JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2015; 2 (6): 382–390

HOSTED BY

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

Evaluation of pavement skid resistance using high speed texture measurement

*Jay N. Meegoda**, *Shengyan Gao*

Department of Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA

ARTICLE INFO

Article history:
Available online 8 October 2015

Keywords:
Skid resistance
High speed laser
Pavement texture
Cumulative traffic volume
Locked wheel skid trailer
Mean profile depth

ABSTRACT

Skid resistance is an important parameter for highway designs, construction, management, maintenance and safety. The purpose of this manuscript is to propose the correlation between skid resistance, which is measured as skid resistance trailer, and mean profile depth (MPD) or the macro surface texture, which is measured by vehicle mounted laser, so that highway agencies can predict the skid resistance of pavement without the use of expensive and time consuming skid resistance trailer, which also causes disruption of traffic in use. In this research skid numbers and MPD from 5 new asphalt pavements and 4 old asphalt pavements were collected using a locked wheel skid trailer and a vehicle mounted laser. Using the data collected, a correlation between the skid number (SN40R) collected by locked wheel skid tester and the texture data or MPD collected by a vehicle mounted laser operating at highway speeds was developed. The proposed correlation for new pavements was positive for MPD values less than 0.75 mm to reach a peak SN40R value, then there was a negative correlation as the MPD increases until the MPD value was equal to 1.1 mm and beyond the MPD value of 1.1 mm to the maximum value of 1.4 mm, SN40R value remained almost constant. There were significant data scatter for the MPD value of 0.8 mm. To explain these results, water film thickness during the friction test was calculated and the critical MPD was defined. The effect of sealed water pool on the SN40R was discussed. The test result showed a similar trend for older asphalt pavements, but with lower SN40R values due to the polishing of pavement micro-texture by traffic. Hence, a reduction factor was proposed for older pavements based on cumulative traffic volume for the above correlation to predict the skid resistance of older pavements.

* *Corresponding author*. Tel.: +1 973 596 2464; fax: +1 973 596 5790.
E-mail address: Meegoda@njit.edu (J. N. Meegoda).

Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2015.09.001

1. Introduction

Literature search shows that when pavements are wet, accidents occur at a rate of 3.9–4.5 times that on dry pavements (NTSB, 1980). The skid resistance alone cannot predict the accident rates since many other factors contribute to accidents, including pavement condition state, prevailing speed, and traffic volume (Henry, 2000; Kuttesch, 2004). However, there is statistically significant correlation between skid resistance and wet accident rate, and the wet accident rate increases with decreasing skid numbers (Kuttesch, 2004). Cairney (1997) and Giles et al. (1965) found that the risk of a skid related crash was small when friction values was above 60 but increased rapidly with skid resistance values below 50. Meanwhile, McCullough and Hankins (1966) recommended a minimum desirable friction coefficient of 0.4 measured at 50 km/h (30 mph) from a study of 571 sites in Texas. Their study examined the relationship between skid resistance and crashes, and found that a large proportion of crashes occurred with low skid resistance and relatively few occurred with high skid resistance. Several transportation agencies have developed specified road friction threshold values that define the lowest acceptable road friction condition after which surface restoration will take place. For example, Maine, Washington, and Wisconsin use 35, 30, and 38, respectively, as their cutoff values (Henry, 2000). Tighe et al. (2000) identified the pavement engineering relationships associated with road safety, and incorporated it to pavement management. Recently, tire pavement skid resistance, especially the wet skid resistance, has been recognized as an important parameter used in network surveys for pavement management, evaluation of surface restoration, specifications for new construction, accident investigations, and winter maintenance on highways etc. However, what is still not known is the exact mechanism, which causes the decrease in pavement friction when a film of water covers the road surface and the effect of pavement surface texture on it. As a result, efforts in better understanding of effect of pavement texture, and its incorporation in the pavement safety equation appears to be a promising direction (Noyce et al., 2007).

Wet skid resistance can be measured directly through full-scale friction measuring devices such as locked wheel trailer conducted in accordance with ASTM (2003a). In this method, a rib or smooth tire is towed at 40 mph. The wheel is locked and allowed to slide for a certain distance, usually the left wheel path in the tested travel lane. The operator applies the brakes and measures the torque for 1 s after the tire is fully locked to compute the correspondent friction value. The measurement is reported as skid number or SN40R and defined as the traction force divided by the dynamic load on the tire. Customarily it is multiplied by a constant (100) (ASTM, 2003a), as indicated below.

$$\mathrm{SN} = 100\left(\frac{F}{W}\right) \tag{1}$$

where F is the traction force applied to the tire at the tire pavement contact, W is the dynamic vertical load on the tire, and SN is the skid number. The characters 'S' and 'R' in 'SN40S' and 'SN40R' represent the smooth tire and the rib tire, respectively. According to the research completed by the Florida Department of Transportation, the rib tire provides skid measurements that are better indicators of safety than measurements by smooth tires (Henry, 2000). Hence in this research rib tires (ASTM) are used and as a result, SN40R values are reported.

Skid resistance between tire and pavement interface has 2 major components, namely, adhesion and hysteresis (Cairney, 1997). Adhesion results from the shearing of molecular bonds formed when the tire rubber is pressed into close contact with pavement surface. These interactions are often dominated by weak Van der Waals forces. Hysteresis results from energy dissipation when the tire rubber is deformed and passed across the asperities of a rough pavement surface. On very rough surfaces, the substrate asperities exert pulsating forces onto the rubber surface which, because of its high internal friction at the appropriate frequencies, results in a large dissipation of energy. The adhesive contribution to rubber friction is much smaller for smooth surfaces, mainly because of the small contact area.

The 2 components of skid resistance are related to the 2 key properties of asphaltic pavement surfaces, that is micro-texture and macro-texture. Micro-texture is a surface texture irregularity which is measured at the micro scale of harshness and is known to be a function of aggregate particle mineralogy for given conditions of weather effect, traffic action and pavement age, while macro-texture refers to the large-scale texture of the pavement as a whole due to the aggregate particle arrangement, which controls the escape of water under the tire and hence the loss of skid resistance at high speeds (RTAC, 1977).

Micro-texture values are commonly estimated using low speed friction measurement devices such as the British Portable Tester (BPT), the Dynamic Friction Tester (DF Tester), and the locked wheel skid trailer operating at low speeds (Wambold and Henry, 1995). These measurements always disturb or disrupt the traffic flow. Macro-texture measurements can be divided into 2 main classes, static measurements and dynamic measurements. Common static macro-texture measurement methods include the sand patch method, the outflow meter, and the Circular Texture Meter (CTM). The dynamic measurements are conducted by vehicle-mounted laser devices, which can collect data at highway speeds. As a result, vehicle mounted laser texture measurement is a promising method for collecting macro-texture data of pavement. Flintsch et al. (2003) and McGhee and Flintsch (2003) correlated CTM measurement and Sand Patch Test, and found a strong correlation.

As mentioned before, skid resistance can be measured directly by locked wheel trailer. However, this method is very expensive and disturbs the traffic flows during the test. So it is not a practical and economical method to continually monitor road surface. The surface macro-texture is a predominant contributor to wet-pavement safety (Anderson et al., 1998; Mahone, 1975) and a coarse macro-texture is very desirable for safe wet-weather travel as the speed increases (Galambos et al., 1997) while the micro-texture and adhesion contributions to skid resistance are just the prevailing influence at the speeds less than 30 mph. So a new friction coefficient prediction model that only uses road macro-surface texture measured by contactless method without disrupting the traffic would allow efficient routine surveys of the road network. This will significantly reduce the need for the ASTM E274 skid resistance trailer to collect the skid resistance data (Meegoda et al., 2003, 2005, Meegoda, 2009; Rowe et al., 2004).

There are several regression models (Ergun et al., 2005; Jackson et al., 2007; Khasawneh and Liang, 2008) relating to pavement surface micro/macro-texture with SN values. However, most of them include the data of the micro-texture and such measurements will disrupt the traffic. In addition, most of the models failed to take into account the effect of water film on skid resistance while analyzing the correlation.

The water film thickness is a significant contributing factor when building a correlation between skid number and pavement texture. Persson et al. (2005) studied rubber friction at low sliding velocities on wet rough substrates, where it has been observed that the friction is typically 20%–30% less than that for the corresponding dry surfaces and by using fluid film lubrication theory they proved that above reduction cannot be completely due to the hydrodynamic effects. Persson et al. (2005) proposed an explanation based on the rubber sealed water pools, namely, regions on the substrate filled with water as shown in Fig. 1. Claeys et al. (2001) built a dynamic friction model to describe the influence of water film thickness on the frictional characteristics between the tire tread and pavement. Claeys et al. (2001) defined 2 different hydroplaning, viscous hydroplaning and dynamic hydroplaning. The fluid at the interface is modeled as viscous and the sink dynamics of the tire (squeezing of water) can be determined using the Navier–Stokes equation, and the effective tire/road contact surface is a function of the time taken by the tire to achieve the contact with the ground. As a consequence, all the parameter calculations are based on the water clearance time or time of sink, which varies for different wheel speeds, tread stiffness, ground pattern characteristics, etc.

This research does not focus on hydroplaning, however, it is worth to note that Claeys et al. (2001) included the road texture in their model. And as a result, the setting time is also a function of amplitude of the road texture, which provided impetus for this research to include the sealing effect of confined pools as shown in Fig. 1. A simple method for understanding this problem would be to use the analogy between the behavior of the tire in the squeezed water film and the sink of a flat plate over a randomly rough surface area. Considering the sink of a flat plate over a rough surface, there are a bulk flow of escaping fluid between the plate and the asperity tips, and an open channel flow between the asperities. As the plate approaches the peaks of the asperities, there is virtually no bulk flow, and the channel flow becomes closed because the plate provides an upper boundary at this position and then the water is sealed off in the cavity of road surface.

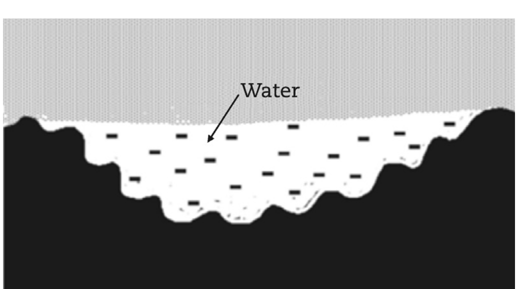

Fig. 1 – Illustration of sealed water pool on pavement surface (Persson et al., 2005).

Fig. 1 shows a wet substrate the water trapped in the large valley forming a pool preventing the rubber from penetrating into the valley. Hence aggregates in this valley would not contribute to the friction force. This rubber sealing effect reduces the sliding friction (Claeys et al., 2001). Please note that the frictional force is due to the normal force acting on the pavement surface. However, if there is water trapped between tire and pavement such as that shown in Fig. 1, then the water is compressed. The bulk modulus of water is infinite and hence water generates pore pressure taking up part of the normal force. This would cause frictional force to reduce.

In this research, SN40R and Mean Profile Depth (MPD) values are collected from 5 new asphalt pavements in New Jersey, and collected data is used to develop a rational mechanism and a supporting correlation between SN40R and MPD values. In the following section, to analyze the test data, the water film thickness during the friction test is calculated and critical MPD is defined. The effect of sealed off water pool on the SN40R is discussed. Finally a comparison is made between the new and old asphalt pavements for the purpose of evaluating the impact of micro-texture on the skid resistance of pavement.

2. Water film thickness during friction test and critical MPD

Pavement wetting system used during the skid resistant measurement, releases $4.0 \times (1 \pm 10\%)$ gal per minute per inch of wetted width $600 \times (1 \pm 10\%)$ mL/(min·mm) at 40 mph. Thus the average water film thickness at a test speed of 40 mph is approximately 0.55 mm, which means, if the volumetric Mean Texture Depth MTD of the pavement is less than 0.55 mm, then the pavement surface is completely covered with water during the skid resistance test. The following correlation between the MTD and MPD (ASTM), where MTD and MPD are in mm, can be used to compute equivalent MPD.

$$\mathrm{MTD} = 0.8\,\mathrm{MPD} + 0.2 \tag{2}$$

When the MTD is equal to 0.55 mm, the corresponding MPD is equal to 0.4375 mm. Here the critical MPD is defined as a depth at which the water just filled all the cavities in the pavement surface. Hence according to Eq. (2), the critical MPD is 0.4375 mm. However, the MPD in the Eq. (2), does not prescribed the method of obtaining a measured profile and its calculation is based on straight line profile.

In this research the dynamic macro-texture measurement by non-contact laser at traffic speeds was used. Hence the above correlation between MTD and MPD should be modified. Flintsch et al. (2003) provided the correlation between MTD (by sand patch test) and MPD (by non-contact laser) (International Cybernetics Corporation (ICC)) as follows with a correlation coefficient of 0.884.

$$\mathrm{MTD} = 0.7796\ \mathrm{MPD} - 0.379 \quad (3)$$

According to the Eq. (3), the critical MPD measured by ICC laser is about 1.19 mm. McGhee and Flintsch (2003) also provided correlation between MTD and MPD by ICC laser with correlation coefficients 0.9028 and 0.7309, according to which the corresponding critical MPD by ICC laser is 1.26 mm and 1.15 mm respectively. Based on the above calculations, one can reasonably estimate the critical MPD by ICC laser to be approximately 1.2 mm.

It should be noted that at low velocities (Persson et al. (2005) used 30 km/h), there is sufficient time for the water to be squeezed from the contact regions between the tire and the road surface, except for water trapped in road cavities and sealed by the road-rubber contact at the upper boundaries of the cavities (Persson et al., 2005). It was also the same at velocity of 64 km/h (40 mph) based on calculation of Persson et al. (2005). Therefore, during the skid resistance test with the MPD smaller than critical MPD, every valley will be filled with water up to the maximum level, where the water remained confined and extra water will be squeezed. As a result, it is reasonable to infer that the primary effect of water on skid resistance during the test is the sealed water pool effect. This effect will be employed to explain the test result in the following sections of this manuscript.

3. Skid number (SN40R) collection and processing

Skid number is collected by full-scale friction measuring devices—locked wheel trailer conducted in accordance with ASTM (2003a). During the test, a rib tire (E-524-88) was towed at 40 mph and the left wheel path in the travel lane was tested. At each milepost (every 0.1 mile), water was added ahead of the test tire and the braking system was activated to lock the test tire for 1 s. The traction force (f_h) and dynamic vertical load (f_v) were measured and the skid number was calculated automatically in real time as shown below.

$$sn(t) = \frac{f_h(t)}{f_v(t)} \times 100 \quad (4)$$

Then SN can be calculated as

$$\mathrm{SN} = \int_0^1 sn(t)\mathrm{d}t \quad (5)$$

The SN value in Eq. (5) was reported as skid number at the corresponding milepost. For the wheel fully locked for about 1 s, the reported SN is the average skid number for 18 m length at each milepost (with 9 m on each side). The 3 trials were performed at each site and thus 3 SN40R values at each milepost were collected and averaged. Please note that New Jersey there has mileposts at every 1/10 of a mile (161 m).

4. Texture data collection and processing

Texture data (profile depth) of pavement surface was collected using a vehicle mounted laser (Selcom 62.5 kHz Laser manufactured by International Cybernetics Corporation) at traffic velocity. The measurement starts manually when the front window of the laser mounted vehicle crosses the starting milepost and the laser collects the profile depth of the pavement surface at an interval of 0.06 mm. The laser was stopped manually when the vehicle passed the end milepost. The 5 trials were performed for each pavement section.

The software provided by the laser vehicle vendor was used to processes the collected laser data (at the interval of 0.06 mm) and reported MPD value for each 100 mm section of the pavement according to ASTM (2003b). The MPD values of 20 m-length section of pavement at each milepost (with 10 m on each side) were collected and averaged. (Please note that for the purpose of taking into account the operating error in skid resistance test, 20 m instead of 18 m is chosen for calculating the average MPD corresponding to each SN40R.)

5. Correlation between SN40R and MPD for asphalt pavement

5.1. *Correlation for new asphalt pavement*

The skid number and MPD data from 5 new asphalt pavements with average pavement age less than 5 years with no other surface treatment after paving were collected using a locked wheel skid trailer (ASTM, 2003a) and a vehicle mounted laser (Selcom 62.5 kHz Laser with system conforms to ASTM (2003b) manufactured by ICC, respectively). The 5 new asphalt pavements sections with age and traffic volume are shown in Table 1. While developing the correlation between the SN40R and MPD, the following procedure was used and the correlation obtained is shown in Fig. 2.

(1) Calculated the average and standard deviation of 3 SN40R values at every 0.1 milepost and discarded the SN40R values with stand deviation greater than 2.

Table 1 – Routes information for the correlation.

Route no.	Route section	Treat year	Total traffic volume per lane
Rt. 29	MP 7.0–6.18 S Ln2	2007 + 1/2	5,149,511
Rt. 29	MP 7.0–8.0 N Ln2	2008	1,179,680
Rt. 29	MP 8.0–7.0 S Ln2	2008	1,179,680
Rt. 29	MP 2.0–1.0 S Ln2	2007 + 1/2	5,149,511
Rt. 73	MP 22.0–23.0 N Ln2	2008	3,689,967
Rt. 27	MP 13.0–15.0 N Ln2	1995	49,167,142
Rt. 27	MP 13.0–15.0 S Ln2	1995	49,167,142
Rt. 175	MP 0.25–1.0 N Ln2	2000	3,173,310
Rt. 175	MP 0.25–1.0 S Ln2	2000	3,173,310

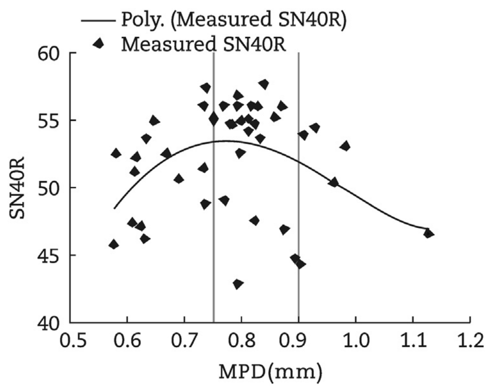

Fig. 2 – Correlation between SN40R and MPD.

(2) Calculated the average of MPD values for the 5 trials and checked the standard deviation. If the standard deviation was high, checked the original file to determine which trial among the 5 trials should be eliminated.
(3) Correlated the average SN40R value at every 0.1 milepost with the corresponding average MPD value.

From Fig. 2, there is no positive linear relationship between SN40R and MPD values, however, there are 2 obvious characteristics of the curve which is divided into 3 segments as described below.

(1) There is no positive correlation between MPD and SN40R. From the above graph, peak of SN40R value occurred when MPD is around 0.75 mm, and after that SN40R values decreased with increasing MPD values until MPD value was equal to about 1.1 mm, which was close to the critical MPD of 1.2 mm. The trend of SN40R for MPD value beyond 1.1 mm is not clear as there is not enough data in this case for new pavements. However, according to the data shown in the following section for old pavements, SN40R does not vary much for MPD value greater than 1.1 mm. The above trend of SN40R with MPD is similar to that published by Jackson (2005) However, the correlation proposed by Jackson (2005) had a peak SN40R value at MPD equal to 1.3 mm (0.05 inches), which was quite different from 0.8 mm in Fig. 2 and there was also a decreasing trend of SN40R after MPD values higher than 3.81 mm (0.15 inches). The probable reason for the difference between 2 results may be the laser calibrations in the 2 tests. Hence, it is suggested that further research is needed to calibrate non-contact laser data using Sand Patch test or by CTM (Flintsch et al., 2003) to obtain MPD values for comparison.
(2) Fig. 2 also showed that SN40R values fluctuated at a MPD value around 0.8 mm. This phenomenon is consistent with the published data by Khasawneh and Liang (2008), where the SN64R also fluctuated at MPD equal to 0.5 mm. It should be noted that, Khasawneh and Liang (2008) collected MPD values using CTM. According to the 2 correlations with correlation coefficients of 0.74 and 0.91, respectively, between CTM measurement and ICC laser measurement proposed by McGhee and Fintch (2003), a CTM measurement of 0.5 mm is equivalent to ICC laser measurement of 0.85 mm and 1.13 mm, respectively. However, the average value, which is about 1 mm, is still different from 0.8 mm observed in this study. The difference may be due to the error of the calibration of laser.

In order to better understand and explain the effect of macro-texture and water film on the skid resistance, the correlation in Fig. 2 is divided into 3 separate sections as shown in Fig. 3 and each is discussed in the following sections.

Based on the previous discussion of MPD values less than the critical MPD value of 1.2 mm, the pavement surface is completely covered by water during the skid test. But as mentioned before, there is sufficient time for the water to be squeezed out from the contact regions between the tire and road surface at test speeds, so the hydrodynamic effect of water is negligible, and the sealed water pool effect, which is related to the roughness of pavement surface, is the main contributor to skid resistance. Here the macro-texture has 2 contributions to the SN40R, one is the hysteresis and the other is related sealed water pool effect. It should also be noted that increasing the macro-texture will lead to decrease of the contact area between the tire and pavement.

Fig. 3(a) shows a positive correlation between SN40R and MPD. The probable explanation for this relationship is that the pavement surface at lower MPD values is relatively smooth. As a result, the sealed water pool effect is not significant and the slightly increase of the MPD does not lead to much decrease of contact area. Thus the primary effect of MPD on skid resistance is its contribution from hysteresis which is the main contributor to the skid resistance at high speed. That is why SN40R increased with the increase of MPD (positive correlation). However, as shown in Fig. 3(a), the correlation was not very high with the correlation coefficient of only about 0.3 and there was a significant data scatter at MPD value of 0.8 mm. The main factor accounting for the low correlation coefficient and for the data scatter is the sealed water pool effect which will be explained below.

Compared with Fig. 3(a), the correlation between SN40R and MPD becomes negative in Fig. 3(b). According to the earlier discussion of macro-texture effect on skid resistance, it can be stated that with the increasing MPD, the contributions of the sealed water pool effect and decreased contact area increase and become greater than the contribution of the macro texture (hysteresis). Hence when MPD increases, the SN40R shows a downward trend.

Both in Fig. 3(a), (b) there is a significant scatter of SN40R values near MPD equal to 0.8 mm. This is the reason for low correlation coefficients of both sections. The main contributing factor for the data fluctuation is the sealed water pool effect as shown in Fig. 4, with 2 probable pavements. According to the ASTM (2003b) (calculating pavement macro-texture mean profile depth), the 2 pavements have the same MPD, but the sealed water pool effects of the 2 pavement are significantly different. As shown in Fig. 4(b), compared with Pavement 1, Pavement 2 has more cavities on its surface. As a result, it has more

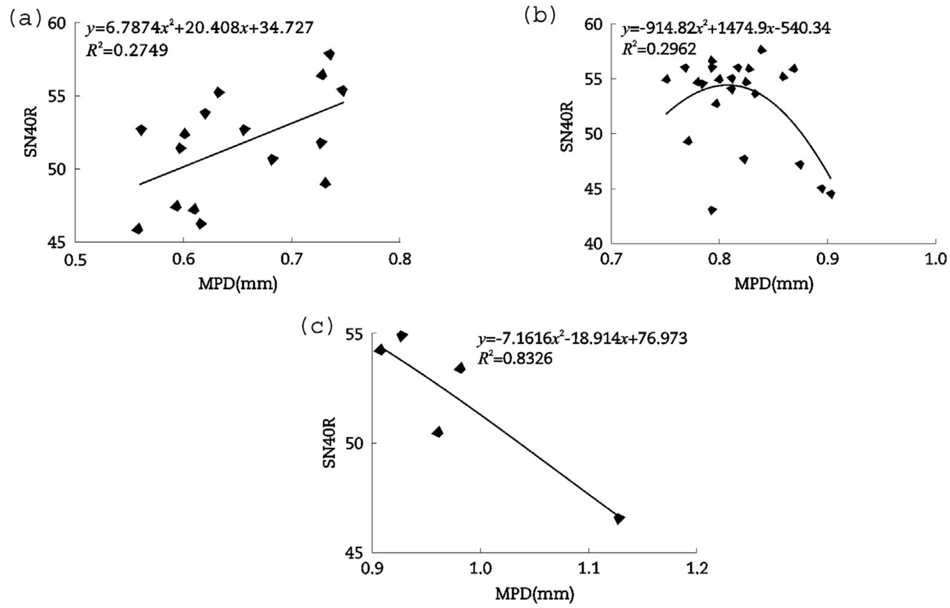

Fig. 3 – Correlation between SN40R and MPD separated into 3 sections. (a) Section 1, MPD < 0.75 mm (b) Section 2, 0.75 mm ≤ MPD ≤ 0.90 mm (c) Section 3, MPD > 0.90 mm.

sealed water pools. It is also true that the Pavement 2 should have higher hysteresis contribution due to the protruding surface. However, as mentioned above, in this section (0.75 mm ≤ MPD ≤ 0.90 mm) the effect of hysteresis on skid resistance is not as great as that of sealed pool and contact area, so the contribution to skidding from hysteresis is less than that of sealed pool effect. As a result, SN40R value for Pavement 2 should be lower than that for Pavement 1 shown in Fig. 4. This would explain why SN40R fluctuates at MPD value of 0.8 mm. As mentioned before, when MPD is lower than 0.8 mm, the road is relatively smooth, hence the sealed pool effect is not a major contributor. However, for MPD values higher than 0.8 mm, with the increasing MPD there is decreased contact area and lower hysteresis. Hence the sealed pool effect is the most significant contributor to SN40R for MPD values around 0.8 mm. That is why the scatter of SN40R values near the MPD value equal to 0.8 mm. In order to better understand this phenomenon and to estimate the skid resistant of the pavements at MPD values near 0.8 mm, it is proposed that Root Mean Square (RMS) value is incorporated into the correlation. Then the comparison of RMS and MPD can indicate the detailed texture, that is, whether it is provided by aggregate protruding from the surface or by cavities in the surface. For example, for 2 pavements having the same MPD (Fig. 4(a), (b)), the pavement with the higher RMS (Pavement 2) will have more cavities and protrudings than the other one. Hence by combining RMS value with MPD, it is possible to decide whether the sealed water pool effect is significant or not.

Fig. 3(c) shows that there is a downward trend of SN40R with increasing MPD values from 0.9 mm to about 1.1 mm, and for MPD values higher than 1.1 mm there is no change in SN40R values. As mentioned before, when MPD value is greater than 0.8 mm, the effects of decreased contact area and increased hysteresis resulting from the increasing MPD values become the principal contributors for the SN40R, especially for MPD higher than the critical value of 1.2 mm (if the deformation of the rubber tire is neglected here, the sealed water pool becomes insignificant when MPD is higher than the critical value). From Fig. 3(c), it can be inferred that in the first part of the graph (0.9 mm < MPD < 1.1 mm), the effect of decreased area plays a major role in contributing to SN40R while after 1.1 mm, with the higher MPD, both effects of decreased area and hysteresis become equivalent. Thus the correlation shows a negative slope in the first part and a small positive slope after that. However, according to the published data by Khasawneh and Liang (2008) the correlation will become positive with the MPD higher than 1.5 mm, which means if pavement is much rougher, the effect of hysteresis will be more important than the decreased contact area to increase of SN40R. However, additional data is needed to validate this observation.

Fig. 3(c) shows a high correlation coefficient with no data scatter when compared with Fig. 3(a), (b). This observation is consistent with the proposed inference that the sealed water

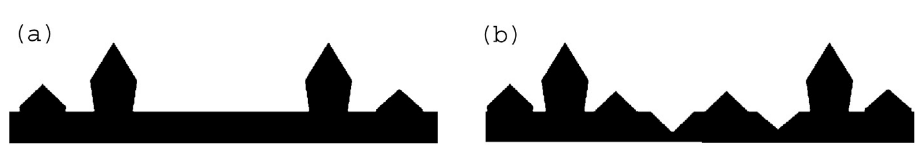

Fig. 4 – Illustration to show the importance of RMS value of texture. (a) Pavement 1. (b) Pavement 2.

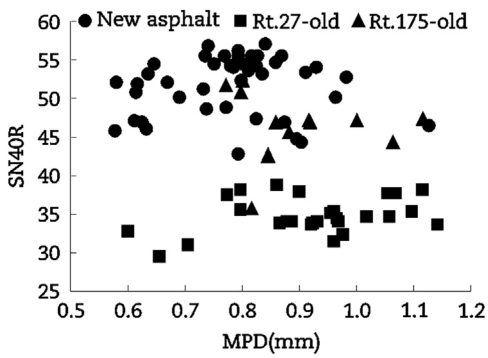

Fig. 5 – Comparison between new and old asphalt pavements.

pool effect is the main factor contributing to the data fluctuation and to a low correlation coefficient in Fig. 3(a), (b). In Fig. 3(c), because the MPD is high, the sealed water pool effect becomes relative insignificant. As a result, the correlation coefficient is higher. The estimated, or predicted, SN40R values from MPD data are calculated as follows (Fig. 3):

(1) For MPD < 0.75 mm, $SN40R = 6.7874\ MPD^2 + 20.408 \times MPD + 34.727$
(2) For 0.75 mm ≤ MPD ≤ 0.90 mm, $SN40R = -914.82 \times MPD^2 + 1474.9\ MPD - 540.34$
(3) For MPD > 0.90 mm, $SN40R = -7.1616\ MPD^2 - 18.914 \times MPD + 76.973$

5.2. Comparison between new asphalt pavement and old pavement

In order to account for the contribution of micro-texture on skid resistance, the comparison between SN40R-MPD correlation for new and old asphalt pavements is presented. The SN40R and MPD data were collected from 4 old asphalt pavements with an average road age of over 20 years. The 4 pavement sections, with age and traffic volumes, are also listed in Table 1. The comparison of results is shown in Fig. 5.

From Fig. 5, one can find that the 2 old asphalt pavements themselves show much different skid resistances from each other. The SN40R values of Rt. 175 were much higher than that of Rt. 27. The correlation between SN40R and MPD values for Rt. 175 is similar to that for a new asphalt pavement (SN40R values fluctuated around MPD value of 0.8 mm and the correlation was similar to that of the new asphalt for MPD values higher than 0.9 mm). The relationship between SN40R and MPD values for Rt. 27 is similar to that of a new asphalt pavement (the trend was almost parallel to that of a new asphalt pavement) but the SN40R values were much lower. The main factor accounting for the difference is the traffic volume. According to the data published by NJDOT, the traffic volume (Annual Average Daily Traffic) for Rt. 27 is 38,487 in 2003, which is almost 19 times of that for Rt. 175. The traffic flow will cause polishing of the pavement surface and consequently a reduction of skid resistance. That is the reason for much lower SN40R values of Rt. 27, when compared with those for Rt. 175 and other new asphalt pavements. Also with traffic volume

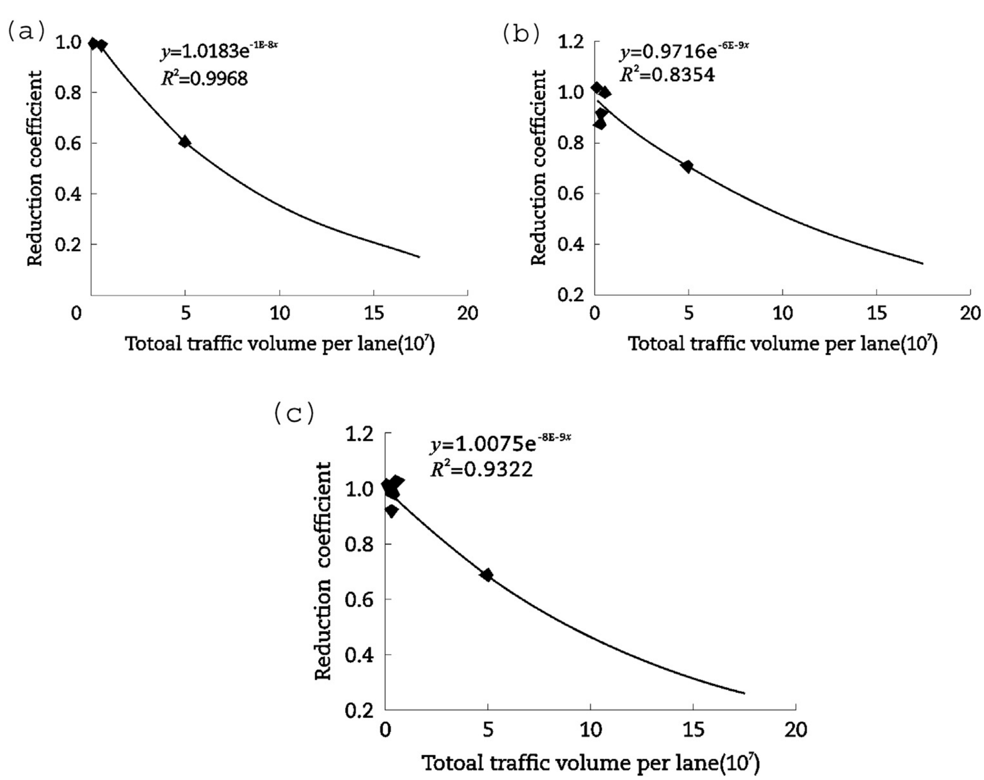

Fig. 6 – Reduction coefficient for cumulative traffic volume for 3 sections. (a) Section 1, MPD < 0.75 mm (b) Section 2, 0.75 mm ≤ MPD ≤ 0.90 mm (c) Section 3, 0.90 mm < MPD < 1.15 mm.

(Annual Average Daily Traffic) of 1932 for Rt. 175, which is also much lower than that for all 5 new asphalt pavements with average traffic volume of 42,000, there is minimal polishing of aggregates. As a result, based on road age, it is treated as an old pavement, based on cumulative traffic volume it can be considered as a new asphalt pavement.

In order to develop a reduction factor for the traffic volume, the measured SN40R and predicted SN40R for the dense graded fine/coarse asphalt pavement are compared with the cumulative traffic volume. Total traffic volume of each pavement is calculated as the reported daily traffic volume × pavement age ×365/number of lanes. Based on the treated year and traffic volume of each pavement (supplied by NJDOT), the correlation between total traffic volume per lane (count from treat year) and reduction coefficient was obtained and shown in Fig. 6. It is noted here that, as the contribution of micro-texture of pavement to SN40R, which is affected by traffic polishing, varies for pavement at different levels of MPD, the separated reduction factors are proposed for 3 aforementioned correlations between SN40R and MPD.

The 3 formulae of reduction factors for SN40R according to different macro-texture values.

(1) For MPD < 0.75 mm, $\lambda = 1.0183\exp(-1E-8x)$
(2) For 0.75 mm ≤ MPD ≤ 0.90 mm, $\lambda = 0.9716\exp(-6E-9x)$
(3) For MPD > 0.90 mm, $\lambda = 1.0075\exp(-8E-9x)$

Fig. 7 shows the comparison between new and old asphalt pavements corrected for the traffic volume. With the proposed reduction, one could use the same correlation (Fig. 3) to predict the skid resistance of a pavement using the texture data obtained from the high speed laser for pavements at different ages and with distinct cumulative traffic volumes.

The above correlation will be used by NJDOT to screen all the roadway pavements belonging to the state of New Jersey using high speed laser, and the predicted skid numbers will be included in their pavement management database. Hence, with the predicted skid numbers, they could reduce the use of expensive locked wheel skid tester and save thousands of taxpayer dollars.

It should be noted that the correlation proposed in this research is both site and equipment specific. All pavements

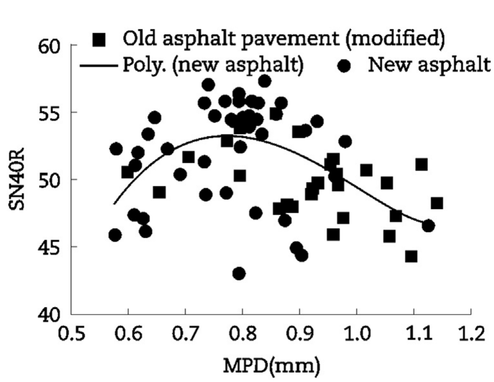

Fig. 7 – Comparison between new and old asphalt pavements corrected for the traffic volume.

tested used 9.5 mm trap rock with similar micro texture values and used ICC laser to develop the proposed correlation. However, attempt was made to provide a mechanistic explanation, so that a similar correlation could be developed for other locations and equipment enabling transportation agencies to develop rapid screening tool to evaluate the skid resistance of their pavements in the network.

6. Summary and conclusions

In this research, a mechanistic explanation and a correlation between skid number (SN40R) and Mean Profile Depth (MPD) of asphalt pavement were proposed based on data collected from 5 new asphalt pavements. The correlation is positive for MPD values less than 0.8 mm, where SN40R value reached a maximum around MPD value of 0.8 mm. Then the data trend shows a negative correlation with increasing MPD until MPD is about 1.1 mm, after which the SN40R values remained constant with increasing MPD values. It was also found that there was a significant scatter of SN40R values around MPD value of 0.8 mm and the sealed water pool effect seems to account for the data scatter. The proposed correlation between SN40R and MPD is similar to that proposed by other researchers. However, because of the difference in calibrations of vehicle mounted laser, there were some inconsistencies between the data from this research and other published data. In order to reduce the data fluctuation at a certain MPD value in the proposed correlation due to the sealed water pool effect, it is proposed to include Root Mean Square (RMS) texture values with MPD values to represent the macro-texture of the pavement.

The comparison of data between old and new asphalt pavements is also presented in this manuscript. The result shows that the trend of correlation for old asphalt pavements is similar to that for new asphalt pavements, but the SN40R for the old pavements are lower than that for the new pavements, which shows the aggregate polishing due to traffic. It is proposed that road age and traffic volume could be incorporated into the correlation or be used as parameters to reflect the polishing of micro-texture due to traffic.

Acknowledgments

This research was sponsored by a research contract from the New Jersey Department of Transportation (FHWA-NJ-2009-020). The contents of this paper reflect the views of authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the views or policies of NJIT, NJDOT or FHWA. This paper does not constitute a standard, specification or regulation. The authors wish to acknowledge the efforts of NJDOT Project Manager Mr. Vincent Nichnadowicz, and also the contributions of NJDOT Manager of the Bureau of Research Ms. Camille Crichton-Sumners, Mr. Nicholas C. Gephart of NJDOT, Dr. Geoff Rowe of ABATech, Mr. Sim Liu, Mr. Eugene Maina and Mr. Manan Shah of NJIT and Mr. Hadi Pezeshki of FHWA.

REFERENCES

Anderson, D.A., Huebner, R.S., Reed, J.R., et al., 1998. Improved Surface Drainage of Pavements. NCHRP Web Document 16. The National Academies of Science, Engineering and Medicine, Washington DC.

ASTM (American Society for Testing and Materials), 2003a. Standards Designations E247-97, Annual Book of ASTM Standards Volume. ASTM, West Conshohocken.

ASTM (American Society for Testing and Materials), 2003b. Standards Designations E1845-01, Annual Book of ASTM STANDARDS Volume. ASTM, West Conshohocken.

Cairney, P., 1997. Skid Resistance and Crashes: a Review of the Literature Research. Report No. 311. ARRB Transport Research Ltd, Vermont South Victoria.

Claeys, X., Yi, J., Alvarez, L., et al., 2001. Tire friction modeling under wet road conditions. In: Proceedings of the American Control Conference, Arlington, 2001.

Ergun, M., Lyinam, S., Lyinam, A.F., 2005. Prediction of road surface friction coefficient using only macro- and micro-texture measurements. Journal of Transportation Engineering 131 (4), 311–319.

Flintsch, G.W., Leon, E.D., McGhee, K.K., et al., 2003. Pavement surface macrotexture measurement and applications. Transportation Research Record 1860, 168–177.

Galambos, V., Hegmon, B., Rice, K., 1997. Pavement Texture and Available Skid Resistance. Office of Research, Federal Highway Administration, Washington DC.

Giles, C.G., Sabey, B.E., Cardew, K.H.F., 1965. Development and performance of the portable skid resistance tester. Chemistry and Technology 38 (4), 840–862.

Henry, J.J., 2000. Evaluation of Pavement Friction Characteristics: a Synthesis of Highway Practice. NCHRP Synthesis 291. Transportation Research Board, National Research Council, Washington DC.

Jackson, N.M., July 2005. "Measuring Pavement Friction Characteristics at Variable Speeds for Added Safety". Final Report to Florida Department of Transportation.

Jackson, N.M., Choubane, B., Holzschuher, C.R., et al., 2007. Measuring pavement friction characteristics at variable speeds for added safety. In: Pavement Surface Condition/Performance Asscessment: Reliability and Relevancy of Procedures and Technoloies, STP 1486. ASTM, West Conshohocken, 2007.

Khasawneh, M.A., Liang, R.Y., 2008. Correlation study between locked-wheel skid trailer and dynamic friction tester. In: TRB 87th Annual Meeting, Washington DC, 2008.

Kuttesch, J.S., 2004. Quantifying the Relationship between Skid Resistance and Wet Weather Accidents for Virginia Data. Master Thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Mahone, D.C., 1975. An Evaluation of the Effects of Tread Depth, Pavement Texture, and Water Film Thickness on Skid Number–speed Gradients. Virginia Highway and Transportation Research Council, Charlottesville.

McCullough, B.F., Hankins, K.D., 1966. Skid resistance guidelines for surface improvements on Texas highways. Highway Research Record: Journal of the Transportation Research Board 131, 204–217.

McGhee, K.K., Flintsch, G.W., 2003. High-speed Texture Measurement of Pavements. National Technical Information Service, Washington DC.

Meegoda, J.N., Rowe, G.M., Jumikis, A., et al., 2003. Detection of Surface Segregation Using LASER. TRB, Washington DC.

Meegoda, J.N., Rowe, G.M., Jumikis, A., et al., 2005. Estimation of surface macrotexture in hot mix asphalt concrete pavements using laser texture data. ASTM Journal of Testing and Evaluation 33 (5), 305–315.

Meegoda, J.N., 2009. Non-contact Skid Resistance Measurement. FHWA-NJ–2009-020. National Technical Information Service, Alexandria.

Noyce, D.A., Bahia, H.U., Yambo, J., et al., 2007. Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements. MRUTC 04-04. University of Wisconsin-Madison, Madison.

NTSB, 1980. Fatal Highway Accidents on Wet Pavement. National Transportation Safety Board, Washington DC.

Persson, B.N.J., Tartaglino, U., Albohr, O., et al., 2005. Rubber friction on wet and dry road surfaces: the sealing effect. Physical Review B 71 (3), 035428.

Rowe, G.M., Meegoda, J.N., Jumikis, A., et al., 2004. NJTxtr-a computer program based on LASER to monitor asphalt segregation. ASCE Journal of Construction Engineering and Management 130 (6), 924–934.

RTAC, 1977. Pavement Management Committee, Pavement Management Guide, Canada. Roads and Transportation Association of Canada, Ottawa.

Tighe, S., Li, N., Falls, L.C., et al., 2000. Incorporating road safety into pavement management. Transportation Research Record 1699, 1–10.

Wambold, J.C., Henry, J.J., 1995. International PIARC experiment to compare and harmonize texture and skid resistance measurements. Nordic Road & Transport Research 6 (2), 28–31.