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Evaluation Of Skid Resistance on Asphalt Pavement Under Rain-Induced Slippery Conditions

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Abstract:
During rain storm events, water builds up on road pavement, thereby reducing the contact between vehicle tires and road surface putting drivers as well as road users into immediate danger, especially at high speeds. This is a considerably dangerous condition of the road and the realistic measurements and prediction of the effect of rainfall event on pavement surface is relevant for road traffic management and safety. In this research, the skid resistant performance of water-induced slippery pavement was characterized by means of a British Pendulum Skid Tester. Through simulating different pavement conditions in the laboratory, the skid resistance of asphalt pavement under various water-induced slipperiness is measured with the use of pendulum friction coefficient tester. Then, the effects of the degree of wetness on skid resistance of dry, wet, water filmed, water ponded and waterflooded pavements are quantitatively analysed. The effect of water thickness on the pavement has been established. Through quantitative analysis, empirical evaluation model of pavement friction coefficient (PFC) under different rain-induced wet conditions has been created. The PFC is classified into five levels, which illustrates the equivalent relationships of skid resistance assessment and asphalt pavement slippery conditions occasioned by rainfall events.

Keywords: Pavement; skid resistance; traffic safety; friction coefficient; texture depth.

1. INTRODUCTION

The latest “Global Road Safety Status Report” by the World Health Organization, established that road traffic injuries have become the eighth leading cause of death, with the annual death rising to about 1.35 million. Direct collision and sideslip have been reported to be the main causes of traffic accidents due to insufficient friction between the vehicle's tire and the road surface (Ke Xiao *et al.*, 2023; Wang et al., 2013). During rain storm events, the presence of more rain water leads to loss of friction between the moving tire and the pavement surface due to a build-up of water thickness underneath the tire. Moore's research shows that when Driving on wet and slippery roads with rain water, the water acts as a lubricant, and the presence of the water film reduces the proportion of the contact area between the tire and the road, and thereby reduces the friction between the tire and the pavement surface (Kuemmel et al. 2000). As the vehicle moves along, the tire squeezes the rain water film on the road surface, and the dynamic water pressure generated reduces the contact area between the tire and the road surface (Ke Xiao *et al.*, 2023). Fwa T. N. (2021) submitted that when the water film on the road surface exceeds a certain thickness, the driver loses the full control of vehicle and this affects the drive safety on the pavement which largely contributes to accident. In order to further study the reasons why the reduction of the friction coefficient leads to the frequent rain collision accidents, a direct correlation between the reduction of the friction coefficient and the depth of the water film, has been established. And this explains that the thicker the water thickness film on the road surface, the lower the coefficient of friction (Wang, 2013; Ke Xiao et al., 2023). Wentao *et al*, 2020 recognized Skid resistant performance of slippery pavement as one of the most important pavement surface characteristics, being associated with both pavement serviceability and traffic safety.

With the evolving rapid development of transportation and traffic system in developing countries with Nigeria inclusive, highway transportation demonstrates the advantages of transportation services due to its suitability, comfort, convenience, speediness and importance**.** In a related submission, (Kuttesch

2004) posits that pavement skid resistance closely relates to traffic accidents and (Kuemmel *et al*. 2000) noted that about 13.5% death by accidents and 25% traffic accidents are due to poor pavement conditions such as the slipperiness. If pavement surfaces are maintained in good conditions, they can provide sufficient friction to ensure safe driving (Fwa T. N. 2021 and Harish *et al*. 2013). It is therefore clear, from the submissions of numerous studies that rain water on asphalt pavement reduces the pavement skid resistance and subsequently leads to potential traffic hazards. The need to document the impact of rain storm events on skid resistance performance of asphalt pavemen***t*** renders further research in this direction very relevant and urgent, providing pertinent data for efficient traffic flow management and control for effective transportation and reduction of traffic accidents.

Findings of geological and geotechnical investigations relating to pavement skid resistance and its influencing factors have been reported in many scholarly works in the past decades. Researchers from VTI conducted a series of work on pavement friction and traffic safety (Nordstrom and Astrom 2001, Wallman and Astrom 2001, Bergstrom et al. 2003). Typically, Nordstrom and Astrom (2001) provided the friction test between full scale tyre and wet, water covered road pavement. Bergstrom et al. (2003) used a portable friction tester to measure the friction on cycleways under various road conditions (e.g. dry, wet, ice, snowy) and ranked the level service as well. Ahammed and Tighe (2009) documented the correlation between traffic and skidding characteristics of wet road surfaces. Plati and Georgouli (2014) pointed out that the seasonal and long-term variations have a significant effect on skid resistance evolution. Based on the testing results of surface friction coefficient for highway under different meteorological conditions, Xie et al. (2006) analysed the main influencing factors of surface friction coefficient and their relationships with weather. The results showed that the weather change is the main factor to make surface friction coefficient change obviously in a short time. Further, Xie and Lv (2006) investigated the skid resistance of highway pavement in laboratory and field experiments. The analysis was made on the relations of skid resistance to pavement temperature and pavement condition, including the pavement after de-icing with snow melting agent. Zhou (2007) pointed out that skid resistance of different pavement conditions is different under the same temperature condition, and the skid resistance under same pavement condition is different as well for various pavement temperatures. Klein-Paste and Sinha (2010 a, b) conducted the rubber-ice and sand-ice friction measurements with a British Pendulum Tester (BPT) at temperatures between -22 and 0 °C, and the effect of loose snow contamination on top of ice was investigated as well. Baurle et al. (2010) established a numerical model for sliding on ice including dry friction and generation of lubrication by water films. The model is verified by comparison with experimentally determined friction coefficients and slider temperatures, Li et al. (2010) utilised pendulum friction tester to test the friction performance of different pavements (new and old AC-16 asphalt pavements, experimental asphalt pavement blocks of SMA-16 and OGFC-13) under the conditions of different surface temperatures, slippery pavements, contaminants and their combinations in terms of British pendulum number (BPN). In order to measure pavement friction coefficient (PFC) under different conditions, Hu and Pan (2011) employed three-axes acceleration apparatus to measure vehicle acceleration during emergency braking, and the friction coefficients were obtained for old asphalt pavement, concrete pavement, snow-covered pavement, new built asphalt concrete and cement concrete pavements. The results have great significance on traffic safety analysis. Fang and Guo (2013) used the pendulum tester to measure skid resistance of two types of pavements under different pavement temperature and ponding conditions, and the friction coefficient of pavements was also obtained through Grip Tester. Based on the test results, a method of dynamic speed limit on expressway under complex climate was presented.

Although those researches have made contributions to understand the pavement skid resistance, these studies are limited and not completed to some extent. For instance, some pavement models used in the test were not actual pavement. Furthermore, the pavement condition was not better simulated in laboratory. Thus, a certain veracity may not be espoused in their test results. In addition, they did not develop a method to evaluate the skid resistance related to traffic safety so that the slippery pavement conditions can be simulated more properly. The actual pavement is replicated in the laboratory and some small size asphalt models are built to simulate various pavements as well. The pendulum tester is employed to test the skid resistance of pavement under various slippery conditions.

Based on the test results, the model for evaluating the friction coefficient will be established and the friction coefficient in terms of wet pavement conditions will be ranked in order to provide references for traffic safety control.

2. MATERIALS AND METHODS

In order to achieve the objectives of the study, an experimental stand (Fig. 2.1) was constructed to facilitate the simulation of rainfall intensities on specifically prepared asphalt slab in the laboratory.

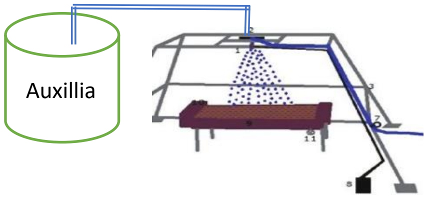


Fig. 2.1: Schematic of rainfall simulator.
1) Spray nozzle; 2) Sprinkler unit; 3). Experimental stand frame, 4) asphalt slab

2.1 Materials
The experimental pavement model (Figure 2.2) is the various asphalt pavement slap samples measuring 750 x 500m and 50mm thick, prepared obtained from Faithplant Global International Services, Calabar,

2.2 Experimental Procedure
2.2.1 Test environment and equipment
-. Introduction of rainfall simulated asphalt pavement conditions in laboratory

Various rain and wet environmental conditions were simulated through the simulated laboratory conditions, including different temperatures and wetting, water flooded conditions. Specifically, pavement under dry, wet, water ponding, and different temperature conditions were simulated with the aid of water sprinkler fitted on the experimental stand as shown in fig. 2.2. The environmental temperature was controlled between 15 and 45 °C, and the rainfall intensity also was controlled and regulated between 160 - 240 mm/h to simulate the rainy environment in the laboratory through the sprinkler device as shown in fig. 2.3

Fig. 2.3: Sprinkler device.

2.1.2 Pendulum friction coefficient tester

The skid resistance refers to the braking resistance of vehicle tyre along the model pavement surface. Normally, measurement of pavement friction through some vehicle testers with relatively high running speed is conducted on a wetted bare pavement surface. The pendulum tester as shown in Figure 2.4 is generally applied worldwide to test the pavement friction in laboratory [ ].

Figure 2.4: BM-III Pendulum friction coefficient tester

It is extremely versatile in its applications to many test situations and has received acceptance globally. This test device hired from Faithplant Global International Services, Calabar, measures low-speed friction (about 10 km/h) of pavement surface (Giles et al. 1964, Southern and Walker 1974). The sliding distance between rubber slider and asphalt pavement surface is about 12.6 cm, the size of rubber block used in the test is 76 mm (Length) *x* 25.4 mm (Width) x 6.35 mm (Thickness) and the rubber type is SBR rubber (styrene butadiene copolymer) (ASTM 2013). The test result is represented by the BPN and the same test was repeated 20 times as one set. That is to say, 20 data record are collected for a test. The rubber block is expected to be replaced after using 200 times to avoid rubber ageing. Our test was less than the 200 times prescribed, and so the change was not necessary in our case. In order to weigh the skid resistance of the asphalt pavement as a whole, the average value of BPN is adopted to enable comparison. The BPN is divided by 100 and can be approximately regarded as the friction coefficient (MoTPRC 2005, Xie and Lv 2006).

2.3 Test Settings

The test arrangement was dependent on the various pavement conditions - dry, wet, water filmed, water ponding and waterflooded as simulated by the sprinkler device. The effect ***of pavement temperature on skid resistance*** was investigated for dry, wet and light water filmed and waterflooded pavements.

2.31. Wet pavement

For wet pavement, the wet condition is simulated by asphaltic slab (750 mm length x 500 mm width by 50 mm thickness). ***The asphaltic slab is put into warm water with*** specified temperature for about 6h to adjust its temperature. The water temperature is controlled in the range of 15 - 45°C. Meanwhile, the skid resistance test of wet pavement under different temperatures is also conducted on the surface of the sampled asphalt pavement slabs in the laboratory. The pavement is wetted by spraying water and exposed to the room air conditions for about 3-6h before testing to reach stable temperature.

2.3.2. Dry Pavement

The sampled asphaltic slab is put into oven to adjust its temperature. The oven temperature is controlled in the range of 15-35°C. The asphalt pavement is aged inevitably, and the stiffness of asphalt and asphalt mixture are substantially increased. The pavement is exposed to warm and air conditions (above 15 °C) for about 3-6h to reach stable temperature.

2.3.4. Water Ponding Pavement (WPP)

Water is sprayed on the pavement surface and the WPP can be controlled and measured through the regulated pump of the water sprinkler device; then, the skid resistance is tested by pendulum tester accordingly.

3. PAVEMENT SLIPPERY TYPES AND SKID RESISTANCE

3.1. Pavement Slippery Types

According to published related statistics, the traffic accident ratio of wet/flooded pavement, water ponding pavement and dry pavement is about 4.2:1.6:1.0 (Xie et al. 2006). They asserted that during the rainfall weather, the traffic accidents increase obviously. The effects of rain water and flooding on the pavement condition and the pavement skid resistance are very different due to different weather conditions in different seasons. Therefore, the pavement conditions are very complicated due to the changing weather and large variation of air temperature.

Compared with the dry asphalt pavement, pavement surfaces will tend to be slippery under various wet weather conditions such as pavements under rain, wet, water ponding, water-filmed and water-flooded. For instance, the pavement tends to be wet due to rainfall and it can be flooded if the drainage of pavement surface is poor or the rainfall intensity is high. When the pavement is heated under intense temperature of 38°C for over 5 hours, the pavement-temperature increases and surface water dries up, the skid resistance obviously increases. With increasing thickness of water on the pavement surfaces, the skid resistance of the pavements decreases proportionately.

According to the water thickness, water on the pavement surfaces can be classified into wet, water film, water ponding and water-flooded.

In summary, the slippery pavement conditions can roughly be categorised as follows:

(1) Wet pavement (not flooded; not ponding);

(2) Water film (thin water thickness that cannot cover pavement texture);

(3) Water ponding (water that just slightly covers pavement texture);

(4) Water-flooded (water that largely covers pavement texture and flows over its surface;

Some typical pavements pictures in the test are shown in Figure 3.1.

Figure 3.1. Pictures for various water-induced slippery asphalt pavements in the laboratory.

Table 1: Data Deviation Analysis for the Various Asphalt Pavement Slipperiness.

Pavement conditions	Temp-erature	BPN	Range	STD	Average BPN
(1) Dry	20 - 40	81–94	3	0.93	87.5
(2) Wet (not flooded; not ponding);	20 – 25	67–69	2	0.78	68.1
(3) Water film (thin water that cannot cover pavement texture);	20 - 25	25–29	4	0.76	27.3
(4) Water ponding (water that just slightly covers pavement texture);	20 - 25	19–21	2	1.22	19.8
(5) Water-flooded (water that largely covers pavement texture and flows over its surface.	20 - 25	13–16	3	1.43	14.9

3.2. Data analysis

In order to understand the scatter of collected data, deviation analysis is conducted. The results are shown in Table 1 and Figure 3.2.

It can be seen from Figure 3.2 that all friction measurements in water-induced slippery cases are subjected to relatively large variability, which leads to more data scatter. But the test results of dry and wet pavements are less scattered with BPN range of 82.5 and Standard Deviation (STD) at 0.93, while BPN range of 67-69 and STD 0.82 are obtained for wet pavement.

The reason can be found from lubricating property of water during the sliding between rubber block and the studied asphalt pavement model. According to test results, the mean and median value of BPN for dry and water-flooded pavement is very wide, indicating the significant impact of varied rain-induced conditions on the resistance performance of the pavement.

It can be also observed from Table 1 that the BPN range and STD tend to *decrease* with increase in the thickness of water trapped between the asphaltic pavement surface and the rubber pad of the friction tester. It is noted here that the only average value of BPN is presented in the following analyses to facilitate the comparison for each type of pavement conditions.

3.3. Pavement skid resistance

For different levels of wetness, pavement skid resistance varies obviously. Figure 3.3 shows the BPNs of five typical slippery levels of pavements with a specified texture (MTD is 0.45 mm). against the degree of pavement surface wetness.

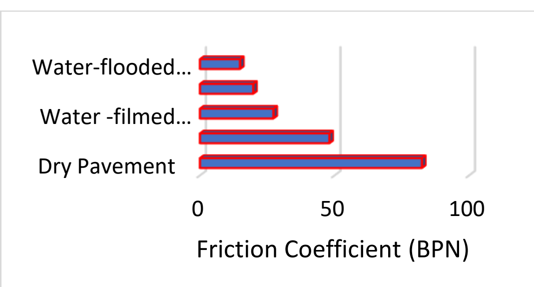


Figure 3.2 Skid resistance of different rain-induced slippery asphalt pavements.

Among these typical slippery pavements, the skid resistance of dry pavement on an average BPN of 83.1 is the best and that of wet pavement ranging from film wetness – flooding and ponding pavements is of average BPN of 17.35) is the lowest friction. The minimum BPN of 13.0 is obtained on a scenario of flooded pavement surface. It can be seen that the difference between the maximum and minimum average BPN is 67.6 which indicates very large differences of skid resistance between the various slippery pavements tested.

It indicates that the skid resistance decreases with increasing pavement surface lubrication by water. When dry pavement temperature is above 35 °C, the average BPN is about 82.5 which value is significantly higher than that of wet, water-filmed, ponding and flooded slippery pavements.

It can be seen from the comparison of Figure 3.2 that the various weather (hydrological) conditions result in different pavement slipperiness. The pavement skid resistances decline sharply especially under surface water ponding and water flooding conditions compared with dry and wet pavement conditions. Therefore, the pavements with water-ponded and water-flooded conditions seriously endanger traffic safety and should be given more attention during design investigation, development as well as traffic management.

4. ANALYSIS OF PAVEMENT SKID RESISTANCE

4.1. Effect *of Pavement Temperature on Dry Pavement Skid Resistance*

It can be seen from Figure 3.3 that at pavement texture depth (MTD) of 1.14 mm and temperature of 15 °C, the skid resistance of asphalt pavement increased with pavement temperature increase and the BPN also increased from 75 to 93 at the pavement temperature increasing from 15 C to about 45 °C. This shows significant skid resistance improvement at pavement temperature increase between 15 and 45 °C. The high temperature makes the asphalt membrane viscous and the tyre rubber softer. Consequently, the skid resistance of asphalt pavement improves due to the fact that contact between the tyre and pavement surface is sufficient and firmer with no water acting as a lubricant between them.

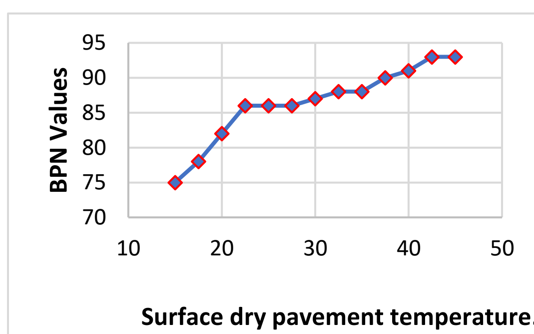


Figure 3.3 BPN vs. temperature of dry pavement

Expectedly, the improvement of pavement skid resistance arises from the physical property change of asphalt pavement under relatively high temperature condition.

For the dry pavement, when temperature is high, the pavement surface is adhesive due to asphalt properties. It shows the adhesion dominates the friction increase. On the whole, the friction of dry asphalt pavement increases with increasing temperature.

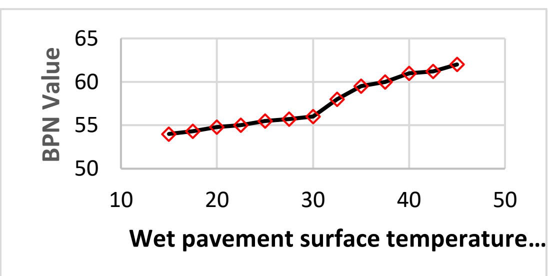
4.2. Effect of temperature on skid resistance of wet pavement

The BPN declines slightly with the increasing pavement temperature from 15 to 30 °C and then increases gently when the pavement temperature increases to 40°C under wet pavement condition. The difference between maximum and minimum BPN of the wet pavement between 30 and 45 is 7.7, showing only a slight improvement of BPN, figure 3.4. The indication is that, the skid resistance variation of wet pavement under different pavement temperature conditions is not significant.

However, it's been established that *the skid* resistance of wet pavement is inferior to that of dry pavement due to the existence of water between the rubber slider and pavement surface.

Under low temperature condition, water thickness is mostly determined by the water film thickness (WFT). This cannot overcover the texture depth of pavement when water film is very thin.

Fig. 3.4 BPN vs. temperature of wet pavement



4.5 Comparing skid resistance of pavement under the effect of water.

The texture depth of a pavement surface was measured with the putty impression method.

In this method, a known volume of silicone putty was moulded into a sphere and placed on the pavement. A metal plate is then placed on it and pressure applied until the plate gets in contact with the pavement. The calculation of the mean texture depth is based on the volume per area of the pressed putty.

The average pavement texture depths of the specimen slabs ranged from 0.55mm to 0.75mm. Rain with intensities varied from 15mm/hour to about 127mm was simulated by means of water sprinkler spraying water onto the pavement slab surfaces.

Water depths were measured using a point gage with a metric scale and vernier giving direct readings accurate to 0.2 mm. Accordingly, BPN under various conditions of water thickness was measured through this method till the texture depth of pavement is overcovered with water.

It can be seen from Figure 9 that BPN of water thickness pavement declines from 32.5 to 10.0 with water thickness increase. At the initial stage, the frictional performance is better because the pavement surface is rough and the kinetic energy reduces greatly due to larger contact area when rubber slider slips on water wet surface. The roughness of pavement reduces with the pavement texture depth being increasingly filled with water, leading to lower skid resistance accordingly.

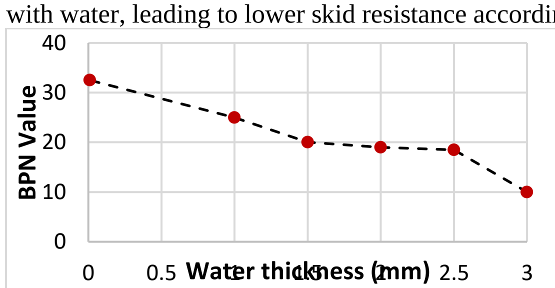


Fig. 3.5 BPN vs. water thickness on pavement

The water film leads to decrease in skid resistance to a significant extent. The lowest value of BPN of 10.1 appears to be when pavement is completely covered with water at 3mm. In the case where water *thickness is nearly 0, BPN rises slightly after pavement* is sprayed with water. It is inferred that the water can impede the contact of tyre and pavement when water film completely covers the pavement surface, especially when the vehicle moves fast. Accordingly, the friction and the skid resistance of the flooded pavement is relatively lower.

5. Empirical evaluation model

Based on the test results and incorporating the expression form of friction coefficient model, the summarised expressions for evaluating PFC under various slippery pavement conditions are shown in Table 3.

Table 2. Referential standard value for friction coefficient of asphalt pavement under various slippery conditions.

Pavement condition	*Referential standard value of PFC*

Dry pavement	*0.61–0.92*
Wet pavement (0 < WFT ≤ 0.15 mm)	*0.45–0.66*
Water film	*0.51–0.60*
Less ponding pavement	*0.42–0.50*
Ponding pavement	*0.12–0.35*
Flooded pavement	*0.13–0.34*

Therefore, the model presented in this study is empirical, though the parameters are not quantified. These parameter values can be easily quantified through test.

For instance, the effect of temperature on road pavement can be regarded as a linear modification, the related parameter Kv can be calibrated through test as well.

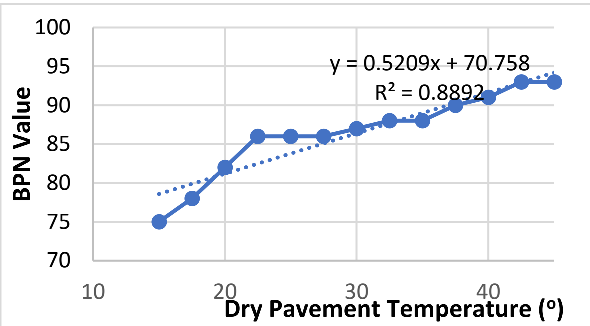


Fig. 3.6 Correlation of BPN with pavement temperature

For instance, the friction coefficient increases with the increasing pavement temperature with a correlation coefficient of about 0.89.

Furthermore, the effect of rainwater on road pavement is established to be linear as shown in fig. 3.6.

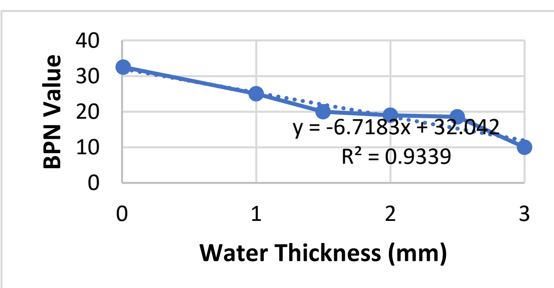


Fig. 3.7 Correlation of BPN with pavement water thickness

There is established a negative correlation R^2 of 0.93 between water thickness on pavement and its friction coefficient. The minimum friction coefficient can be evaluated as about 0.35 based on test results.

To facilitate the practical engineering application, reference standard values of PFC under various pavement conditions are recommended through incorporating the test results and shown in Table 2.

6. Friction coefficient rank

Weather variation has been reported as the most important natural factor affecting the friction property of expressway pavement and gives rise to traffic accidents. *[ ].* When the vehicle drives on road, the main factor which influences braking effectiveness and braking distance is the friction coefficient. The larger friction coefficient results in better braking performance and shorter braking distance to ensure the vehicle safety. On the contrary, the smaller friction coefficient leads to worse braking performance, and the braking distance is prolonged and endangers the vehicle safety.

Under the rainstorm events, rainwater creates lubricating behavior between pavement surface and tyre. The friction performance of the pavement is obviously affected. The laboratory test results showed that for the same asphalt pavement slab at the same temperature, the friction coefficient is between 0.94 for a dry pavement and 62 for a wet pavement

It can be seen that the weather variations can decrease the friction coefficient or lead to remarkable changes of the friction coefficient in a short time. In particular, in the Niger Delta region of Nigeria, where heavy intensity of rains is experienced in the rainy seasons, lots of traffic accidents incidences are recorded. Hence, the research on the relationship between the friction coefficient and meteorological conditions is relevant in espousing preventive measures to ameliorate and reduce the road accident.

7. Concluding remarks

Although researchers in this area have made contributions to understanding the pavement skid resistance, data on the impact of hydrological dynamics on asphalt pavement skid resistance is not adequately provided. Furthermore, the pavement conditions are not adequately simulated in the laboratory to consider the impact of rainfall intensity on the skid resistant property of pavement surface. In this study, the actual pavement is constructed in the laboratory and some small size asphalt mixture models are built to simulate various pavements behavior under various rain-induced slippery conditions.

Through simulating different wet pavement conditions in various rain and temperature conditions in the laboratory, the skid resistances of asphalt pavement were tested by using the pendulum friction coefficient tester. The variation of skid resistance of different types of rain-induced slippery pavement conditions were investigated. The effect of rainfall on the skid resistance of dry, wet and flooded asphalt pavements are quantitatively discussed. Through quantitative analysis, the empirical evaluation model of PFC under different pavement conditions is established and the surface friction rank is classified into 5 levels.

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