The Effects of Surface Textures on Frictional Noise and Skip Resistance Based on Indoor Experiments

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ABSTRACT

Past researches indicated the richer texture provided higher skip resistance ability, but induced louder noise. The objective of this paper is to seek an optimal surface texture which can lead to lower noise and maintain reasonable skip resistance by means of indoor measurements of frictional noise and skip resistance on lab-compacted asphalt slabs. Four aggregate gradations were selected and lab-compacted slabs are prepared. Before and after abrasions by the Dorry abrasion testing machine, BPNs (British Pendulum Numbers) on the test samples were measured by a BP, simultaneously frictional noise levels were measured by a noise meter. Then, surface textures of these samples were scanned with a 3D laser scanner and were characterized by newly-developed texture depth cumulative curve (TDCC). Regression method was utilized to investigate the relationship between noise levels, skip resistance and texture. The result shows that, the distribution of texture depth of samples can be captured by developed TDCC and characterized by parameter a_d of this curve. BPN values and noise levels are mostly controlled by CRTD less than 2mm. After initial optimization of surface texture, frictional noise can be decreased from 75.0 dB to 74.1 dB and skip resistance (BPN) was maintained at 62. The findings help to optimize surface texture to achieve lower noise and reasonable skip resistance.

1 INTRODUCTION

The traffic noise is the main resource of noise pollution in the city (*1*-*3*). With the development of automotive industry, the noise of power unit is reduced and tire/road noise becomes the dominated ingredient of the traffic noise. Compared with noise barriers along the roadside, reduction of tire/road noise at the source is one of the most cost-effective ways to mitigate noise levels. Although many issues are still unsolved, it is clear that the optimization of road surface can reduce the tire/road noise effectively (*4*). And the potential of tire/road noise reduction is estimated to be 1-2dB for cars and up to 2dB for trucks (*5*). The depth of texture is usually characterized by the mean texture depth (MTD), past measurements indicated that the tire/road noise decreased with the decrease of MTD (*6*-*8*), but it is not enough to capture the distribution of texture depth. In addition, Shen and Der-Hsien et al (*9*-*10*) found that the resistivity and shape factor affect peak frequency and the range of effectiveness. The noise measurement methods, including Controlled pass-by (CPB), statistical pass-by (SPB), Close-proximity (CPX) and On-board Sound Intensity (OBSI), were used or developed to measure the tire/road noise, usually large scale of experimental sites and a lot of equipments are required (*11*-*12*).

Some researches indicate that lower MTD induces the reduction of skip resistance ability of pavement (*13*-*15*). It means that if MTD is decreased excessively to reduce the noise level, the skip resistance would also reduce a lot and increases the probability of the accident. So the skip resistance should be considered and ensured within a reasonable range when taking decreasing MTD as the method of reducing the noise level. Moreover, the distribution of texture depth cannot be got from MTD since it is the mean value of texture depth, which implies that the different distribution may get the same MTDS, but the BPN value and noise level are quite different. Therefore, a new experiment method which is convenient and can measure the noise and skip resistance synchronously is needed. And the optimal surface texture which can lead to lower noise and maintain reasonable skip resistance should be researched.

In this paper, four aggregate gradations were selected and lab-compacted slabs are prepared. Before and after some abrasions by the Dorry abrasion testing machine, BPNs (British Pendulum Numbers) on these slabs were measured by a BP, simultaneously frictional noise levels were measured by a noise meter. Surface textures of these slabs were scanned with a 3D laser scanner and were characterized by newly-developed texture depth cumulative curve (TDCC). The effects of surface textures on frictional noise and skip resistance were investigated by using regression method. Finally, an optimal surface texture which can lead to lower noise and maintain reasonable skip resistance was proposed.

2 METHODOLOGY

2.1 Compaction of Slabs

Four groups of asphalt concrete slabs are compacted to 300mm long, 300mm wide and 50mm thick with basalt aggregates and unmodified bitumen. The properties of the bitumen are: softening point 44.0 ^{0}C, penetration (at 25 ^{0}C) 103 (0.1mm) and ductility (at 15 ^{0}C) 105mm. The four different gradations of 12.5-mm SMA are shown in Figure1. The aggregate passing ratios at 0.075mm and 9.75mm sieve are the same, i.e., 10% at 0.075mm sieve and 63.5% at 9.5mm sieve, but passing ratios of sieves from 0.075mm to 4.75mm vary to govern the surface texture of slabs. The bitumen aggregate ratio of all slabs is 6.0%. The slabs in Group 1 are made with the finest aggregates, passing ratio at 4.75mm sieve reaches 34.0%, while the slabs in Group 4 are made with the coarsest aggregates, whose passing ratio can reach the minimum value, 20.0% at 4.75mm sieve. Group 2 and Group 3 are made with the chosen gradations, whose passing ratios meet the two-third point and one-third point of the passing ratio range of each sieve, respectively. Two duplicates (slabs) are prepared for each group.

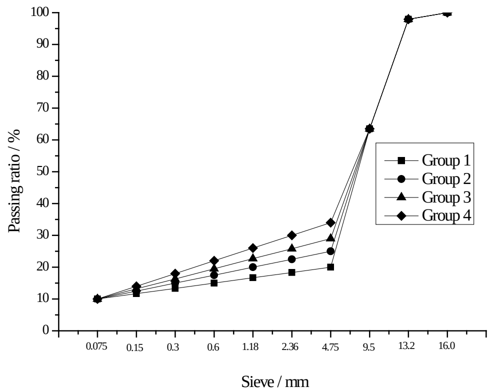
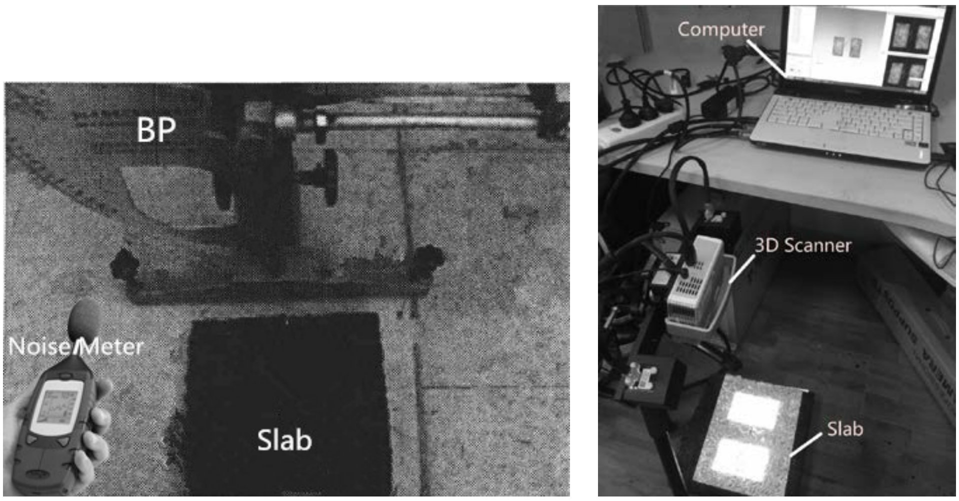


FIGURE1 Aggregate Gradation Curve of Slabs

2.2 Data Collection before Abrasion

The experiment is conducted in closed and quiet indoor environment where background noise is lower than 50 dB. The skip resistance (BPN values) of the new slab (before abrasion) is collected by a British pendulum (BP). Meanwhile, the overall frictional noise is measured by a portable sound level meter (Figure 2(a)), which located 50cm higher than and 50cm away from the experimental area (about 126mm×76mm) on each slab. Bundled software is used to extract the 1/3-Octave band frictional noise. Then, a 3D scanner illustrated in Figure2 (b) is used to capture the 3D texture of slab surface. Due to the limitation of the scanner, a white contrast intensifying agent should be painted on the experiment area of the slab before the scanner captures the 3D texture.



(a) BPN and noise measurement (b) Texture scanning

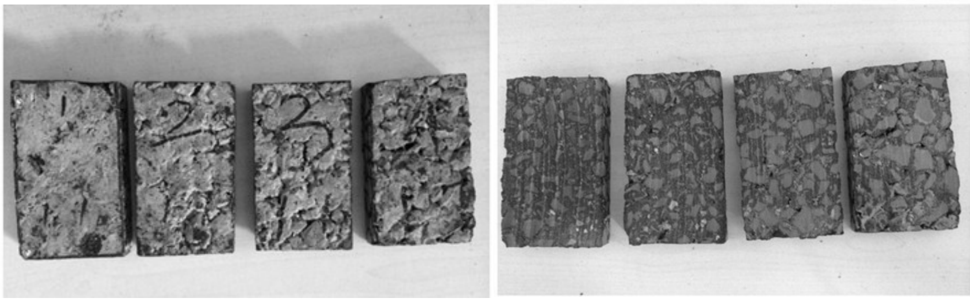
FIGURE2 BPN and Noise Measurement and Texture Scanning.

The depth of texture is usually characterized by the mean texture depth (MTD), but it is not enough to characterize the distribution of texture depth. To address this issue, a curve called texture depth cumulative curve (TDCC) is developed, details about this curve is explained in

Section 3.

2.3 Abrasion

There is an asphalt film on the surface of the new slab. In order to investigate long-term behavior, the Dorry abrasion testing machine is used to abrade the asphalt film. Due to the size limitation of Dorry test sample, the slabs must be cut into small test samples (91.5mm×53.5mm) before abrasion test. After 500 abrasions, obviously the initial asphalt film of each test sample is partially removed in Figure3.



(a) Before abrasion (b) After abrasion

FIGURE3 Dorry Test Samples before and after Abrasion (500 circles)

2.4 Data Collection after Abrasion

The size of Dorry test samples (91.5mm×53.5mm) is smaller than the BP experimental area (126mm×76mm), so 53.5mm can be used as the width of BP experiment area after abrasion. In order to prevent BP from hitting the edge of test sample, 60mm length is required. A control group is reserved whose sizes are the same but without abrasion. The BP experiment and 3D scanning test are performed on abraded and control test samples to get the BPN, the frictional noise and the 3D texture.

3 RESULTS

3.1 Experiment Results

The BPNs, frictional noises and corresponding MTDS (mean texture depth of scan) of four groups are showed in Table1, all values (before abrasion and after 500 abrasions) are included.

MTDS is a parameter similar to MTD but collected by the 3D scanner. Former researches indicated that a larger MTD usually induced higher BPN value and more noises. But the BPN values of each group are not distinguished from each other significantly in Table1. The reason may be that there is an asphalt film on the surface of new slabs. The skip resistance abilities between new slabs are similar. Moreover, noise levels of Group 2 in Table 1 do not agree with the past conclusion that larger MTD leads to more noises.

TABLE1 BPNs, Frictional Noises and Corresponding MTDS of Four Groups

Group	Before abrasion			After 500 abrasions						
	MTDS (mm)	BPN	Noise (dB)	MTDS (mm)	BPN_{60A}	BPN_{60}	BPN_A	$Noise_{60A}$ (dB)	$Noise_{60}$ (dB)	$Noise_A$ (dB)
1.1	1.54	71	74.4	1.42	23.0	27.0	60.1	67.8	67.9	73.9
1.2	1.48	70	74.1	1.45	22.5	26.5	59.9	67.6	67.7	74.0
1.3	1.50	70	74.3	1.49	23.5	26.5	62.1	67.7	67.8	74.1
1.4	1.64	70	74.6	1.56	22.5	27.0	58.3	68.0	68.1	74.4
Mean 1	**1.54**	**70.3**	**74.4**	**1.48**	22.9	26.8	**60.1**	67.7	67.8	**74.1**
2.1	1.83	70	74.2	1.73	23.5	26.5	62.0	67.4	67.6	73.8
2.2	1.71	71	73.9	1.68	23.5	27.5	61.1	67.6	67.8	74.0
2.3	1.88	72	74.0	1.73	23.0	27.5	63.7	67.7	67.9	74.1
2.4	1.78	72	74.3	1.74	24.0	26.5	61.8	67.2	67.4	73.6
Mean 2	**1.80**	**71.3**	**74.1**	**1.72**	23.5	27.0	**62.0**	67.5	67.7	**73.9**
3.1	1.92	71	74.6	1.88	24.5	27.5	62.9	67.5	67.9	74.2
3.2	2.01	72	74.6	1.95	25.0	28.0	64.3	67.7	68.1	74.4
3.3	1.99	72	74.5	1.91	24.5	27.0	65.3	67.5	67.9	74.2
3.4	1.95	71	74.4	1.90	25.5	27.5	64.8	67.9	68.3	74.4
Mean 3	**1.97**	**71.5**	**74.5**	**1.91**	24.9	27.5	**64.7**	67.6	68.0	**74.3**
4.1	2.48	72	74.7	2.38	26.5	28.0	68.1	67.8	68.2	74.6
4.2	2.43	73	75.3	2.36	26.0	28.5	66.1	67.7	67.9	74.5
4.3	2.56	72	75.1	2.45	26.5	28.0	67.7	68.1	68.5	74.9
4.4	2.53	72	74.9	2.41	26.5	28.5	67.4	67.9	68.3	74.7
Mean 4	**2.50**	**72.3**	**75.0**	**2.40**	26.4	28.3	**67.3**	67.8	68.2	**74.7**

The BPN correction value of test sample after abrasion (BPN_A) can be calculated by,

$$BPN_A = BPN_{60A} / BPN_{60} \times BPN \quad (1)$$

Where, BPN_A refers to the BPN correction value of test sample with abrasion;
BPN_{60A} presents the BPN value on test sample with abrasion;
BPN_{60} denotes the BPN value on test sample without abrasion;
BPN presents the BPN value on slab without abrasion.

Similarly, the Noise correction level of test sample after abrasion ($Noise_A$) can be achieved by,

$$Noise_A = Noise_{60A} / Noise_{60} \times Noise \quad (2)$$

Where, $Noise_A$ refers to the BPN correction level of test sample with abrasion;
$Noise_{60A}$ presents the noise level on test sample with abrasion;
$Noise_{60}$ denotes the noise level on test sample without abrasion;
Noise presents the noise level on slab without abrasion.

The BPN values decrease since the asphalt films on the surfaces of test samples are partially lost after abrasion test. The BPNs of Group 1 which blends with the finest aggregates drop significantly while those of Group 4 which has coarsest gradation decrease slightly. This means that coarse aggregates can withstand more abrasions. As for frictional noise, only up to 0.2 dB decreases after abrasion.

MTDS also decreases with the abrasion, but the similar MTDS induces different BPN value and noise level due to that MTDS can not characterize the distribution of texture depth. It means that the different distribution may get the same MTDS. For example, Sample 2.3 and Sample 3.1 have similar MTDS, but the BPN and noise level are different. The BPN value in Sample 2.3 is 1 more than that of Sample 3.1, but the noise level of Sample 2.3 is 0.6 smaller than that of Sample 3.1.

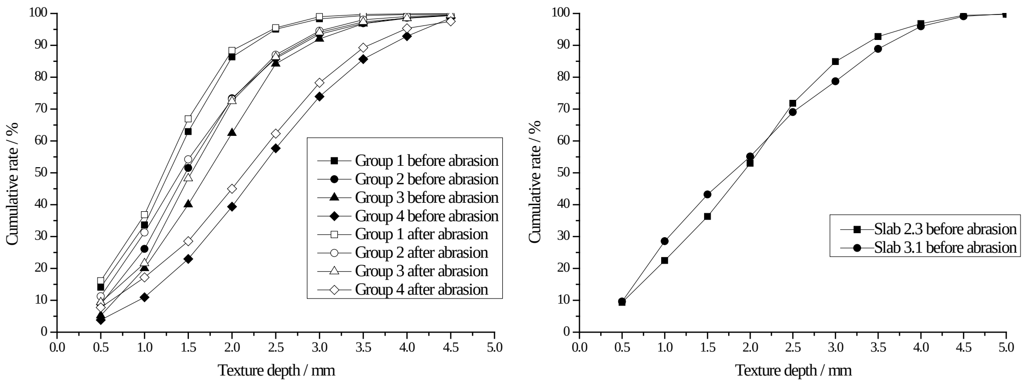
3.2 Texture Depth Cumulative Curve

To overcome the issues of MTDS, a curve called texture depth cumulative curve (TDCC), similar to gradation curve, is developed by connecting the cumulative rate points by straight lines of each texture depth. Differing from MTDS, the TDCC can be used to capture the distribution of the surface texture depth. The cumulative percentages of texture depth of four groups are indicated in Table 2 and presented in Figure 4 (a).

TABLE2 Cumulative Percentage of Texture Depth of Four Groups

Group	Texture Depth (mm)								
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
1-B	14.08	33.64	62.93	86.35	95.07	98.34	99.34	99.65	99.74
1-A	16.15	36.83	66.89	88.36	95.53	98.99	99.71	99.91	99.93
2-B	8.78	26.12	51.53	73.38	85.91	93.49	96.93	98.66	99.44
2-A	11.23	31.27	54.19	73.11	87.03	94.53	98.02	99.02	99.52
3-B	5.23	20.04	40.07	62.47	84.22	92.02	96.82	98.46	99.32
3-A	9.37	21.65	48.25	72.49	86.37	94.02	97.35	98.53	99.44
4-B	3.84	10.93	22.96	39.39	57.68	73.92	85.70	92.88	98.60
4-A	7.73	17.18	28.53	45.01	62.33	78.28	89.28	95.33	97.55

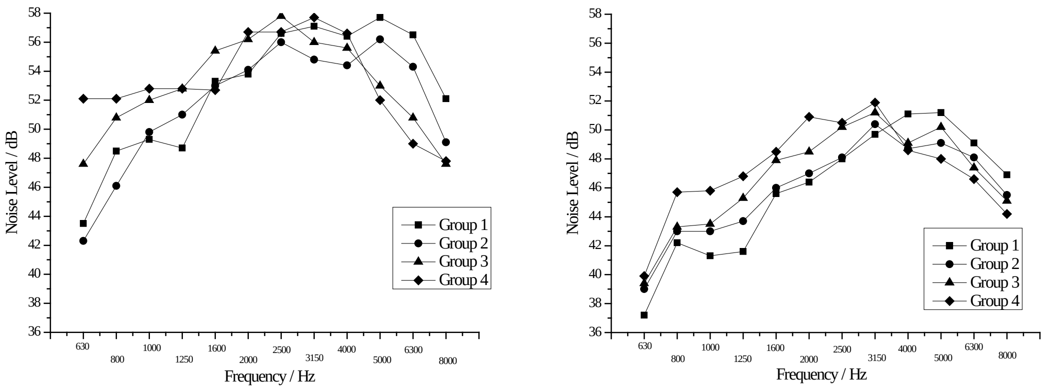
Note: B refers to before abrasion and A represents after abrasion.



(a) All samples (b) Sample 2.3 and Sample 3.1

FIGURE4 Texture Depth Cumulative Curve of Slabs

From the figure of TDCC above, the group with fine aggregate has higher cumulative rate at each depth, especially the depth less than 2mm. And the abrasion does not change the surface texture significantly and the asphalt films are partially removed, which induces increase of cumulative rate of texture depth (CRTD) less than 2mm. The CRTD more than 2mm is almost constant after abrasion, except Group 4. The TDCCs of Sample 2.3 and Sample 3.1 are showed in Figure 4(b) above. The MTDSs of these two slabs are similar, but Sample 2.3 has a higher cumulative rate of the depth less than 2mm while Sample 3.1 has a higher CRTD more than 2mm. Also, the TDCCs of Group 2 and Group 3 are illustrated in Figure 4 (a) above. The CRTD more than 2mm are similar, but the difference of BPN and noise level between Group 2 and Group 3 are significant. This implies that, the relationship between noise level, BPN and CRTD less than 2mm may be existed. The higher CRTD less than 2mm may induce lower BPN value and these rates may influence the noise level. Hence, Figures of 1/3-Octave band frictional noise curve are showed in Figure 5. The peak values of noise level of each group are similar, but the noise level of frequency less than 4000Hz decreases with the increase of CRTD less than 2mm. And the frequency of curve interleaving is nearly 3150Hz before abrasion and nearly 4000Hz after abrasion.



(a) Before abrasion (b) After abrasion

FIGURE5 1/3-octave Band Frictional Noise Levels of Samples before and after Abrasion

4 DISCUSSION

As mentioned above, the relationship between noise level, BPN and CRTD less than 2mm may be existed. However, the rates are constituted by four components, the cumulative rate of 0.5mm, 1.0mm, 1.5mm and 2.0mm. The expression of these rates is too complicated and the trend of these rates must be researched. Because the cumulative rate is absolutely positive and grows rapidly with the increasing of texture depth, the exponential function is suitable to fit the cumulative rate.

4.1 Characteristic Parameters of Cumulative Rate versus Texture Depth Curve

The CRTD less than 2mm in all TDCC are extracted and exponential function (eqn.3) is used to fit, as shown in Figure6, eqn.4 and eqn.5.

$$Y = a_d \times X^b \qquad (3)$$

Where X denotes texture depth (mm);

Y refers to cumulative rate corresponding to X, and

a_d and b present the characteristic parameters.

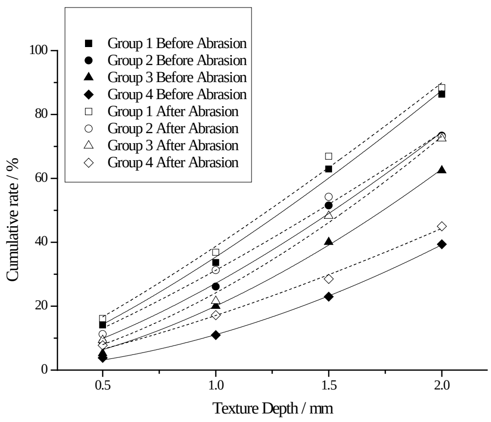


FIGURE6 Exponential Fitting of CRTD less than 2mm

$$\begin{cases} Y_{1B} = 35.42X^{1.30}, & R^2 = 0.99 \\ Y_{2B} = 27.18X^{1.45}, & R^2 = 0.99 \\ Y_{3B} = 20.05X^{1.64}, & R^2 = 0.99 \\ Y_{4B} = 11.09X^{1.82}, & R^2 = 0.99 \end{cases} \quad \text{(Before abrasion)} \qquad (4)$$

$$\begin{cases} Y_{1A} = 38.74X^{1.21}, & R^2 = 0.97 \\ Y_{2A} = 31.25X^{1.25}, & R^2 = 0.99 \\ Y_{3A} = 23.51X^{1.46}, & R^2 = 0.98 \\ Y_{4A} = 15.51X^{1.46}, & R^2 = 0.95 \end{cases} \quad \text{(After abrasion)} \qquad (5)$$

Above equations show that, the decreasing of CRTD less than 2mm induces the rapid decrease of parameter a_d and slight increase of parameter b. Moreover, parameter a_d almost increases by 4 after the abrasion because the CRTD less than 2mm is increased after the abrasion. The value of independent variable X is small and the value range of X is narrow, from 1.2 to 2.0. This indicates b has no obvious impact on the cumulative rate Y. However, the CRTD less than 2mm is influenced most by the parameter a_d, also a_d has an obvious change in different groups. So the characteristic of this curve can be represented more effectively by parameter a_d.

4.2 Skip Resistance versus Characteristic Parameter

Above shows that the increase of CRTD less than 2mm induces the increase of parameter a_d and leads to the decrease of BPN. Thus, the BPN should decrease with the increasing of parameter a_d. To address long-term condition of asphalt pavement, the BPN data after abrasion and parameter a_d after abrasion are selected. The linear fitting is illustrated in Figure 7.

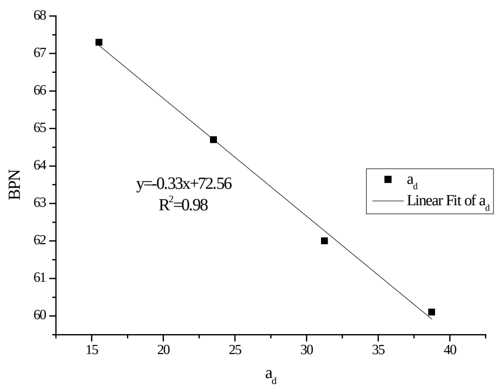


FIGURE7 Relationship between BPN and Parameter a_d

$$BPN = -0.33a_d + 72.56 \quad (6)$$

The relationship between BPN and parameter a_d is showed in eqn.6 above. The reliability of this equation is strong according to R^2 (0.98). This indicates that parameter a_d is a characteristic value of CRTD less than 2mm. This equation can be utilized to achieve the particular value of BPN or to ensure the skip resistance ability based on texture.

4.3 Frictional Noise versus Characteristic Parameter

The experiment results show that the lowest frictional noise value appears in Group 2, whatever before or after abrasion. Past researches indicate that noise can be reduced by proper texture depth and noise will increase when texture is rough. So, the balance point of the surface texture depth may lead to the lowest noise. To seek the lowest noise point, a polynomial formula $y = a(x-b)^2 + c$ is selected to relate noise levels with parameter a_d. The fitting results can be found in Figure 8, eqn.6 and eqn.7.

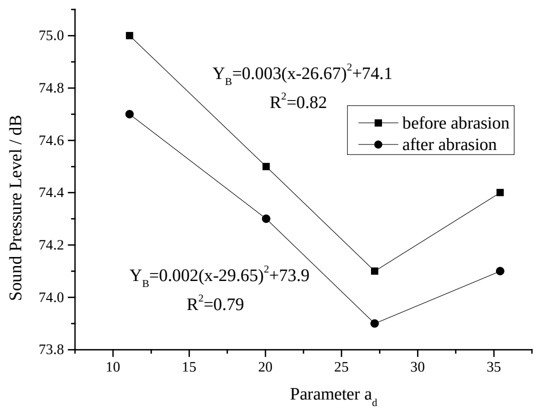


FIGURE8 Relationship between Noise Level and Parameter a_d

$$N_B = 0.003(a_d - 26.67)^2 + 74.1 \quad (7)$$

$$N_A = 0.002(a_d - 29.65)^2 + 73.9 \quad (8)$$

Where, N_B and N_A refer to frictional noise levels before and after abrasion.

The lowest noise level before and after abrasion are showed in eqn.7 and eqn.8 above. When parameter a_d equals to 26.67 before the abrasion, the N_B will lead to the lowest value 74.1. Also, a_d which equals to 26.67 before abrasion increases to nearly 30 after abrasion. The texture which leads to the lowest overall noise level is not affected by the abrasion. Thus the surface texture can be optimized according to the eqn.7 and eqn.8 to achieve the lowest overall noise level. In addition, the noise level slightly decreases after the abrasion since abrasion decreases the BPN value in same samples and decreases the transform of kinetic energy.

4.4 Seeking an Optimal Surface Texture

The objective of this paper is to seek an optimal surface texture which can lead to lower noise and more reasonable skip resistance. Hence, the texture which induces the lowest noise must be considered first. a_d is selected according to eqn.8 above and this value of a_d must be substituted into eqn.6 to predict the ability of skip resistance. So choose 29.65 as the value of a_d after abrasion, the BPN value forecast by eqn.6 is 62.7.

Parameter a_d is the characteristic value of CRTD less than 2mm and these rates can be calculated by using the eqn.4 and eqn.5. For example, the a_d equals 26.67 before abrasion to achieve the lowest noise level, the parameter b approximately equals to 1.5 according to eqn.4. The CRTD less than 2mm can be computed by,

$$\begin{cases} Y_{0.5} = 26.67 \times 0.5^{1.5} = 9.43 \\ Y_{1.0} = 26.67 \times 1.0^{1.5} = 26.67 \\ Y_{1.5} = 26.67 \times 1.5^{1.5} = 49.00 \\ Y_{2.0} = 26.67 \times 2.0^{1.5} = 75.43 \end{cases} \tag{9}$$

The optimal surface texture which induces lower noise and maintain reasonable skip resistance can be achieved by making the CRTD less than 2mm equal to eqn. 9 above. The friction noise level is 74.1dB and the BPN value maintains 62.7 on this surface texture.

4.5 Achieving the Optimal Surface Texture

To obtain above optimal CRTD less than 2mm, the relationship between surface texture and aggregate gradation should be investigated. Only passing ratios of sieves from 0.075mm to 4.75mm are considered in this paper since CRTD less than 2mm are mainly controlled by them. Here, a simple parameter k is proposed to characterize aggregate gradation, which is the slope of gradation from 0.075mm to 4.75mm sieve, as shown in Figure1. The ordinate is the difference of passing ratio between two sieves and the horizontal ordinate is the difference of order number (ordering the sieves from small to large) between the same sieves. Parameter k can be calculated by,

$$k = \frac{P_{4.75} - P_{0.075}}{N_{4.75} - N_{0.075}} \tag{10}$$

Where, $P_{4.75}$ and $P_{0.075}$ denote passing ratios of 4.75mm and 0.075mm sieve, respectively; $N_{4.75}$ and $N_{0.075}$ present the order numbers of 4.75mm and 0.075mm sieve, respectively.

For example, in the Group 1, $k_1 = \frac{34-10}{7-1} = 4$. Similarly, in the Group 2, Group 3 and Group 4, k_2, k_3 and k_4 are equal to 3.14, 2.50 and 1.43, respectively.

The linear function is used to relate the texture parameter a_d with the gradation parameter k. The data of parameter a_d before abrasion can be found above in eqn.4. The fitting result is presented in Figure 9 and eqn.11.

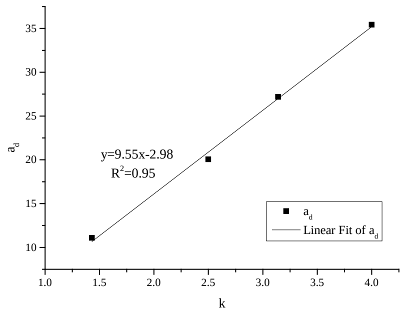


FIGURE9 Relationship Between a_d and k

$$a_d = 9.55k - 2.98 \qquad (11)$$

This above equation builds the relationship between the parameter a_d and gradation design. And it can be used to calculate the gradation slope k to make higher probability to achieve specific value of a_d. k equals to 3.10 when a_d is 26.67. The passing ration of sieves from 0.075mm to 4.75mm can be computed by eqn.12:

$$P_i = k(N_i - N_{0.075}) + P_{0.075} \qquad (12)$$

Where, P_i denotes passing ratios of sieve i.

N_i presents the order numbers of sieve i.

$$\begin{cases} P_{0.15} = 3.1\times(2-1)+10 = 13.1 \\ P_{0.3} = 3.1\times(3-1)+10 = 16.2 \\ P_{0.6} = 3.1\times(4-1)+10 = 19.3 \\ P_{1.18} = 3.1\times(5-1)+10 = 22.4 \\ P_{2.36} = 3.1\times(6-1)+10 = 25.5 \\ P_{4.75} = 3.1\times(7-1)+10 = 28.6 \end{cases} \qquad (13)$$

These optimal passing ratios of sieves from 0.075mm to 4.75mm are achieved as showed in eqn.13. The optimal surface texture which can lead to lower noise and maintain reasonable skip resistance can be achieved by adjusting to gradation of aggregate. This method is simple but not accurate. With the development of road paving, the precise control of parameter a_d could be realized in the future.

5 CONCLUSIONS

The surface texture governs the skip resistance ability and noise level. BPN and the 1/3-octave band frictional noise levels are measured simultaneously. Texture depth cumulative curve (TDCC) was developed to characterize the surface texture of samples. The relationships among skip resistance (BPN), noise level and surface texture are investigated. Some conclusions are drawn as follows:

(1) The distribution of texture depth of samples can be captured by developed TDCC and characterized by parameter a_d of this curve. BPN values and noise levels are mostly controlled by

CRTD less than 2mm.

(2) The BPN value increases and noise value decreases firstly and then increases with the decreasing of parameter a_d. The peak frequencies of frictional noise are nearly 4000 to 5000Hz and the peak frequencies increase slightly with the increase of parameter a_d.

(3) The optimal surface texture can be achieved by selecting the optimum value of a_d. Frictional noise decreases from 75.0 dB to 74.1 dB and reasonable skip resistance (BPN) of 62 is maintained when a_d is taken as 26.67.

(4) The surface texture feature is influenced by the aggregate gradation. Parameter a_d increases with the increase of gradation slope k. The texture which can lead to lowest value and reasonable skip resistance can be achieved by adjusting the aggregate gradation.

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