THE EFFECT OF ASPHALT PAVEMENT TEXTURE ON BRAKING DISTANCE

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ABSTRACT

To simulate three dimensional asphalt pavement texture in the field using finite element software, Iterated Function System (IFS) fractal interpolation method in Matlab software was used in this study based on laboratory measured data. The data obtained from Matlab were imported into finite element software ABAQUS, and three dimensional finite element model of tire-pavement interaction was accordingly established. In this model, mean texture depth (MTD) and content of coarse and fine aggregates of pavement varied and led to different braking distance of the tire. Simulation results indicated that braking distance decreased with the increase of MTD, and this tendency became more obvious when the initial braking speed and braking deceleration were higher. However, this tendency appears to be moderate when the MTD exceeds a specific range. It also shows that the braking distance decreased with the content of coarse aggregates increasing and the content of fine aggregates decreasing. There were no significant differences in the decrease of braking distance due to the increase of coarse aggregates and the decrease of fine aggregates, implying that the influence of coarse and fine aggregates content on tire braking distance was close to each other.

Keywords: asphalt pavement texture, IFS fractal interpolation, finite element model, tire-pavement interaction, braking distance.

INTRODUCTION

Pavement texture plays an important role in skid resistance, in either dry or wet condition. A number of studies and field tests have been conducted to test the effects of pavement texture on skid resistance. To clarify these effects and avoid exhausting laboratory and field tests more effectively, finite element simulation method was introduced in this paper to analyze tire-pavement interaction. Finite element simulation method has been used in this field for years. White et al. analyzed the pavement response under a moving aircraft load by using a three dimensional finite element model. In that mode, pavement was considered as a layered structure with three materials: asphalt mixture, granular material and cohesive soils (White et al., 1995). Chatti developed a dynamic model to analyze discontinuous rigid pavements subjected to moving transient loads in the time domain and frequency domain. He built the model of the pavement slabs using a four-noded, twelve-degree-of-freedom, medium thick-plate bending element (Chatti, 1992). Meng established a low profile radial smooth tire to roll over the rigid pavement. Different tire pressure and load levels, moving speeds, slip angles, braking or traction, and friction are applied in the simulation (Meng, 2002). Ong and Fwa built tire and pavement surface with grooves. Three basic grooving configurations were considered: ungrooved, longitudinally grooved, and transversely grooved (Ong. et al., 2010). Moreover, studies on tire/fluid/pavement multi-field coupling can also be found in previous studies (Wolters, et al., 2002; Ong. et al., 2007; Ong. et al., 2010; Ji, 2004). Pavement texture in finite element analysis that has been studied in former studies were mostly smooth or with longitudinal or transverse groove. This kind of simulation significantly helped simplify the numerical simulation process, resulting in less calculation time and more simple interaction conditions. However, there were still big differences between the pavements built in the simulation and in the real field, so the work needs to be done to build better model which can represent the pavements in real condition.

In this paper, to simulate three dimensional asphalt pavement texture in the field using finite element software, Iterated Function System (IFS) fractal interpolation method in Matlab software was used in this study based on laboratory measured data. The data obtained from Matlab were imported into finite element software ABAQUS, and three dimensional finite element model of tire-pavement interaction was accordingly established. Braking distance was chosen to evaluate skid resistance of pavement with different textures. based on different mean texture depth (MTD) and/or different content of coarse and fine aggregates of pavement, braking distance of the tire can be determined. The skid resistance of asphalt pavement with different MTD and aggregates content can then be analyzed accordingly. The study results will provide useful information in terms of choosing asphalt mixture that can provide relatively high skid resistance pavement.

FRACTAL SIMULATION

Three dimensional pavement texture data can be obtained through many ways, such as by field test or numerical simulation. A numerical simulation method, Fractal Interpolation, was introduced in this study to simulate pavement texture. This method has been widely used in pavement engineering, such as in fields of describing pavement performance and mixture grading composition. An evaluation index named fractal dimension (D) could be determined in this method. As to pavement skid resistance, fractal interpolation method has been used to describe shape characteristics of aggregate. It indicated that aggregate coarse extent increased with increased of D (Li, et al., 1993). This method was also used to describe smoothness or roughness of pavement texture, and former research showed that pavement texture became rougher with the increase of D value, so a lower D value represents a smoother pavement texture (Kokkalis, et al., 1998). The advantages of using fractal interpolation method in pavement texture simulation include that (1) it can effectively simulate irregular shape of aggregates; (2) evaluation index D employed in fractal theory can effectively reflect changes of pavement texture; (3) fractal dimension acted as a bridge between macroscopic and microscopic texture (Li, et al., 1995).

In this study, using the limited field measured pavement data fractal theory was applied to simulate three dimensional pavement texture data. In fractal theory, numerous interpolation methods have been used and every method has its own application scope. For example, some can be used for a relatively large scale simulation, like shape of mountain or coastline, while others may be applied for a relatively small scale numerical analysis, such as abrasion analysis between bearings. Amongst numerous interpolation methods ,IFS method was chosen in this study to conduct pavement texture simulation. During simulation process, two issues are supposed to be specially addressed. The first one lies in boundary continuity, which should be set carefully to assure the continuity of data. The other one is Vertical ratio factor $\alpha_{n,m}$. When $\alpha_{n,m}$ close to 1, the pavement texture proved to be rougher, and $\alpha_{n,m}$ close to 0 indicated a smoother pavement texture.

The simulation procedures in Matlab included the following steps: (1) Input laboratory measured three dimensional pavement texture data; (2) Calculate parameters that are necessary for IFS interpolation method; (3) Conduct iteration process (Zhang, 2011). Iteration times depend on particular parameters in Matlab. Obviously, too many iteration times will take a large amount of time. The final simulation results can be seen in figures 1 and 2.

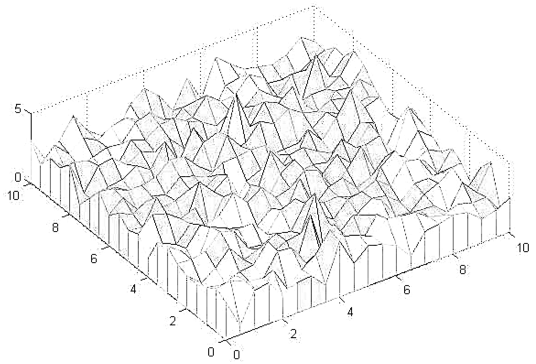


Figure 1 Pavement texture before IFS

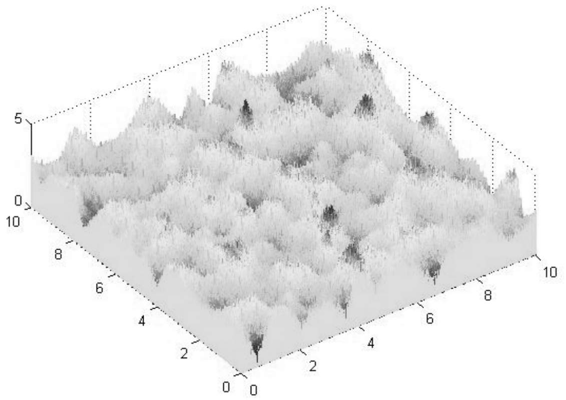


Figure 2 Pavement texture after IFS

Figures 1 and 2 show that before and after IFS interpolation was conducted, outline of pavement similar to each other. However, pavement texture after IFS becomes rougher and more similar to real asphalt pavement texture. Therefore, IFS interpolation method turns out to be an effective way in asphalt pavement texture simulation.

FINITE ELEMENT SIMULATION

Three dimensional pavement texture data from Matlab were imported into finite element analysis software ABAQUS to simulate asphalt pavement texture. A tire model was also established, and interaction between tire and pavement was defined.

Tire Model

A smooth tire model was used and its type is 175 SR14. A real tire always contains a lot of parts and the tire model used in this study was simplified into three parts. The parameters are presented in table 1. The tire model can be seen in figure 3.

Table 1 Properties of three tire parts

Parameters Tire parts	Poisson's ratio	Elastic modulus(GPa)	Density(kg/m^3)
Tread and sidewall	0.3	0.0987	1100
rim	0.3	100.0	7800
Cord and bead	0.3	172.2	5900

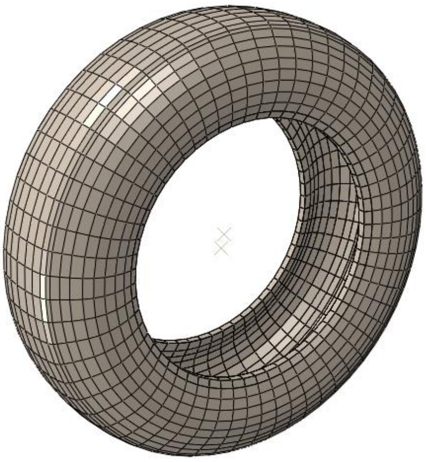


Figure 3 Tire model

The effectiveness of the tire model was also verified using subsidence. Komandi G tire subsidence formulation was chosen as the verified criterion.

$$h = C\frac{KQ^{0.85}}{W^{0.75}D_0^{0.43}P^{0.6}} \tag{1}$$

where:

C : design parameter, for radial tire used in this study C equals to 1.5

W: cross section width of pneumatic tire

P: tire pressure

D_0: outside diameter of pneumatic tire

The parameter K can be calculated as following,

$$K = 15\times10^{-3}W + 0.42 \tag{2}$$

According to the experience formula (1), tire subsidence under three loads, namely 3300N, 2475N and 1650N, were determined. Subsidence in the tire model was also calculated, results can be seen from figure 4.

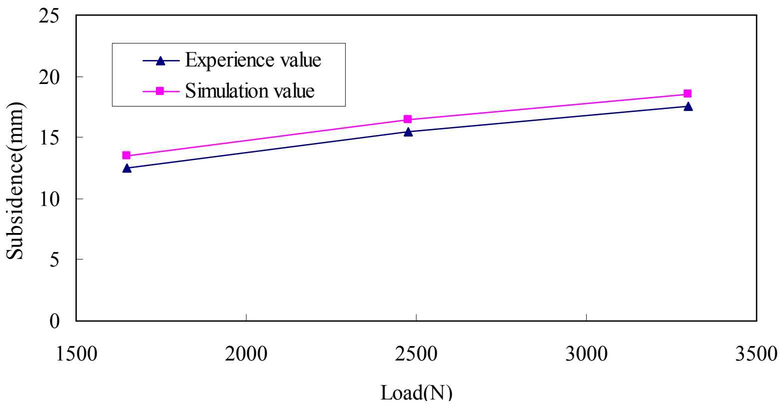


Figure 4 Subsidence of tire

From figure 4, it is thus clear that subsidence values of experience and simulation are close to each other and the change tendency is identical, which means that the tire model used in the study is suitable.

Pavement Model

Pavement texture data exported from Matlab were imported into ABAQUS. These data from Matlab are three dimensional coordinates and some transfer orders are needed to make these data readable by finite element software (ABAQUS documentation),. Final pavement model can be seen from figure 5.

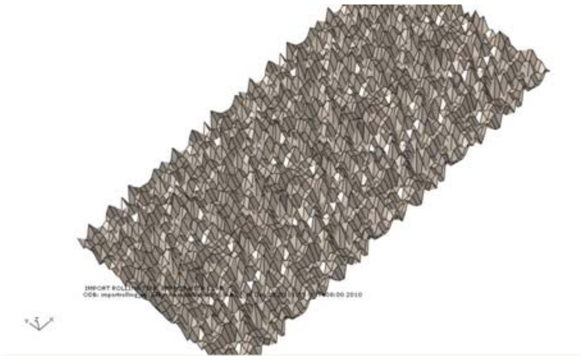


Figure 5 Pavement model

Figure 5 indicated that asphalt pavement texture in ABAQUS is similar to that in Matlab, meaning that the data import process was successful. Besides, the import process did not change aggregates shape and pavement texture, which guaranteed the simulation results in ABAQUS can reflect skid resistance of asphalt pavement texture accuately.

Coupling Between Tire and Pavement

Coupling between tire and pavement was defined using coulomb friction law as following:

$$\tau = \frac{F_T}{\mu\lambda} \tag{3}$$

where:

F_T: tangential force

μ: friction coefficient

λ: normal force

Tire-pavement model is shown in figure 6.

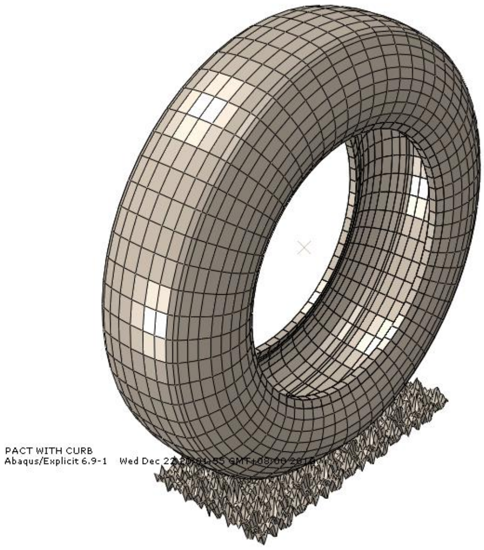


Figure 6 Tire-pavement interaction model

Mean Texture Depth

Mean Texture Depth (MTD) is regarded as an important index in pavement skid resistance evaluation. In this paper, by changing MTD value, different tire braking distances were obtained. In field test, MTD is usually detected by sand patch test, but since this test method requires hand operation, test results of same asphalt mixture may vary due to manual error. So another index Mean Profile Depth (MPD) was firstly introduced in this study. The proposal of MPD was to make up for the disadvantages of sand patch test, and the MTD value will be calculated through an experience equation. Physical meaning of MPD can be seen from figure 7.

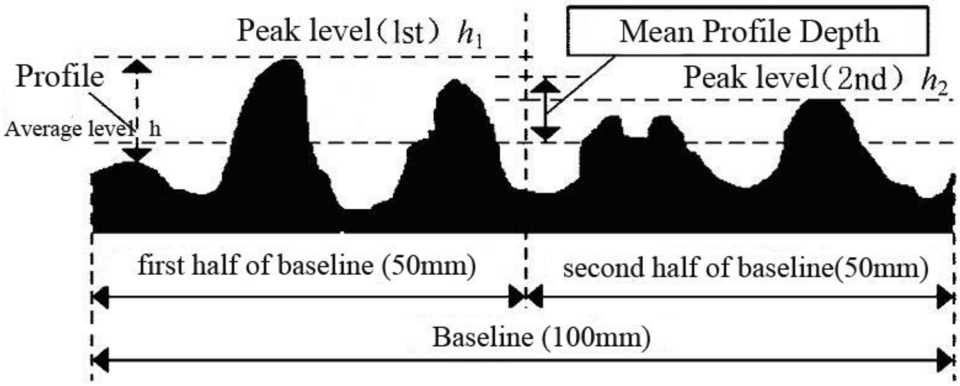


Figure 7 Mean Profile Depth

Calculation of MPD was conducted based on a 100mm sample scope. The sample can be evenly divided into two parts, with a length of 50mm for each. From each part a peak value can be obtained, namely peak level 1^{st} and peak level 2^{nd}. An average level is also necessary when calculating MPD. MPD (MPD in the formula 4) can be obtained from the following equation,

$$MPD = \frac{h_1 + h_2}{2} - h \tag{4}$$

where:
h_1: peak level 1^{st}
h_2: peak level 2^{nd}
h: average level

Table 1 shows three dimensional data of SMA-13 used In this study,.

Table 2 Three dimensional data of SMA-13

Number	1	2	3	4	5	6	7	8	9	10
x_i	3.024	3.652	12.147	12.575	14.628	16.168	21.130	22.849	22.614	26.519
y_i	3.024	3.652	12.147	12.575	14.628	16.168	21.130	22.849	22.614	26.519
z_i	1.460	0.347	0.563	0	1.483	0	-0.815	-0.628	-0.142	1.493
Number	11	12	13	14	15	16	17	18	19	20
x_i	33.191	42.858	44.740	57.178	60.514	61.284	68.564	74.749	82.876	100
y_i	33.191	42.858	44.740	57.178	60.514	61.284	68.564	74.749	82.876	100
z_i	1.922	-2.225	1.629	1.277	-0.243	1.312	1.112	-1.712	1.620	0

In table 2, numbers 1 to 13 were seen as the first half baseline, then h_1 should be 1.922mm, numbers 14 to 20 were seen as the second half baseline, then h_2 should be 1.620, h was calculated as 0.388mm. According to the data and the equation presented above, the MPD can be calculated as 1.383mm, the MTD then can be obtained by the following equation,

$$ETD = 0.8MPD + 0.2 \tag{5}$$

where:
ETD: Estimated Texture Depth
MPD: Mean Profile Depth

The MTD value is used as a control value when pavement texture was obtained in Matlab. In other words, the average value of pavement MTD in Matlab was set as 1.306mm. Pavement texture seen from X-Z direction is presented in figure 8. Although, there are lots of peaks and nadir showed in figure 8, the average value of these points is 1.036mm.

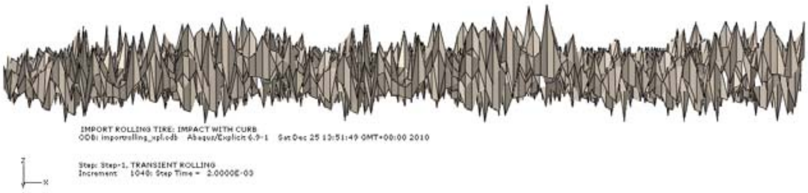


Figure 8 Pavement texture in X-Z direction

SIMULATION RESULTS

After establishing tire-pavement interaction model, efforts were made to transfer the tire on the pavement. Three initial braking speed, 25km/h，50km/h and 75km/h were used. Braking decelerations were set as -5 m/s^2，-6 m/s^2 and -7m/s^2. The length of pavement varied when using different initial braking speed, namely a relatively short length for 25km/h, medium length for 50km/h, and long length 75km/h. Varied length of pavement will save a lot of calculation time since a long pavement is not necessary for a relatively low initial braking speed.

Influence of MTD

To analyze the influence of MTD on pavement skid resistance, seven different MTD values were used, including 0.706mm，0.906mm，1.106mm，1.306mm, 1.506mm，1.706mm and 1.906mm. The braking distance simulation results are presented in table 2.

Table 3 shows that braking distance decreased with the increase of MTD value, and this tendency became more significant when braking started at a relatively high speed (75km/h). The probable reason is that MTD value is an index that reflects pavement macro-texture, and study result shows that a bigger MTD value indicated a rougher pavement texture, which means a high skid resistance.

Table 3 Braking distance simulation results for different MTD

Braking deceleration (m/s^2)	a=-5			a=-6			a=-7		
Initial braking speed (km/h)	25	50	75	25	50	75	25	50	75

0.706	6.47	21.54	45.86	5.59	18.33	39.42	5.34	15.04	34.45
0.906	6.22	21.22	45.46	5.26	17.92	38.95	4.87	14.57	33.84
1.106	6.01	20.92	45.09	4.97	17.53	38.46	4.4	14.02	33.21
1.306	5.86	20.65	44.67	4.65	17.09	37.98	4.01	13.61	32.67
1.506	5.55	20.27	44.29	4.31	16.64	37.41	3.59	13.16	32.15
1.706	5.47	20.15	44.07	4.19	16.41	37.12	3.43	12.92	31.93
1.906	5.39	19.92	43.82	4.06	16.22	36.84	3.21	12.68	31.67

In table 3, define 0.706=x_1, 0.906=x_2, ⋯⋯， 1.906=x_7, using x_{i-1} minus x_i, the change rate of braking distance due to MTD can be obtained, as shown in table 4.

Table 4 Change rate of braking distance by MTD

Braking deceleration (m/s^2)	a=-5			a=-6			a=-7		
Initial braking speed (km/h)	25	50	75	25	50	75	25	50	75
x_1-x_2	0.25	0.32	0.4	0.33	0.41	0.47	0.47	0.47	0.61
x_2-x_3	0.21	0.3	0.37	0.29	0.39	0.49	0.47	0.55	0.63
x_3-x_4	0.15	0.27	0.42	0.32	0.44	0.48	0.39	0.41	0.54
x_4-x_5	0.31	0.38	0.38	0.34	0.45	0.57	0.42	0.45	0.52
x_5-x_6	0.08	0.12	0.22	0.12	0.23	0.29	0.16	0.24	0.22
x_6-x_7	0.08	0.23	0.25	0.13	0.19	0.28	0.22	0.24	0.26

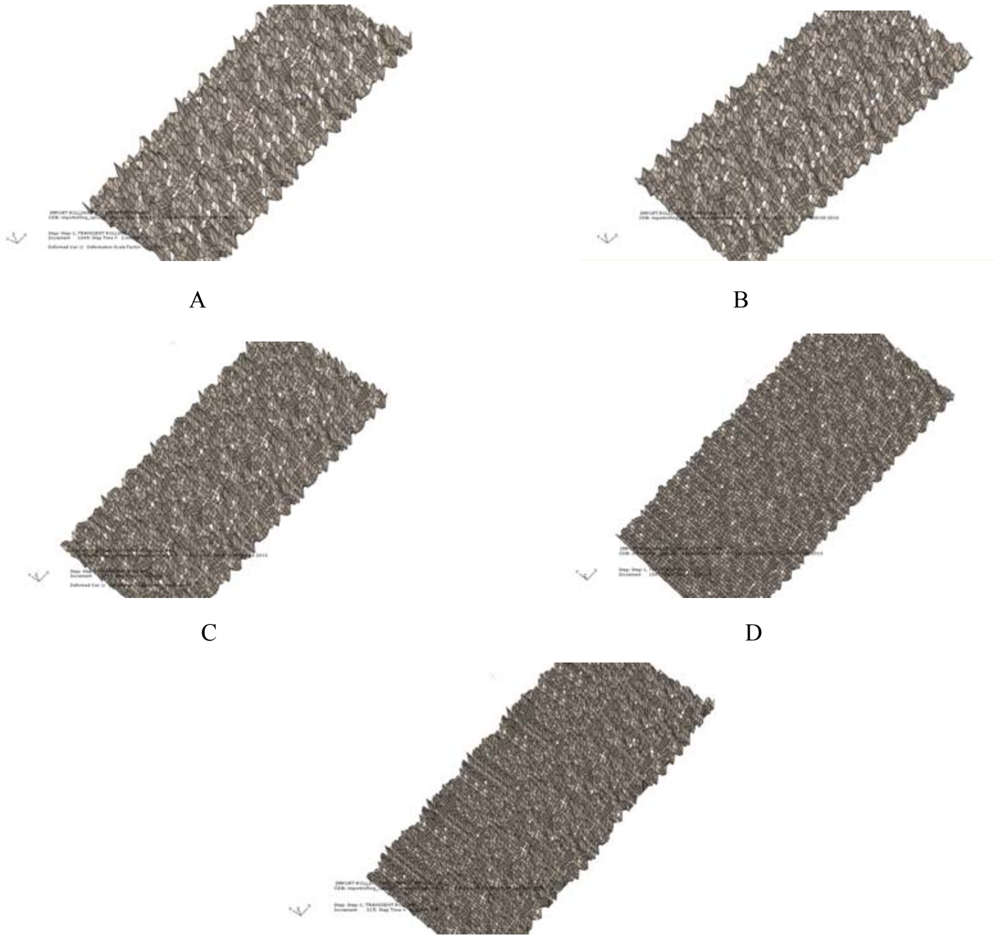
Table 4 indicates that between 0.706mm and 1.506mm (x_1-x_2、x_2-x_3、x_3-x_4 and x_4-x_5), braking distance decreased with the increase of MTD value, and the change rate is relative high. Nevertheless, between 1.506mm and 1.906mm(x_5-x_6 and x_6-x_7), the change rate of MTD value is relatively low, indicating that improved pavement skid resistance due to increased MTD value begins to get limited. This means that to get a high skid resistance pavement, it is not good to set an excessively high MTD value. Besides, pavement texture with high MTD may give rise to water susceptibility and need a higher compaction effort.

Influence of Coarse and Fine Aggregate Content

The content of coarse and fine aggregate can cause changes of pavement texture, thus influence pavement skid resistance. Based on the present asphalt pavement, change of coarse and fine aggregate content were obtained to analyze braking distance.

Aggregate content change was realized by regulating three dimensional pavement data density. Based on the pavement texture in figure 5, 10% content of data were evenly deleted, and then the space of those deleted data became empty and adjacent two data will connected together. Content changes of other level can be realized in the same way. Finally, five kinds of aggregate contents were obtained, namely 10% and 20% added fine aggregate, 10% and

20% added coarse aggregate, and the original pavement texture. Simulation results can be seen as in figure 9.



A B C D E

Figure 9 Pavement model with different coarse and fine aggregate contents

The braking distance simulation results are presented in table 5. From the table, it can be seen that braking distance decreased with the increase of coarse aggregate content, and increased with the increase of fine aggregate content. This is mainly because that coarse aggregate is an important part to form pavement macro-texture. When coarse aggregate content increased, pavement macro-texture becomes coarser, and MTD accordingly increased, resulting in higher pavement skid resistance. When fine aggregate content increased, pavement macro-texture becomes smoother, and MTD accordingly decreased, resulting in lower pavement skid resistance.

Table 5 Influence of different aggregate content on braking distance

Braking deceleration(m/s^2)	a=-5			a=-6			a=-7		
Braking Initial Speed(km/h)	25	50	75	25	50	75	25	50	75
A（20%）	5.21	18.84	41.82	4.36	16.12	35.01	3.82	12.25	29.17

B（10%）	5.68	19.97	43.85	4.58	16.92	37.66	3.92	13.49	31.01
C（0%）	5.86	20.65	44.67	4.65	17.09	37.98	4.01	13.61	32.67
D（-10%）	6.08	21.08	45.53	5.08	17.59	39.07	4.26	14.26	34.12
E（-20%）	6.28	22.08	47.87	5.36	18.06	41.38	4.37	14.99	36.12

The relative influence of different aggregate contents on braking distance can be seen in table 6.

Table 6 Influence extent of different aggregate content to braking distance

Braking deceleration (m/s^2)	a=-5			a=-6			a=-7		
Braking Initial Speed (km/h)	25	50	75	25	50	75	25	50	75
C-A	0.65	1.81	2.85	0.29	0.97	2.97	0.19	1.36	3.5
C-B	0.18	0.68	0.82	0.07	0.17	0.32	0.09	0.12	1.66
C-D	0.22	0.43	0.86	0.43	0.5	1.09	0.25	0.65	1.45
C-E	0.42	1.43	3.2	0.71	0.97	3.4	0.36	1.38	3.45

From table 6, it can be seen that increase of coarse aggregate content significantly affected braking distance with relatively high initial braking speed, but it did not affect braking distance with low braking initial speed. This is because that coarse aggregate increase pavement macro-texture, which worked critically in relatively high initial braking speed.

Furthermore, there were no big differences between the shortened distance due to increase of coarse aggregates and lengthened distance due to increase of fine aggregates. Consequently, the influence degree of coarse and fine aggregate on braking distance seems to be close.

CONCLUSIONS

IFS fractal interpolation method was used in this paper to simulate asphalt pavement texture. Three dimensional pavement texture data from fractal method were imported into finite element software to simulate asphalt pavement. In finite element software ABAQUS, a smooth tire was also established and tire-pavement coupling was defined. Braking distance of tire was chosen to determine the influence of MTD and aggregate content on pavement skid resistance. Results from this study can be summarized as following.

(1) IFS interpolation method is a good method to simulate asphalt pavement texture. Outline of pavement before and after IFS interpolation similar to each other.

(2) Asphalt pavement texture in finite element software can be obtained from IFS interpolation method, and data transfer did not cause shape changes of aggregates and pavement texture.

(3) Braking distance decreased with the increase of MTD value, but this tendency becomes

moderate when MTD value exceeds 1.506mm.

(4) Asphalt pavement skid resistance decreased with the increase of coarse aggregate content, and increased with the increase of fine aggregate content. Nevertheless, this is also effective at a relatively high initial braking speed.

RECOMMENDATIONS

Several recommendations are given based on the results obtained from this study:

(1) Only original data from SMA-13 are used in this paper, more mixture types are supposed to be concluded when using fractal interpolation method to simulate three dimensional pavement texture.

(2) The tire employed in this paper is a smooth one. However, a tire with curve will be better to simulate interaction between tire and pavement in the real field.

(3) The pavement used in this study is characterized as rigid body, but this simplified interaction of tire-pavement model is not consistent with real situation. Therefore, material properties of pavement are supposed to be added in the following study.

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REFERENCES

ABAQUS 6.9 documentation. http://abaqusdoc.ucalgary.ca/v6.9/

Chatti (1992). K. “Dynamic Analysis of Jointed Concrete Pavements Subjected to Moving Transient Loads.” Ph. D. Dissertation, The University of California, Transportation Center.

Ji, Tianjian (2004). “Effect of Rainfall on Adhesion Coefficient of Tire-Pavement Interface.” Ph. D. Dissertation, Southeast University, School of Transportation.

Kokkalis, Alexandros G. and Panagouli, Olympla K. (1998) “Fractal Evaluation of Pavement Skid Resistance Variations, Ⅰ: Surface Wetting.” *Chaos, Solitons and Fractals*, 9(11), 1875-1890.

Li, G.Q., and Deng, X.J. (1995). “Fractal effect of grading aggregate”, *Concrete* 1, 3-7.

Li, Lan, Chan, Paul, Zollinger, Dan G., and Lytton, Robert L. (1993). "Quantitative Analysis of Aggregate Shape Based on Fractals", *ACI Materials Journal*, 90(4), 357-365.

Meng, Lan (2002). Truck "*Tire/Pavement Interaction Analysis by the Finite Element Method.*" Ph. D. Dissertation, Michigan State University, Department of Materials Science and Mechanics.

Ong, G. P. and Fwa, T. F. (2010). "Relative Effectiveness of Grooves in Tire and Pavement in Reducing Vehicle Hydroplaning Risk." *Transportation Research Board 89th Annual meeting*, Washington, D.C.

Ong, G. P. and Fwa, T. F. (2010). "A Mechanistic Interpretation of Braking Distance Specifications and Pavement Friction Requirements." *Transportation Research Board 89th Annual meeting*, Washington, D.C.

Ong, G. P. and Fwa, T. F. (2007). "Wet-Pavement Hydroplaning Risk and Skid Resistance: Modeling." *ASCE Journal of Transportation Engineering*, 2007, 133(10): 590-598.

Wolters, A. S., and Grogg, M. G. (2002). "*HMA Pavement Smoothness- Characteristics and Best Practices for Construction*." Publication No. FHWA-IF-02-024, Federal Highway Administration, Washington DC, 32.

White, T. D., Zaghloul, S. M., Anderton, G. L., and Smith D. M. (1995). "Using of a Three-Dimensional, Dynamic Finite Element Mode to Study the Effect of Unbound Layer Characteristics on Pavement Response to a Moving Aircraft Load." *Transportation Research Board 74th Annual meeting*, Washington, D.C.

Zhang, W.G. (2011). "*Research on Design Method of Skid Resistance Asphalt Mixture Based on Pavement Texture*", Master's Thesis, Southeast University, School of Transportation, 19-23.