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Shih-Huang Chen
Dept. of Civil Engineering, National Central University, Taiwan, R.O.C, hippo60124@gmail.com

Kuan-Lun Hsu
Dept. of Transportation Technology and Management, Feng Chia University, Taichung, Taiwan, R.O.C.

Pei Liu
Dept. of Transportation Technology and Management, Feng Chia University, Taichung, Taiwan, R.O.C.

Hung-Wen Chung
Dept. of Civil Engineering, National Central University, Taiwan, R.O.C

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PRELIMINARY STUDY ON THE CORRELATION BETWEEN TWO-DIMENSION SURFACE TEXTURE AND FRICTION

Shih-Huang Chen[1], Kuan-Lun Hsu[2], Pei Liu[2], and Hung-Wen Chung[1]

Key words: texture, friction, 2D Laser.

ABSTRACT

The friction of pavement is mainly determined by the microtexture of the surface layer. However, the finer degree of microtexture makes it impossible to observe with naked eye. The object of this study was to develop a High Definition Scan Texture Machine (HDSTM) with 2D Laser CCD to support previous research on the correlation between texture and friction. In addition, this study proposed seven different parameters and sought to find an index for an ideal correlation that could represent the entire pavement texture. By assessing the test results, the Segment of Average Profile Depth (SAPD) was selected as the texture parameter for the threshold standard of pavement friction out of various 2D texture parameters. The SAPD had high correlation with British Pendulum Number (BPN) in wet and dry surface conditions and the texture data had sufficient samples to support the high correlation with BPN. Based on the results of in this study, 2D texture, SAPD, is recommended as an important index for engineers to evaluate the surface friction in the Highway Maintenance Office.

Due to the influence of extreme weather, the accumulated water on road surfaces may not be fully channeled out via the vertical and horizontal slope of the road design. Thin water films may form, reducing the friction between the vehicle tires and the pavement surface and creating a skid situation for vehicles. This study, through a literature review and research of the characteristics of pavement surface texture, sought to identify the key influence of friction and structuralize the relationship between surface texture and friction. The High Definition Scan Test Machine (HDSTM) was utilized for its accuracy to improve artificial operation error of measuring texture from the Sand Patch Method. This study tried to discover the correlation between texture and friction. Chen et al. (2010) claimed that high definition laser CCD could be used to measure texture for friction prediction. Xie et al. (2008) estimated the Friction Number (FN) by using the texture laser test. Their research applied the laser system with standards of 12 bit digital resolution and a 150 kHz frequency of 5 mils max test resolution. It was installed and testing was conducted on a vehicle with speeds over 60 miles/hr, and laser detecting pavement surface accuracy was achieved up to 0.03 mm (Xie et al., 2008). Lin (2008) had a preliminary study of correlation between one dimension pavement texture and friction and developed a pavement High Definition Circular Texture Machine (HDCTM), had a higher definition than the conventional CTM, to accurately classify the depth of the shallow and deep textures. The statistical analysis of simple regression was adopted to discover the relationship between the sum of the texture and the BPN. The correlation coefficient (γ) and the coefficient of determination (R^2) were 0.7 and 0.6, respectively. The sum of texture in his study had high correlation with BPN. Under the condition of wet dense-graded asphalt concrete (DGAC), the correlation coefficient and the coefficient of determination between the surface texture and the BPN were 0.5 and 0.3, respectively, which reflected a norm of middle correlation. Hanson et al. (2004) claimed that the results was no significant difference between CTM and Sand Patch Method. Oliver (2009) claimed that the pavement surface texture was the main source of the friction. The finer textures would be able to provide a brake-ability of vehicle below 60-70 km/hr, whereas rough textures would be able to provide a brake-ability of vehicle above 90-100 km/hr. Tighe et al. (2009) claimed that to ensure the safety of a moving vehicle, the contact between the tires and the pavement required substantial friction. From the pavement surface engineering, two parameters were defined: microtexture and macrotexture. Microtexture mainly provides for a more direct contact between the tires and the pavement, whereas the macrotexture provides for the function of pavement drainage. The skid resistance of pavement surfaces is mainly determined by the microtexture of the surface. Another study found that available friction fluctuates at 0.35 BPN per 1°C change in prevailing ambient or pavement surface temperature with an

Paper submitted 10/06/12; revised 12/31/13; accepted 03/26/14. Author for correspondence: Shih-Huang Chen (e-mail: hippo60124@gmail.com).
[1] Dept. of Civil Engineering, National Central University, Taiwan, R.O.C.
[2] Dept. of Transportation Technology and Management, Feng Chia University, Taichung, Taiwan, R.O.C.

overall eight BPN seasonal fluctuation (Alauddin et al., 2010). Several researchers claimed that larger mean texture depth leads to better skid resistance. It is important to maintain the function of drainage of the texture on manhole covers (Chou and Lee, 2013). The main motivation for this study was to extend the previous research with improved laser CCD and test methods. By capturing the surface texture using two Laser CCD, in comparison with the previous single-point laser, a much clearer distribution of the condition of textures within the scanned area was accomplished. For the same reason, in order to obtain more stable data collection, development of newer test instruments was required to support the analysis of texture characteristics. This study subsequently applied the standards of ASTM E 2157 to develop a High Definition Scan Texture Machine (HDSTM) with 2D Laser CCD to support the study on the correlation between texture and friction.

I. STUDY PLAN

1. Mixture and Specimen

The specimen size is 50 cm × 50 cm × 5 cm, and all samples were compacted by compaction roller to simulation the actual pavement in field. The mixture was nDGAC, maximum nominal aggregate size was 19 mm, gradation met ASTM D3515 specification, and Marshall Design, Asphalt Institute MS-2, is adopted to the mixture design of this study. The combination was the most popular asphalt concrete in Taiwan. Before scan by Laser CCD and BPN test, all specimens were curing over 24 hrs, and the total number of specimens is 10.

2. HDSTM

HDSTM was a self-developed machine funded by the SHC Lab., and HDSTM was developed in accordance with the standards of ASTM E 2157. The purpose was to improve the laser Circular Texture Machine insufficiency of HDCTM, and increase the definition of the Laser CCD. As result, the HDSTM was developed to apply the laser scanning on pavement texture. This improved machine allowed the test area of the HDSTM to be closer to the BPN testing area. By adopting the HDSTM, this study expected the index of the laser texture to be more aligned with the real condition. From the texture testing, it seeks to discover the influence of friction from the difference between the shallow and deep textures. Furthermore, through the increased scanning range of the HDSTM, the texture data of the actual pavement condition was increased. In addition to the increased texture data available to analyze the pavement ratio of the shallow and deep textures, the influence of friction from the different depths of textures could also be comprehended. The values of the tested textures allow researchers to proceed further on the correlation between the BPN and the different texture parameters, as well as explore the contribution level of different texture parameters. From Fig. 1, the differences between the HDCTM and the HDSTM are apparent. While both operate under the same speed of 6 m/min, from the diagram it can be seen that the HDCTM collects texture data through laser testing in a single-point clockwise direction, whereas the HDSTM collects texture data through laser testing in a circular clockwise direction. Therefore, the scale of the collected surface texture data corresponds more to the friction test range. Since the texture data are greater, the obtained pavement texture information would be more sufficient.

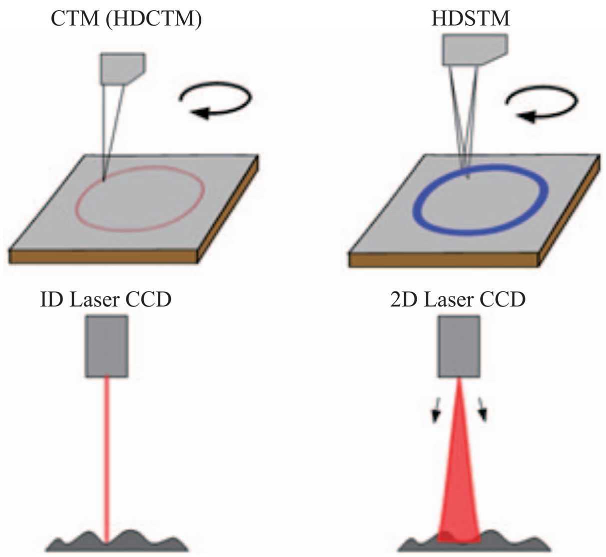


Fig. 1. HDCTM and HDSTM.

3. British Pendulum Tester (BPT)

This study adopted the BPT to conduct laboratory test of friction coefficient. The BPT is a type of mobile surface friction test instrument which can be used for laboratory and on-site test. It was developed by the British Road Research Laboratory. The BPT test is in accordance with the standards of ASTM E 303. ASTM E303 does not regulate temperature calibration; however, an acceptable temperature adjustment method is available in the "Paving Method Guide Book" published by the Japan Road Association. Within the temperature scope of 1~35 Deg. C, the BPN adjustment is as follows:

$$C_{20} = -0.0071t^2 + 0.930t - 15.79 + C_t \quad (1)$$

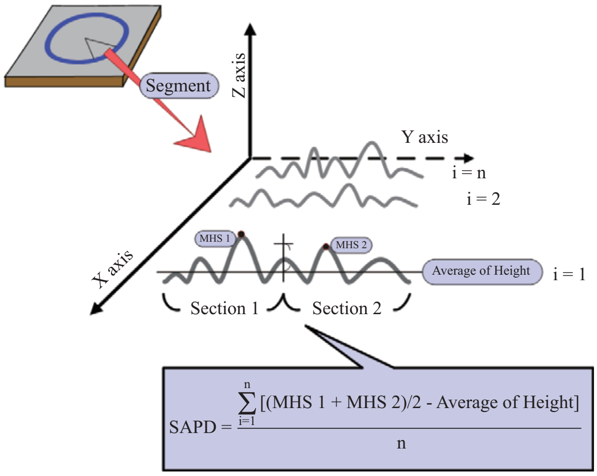
where,

- C_{20} was adjustment of BPN at 20 Deg. C
- C_t was the acquired BPN after testing the surface Temperature of Deg. C
- t was the test surface temperature (Deg. C)

In this study, BPN (wet) was meaning the test value is carried in the wet surface condition, and BPN (dry) is meaning the test value is conducted in the dry surface condition.

4. 2D Texture Parameter Exploration

This study categorized the samples of 50 cm × 50 cm × 5



where,
SAPD denotes the Segment Average Profile Depth
MHS 1 denotes the maximum peak of 1st section
MHS 2 denotes the maximum peak of 2nd section
Average of Height: average texture of this profile

Fig. 2. Definition of SAPD.

cm in 360° circles, and labeled the samples from A to H into eight equal segment of 45°. In this study, each equal segment was defined as a segment. The HDSTM was able to detect 280 to 300 texture profiles for each sample, and every profile was able to detect 560 to 600 points. Therefore, every segment had about 35 to 37 profiles. Using the pavement texture established with the HDSTM, four steps of data dissection, data screening, data arrangement, and data calculation followed in order to calculate different types of 2D texture parameters. This study proposed seven different parameters and sought to find an index that correlated to friction and was able to represent the entire pavement textures. Following are the seven different types of texture parameters we established:

(1) Peak of Texture
Each segment included about 35 profiles. By selecting the highest texture value of each profile and averaging the sum of the highest values, the texture value of such segment could be determined.
(2) Average of Texture
Each segment included about 35 profiles. By selecting the average value of every profile and averaging the sum of the average values of all 35 profiles, the texture parameter factor of each segment could be determined.
(3) Segment of Average Profile Depth (SAPD)
In accordance with ASTM E 1845, this profile set was divided into two areas. By selecting the highest point from both areas, the average value of the two was obtained. Then, the average value of the profile was obtained by deducting the highest point average value from the profile average value. This parameter texture value was to be the most important texture value in this study. The calculation of SAPD is shown in Fig. 2 (Lin, 2008).
(4) Mean of Average Profile Depth (MAPD)
The entire pavement profile textures were divided into eight segments, and the SAPD from each segment was summed to obtain an average value.
(5) Sum of Positive Shallow Texture (SPST)
In this study, the textures above the average were defined as the Positive Texture, whereas the values below the average value were defined as the Negative Texture. Through differentiation of the Positive Texture and Negative Texture, we then focused on Positive Texture, which was further categorized into the Positive Shallow Texture and Positive Deep Texture. This study defined the scope of SPST between the profile average value and profile average value + 0.5 mm as the shallow texture depth.
(6) Sum of Positive Deep Texture (SPDT)
The scope of this value was defined as values greater than the profile average + 0.5 mm, which this study defined as the deep texture depth.
(7) SPST+SPDT
The SPST and SPDT were combined into the 2D texture parameter, from which we then conducted our correlation analysis with friction.

5. HDSTM Validation

Before conducting the HDSTM test on the pavement surface texture, it was necessary to verify if the instrument would meet the requirements of this study. Through a self-validation method, the accuracy of the HDSTM testing scope was verified. By placing the HDSTM on a marble surface and adjusting its horizontal level with a gradiometer, the laser accuracy validation was conducted. For the accuracy validation of the HDSTM, the block gauge for HDSTM was utilized to test whether the laser was able to detect the thickness of the block gauge. During the self-validation of the HDSTM, different thickness of block gauge and thin objects were utilized. However, the primary testing was to verify whether the HDSTM was able to detect the 10^{-3} millimeter thick block gauge in order to meet the accuracy requirements. Lastly, the HDSTM was connected to a computer to conduct texture test validation. From the results, we were able to observe the block gauge from the validation, which certified that the validation had achieved the accuracy requirement. This study also used the Sand Patch Method to verify whether the HDSTM was able to conduct our tests. Through the Sand Patch Method, the Mean Texture Depth (MTD) was tested and verified its correlation with the Mean of Average Profile Depth of the laser texture test. The γ value was 0.9, was showed in Fig. 3, which indicated that there was high correlation.

II. RESULTS

This study sought to understand the pavement texture and correlation between the BPN (dry) and BPN (wet). By utilizing the BPN test on every segment, the tests were classified into surface dry and wet conditions. Observation from test

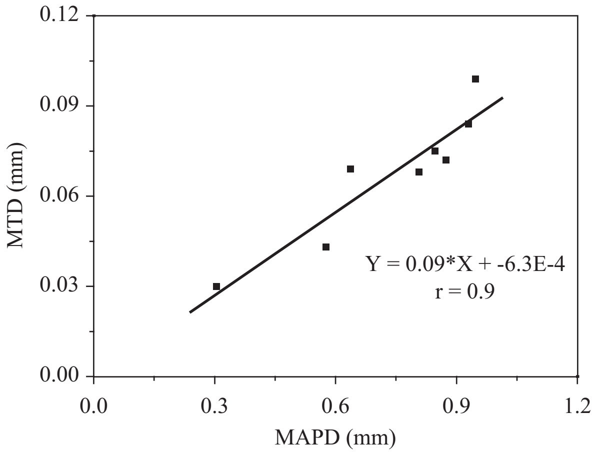


Fig. 3. Relationship between MAPD and MTD.

results, the average value of BPN (dry) is about 55, whereas the BPN (wet) had an average value of about 30. The difference between the two was about 25. The possible reason was that during the test, the BPN (dry) had a greater contact area surface of slide and DGAC. As for the BPN (wet), there was a layer of thin water film covering the pavement surface texture that caused the BPN (wet) to be significantly lower than the BPN (dry). From the HDSTM scan, the texture profiles of 10 specimens of DGAC were conducted.

The results of correlation analysis between BPN and various parameters were showed as Fig. 4 and Fig. 5. Observation from the results in Fig. 4 in dry condition, among the lowest values were the Average of Texture, SPST and SPDT, for which the γ was 0.7. The highest values were the SAPD, MAPD, and SPSS+SPDT, for which the γ was 0.9. The results in wet condition were very similar to the results in dry condition, and the only difference was the correlation coefficient of SPST was raising to 0.8. From the aspect of correlation comparison and assessment, it was significant that SPAD, MAPD, and SPST+SPDT had better prediction performance in the BPN (dry) and BPN (wet). These results will be analyzed comprehensively in the next section.

As for the explanation aspect, through the coefficient of determination to compare and assess various texture parameters, following are the coefficient of determination summaries of the 2D texture parameter variance presented in Fig. 6. It was observed that the various pavement texture parameters towards BPN (dry) had greater variations. Among the lowest values were the average of texture, SPST, and SPDT, for which R^2 was 0.5. The highest value was MAPD, which was 0.9. From Fig. 7, various pavement texture parameters towards BPN (wet) had greater variations. Among the lowest values were the average of texture and SPDT, for which the γ value was 0.5. The highest values were MAPD and SPST+SPDT, for which the γ achieved was 0.8. Therefore, from the aspect of explanation comparison and assessment, various 2D texture parameters showed significant differences. It was significant that SPAD, MAPD, and SPST+SPDT could be

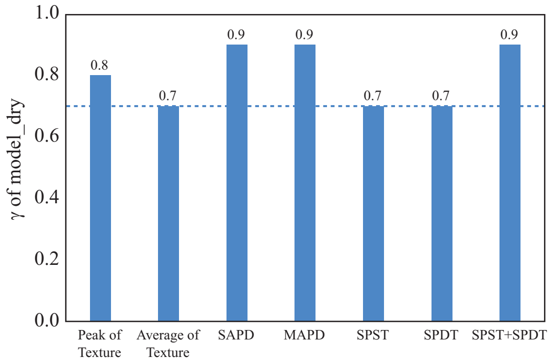


Fig. 4. γ of friction (dry) prediction models.

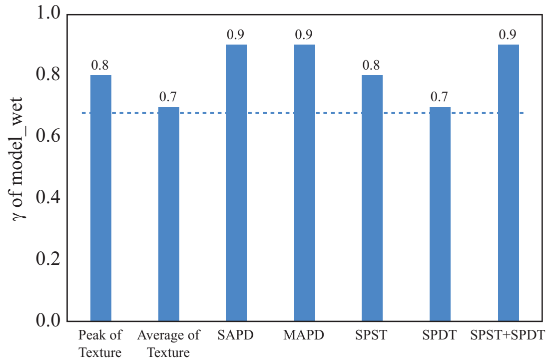


Fig. 5. γ of friction (wet) prediction models.

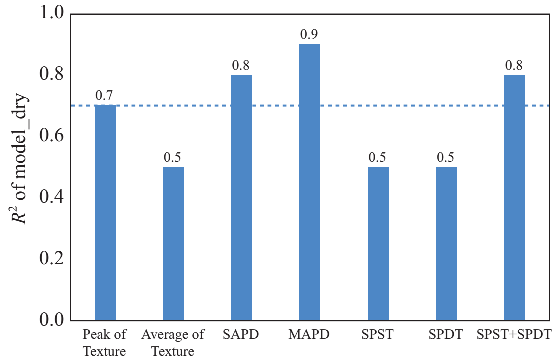


Fig. 6. R^2 of friction (dry) prediction models.

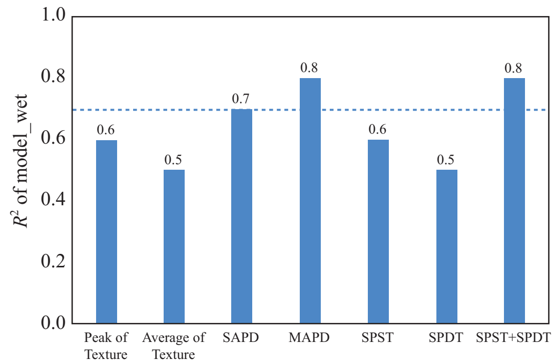


Fig. 7. R^2 of friction (wet) prediction models.

Table 1. Best forecasting model of BPN using SAPD.

BPN	Forecasting model of friction
Dry	$Y_1 = 13.27X + 44.66$
Wet	$Y_2 = 8.43X + 23.21$

Y_1 = BPN (Dry), Y_2 = BPN (Wet), X = SAPD

better explained in the BPN (dry) and BPN (wet), whereas average of texture, SPST, and SPDT were not easily explained. The best forecasting model of BPN using SAPD was showed as Table 1.

III. PRELIMINARY MODEL ESTABLISHMENT OF 2D TEXTURE PARAMETER

By comparing and evaluating the different 2D texture parameters in last section, SAPD was the best parameter to BPN forecasting model. Although MAPD and BPN had better correlation, the number of data were insufficient. Therefore, this study selected SAPD, owned second highest in correlation and R^2 to BPN, to establish prediction model. Through the tested values of SAPD and BPN, the obtained correlation profiles indicated that SAPD presented a high positive correlation in BPN (dry) and BPN (wet). Moreover, it was observed that in the correlation trend between SAPD and BPN (wet), as SAPD increased, both BPN (dry) and BPN (wet) also increased. Despite of R^2 in BPN (dry) could achieve 0.8; R^2 in BPN (wet) could achieve the explanation ability of 0.7. This study applied SPSS 15.0 as the statistical software to establish a forecasting model for SAPD and BPN.

Dry Friction Model Construction:

Dry Friction Forecasting Model of SAPD and BPN (dry) was as following:

$$\text{BPN (dry)} = 13.27\text{SAPD} + 44.66 \quad (2)$$

The friction coefficient (μ) transfer formula, established by Chen (1980), with BPN was as following:

$$R_{20} = \frac{300\,K\mu}{3+\mu} \quad (3)$$

where,
R_{20} = adjust to BPN of 20 Deg. C
μ = Friction Coefficient
K = constant around 1.08~1.13, generally use1.1

ASTM E 274 standard to derive Friction Number (FN):

$$\text{FN} = 100\mu \quad (4)$$

First, insert Eq. (2) into Eq. (3) to obtain relation between SAPD texture value and friction coefficient:

Table 2. Friction specification of Florida DOT and proposed standard of SAPD.

	Vehicle Speed (mile/hr)	Maintenance	Investigation	Standard
FN_{40} (Florida DOT)	≤45	25	26-28	30
	>45	27	28-30	35
SAPD (Proposed by this study)	≤45	0.258	0.369-0.588	0.805
	>45	0.479	0.588-0.805	1.337

$$\mu = \frac{133.98 + 39.81\text{SAPD}}{285.34 - 13.27\text{SAPD}} \quad (5)$$

Then, insert Eq. (3) into Eq. (4) to obtain relation between SAPD and FN:

$$\text{FN} = \frac{133.98 + 39.81\text{SAPD}}{285.34 - 13.27\text{SAPD}} \quad (6)$$

Wet Friction Model Construction Section:

Wet Friction Forecasting Model of SAPD and BPN (wet):

$$\text{BPN (wet)} = 8.43\text{SAPD} + 23.21 \quad (7)$$

Insert Eq. (7) into Eq. (3) to obtain relation between SAPD texture value and friction coefficient:

$$\mu = \frac{69.63 + 25.29\text{SAPD}}{306.79 - 8.43\text{SAPD}} \quad (8)$$

Then, insert Eq. (8) into Eq. (4) to obtain relation between SAPD and FN:

$$\text{FN} = \frac{69.63 + 25.29\text{SAPD}}{306.79 - 8.4350\text{SAPD}} \quad (9)$$

The upper part of Table 2 is the Friction standard of Florida DOT. When the highway design speed is more than 45 mile/hr, FN_{40} should be greater than 35 and the pavement could offer sufficient friction for driver. If FN_{40} is about 26-28, the pavement should be investigation and monitor. Under FN_{40} is 25 or less, the friction of pavement is insufficient, the surface maintenance is immediately necessary.

In this study, we already got the FN_{40} and SAPD transfer equation was showed in Eq. (9), and the study tried merging Eq. (9) into Florida DOT friction. The results were showed in the lower part of Table 2, When the highway design speed is greater than 45 mile/hr, SAPD should be greater than 1.337 and the pavement is safe for driver. If SPAD is about 0.558 to 0.805, the pavement should be pending monitor. The worse situation SAPD is 0.258 or less, driving on this pavement is dangerous, the surface should be reconstructed immediately. The proposed specification of SAPD under design speed is lower than 45 mile/hr is also showed in Table 2.

IV. CONCLUSION

(1) Compared with 1D texture of CTM, the 2D texture of HDSTM could get better capacity and accuracy to predict friction, the HDSTM is worthy to further study and development.

(2) The sum of the integrated deep and shallow texture depths had high correlation with BPN. Therefore, this study illustrated that SPST and SPDT have a complementary relationship with BPN, and each has a different influence level on friction.

(3) Based on evaluation of various 2D texture parameters in this study, the SAPD was the best feasible parameters to predict BPN. In surface wet condition, the best forecasting model is BPN (wet) = 8.43SAPD + 23.21; In surface dry condition, the best forecasting model is BPN (dry) = 13.27SAPD + 44.66.

(4) If the highway design speed is greater than 45 mile/hr, SAPD should be greater than 1.337 and the pavement is safety for driver. If SPAD is about 0.558 to 0.805, the pavement should be pending monitor. When SAPD is 0.258 or less, it is the worse situation, driving on this pavement is dangerous, and the surface should be reconstructed immediately.

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