International Journal of Bridge Engineering (IJBE), Vol. 12, No. 1, (2024), pp. 01-13

DEVELOPING AN ABRASION MODEL FOR CONCRETE PAVEMENT MACROTEXTURES

Mohammad Hossain Jalal Kamali[1], Abolfazl Hassani[2],
Reza Jalalkamali[3], Seyed Jafar Hejazi[4]

[1] University of Gonabad, Faculty of Engineering, Iran
[2] Tarbiat Modares University, Faculty of Civil and Environmental Engineering, Iran
[3] Shahid Bahonar University of Kerman, Faculty of Civil Engineering, Iran
[4] Shahid Chamran University of Ahvaz, Faculty of Civil Engineering and Architecture, Iran
e-mail: m.jalalkamali@gmail.com, jalalkamali@gonabad.ac.ir

ABSTRACT: Concrete pavements are increasingly gaining global traction, Iran included, driven by the distinctive attributes inherent in concrete, notably its durability and strength. The need for meticulous rehabilitation of vehicular bridges in instances of pavement deterioration underscores the suitability of concrete pavements for such applications. Consequently, the escalating preference for concrete pavements has heightened concerns regarding their safety to an unprecedented extent. A critical factor affecting the safety of concrete pavements is surface friction. Traffic loading over time results in the surface micro and macro texture deterioration, reducing the coefficient of friction of pavement, which is a matter of safety. In this study the abrasion of five different macro textures (and non-textured concrete as a control sample), subjected to an abrasion test using a Rotational Abrasion Device, has been measured and related to macro texture type, loading amount, and loading speed and repetition, as independent variables in a linear regression model. The results show that the macro texture type has a great impact on the abrasion of the concrete surface. The grooved and non-textured concrete surfaces had the highest and lowest abrasion, respectively. When comparing the effects of the various load characteristics, loading repetition is around 45% more influential than the applied load. In addition, the findings showed that the loading speed has an inverse influence on the amount of abrasion, which means that the amount of abrasion is reduced when the loading speed is increased.

KEYWORDS: Concrete Pavement; Macro Texture; Abrasion Resistance; Loading Condition; Abrasion Model.

1 INTRODUCTION

As a first step, the introduction provides a brief overview of the topic and presents a brief review of relevant previous research, followed by a discussion of the significance of the current study.

1.1 Literature review

Roads provide mobility for people, goods, and services, which is essential to people's lives. It is extremely important to the engineers to provide a smooth and safe pavement. Highway’s safety is influenced by two factors: geometry design and pavement characteristics [1]. Pavements are generally categorized to two types: rigid and flexible, among which, asphalt concrete is most common, followed by cement-based concrete [2]. In comparison to asphalt pavements, concrete pavements are more durable; however, their frictional parameters, which are influenced by surface texture, remain a challenge. Skid resistance determines the safety of vehicles when braking on the highway. Insufficient skid resistance can lead to unsafe driving and traffic accidents [3-5].

Pavement surface texture can be defined as the deviation from the true plane surface within a specified wavelength range [6]. Based on wavelength (λ) and vertical dimension (A), surface textures can be divided into three categories: micro-, macro- and mega texture, with $\lambda < 0.5$ mm (A < 0.2 mm), 0.5 mm < λ < 50mm (0.2 mm < A < 10 mm) and 50 mm < λ < 500 mm (1 mm < A < 50 mm), respectively. Wavelengths longer than the upper limit of the mega-texture are defined as roughness or smoothness [7].

Abrasion resistance refers to the ability of hardened concrete surfaces to withstand abrasive forces (e. g. rubbing, rolling, sliding, friction forces and impact forces) [8]. The conditions of freezing and thawing in cold regions or chemical substances present in the special application of concrete surfaces can also cause concrete abrasion [9, 10]. Abrasion of concrete surface can be classified as follows [11]:

- Abrasion on concrete floors.
- Abrasion of concrete pavements by heavy trucks and cars with and without studded tires or snow chains (attrition, plus scraping and percussion).
- Abrasion on hydraulic structures such as dams, spillways, bridge piers, and abutments caused by abrasive materials carried by flowing water (erosion).
- Abrasion on concrete dams, spillways, tunnels, and other water-bearing systems where high velocities and negative pressures exist. This is commonly known as cavitation erosion (cavitation).

In accordance with the tire-pavement reaction, running over a vehicle on a road surface results in abrasion of the pavement surface texture. Macro texture abrasion can result in a 60% reduction in frictional index, depending on the type of aggregate and mix design [12]. Macro texture of the pavement surface can also prevent the occurrence of hydroplaning during rain by providing proper drainage or retaining water in its empty spaces [13].

The mix design of cement concrete pavements, such as cement content, water-to-cement ratio, aggregate-to-cement ratio, aggregate size, etc., play an important role in mechanical properties, and hence, the abrasion resistance. However, the surface functionalities of cement concrete pavement are provided by cement paste in the uppermost zone. In concrete pavements, the functional properties (i.e., skid resistance, acoustic properties, drainage capacity, etc.) are basically related to the surface texture of the pavement and the mix design of the concrete [8, 14, 15].

The effect of macro and micro texture on skid resistance has been studied in several researches. Many studies have found that micro texture has a significant impact on pavement skid resistance. There are also studies that showed pavement friction is affected by macrotexture in addition to micro texture [16-19]. Experimental results indicate that increasing the macro aggregate content improves skid resistance, polishing resistance, exposed aggregate peak number, and compressive strength [20]. The important macro texture parameters, such as the largest aggregate size in concrete, the grooving angle and width of the grooves, are known to affect the skid resistance of concrete surface [21]. Additionally, pavement macro texture has a significant influence on frictional properties, noise, and ride quality according to its depth, spacing, and orientation [22].

Using a new test of their own design, Yu et al. examined the width, depth, and spacing of grooves in concrete surfaces in comparison with the frictional properties and abrasion resistance of concrete pavements. As a result, the groove spacing had the greatest influence on the frictional parameters affecting vehicle steering. Based on an analysis and comprehensive comparison of the influences of various parameters, it was determined that the combination of width, depth, spacing, and groove group width, respectively, in 8 mm, 3 mm, 15 mm, and 50 mm, could balance skid resistance performance and driving stability [23].

Adresi et al. studied the effects of micro- and macrotexture on the abrasion and skid resistance of roller compacted concrete pavements (RCCP). They textured the concrete surface by seeding, stamping, and brooming. They found that abrasion reduced the skid resistance of the RCCP specimens by about 10%. Additionally, statistical studies revealed that skid resistance was completely determined by the type of macrotexture, with broomed macrotextures having the highest skid resistance and seeded macrotextures having the lowest skid resistance [24].

In order to create macro texture on concrete pavement surfaces, a number of methods are available, which can be categorized into two categories; texturing plastic concrete and texturing hardened concrete [25]. The most common texturing method are listed below [26]:

- Plastic brushing/brooming
- Transverse and longitudinal burlap dragging
- Transverse and longitudinal artificial turf dragging

- Transverse Tinning
- Longitudinal Tinning
- Transverse and longitudinal grinding
- Grooving
- Abrading/ Shot blast
- Exposed Aggregate Concrete (EAC) surfacing

ASTM standards give following standards for testing [27];

- ASTM C 418: Test method for abrasion resistance of concrete by sand blasting
- ASTM C 944: Test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method
- ASTM C 779/ C 779M: Test method for abrasion resistance of horizontal concrete surfaces
- ASTM C 1138: Test method for abrasion resistance of concrete – Underwater Method
- ASTM C 1747/C1747M-13: Standard test method for determining potential resistance to degradation of pervious concrete by impact and abrasion
- ASTM C1803-15: Standard guide for abrasion resistance of mortar surfaces using a rotary platform abraser

1.2 Objective and scope of this study

It has been mentioned earlier that concrete pavements should be textured in order to improve safety by providing appropriate frictional properties. In order to determine the appropriate rehabilitation timing in the pavement management system, it is necessary to determine the abrasion behavior of each texture.

This study compares the abrasion resistance of five commonly used macro textures, and a comprehensive regression model is developed in order to determine surface abrasion at different loading amount, speeds, and repetitions.

2 MATERIAL AND METHOD

2.1 Sample preparation

For the preparation of concrete samples, aggregates were obtained from a mine, located in the southwest part of Tehran Province. A number of common tests were conducted on the material in order to ensure that it meets the requirements of the standard regulation. Table 1 presents the results of some tests performed on these materials. The cement used in the study was also subjected to a compressive strength test, XRF analysis, and other cement specifications. The results of which are presented in tables 2, 3 and 4.

The ACI-211 Standard was used to determine the concrete mix design [28]. Table 5 presents the mix design details, as well as the compressive and flexural strengths of concrete.

Table 1. Some specifications of fine-grained and coarse-grained aggregates

Property	Standard code	Fine aggregate	Coarse aggregate
Specific Gravity (Kg/m3)	ASTM C136	2670	2670
Bulk Specific Gravity (Kg/m3)	ASTM C29	-	1641.4
Water Absorption in SSD (%)	ASTM C127	2.6	1.3
Fineness Modulus	ASTM C136	2.85	-
Sand Equivalent (%)	ASTM D2410	80	-
Aggregate Fractured Percent in two side (%)	ASTM D5821	-	78.3
Flat and elongated particles (%)	ASTM D4791	-	7.5
Aggregate soundness using Sodium Sulfate (%)	ASTM C88	-	9.5
Aggregate soundness using Magnesium Sulfate (%)	ASTM C88	-	12.6
Los Angeles Abrasion Test (%)	ASTM C131	-	12
Impact Resistance (%)	BS 812	-	8.1

Table 2. Compressive strength cement tests results

3-day compressive strength	Minimum 3-day compressive strength	7-day compressive strength	Minimum 7-day compressive strength
12.5 MPa	12 MPa	21.9 MPa	19 MPa

Table 3. XRF analysis results of cement

Component	Percentage	Component	Percentage
L.O.I	1.85	SO3	3.208
CaO	62.208	MgO	2.731
SiO2	18.492	K2O	0.811
Al2O3	4.026	Ti2O	0.366
Fe2O3	3.777	Cl	0.173
Total		97.642	

Table 4. Other cement specifications

Property	Specific surface	Specific gravity	Initial setting time	Final setting time
Standard No.	ASTM C204	ASTM C188	ASTM C191	ASTM C191
Results	3250cm2/gr	3.15 gr/cm3	80 min	186 min

Table 5. Concrete mix design

Materials	Gravel (Kg/m3)	Sand (Kg/m3)	Cement (Kg/m3)	Water (Kg/m3)	W/C ratio	28 days Compressive Strength (MPa)	28 days Flexural Strength (MPa)
	1091	670	400	176	0.44	40.89	6.67

In this study, a new rotational abrasion device was utilized to measure the abrasion resistance of concrete pavements [29]. Samples were prepared in circular sector molds as shown in figure 1.

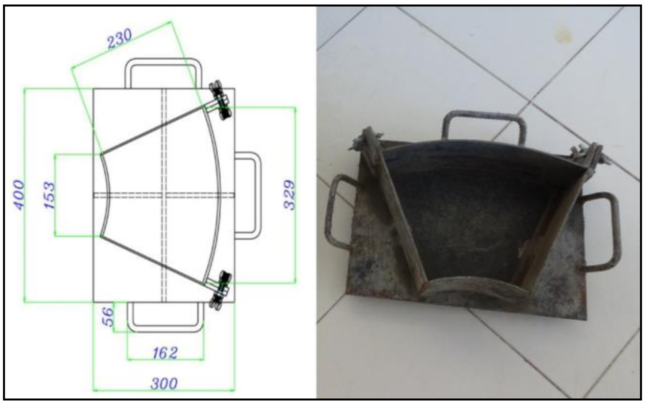

Figure 1. Rotational abrasion device molds

2.2 Samples texturing

Surface texturing of concrete pavements can be achieved in several ways, as described in the introduction. According to the laboratory facilities and equipment, five texturing methods were used in this research. As a control sample, plane concrete samples were prepared. Below is a brief explanation of how each texturing method is implemented. The notation used for methods are given as well.

- Non-textured concrete (N.T):
  The surface of the N.T concrete sample was levelled using a metal trowel, and no other operations were performed.
- Turf dragged concrete (T.D):
  In this case, the surface of the sample is levelled with a metal trowel, and then artificial grass is drawn over the surface.
- Grooved concrete (G):
  The samples were first levelled with a metal trowel, and after curing, the grooves were created on its surface. Considering similar studies, the distance between grooves was chosen to be one inch (2.5 cm), and the groove depth to be approximately 4.5 mm.
- Parallel and Perpendicular Brushed Concrete (Par.B and Per.B):
  Instead of longitudinal and transverse grooves, two terms parallel and perpendicular to the direction of traffic movement were used for the brushing process. After levelling the samples using a metal trowel, a plastic brush was used to create a macro texture (parallel and perpendicular to traffic movement).
- Burlap Dragged Concrete (B.D):
  Using this method, the surface of the samples was levelled with a metal trowel, and then a burlap was used to create a macro texture. In order to ensure that the used burlap is not dry when pulled over the concrete (causing

issues such as absorption of concrete water and disturbance in the concrete curing process), the burlap was washed and Wrung before use.

3 ABRASION RESISTANCE TEST

This research used a rotational abrasion device that was designed, manufactured, and patented for the first time in Iran by Mr. Houshangi under the supervision of Dr. Abolfazl Hassani (Iranian Patent Number: A/89-29675).

Seven samples were made according to Figure 1, placed inside the device and locked in place with the built-in locks. During the movement of device (which is naturally associated with vibration), samples stay still and the wheels move uniformly over them.

In this test, samples were loaded with metal wheels. The loading intensity should be chosen to simulate the real situation. It has been common in similar studies to use a metal wheel to simulate concrete pavement surface abrasion under traffic loading. In previous studies, a wheel with diameter and width of 12 and 3.5 cm was used, and an applied load of 890 newtons was applied to simulate the Equivalent Single Axle Load [30, 31]. This research used wheels with diameters and widths of 20 and 6.5 cm, respectively. In order to produce the same pressure, created by the wheel in mentioned studies to simulate ESAL, the load applied by Rotational Abrasion device was determined as 2754.6 newtons (approximately 280 kilograms), considering its wheel proportions.

Since this device has the capacity to load, up to 450 kg on each wheel, in this research 120, 200, 280, and 360 kg loads were used in order to investigate the effect of load intensity on the abrasion rate of concrete samples. Since Rotational Abrasion device exerts loadings through two wheels, each loading cycle included two-wheel passages.

Concrete pavement abrasion is usually measured by weight analysis of samples. In this study, the samples were weighed before they were placed in the test apparatus, and (considering that one of the studied parameters was number of loading cycles) the samples were weighed again after a certain number of loading cycles (50, 100, 200, 300, 400 and 500). To study the effect of loading speed on concrete abrasion, three different loading speeds of 5, 8 and 12 rpm were used.

4 CONCRETE ABRASION TEST RESULTS

The following figures demonstrate the weight loss changes versus loading cycles, for the speed of 8 rpm. In each figure, the weight loss trend is given for different textures. The results of different loading intensities are provided in Figures 2 to 5.

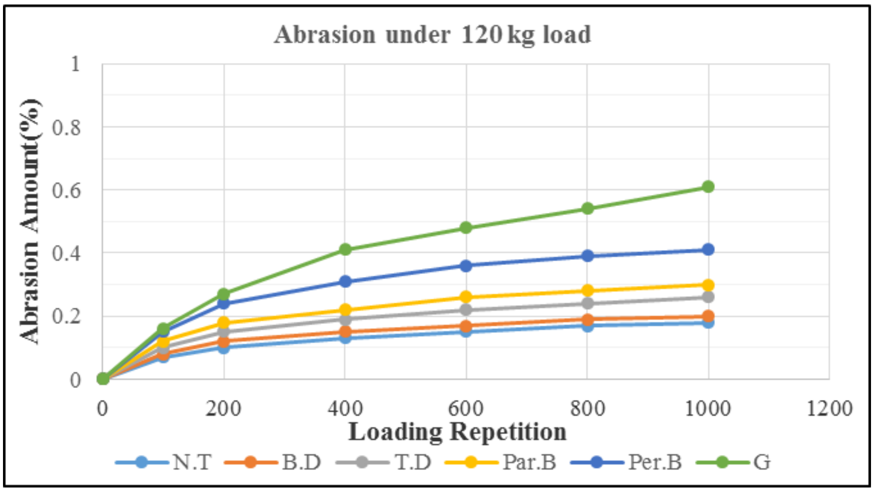

Figure 2. Abrasion in samples with different textures, applied load of 120 kg

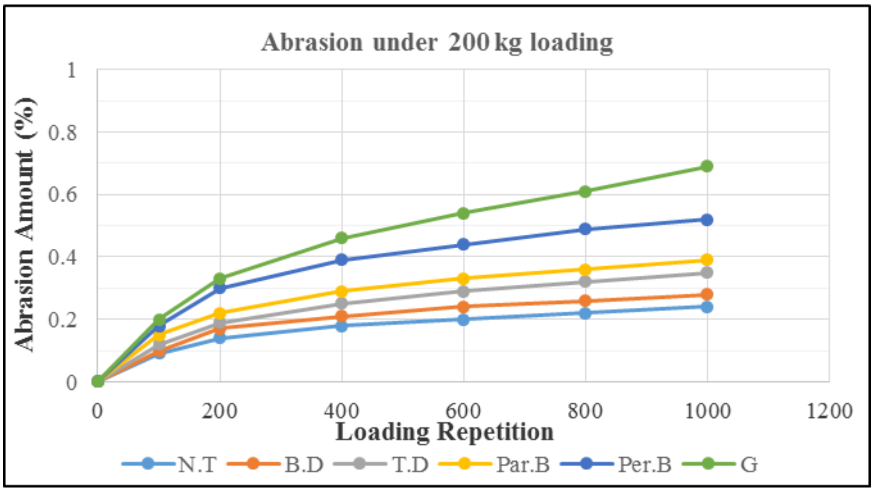

Figure 3. Abrasion in samples with different textures, applied load of 200 kg

For all loading values, it is evident that the non-textured samples exhibit the lowest level of abrasion. Other samples textured by burlap dragging, turf dragging, parallel brushing, perpendicular brushing, and grooving have the lowest to highest wear rates, respectively. Furthermore, it is evident that the rate of abrasion at the beginning of the loading is higher. With the exception of grooving samples, all abrasion trends follow approximately the same pattern.

Detailed examination of samples determined that the trend of the abrasion rate in the grooved samples at the end of the loading period is not solely due to wear of the surface, but is also caused by fractures within the grooves.

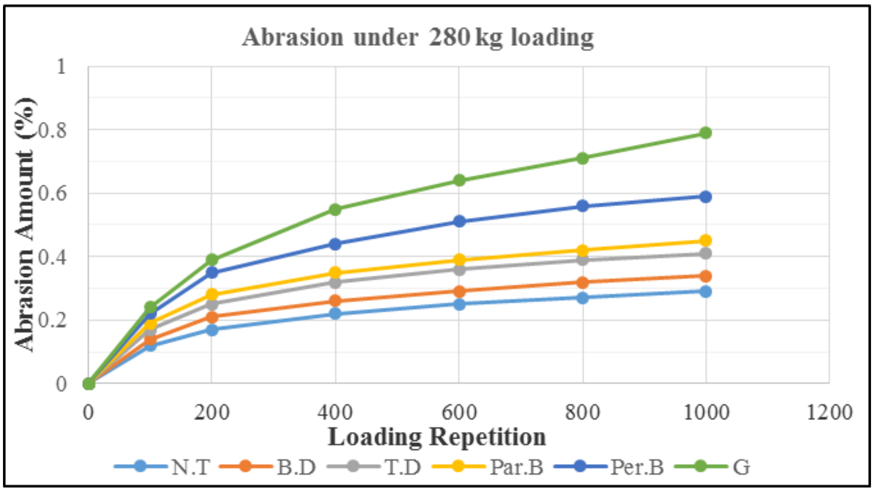

Figure 4. Abrasion in samples with different textures, applied load of 280 kg

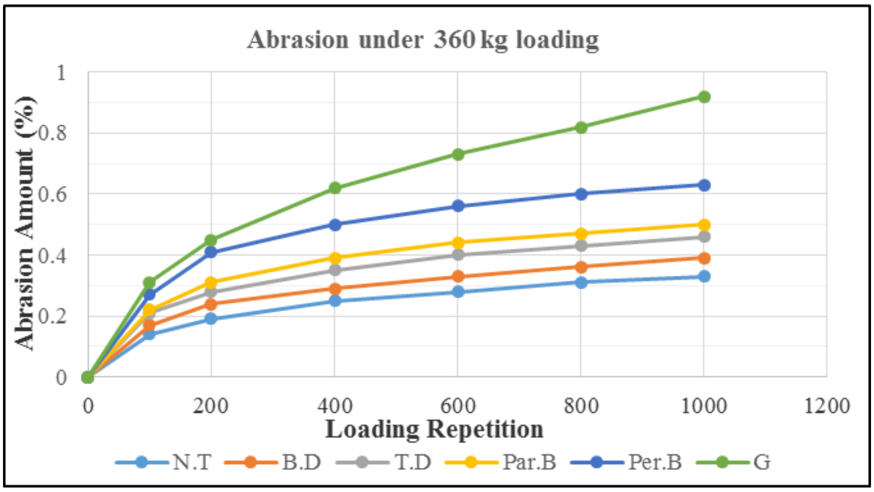

Figure 5. Abrasion in samples with different textures, applied load of 360 kg

5 DEVELOPING LINEAR REGRESSION MODEL FOR SURFACE ABRASION TABLES

A comprehensive abrasion model to include the influence of all mentioned factors, simultaneously, can be beneficial in many ways; concrete abrasion can be estimated in a more accurate and detailed manner, and it also eases the comparison between the impacts of different factors. Thus, a linear regression model was developed to examine the relationship between abrasion (AA: Abrasion Amount in percent) and the following variables:

- LA: Loading Amount in kg

- LR: Loading Repetition
- LS: Loading Speed in rpm
- XI: Dummy variable of X texture type (X Identifier)

The effect of texture types was applied in the model, using five dummy variables. When the data of any texture type was acquired for regression modelling, its corresponding dummy variable was set to one, and other dummy variables were set to zero. When the data of untextured samples was given to the model, all five dummy variables were left as zeros.

$$AA=-3.394-1.028\times LS+0.057\times LR+0.07\times LA+3.372\times BDI+$$
$$8.413\times TDI+11.747\times ParBI+21.371\times PerBI+32.408\times GI$$

Results of the linear regression modelling of the data are presented in Tables 6 to 8. Statistical parameters of the developed model, such as R, R square, and Adjusted R square are presented in Table 6. The ANOVA analysis is given in Table 7, and in Table 8 the standardized and unstandardized coefficients of variables are provided.

Table 6. Model summery

R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
				R Square Change	F Change	df1	df2	Sig. F Change
.940[a]	.883	.881	5.838	.883	399.506	8	423	.000

a. Predictors: (Constant), GI, LA, LR, LS, BDI, TDI, ParBI, PerBI

Table 7. ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	108942.640	8	13617.830	399.506	.000
Residual	14418.661	423	34.087		
Total	123361.301	431			

Dependent Variable: AA
Predictors: (Constant), GI, LA, LR, LS, BDI, TDI, ParBI, PerBI

A comparison of the standardized coefficients of the variables of the regression model in Table 8, reveals that between the two loading-related variables, repeated loading cycles variable has a greater effect than the load intensity variable, by 45 percent, approximately. The amount of concrete abrasion decreased with the increase of loading speed, as expected, but this effect is less pronounced compared to other variables effect.

Comparing the values of standardized coefficients column in Table 8 reveals that macro-texture type may have a significant impact on concrete pavement abrasion. The impact is the least for burlap dragged texture, and the most for grooved texture. The authors have shown in a previous study that weight loss in grooved samples is not only a result of abrasion, but also due to cracking of concrete near the grooves edges. The numbering should be right-justified. An example is given in Eq. 1.

Table 8. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
(Constant)	-3.394	1.384		-2.452	.015	-6.114	-.673
LS	-1.028	.098	-.174	-10.497	.000	-1.221	-.836
LR	.057	.002	.538	32.370	.000	.054	.061
LA	.070	.003	.369	22.227	.000	.064	.076
BDI	3.372	.973	.074	3.466	.001	1.460	5.285
TDI	8.413	.973	.186	8.645	.000	6.500	10.325
ParBI	11.747	.973	.259	12.072	.000	9.835	13.660
PerBI	21.371	.973	.471	21.962	.000	19.458	23.283
GI	32.408	.973	.715	33.305	.000	30.496	34.321

6 CONCLUSIONS AND RECOMMENDATION

In this study, the affecting factors on concrete pavement abrasion, such as load intensity, loading frequency and repetition, and also different macro-texture types were evaluated. Moreover, a comprehensive linear regression model was developed on experimental data of all samples simultaneously, to estimate pavement abrasion. Major findings of the research are as followed:

- Pavement texturing can significantly increase skid resistance that improves the safety. However, texturing can also lead to a higher abrasion rate under traffic loading.
- Abrasion rate of pavement macro-texture is remarkably higher in the beginning of loading. The main reason is that pavement surface is less resistant to abrasion due to weathering.
- Pavement macro-texture abrasion may highly vary depending on the type of macro-texture, e.g. a perpendicularly brushed texture has an abrasion rate, 7 times higher than of a burlap dragged texture, in average.

The following proposals can be considered for further studies:

- Abrasion test can be performed in different weather conditions to study the effect of factors like air humidity and temperature.
- Surface friction can be measured along with abrasion to develop a regression model to estimate surface friction.

ACKNOWLEDGMENTS

Authors wish to express their gratitude to Dr. Mohammad Mahdi Dibaee for his assistance.

REFERENCES

[1] Monajjem, M.S., M.H. Jalal Kamali, and M.S. Ayubirad, Studying the effect of spiral curves and intersection angle, on the accident ratios in two-lane rural highways in Iran. Promet-Traffic&Transportation, 2013. 25(4): p. 343-348.
[2] Tayabji, S.D., et al., Advanced high-performance materials for highway applications: A report on the state of technology. 2010.
[3] Jalal Kamali, M.H., A. Hassani, and J. Sodagari, Investigation the Relation between Skid Resistance and Mean Texture Depth in Concrete Pavements. JOURNAL OF CONCRETE RESEARCH. Vol. 25. 2019. 27-38.
[4] Kudrna, J., et al. Road skid resistance influence on the number of crash accidents. in International Conference on Safe Roads. 2006.
[5] Wang, D., et al., A study of the laboratory polishing behavior of granite as road surfacing aggregate. Construction and Building Materials, 2015. 89: p. 25-35.
[6] International, A., Standard practice for calculating pavement macrotexture mean profile depth. 2019, ASTM International.
[7] Zuniga-Garcia, N. and J.A. Prozzi, Contribution of micro-and macro-texture for predicting friction on pavement surfaces. 2016.
[8] Warudkar, A. and S. Elavenil, A Comprehensive Review on Abrasion Resistance of Concrete. International Journal of Applied Science and Engineering, 2020. 17(1): p. 29-43.
[9] Wu, F., X. Chen, and J. Chen, Abrasion resistance of concrete under coupled debris flow and freeze-thaw cycles. Wear, 2023. 524-525: p. 204805.
[10] Chindaprasirt, P. and C. Ridtirud, Abrasion and sulfuric acid resistance of floor concrete polishing. Materials Today: Proceedings, 2023.
[11] Klieger, P., Significance of tests and properties of concrete and concrete-making materials. Vol. 169. 2006: ASTM International.
[12] Gonzalez, M., A. de Oliveira Lima, and S.L. Tighe, Nanoconcrete for Rigid Pavements:Abrasion Response and Impact on Friction. Transportation Research Record, 2014. 2441(1): p. 28-37.
[13] Fwa, T., Skid resistance determination for pavement management and wet-weather road safety. International journal of transportation science and technology, 2017. 6(3): p. 217-227.
[14] Jalalkamali, R., et al., An investigation of the relationship among skid resistance, mean texture depth and abrasion resistance for different macrotextures of concrete pavements. Civil Engineering Infrastructures Journal, 2021. 54(2): p. 301-317.
[15] Jiang, W., Y. Huang, and A. Sha, A review of eco-friendly functional road materials. Construction and Building Materials, 2018. 191: p. 1082-1092.
[16] Jalal Kamali, M.H., A. Hassani, and J. Sodagari, Investigating the relation among British pendulum number, mean texture depth and asphalt content in hot mix asphalt. Journal of Rehabilitation in Civil Engineering, 2020. 8(1): p. 87-96.
[17] Liu, Q. and A. Shalaby, Relating concrete pavement noise and friction to three-dimensional texture parameters. International Journal of Pavement Engineering, 2017. 18(5): p. 450-458.
[18] Peng, Y., et al., Finite Element Method-Based Skid Resistance Simulation Using In-Situ 3D Pavement Surface Texture and Friction Data. Materials, 2019. 12(23): p. 3821.
[19] Wang, D., et al., Development of aggregate micro-texture during polishing and correlation with skid resistance. International Journal of Pavement Engineering, 2020. 21(5): p. 629-641.
[20] Šernas, O., et al., The effect of exposed aggregate concrete gradation on the texture characteristics and durability. Construction and Building Materials, 2020. 261: p. 119921.
[21] Fakhri, M. and M. Taribakhsh, Influence of aggregate grading and creation of macrotexture with the tinning method on the skid resistance of concrete pavements. 2012.
[22] Ardani, A.A., Implementation of Proven PCCP Practices in Colorado. 2006.
[23] Yu, J., et al., Optimizing the texturing parameters of concrete pavement by balancing skid-

resistance performance and driving stability. Materials, 2021. 14(20): p. 6137.
[24] Adresi, M. and G. Lacidogna, Investigating the Micro/Macro-Texture Performance of Roller-Compacted Concrete Pavement under Simulated Traffic Abrasion. Applied Sciences, 2021. 11(12): p. 5704.
[25] Lu, G., et al., Comparison of the polishing resistances of concrete pavement surface textures prepared with different technologies using the aachen polishing machine. Journal of Materials in Civil Engineering, 2021. 33(9): p. 04021226.
[26] Hall, J., et al., Guide for pavement friction. Final Report for NCHRP Project, 2009. 1: p. 43.
[27] Kumar, G.B.R. and U.K. Sharma. Standard Test Methods for Determination of Abrasion Resistance of Concrete. 2013.
[28] 211, A.C., Standard practice for selecting proportions for normal, heavyweight and mass concrete. . American Concrete Institute.
[29] Jalal-Kamali, M.-H., A. Hasani, and J. Sodagari, Introduction and Application of Rotational Abrasion Device to Determine Concrete Pavement Abrasion. Civil Engineering Infrastructures Journal, 2019. 52(2): p. 295-308.
[30] Dong, Q., et al., Investigation into Laboratory Abrasion Test Methods for Pervious Concrete. Journal of Materials in Civil Engineering, 2013. 25: p. 886-892.
[31] Wu, H., et al., Laboratory Evaluation of Abrasion Resistance of Portland Cement Pervious Concrete. Journal of Materials in Civil Engineering, 2011. 23: p. 697-702.