using modified asphalt is 36% lower than that of unmodified asphalt.

The shear strain for the case of modified asphalt is 58% less than that for unmodified asphalt at deeper bonding layer (depth more than 0.25 mm), but comparable at upper bonding layer (depth less than 0.25 mm). Using modified asphalt can significantly reduce the horizontal and shear strain at the lower bonding layer, because of its reinforcing effect due to higher viscosity of modified asphalt. The resistance to deformation at the asphalt-aggregate layer is significantly improved by modified asphalt. This is consistent with the findings in [5,6,16], which is based on laboratory experiment.

4.2. Effect of temperature

Chip seal is temperature sensitive due to that asphalt is thermal plastic material. Three temperatures (5, 20, and 40 °C) are evaluated in this study to demonstrate how temperature affects the aggregate retention in the chip seal. Higher temperature reduces the stiffness and viscosity of asphalt. As such, the effect of temperature is expressed by stiffness and viscosity in Burger's model, as shown in Table 3.

Fig. 5(a) and (b) present the effect of temperature on horizontal strain and shear strain, respectively. The horizontal strain at 5 °C is reduced by 49–82% as compared to that at 20 °C, however, at 40 °C, the maximum horizontal strain lies at the bottom of bonding layer, which is approximately five times that at 20 °C. It is seen that lower temperature contributes to the lower horizontal strain, but at higher temperature, the horizontal strain increases rapidly, which results in a weak bonding between aggregate and asphalt and thus prone to less aggregate retention.

Table 3
Material properties at 5 and 40 °C.

Material	E_1 (MPa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa·s)
Asphalt at 5 °C	16.8	28.9	4.51	7.61
Asphalt at 40 °C	0.0157	0.0129	0.00585	0.0043
Mastic at 5 °C	4.50	67.5	5.92	21.1
Mastic at 40 °C	0.13	0.02	0.03	0.05

With regard to the shear strain with depth in Fig. 5(b), temperature does not significantly affect shear strain at the upper layer, however, the shear strain increases with increasing temperature at the lower bonding layer, especially at 40 °C. The shear strain at 40 °C is 9–17 times that at 20 °C. In summary, temperature plays a significant role in shear strain at the interface: the shear strain increases with increasing time and depth. Lower temperature is beneficial for bonding, but high temperature deteriorates the stability of aggregate on asphalt.

4.3. Effect of loading level

The load level of 100 kN, pressure of 0.7 MPa is used as a standard load to compute the critical response in the interface. To evaluate the effect of loading level on the response of bonding layer, a total of six scenarios are studied: idling (20% of standard load), standard, overload (120% of standard load), overload (140% of standard load), overload (160% of standard load), and overload (200% of standard load). Fig. 6(a) shows the horizontal strain under different loading scenarios. As seen, there is a consistent trend for all horizontal strain curves that the maximum horizontal strain occurs at the middle of bonding layer (depth close to 2.5 mm). The higher loading level introduces the higher horizontal strain, which is expected. It indicates that traffic loading is critical for the critical response in the bonding layer. Heavy traffic has been found to cause more aggregate loss in chip seal [17,18].

Mises stress is associated with shear stress and distortion energy which is considered to be a safe haven for design engineers. If the maximum value of Mises stress in more than the strength of material, the material would fail, especially when the material is ductile in nature. Since asphalt and mastic are ductile materials it is appropriate to evaluate the Mises stress distribution in the bonding layer. Fig. 6 (b) presents the Mises stress with depth at different loading levels. The loading level has little effect on the Mises stress in the upper bonding layer (less than 2.5 mm in this study), but has a significant effect on the Mises stress in the lower bonding layer. The Mises stress in the lower bonding layer

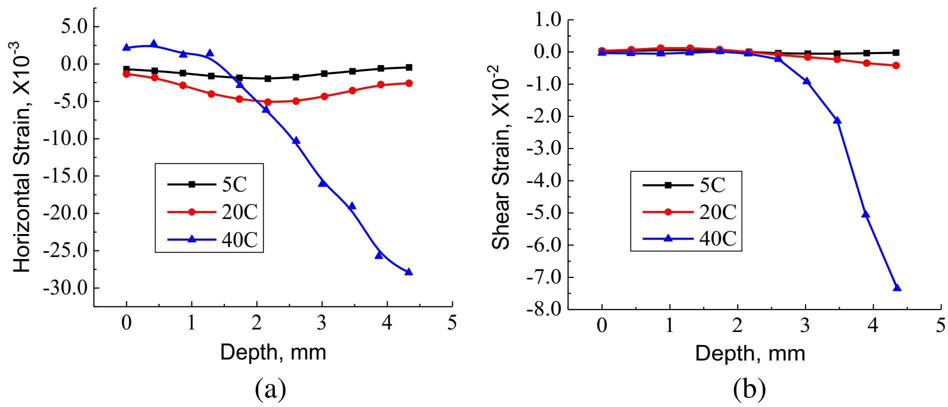


Fig. 5. Critical Response at the aggregate-asphalt interface under different temperatures: (a) horizontal strain and (b) shear strain.

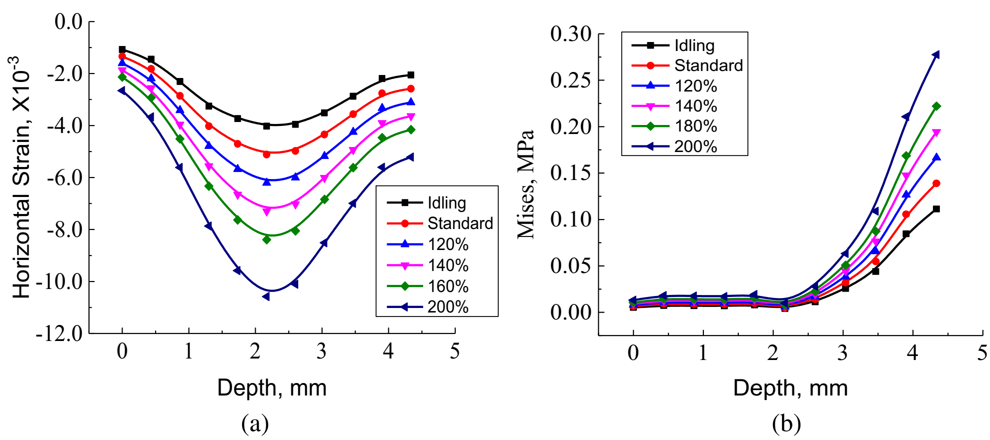


Fig. 6. Critical Response at the aggregate-asphalt interface under different loading levels: (a) horizontal strain and (b) shear strain.

increases with loading level. The higher the Mises stress, the higher shear the bonding layer is subjected to, and thus easier to result in shear deformation. Therefore, it is important to prevent overloading for low volume road with chip seal used, without compromising too much aggregate retention.

4.4. Effect of horizontal loading

The horizontal loading due to the vehicle impacts the response in the chip seal bonding layer. A horizontal load is taken as 15% vertical load in value. Fig. 7(a) presents the horizontal strain in the bonding layer for two cases: with and without horizontal loading. As seen, the horizontal strain in the bonding layer is increased by 24–44% for the case of considering horizontal loading, as compared to that for the case of only considering vertical loading. This increase is more significant in the lower bonding layer (depth higher than 2.5 mm) than in the upper bonding layer (depth less than 2.5 mm).

As shown in Fig. 7(b), the shear strain in the bonding layer for the case of considering horizontal loading is higher than that for the case of only considering vertical loading. At the lower bonding layer, shear strain is increased by 86%. This illustrates the significant effect of horizontal loading on the shear strain at the lower bonding layer.

4.5. Effect of aggregate shape

Aggregate shape is critical for the durability of chip seal. The aggregate shape is characterized by the ratio of length to height. The higher the ratio, the needle or flat shape the aggregate exhibits. Three scenarios of aggregate shape in terms of length and height were considered in this study: 14 mm × 3 mm, 14 mm × 6 mm, and 14 mm × 9 mm.

Fig. 8 presents the maximum horizontal strain and shear strain in the bonding layer for three aggregate shape cases. Comparable maximum horizontal strain is seen regardless of aggregate shape. This indicates that the aggregate shape has little effect on the maximum horizontal strain in the interface. However, aggregate shape affects the maximum shear strain. The maximum shear strain increases with higher ratio of length to height. This is to say, the aggregate having a needle or flat shape (high ratio of length to height) will result in increasing shear strain in the interface. The

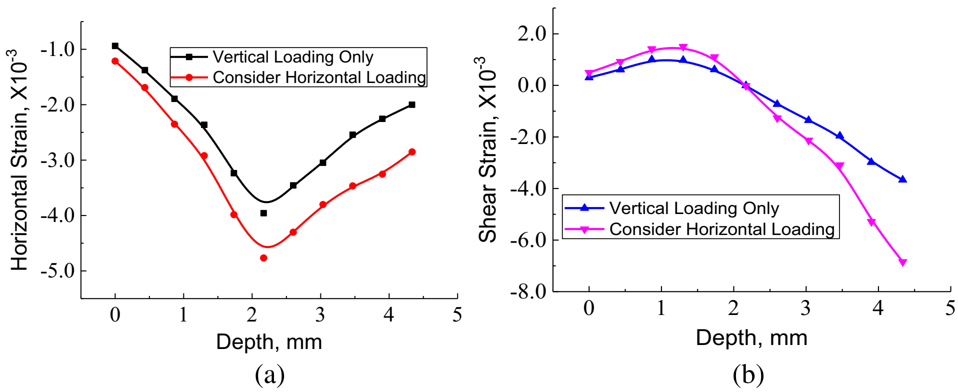


Fig. 7. Critical Response at the aggregate-asphalt interface with and without horizontal loading: (a) horizontal strain and (b) shear strain.

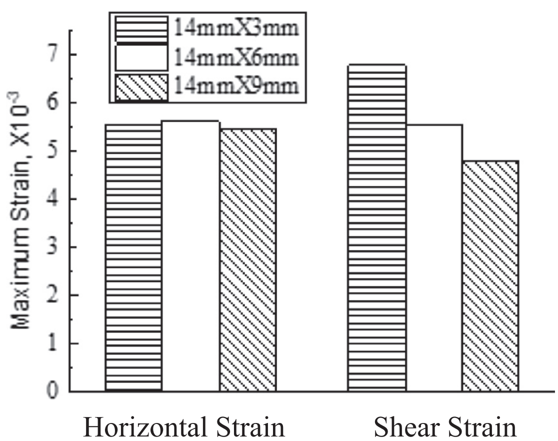


Fig. 8. Maximum strain in the bonding layer for three aggregate shapes scenarios.

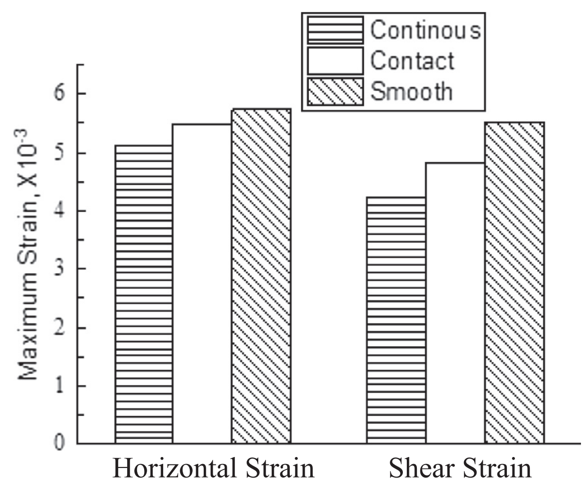


Fig. 9. Maximum strain of aggregate-asphalt interface under different bonding conditions.

reasons lie in that the needle or flat shape aggregate demands less surface areas to interact with asphalt, and thus resulting in less shear resistance. Therefore, it is of importance to assess the aggregate shape in the chip seal before its application.

4.6. Effect of contact condition

Three contact conditions between the asphalt and aggregate are evaluated on the horizontal strain in the bonding layer: smooth, contact, and continuous. The friction coefficient of 0, 0.8, and 1 are defined in ABAQUS to characterize smooth, contact, and continuous cases, respectively. Fig. 9 presents the maximum horizontal strain and maximum shear strain in the bonding layer for these three contact conditions. The "smooth" case shows the highest value for both maximum horizontal strain and shear strain, followed by "contact" case and "continuous" case. As such, more contact area between aggregate and asphalt, which ensures more sufficient bonding, contributes more significantly to the resistance to horizontal and shear deformation.

4.7. Statistical analysis

The analysis of variance (ANOVA) statistical analysis is further conducted to rank the significance of each factors on the critical response (i.e. horizontal strain and shear strain in this study) in the bonding layer. Table 4 presents the ANOVA result for horizontal strain. All the factors except contact condition have significant effect on the horizontal strain in the bonding layer. The ranking on the significance of factor on the horizontal strain follows: Temperature > Loading Level > Asphalt Type > Horizontal Loading > Aggregate Shape.

Table 5 presents the ANOVA result for shear strain. With p-value of all factors less than 0.05, all factors have significant effects on the shear strain in the bonding layer. The ranking on the significance of factor on the shear strain follows: Temperature > Horizontal Loading > Asphalt Type > Loading Level > Aggregate Shape > Contact Condition. As seen, temperature plays most significant role in aggregate retention in terms of both horizontal strain and shear strain in the interface.

Table 4
ANOVA result for horizontal strain.

Source	Sum of squares	Degree of freedom	Mean square	*F*-value	*p*-Value
Asphalt Type	5.90×10^{-7}	1	5.90×10^{-7}	109.349	1.38×10^{-4}
Loading Level	2.91×10^{-5}	4	7.28×10^{-6}	1348.465	9.13×10^{-8}
Aggregate Shape	1.11×10^{-7}	2	5.56×10^{-8}	10.292	1.69×10^{-2}
Temperature	5.16×10^{-4}	2	2.58×10^{-4}	47760.426	1.98×10^{-11}
Contact Condition	6.56×10^{-8}	3	2.19×10^{-8}	4.049	8.32×10^{-2}
Horizontal Loading	9.76×10^{-7}	1	9.76×10^{-7}	180.713	4.08×10^{-5}
Error	2.70×10^{-8}	5	5.40×10^{-9}	–	–
Sum	1.50×10^{-3}	19	–	–	–
Adjusted Error Sum	5.56×10^{-4}	18	–	–	–

Table 5
ANOVA result for shear strain.

Source	Sum of squares	Degree of freedom	Mean square	*F*-value	*p*-Value
Asphalt Type	5.66×10^{-6}	1	5.66×10^{-6}	98.219	1.78×10^{-4}
Loading Level	1.78×10^{-5}	4	4.46×10^{-6}	77.347	1.10×10^{-4}
Aggregate Shape	5.83×10^{-6}	2	2.92×10^{-6}	50.591	4.81×10^{-4}
Temperature	4.27×10^{-3}	2	2.13×10^{-3}	37015.352	3.75×10^{-11}
Contact Condition	3.41×10^{-6}	3	1.14×10^{-6}	19.729	0.003
Horizontal Loading	1.10×10^{-5}	1	1.10×10^{-5}	190.082	3.60×10^{-5}
Error	2.88×10^{-7}	5	5.76×10^{-8}	–	–
Sum	0.006	19	–	–	–
Adjusted Error Sum	0.005	18	—	–	–

5. Summary of findings

This study evaluates six factors that affect the aggregate retention on the chip seal. Macrostructure model for pavement structure and mesostructure model for chip seal are established based on 2-D finite element model. The horizontal strain and shear strain in the bonding layer are evaluated in terms of different factors, which mechanistically link to the aggregate retention in the chip seal. The findings are summarized as follows:

- With respect to asphalt type, the modified asphalt can effectively reduce the shear strain in the aggregate-asphalt bonding layer in chip seal. It is recommended to use modified asphalt to achieve aggregate retention in chip seal.
- The aggregate shape does not have significant effects on the horizontal strain in the bonding layer, but it has significant effects on the shear strain. Aggregates having needle shape (higher ratio of length to height) result in higher shear strain in the bonding layer, which is negative for aggregate retention on chip seal.
- The shear deformation of aggregate-asphalt bonding layer increases rapidly with increasing temperature. Higher traffic loading and horizontal loading also increase shear deformation. Therefore, prevention of overloading in low volume road where chip seal is used is much needed to ensure aggregate retention, especially in summer.
- Two critical responses are analyzed in this study which are horizontal strain and shear strain. Shear strain response is affected by all six factors investigated in this study, and it is recommended to use shear strain as critical response for evaluating aggregate retention in chip seal. The ranking on the significance of factor on the shear strain follows: Temperature > Horizontal Load ing > Asphalt Type > Loading Level > Aggregate Shap e > Contact Condition.
- Temperature plays the most significant role in aggregate retention of chip seal. Lower temperature is beneficial for bonding, but high temperature deteriorates the stability of aggregate on asphalt. As such, selecting appropriate asphalt binder based on climate condition is critical for aggregate retention. Future study is recommended on considering angularity of aggregate that relate to aggregate retention in chip seal.

Future study will consider the effect of other environmental factors, such as rain, snow, and temperature variation, as well as fine-tuning aggregate shape modeling. As this study focused on the interface layer between aggregate and binder, future study is also recommended on the analysis beyond interface layer as well as developing model that can characterize the chip seal on the existing HMA pavement.

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