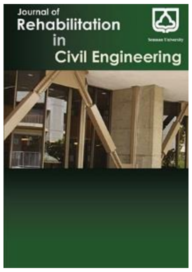
Journal of Rehabilitation in Civil Engineering 8-1 (2020) 87-96



Journal homepage: http://civiljournal.semnan.ac.ir/

Investigating the Relation among British Pendulum Number, Mean Texture Depth and Asphalt Content in Hot Mix Asphalt

M.H. Jalal Kamali[1], A. Hassani[2*] and J. Sodagari[3]

1. Ph.D. Candidate, Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Iran
2. Professor, Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Iran
3. Part Time Lecturer, Faculty of and Environmental Civil Engineering, Tarbiat Modares University, Iran

Corresponding author: *hassani@modares.ac.ir*

ARTICLE INFO

Article history:
Received: 06 October 2018
Accepted: 10 June 2019

Keywords:
Mean Texture Depth,
British Pendulum Number,
Pavement Texture,
Asphalt Content,
Friction.

ABSTRACT

Pavement surface texture and its skid resistance are two key safety parameters of highways, which both are influenced by pavement characteristics. In the present study, a newly constructed asphalt pavement (Qom-Garmsar freeway) in Iran is examined. The goal is to inspect the relation between skid resistance and pavement texture in order to asphalt content changes in Hot Mix Asphalt. Mean Texture Depth (MTD) and British Pendulum Number (BPN) are being applied to quantify pavement texture and skid resistance, respectively. The results show that the asphalt content has a significant effect on MTD and consequently, BPN in loaded pavements, as well as non-loaded pavements. The result revealed that the lowest BPN value obtained, when the asphalt content is about the optimum value. Moreover, it is demonstrated that using asphalt contents less and more than the optimum value, results in BPN improvement. Asphalt content increasing, around optimum value, leads to MTD decrease. The results also reveal that by increasing the MTD, the BPN decreases to 75 (in MTD value of 0.62 mm) and then increases.

1. Introduction

Pavement friction specifies the safety level of road and plays an important role in reduction of the multiplicity of accidents as a result of slipping on both dry and wet pavements. The force between vehicle’s tire and pavement is an essential component in vehicle-pavement interaction which provides the possibility of vehicle accelerating, maneuver and safe stop distance [1, 2].

Skid resistance is a frictional force which occurs at the contact surface of vehicle’s tire and pavement which depends on different

DOI: 10.22075/JRCE.2019.16124.1304

parameters including the characteristics of pavement and tire. Friction is defined as the resistance of an object encounters in moving over another object [3]. Many parameters such as pavement texture, vehicle's speed and the presence of water could affect the friction between tire and pavement. Other parameters such as construction and texturing procedure, the material applied and their weathering level could influence pavement texture, as well [2].

Many people perish in car accidents in Iran every year, as elsewhere in the world. Confirming to reports, in 2003, about 157000 accidents occurred in Canada which resulted in the death of about 2766 people. From March 2018 to March 2019, 17183 people passed away due to car accidents, in Iran, with about 1.2% growth in the fatality compared to the previous twelve months [4-7].

Pavement texture is defined as deviation of surface smoothness from a completely smooth surface. This deviation occurs in three levels, each of which is specified by two parameters; wavelength (λ) and amplitude (A). Permanent International Association of Road Congresses (PIARC) presents three following different levels of pavement texture [8]:

1. Micro-texture: in this form of texture, wavelength is less than 0.5 millimeter and its amplitude is between 1 and 500 micrometers. The characteristics of this type of texture are determined by microscopic properties of materials used in pavement.

2. Macro-texture: in this type of texture wavelength is considered somewhere between 0.5 and 50 millimeters and amplitude is between 0.1 and 20 millimeters. Macro-texture is affected by mix design (e.g. shape, size and gradation of aggregate), paving method and the procedure of creating texture (e.g. tinning, grooving and size of grooves).

3. Mega-texture: in this type of texture wavelength is considered somewhere between 50 and 500 millimeters; and amplitude varies from 0.1 to 50 millimeters.

Effective parameters of asphalt pavement textures are categorized as follows [9];

- Nominal size of aggregate of a concrete and asphalt pavement

- Coarse and fine aggregate material, durability, shape, and angularity which are related to its main rock and the process of production

- Asphalt content and viscosity

- Mix design gradation which is effective on stability and porosity in porous pavements

- Air void in asphalt pavement which is vital for drainage and providing surface friction, and also wastage of the resulting noise

- Layer thickness: The thicker the layer, the better drainage condition in porous pavements, and also more reduction in the resulting noise.

- Groove size and direction: Groove can be applied in longitudinal, transversal and diagonal forms. The direction of grooves affects the resulting noise. Distances between grooves affect not only the texture amplitude, but also the produced noise frequency.

- Isotropic or anisotropic: Consistency in the surface texture in all directions minimizes the resulting noise.

2. A Review on the Developed Relation between Pavement Texture and Friction

In a research that is conducted on concrete pavements, the effect of texturing was investigated on Skid Number. A concrete pavement, loaded by traffic passage for four years, which was tinned transversely with 19 millimeters space and identical width and depth of 3.2 millimeters, eventuated in a measured Skid Number of 47. However, the test was repeated on a similar concrete pavement with the same longitudinal grooves and resulted in a skid number of 33. The reasons of this variation were not clarified. Moreover, the test was repeated for a burlap dragged pavement and resulted in Skid Numbers of 35 and 20 for passing lane and traffic lane, respectively [11].

In another research which was done on concrete pavements, it was demonstrated that in some textures, such as brushed and turf dragged, macro texture and skid resistance are strongly related to each other, however in some cases, grooved and burlap dragged, there is no relation between BPN and MTD [12]

Yager and Buhlman [11] didn't find any relation between British Pendulum Number and macro-texture of pavements in an investigation on measuring macrotexture and drainage in a variety of concrete and asphalt surfaces. However, Olek et al. [13] proposed a linear correlation between those parameters. Wambold et al. [14] resented a relation between BPN and International Friction Index (IFI) carried out from PIARC experiments:

$$F60 = 0.0079\ BPN + 0.0778 \quad (1)$$

Where, F60 is IFI at 60 km/h.

Fwa et al. [15] inspected the aggregate gradation in an asphalt pavement and grooves spacing of a concrete pavement at the interface of tire and pavements by British Pendulum device. The results exhibited that the aggregate grading has a notable impact on the skid resistance of asphalt pavement.

Ahammed and Tighe [16] indicated that some parameters such as coarse to fine aggregate ratio in asphalt mix (CA/FA) and Voids in Mineral Aggregate (VMA) have significant effects on MTD, and with an increase in VMA, the MTD is decreased. Moreover, the authors developed an equation to relate MTD to CA/FA which is presented below:

$$MTD = 0.051+0.296(CA/FA) \quad (2)$$

Where MTD is Mean Texture Depth in mm.

In a research on concrete pavements, was displayed that by increasing the MTD to 1.81 mm, BPN achieves its maximum value and hence, by increasing the MTD more than 1.81 mm the BPN decreases. It occurs as a result to an increase in MTD at first stages, and the involvement of tire and pavement increases. Afterward, it remains constant or may decrease. It should be mentioned that, on this research the macro-texture of the pavement was provided by grooving on its surface [5].

There are some researchers conducted to explore the relation between HMA characteristics, such as asphalt content and aggregate gradation, on micro and macrotexture. Ahadi and Nasirahmadi [17] cliamed that by increase of asphalt content, skid resistance of HMA decreases. Asi [18] investigated the skid resistance of different asphalt concrete pavements and demonstrated that increasing the asphalt content more than optimum value, decreases the skid resistance. The research also remarked that HMA designed by Superpave mix design method shows better skid number than mixes designed by Marshall method.

As it was mentioned above, pavement surface skid resistance plays an important role on road safety. Therefore, it should be taken into account in road construction and operation. In asphalt pavements aggregate gradation and bitumen changes can affect on surface MTD and consequently Skid resistance.

3. Objective and Research Outline

The main goal of current research is to investigate the existence of relation between skid resistance and macro texture in asphalt pavements. The other one is determining the effect of binder content on both skid resistance and macro texture.

In order to accomplish this goal, two segment of Qom-Garmsar freeway, 22 traffic loaded section and 26 non- traffic loaded section, selected and British Pendulum Test and Sand Patch Test were performed to determine skid resistance and mean texture depth, respectively. Eventually, the results are discussed.

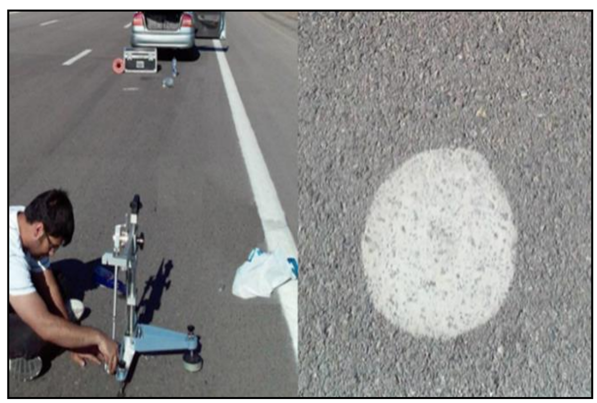
4. Experimental Results and Discussion

The research is conducted on the newly constructed parts of the Qom-Garmsar highway in Iran. The whole testing area had similar mix design, aggregate type and gradation, bitumen and construction procedure. The field investigation was divided into two stages; traffic loaded and non-traffic loaded, Where the most passing vehicles were heavy trucks. The gradation and optimum asphalt content of HMA applied in this highway has presented in Table 1.

As it is evident in figure1. Part (b), according to ASTM E965 the macro-texture of asphalt pavement was determined by Sand Patch Test [19,20]. Moreover, as displayed in figure 1. Part (a), according to ASTM E303 [21], BPN was determined for each investigated point, applying British Pendulum instrument as an index of pavement skid resistance.

Table 1. HMA mix design.

	Passing (%)							Asphalt Content (%)
	.075 (mm)	0.3 (mm)	2.36 (mm)	4.75 (mm)	9.5 (mm)	19 (mm)	25 (mm)	
Upper Limit	7	17	42	58	77	100	100	4.35
Lower Limit	2	7	30	44	63	90	100	



(a) (b)

Fig. 1. Conducting a) British Pendulum testing in the wheel path b) Sand Patch testing on the surface.

Surface temperature affect the British Pendulum test results as a result of viscoelastic properties of slider rubber. The BPN data were modified, regarding to the surface temperature, using equation 3 [22].

$$BPN_{20} = \frac{BPN_T}{1-0.0062\times(T-20)} \tag{3}$$

Where BPN_{20} and BPN_T are British Pendulum Numbers at surface temperature of 20°C and testing surface temperature of T, respectively.

Table 2. Measured data on without traffic loaded segments.

Measured BPN	Temp.	Modified BPN	MTD (mm)	A.C (%)
58.00	46	69.15	0.63	4.47
70.30	49	85.71	0.75	4.23
66.50	43	77.56	0.70	4.33
72.00	43	83.97	0.67	4.56
73.50	43	85.72	0.49	4.70
69.80	46	83.21	0.46	4.65
67.50	45	79.88	0.55	4.58
69.60	46	82.98	0.49	4.63
83.30	43	97.15	0.80	4.02
73.00	44	85.76	0.51	4.38
62.30	45	73.73	0.54	4.42
61.30	43	71.50	0.61	4.35
60.30	44	70.84	0.60	4.27
75.00	43	87.47	0.54	4.70
77.50	45	91.72	0.83	4.08
78.60	46	93.71	0.80	4.01
83.40	42	96.57	0.81	4.00
69.80	48	84.46	0.76	4.15
90.20	45	106.75	0.90	3.98
83.60	43	97.50	0.82	4.20
84.20	45	99.64	0.85	4.10
82.10	42	95.07	0.75	4.06
80.50	46	95.97	0.81	4.10
69.80	45	82.60	0.71	4.20
77.10	40	88.01	0.48	4.61
85.80	45	101.54	0.88	4.00

An asphalt sample core was extracted from each location where the mentioned tests were carried out, to precisely determine asphalt content, and aggregate gradation. Asphalt content was determined using ASTM D2172 procedure for quantitative extraction of asphalt binder from asphalt mixtures. The residuary aggregates were then sieved to acquire its gradation [23].

Table 3. Measured data on with traffic loaded segments.

Measured BPN	Temp.	Modified BPN	MTD (mm)	A.C (%)
60.60	46	72.25	0.78	4.29
59.00	43	68.81	0.72	4.33
61.75	47	74.17	0.68	4.40
67.25	44	79.01	0.69	4.47
66.50	48	80.47	0.50	4.60
66.75	49	81.38	0.52	4.61
64.00	44	75.19	0.69	4.33
73.75	47	88.58	0.84	4.11
72.50	47	87.08	0.71	4.21
68.50	46	81.66	0.69	4.31
58.50	47	70.26	0.65	4.23
54.00	44	63.44	0.68	4.50
65.00	45	76.92	0.59	4.36
69.20	42	80.13	0.57	4.65
70.50	43	82.23	0.56	4.35
75.60	45	89.47	0.69	4.12
71.50	47	85.88	0.73	4.25
59.80	45	70.77	0.58	4.35
63.80	48	77.20	0.65	4.50
70.60	45	83.55	0.73	4.19
78.20	43	91.21	0.80	4.10
73.60	44	86.47	0.63	4.21

Table1 and 2 present the measured data in two sites, with and without traffic loading. The BPN versus MTD plots, for both sites, are illustrated in figure 2 and 3 and the best fits have been carried out. It can be noted that the data measured on the traffic-loaded site do not follow a specific trend; however, the data related to non-loaded track have a correlation which has been determined.

As presneted in figure 2, there is a meaningful relationship between BPN and MTD with a regression coefficient of 0.776. When MTD increases from 0.45 to 0.60, the BPN decreases from 86 to 78 and then by increasing MTD from 0.60 to 0.80, BPN increases from 78 to 110.

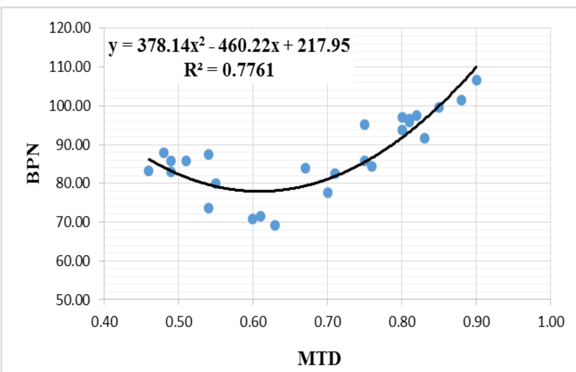


Fig. 2. BPN versus MTD, non-loaded pavement.

Some researchers have been believing that the slider of British Pendulum Portable Tester engages only the portion of the asperities which are subjected to polishing by traffic, hence BPN could be deliberated as a measurement of micro-texture [24]. However, it is intelligible that the measured BPN is influenced by macro-texture as well as, the surface indents entrap the slider. In this research, since the material used in the entire sampling site was invariant and moreover, micro-texture strongly depends on material properties, the BPN variation is mainly due to macro-texture. The relation between BPN and MTD is obtained as presented in Equation 4.

$$BPN = 378.14\,(MTD)^2 - 460.22\,(MTD) + 217.95\ (R^2=0.776) \quad (4)$$

There is a significant difference between the trend of BPN with MTD, found in this research and those which were presented by previous researchers. The difference might be owing to the thin layer of bitumen covering aggregates, in the newly constructed pavement through which no vehicle had passed. According to ASTM E303 for British Pendulum Test, water must be sprayed on the pavement before the test. Moreover, the apparatus must be set up in a way which slider's drag distance on the pavement becomes 12.5 centimeters. Slider's rubber gets pressed to the pavement surface during the passage, and as a result of the presence of water and a thin film of bitumen on the surface, the resulting friction between rubber and pavement surface decreases.

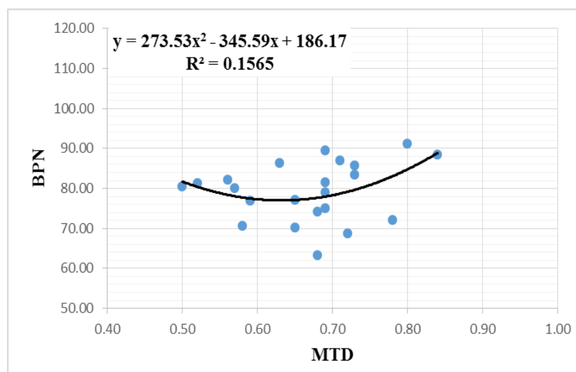


Fig. 3. BPN versus MTD on the wheel path of loaded pavement.

As illustrated in Figure 4 part (a), MTD values more than 0.7, indicate that macro-texture is large enough to entrap the rubber, and prevent slider from slipping, which results in BPN enhancement. As demonstrated in Figure 4 part (b), reducing surface MTD leads BPN to drop, about 19 percent from its initial value. This drop is due to the elimination of surface indentation, in which slider less likely tangles. Smoother macro-texture (with an MTD about 0.5 or less), depicted in Figure 4(c), is followed by BPN gain, up to 10 percent. This event is more noticeable in the non-loaded pavement, which demonstrates the effect of thin binder film, covering aggregates, on the skid properties. Since the considered pavement was newly constructed, the thin binder film still preserved its adhesiveness, which can clarify the mentioned BPN gain. Another explanation of the BPN rise might be forming of a completely attached junction between slider and pavement surface, owing to the presence of binder film, under the pressure of slider's flat rubber, likewise what happens in "wringing effect". Wringing effect or simply Wringability is defined as the ability of two ultra-smooth surfaces to adhere tightly to each other in the absence of external means. The sources of the forces holding surfaces together are thought to come from [25]:

- Air pressure from the surrounding environment, as the air is squeezed out when the surfaces are slid together
- Surface tension from water acts as a glue to hold them together
- When two very flat surfaces are brought into such close contact with each other, allows an interchange of electrons between the atoms of the separate interfaces, which generates an attractive molecular force.

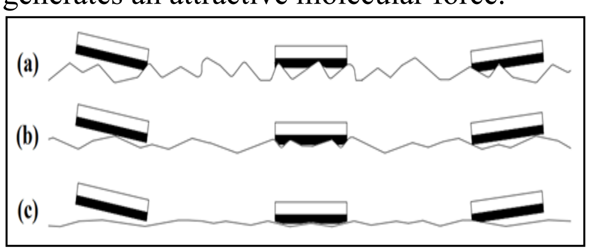


Fig. 4. An exaggerated scheme of slider slipping on different pavement surfaces.
(a) MTD<0.5, (b) 0.5<MTD<0.7, (c) 0.7<MTD

The trend obtained in Figure 2 can be confirmed considering the relation of BPN and asphalt content. As illustrated in Figure 5, it is evident that with an increase of asphalt content from 4.0 to optimum content (4.35%) the BPN decreases, while the increase of asphalt content more than optimum value leads to a BPN enhancement.

The variation of BPN versus asphalt content is not limited to non-loaded tracks. This hypothesis can include both loaded and non-loaded pavements. Figure 6 presents this trend for both sections (loaded and non-loaded), which the mentioned trend is repeated with a significant coefficient of determination ($R^2 = 0.696$).

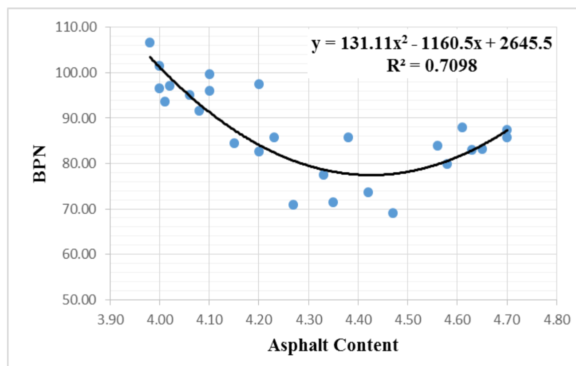


Fig. 5. BPN versus Asphalt Content for non-loaded track.

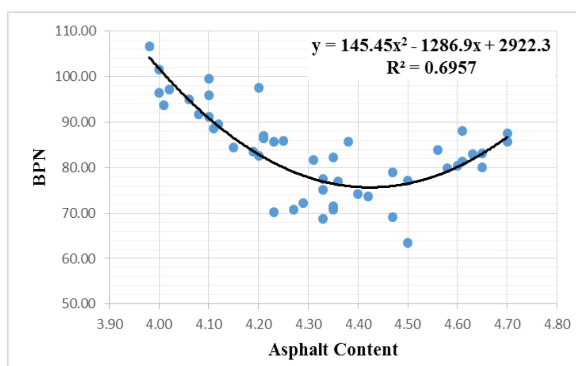


Fig. 6. BPN versus Asphalt Content for loaded and non-loaded pavement.

Asphalt content plays a key role in pavement properties; while it is higher content results in a better workability and ease of compaction, on the other hand, it can be followed by problems such as asphalt bleeding, loss of shear strength and etc. Considering the lubricating role of asphalt binder in HMA, it is clear that increase in asphalt content leads to less air content and subsequently less MTD.

The relation between BPN and asphalt content, presented in Figure 5, can be evaluated in three stages:

- asphalt content less than optimum value results in insufficient compaction and consequently rougher surface (higher MTD) which was displayed before to be followed by higher BPN.

- asphalt content, about optimum value, leads to a proper compaction producing a moderate MTD which is known to yield a drop in BPN

- Asphalt content exceeds its optimum value, the excess asphalt binder induces a smoother surface and lower MTD, as well as presumably bleeding.

Bleeding in HMA pavements is known to reduce skid resistance in presence of water. Since this research is implemented shortly after the pavement construction, the binder was still adhesive, and also soft enough to deform to an even face under the passage of pendulum slider, and consequently let “wringing effect” occur. The stated relation of MTD and asphalt content is highlighted in Figure 7.

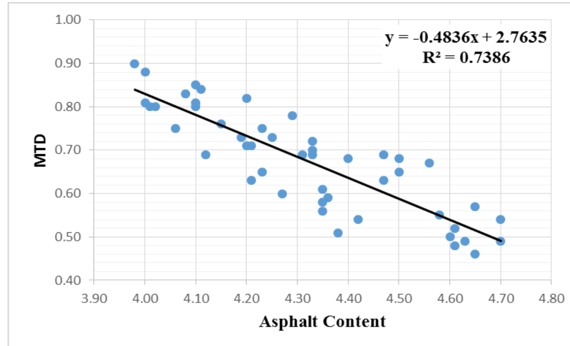


Fig. 7. Mean Texture Depth versus asphalt content.

5. Conclusion and Recommendation

In this study the asphalt content of the samples was varied in a short scale above and below the optimum value and the interactions of three parameters: asphalt content, MTD, and BPN were evaluated. Following conclusions were drawn:

1. In non-loaded segment increasing the MTD from 0.45 to 0.60 causes a decrease in BPN from 86 to 78 and then, when MTD alters from 60 to 0.80, BPN grows from 78 to 110.

2. The parameters compaction and MTD were strongly affected by the asphalt content. Increasing the asphalt content by 0.5% around the optimum value leads to a 0.25 mm drop in MTD.

3. Augmentation of BPN and subsequent enhancement of skid resistance are resulted from the asphalt content higher than the optimum value. This is while the raise in BPN value is not of practical significance, because the BPN achieved by the high amount of asphalt content, is an outcome of unaged binder adhesion and wringing effect, which is not sufficiently durable. Put it differently, the excess asphalt content hardens by time as a result of ageing, and thus it will not be deformed when contacting

with vehicle tires to cause wringing. The hardened asphalt, on the pavement surface, results in BPN value reduction in presence of water, as has been proved by other researchers.

4. The asphalt content lower than the optimum value raises many challenges such as ravelling, loss of shear strength, inaccessibility to target compaction, and etc. Moreover, the BPN value attained in this situation will decrease by the compaction inducted by traffic loading.

5. Loaded pavements, as well as non-loaded pavements, demonstrated the lowest BPN value when the asphalt content is about the optimum value. However, the achieved BPN value is more sustainable during traffic loading.

6.There is no meaningful relationship between MTD and BPN on the wheel path of heavy vehicles. It may be related to the insufficient initial compaction and changes of macro-texture due to extra compaction during the heavy traffic loading.

7. During the passing of heavy vehicles, a road with insufficient compaction in asphalt pavement experienced extra compaction in the wheel path. This would change the macro texture and skid resistance. Since skid resistance is the key parameter on the road safety, and it depends on mix grading and pavement compaction, it can be one of the important subjects to study in future to determine the effect of each parameter on the skid resistance.

Acknowledgement

Authors wish to express their gratitude to Dr. Solatifar, Ms. Moshtaghi, Mr. Sepahvand and Mr. Ayubirad for their assistance.

REFERENCES

[1] Jalal Kamali, MH., (2012). “The feasibility of using transition curve in road design to improve safety". M.Sc. Thesis, Department of Civil Engineering, Shahid Chamran University of Ahvaz, Iran.

[2] Karimi, N., (2013). “Design and manufacturing an automatic measuring pavement skid resistance system based on image processing approach ". M.Sc. Thesis, Department of Civil Engineering, Amirkabir University of Tehran, Iran. 2013

[3] Wallman, C. G., & Åström, H. (2001). Friction measurement methods and the correlation between road friction and traffic safety: A literature review. Statens väg-och transport forsknings institut.

[4] Monajjem, M. S., Kamali, J., Hossain, M., & Ayubirad, M. S. (2013). Studying the effect of spiral curves and intersection angle, on the accident ratios in two-lane rural highways in Iran. Promet-Traffic&Transportation, 25(4), 343-348 DOI: 10.7307/ptt.v25i4.332

[5] Ahammed, M. A., & Tighe, S. L. (2008). Pavement surface mixture, texture and skid resistance: A factorial analysis. Airfield and Highway Pavements, 329, 370-384. DOI: 10.1061/41005(329)32

[6] Viner, H., Sinhal, R., & Parry, T. (2004). Review of UK skid resistance policy. Preprint SURF.

[7] Iranian legal medicine organization. http://en.lmo.ir/

[8] PIARC World Road Association. (1987, September). Report of the committee on surface characteristics. In Proceeding of XVIII World Road Congress (pp. 13-19).

[9] Hall, J. W., Smith, K. L., Titus-Glover, L., Wambold, J. C., Yager, T. J., & Rado, Z. (2009). Guide for pavement friction. Final Report for NCHRP Project, 1, 43. DOI: 10.17226/23038

[10] Mahone, D. C. (1977). Texturing new concrete pavements (No. VHTRC 77-R25). Virginia Transportation Research Council.

[11] Yager, T. J., & Bühlmann, F. (1982). Macrotexture and drainage measurements on a variety of concrete and asphalt surfaces. In Pavement Surface Characteristics and Materials. ASTM International. DOI: 10.1520/STP28460S

[12] Olek, J., Weiss, W. J., & Garcia-Villarreal, R. (2004). Relating surface texture of rigid pavement with noise and skid resistance.

[13] Jalal Kamali, M.H., Hassani, Abolfazl and Sodagari, Javad. (2019). Investigation the Relation between Skid Resistance and Mean Texture Depth in Concrete Pavements. Concrete Researsh, Volume 12, Issue 1 - Serial Number 25, Spring 2019, pp 27-38. DOI: 10.22124/JCR.2018.9079.1242

[14] Wambold, J. C., & Henry, J. J. (2002). NASA Wallops Tire/Runway Friction Workshops: 1993-2002 (No. TP 14190E).

[15] Fwa, T. F., Choo, Y. S., & Liu, Y. (2003). Effect of aggregate spacing on skid resistance of asphalt pavement. Journal of transportation engineering, 129(4), 420-426. DOI: 10.1061/(ASCE)0733-947X(2003)129 :4(420)

[16] Ahammed, M. A., & Tighe, S. L. (2011). Asphalt pavements surface texture and skid resistance—exploring the reality. Canadian Journal of Civil Engineering, 39(1), 1-9. DOI: 10.1139/l11-109

[17] Ahadi, M. R., & Nasirahmadi, K. (2013). The effect of asphalt concrete micro & macro texture on skid resistance. Journal of Rehabilitation in Civil Engineering, 1(1), 15-28. DOI: 10.22075/JRCE.2013.2

[18] Asi, I. M. (2007). Evaluating skid resistance of different asphalt concrete mixes. Building and Environment, 42(1), 325-329. DOI: 10.1016/j.buildenv.2005.08.020

[19] ASTM E965-15, (2015). Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique, ASTM International, West Conshohocken, PA

[20] Woodward, D. (2016). Wet skid resistance.

[21] ASTM E303-93, (2013). Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester, ASTM International, West Conshohocken, PA.

[22] Ongel, A., Kohler, E., Lu, Q., & Harvey, J. (2008). Comparison of surface characteristics and pavement/tire noise of various thin asphalt overlays. Road Materials and Pavement Design, 9(2), 333-344. DOI: 10.1080/14680629.2008.9690121

[23] ASTM D2172 / D2172M-17, (2017), Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures, ASTM International, West Conshohocken, PA.

[24] Henry, J. J. (2000). Evaluation of pavement friction characteristics (Vol. 291). Transportation Research Board.

[25] Raymond, N., & Soshi, M. (2016). A study on the effect of abrasive filament tool on performance of sliding guideways for machine tools. Procedia CIRP, 45, 223-226. DOI: 10.1016/j.procir.2016.02.169