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Influence of Permeable Rigid Pavement on Vehicular Slip Resistance on Curved Sections of a Highway

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Abstract*– The presence of moisture on a pavement causes sudden changes in direction, decreased speed and even vehicular accidents, because the slip resistance is reduced. Therefore, it forces the driver to travel in a more conservative way. This article evaluates the slip resistance of a permeable concrete pavement considering curved sections, which are critical points with difficulty in maneuvering. In addition, the comparison of the International Friction Index (IFI) of two prototypes is developed by carrying out the British Pendulum and Sand Circle test. Therefore, the friction coefficient F(s) at different speeds is determined. The results indicate that, in the critical condition, that is, when the tire is new, the friction F(s) of the permeable pavement is 44.5% greater compared to a conventional pavement when the speed is 60 km/h. This is, how the values obtained contribute to meeting the ideal conditions of a road design. Therefore, the stopping visibility distance requirements for the permeable is 13.8% less than the distance required for the conventional pavement when presenting a speed of 60 km/h.

Keywords*-- Permeable pavement, IFI, slip resistance, British pendulum, pavement texture.

I. Introduction

The presence of moisture on the surface of any pavement represents one of the factors that influence the decrease in vehicle speed. Likewise, they cause drivers to make a sudden change of direction in their path, which could trigger traffic accidents. In this sense, it is an unfavorable condition, since it reduces pavement-tire friction. It should be noted that as the thickness of the water film increases, the resistance to vehicular slip decreases. Therefore, in the absence of adequate adherence, the probability of the vehicle sidetracking and triggering a fatal accident increases.

Likewise, there are more critical conditions such as curved sections and when the driver applies the brakes there is more vulnerability to said accidents. In fact, the Sierra is one of the places where continuous rainfall predominates throughout the year. Especially in the winter season, it rains for many hours and is characterized by having a large presence of curves on the roads. For this reason, on the roads of this region, drivers tend to reduce speed to avoid vehicular slip. Consequently, operating indicators also decrease.

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II. State of the Art

Road surface moisture caused by rainfall accounts for more than a third of weather-related vehicular accidents [1]. Additionally, wet weather conditions cause water to accumulate on the pavement surface and tire [2]. Consequently, they affect the maneuvers carried out by the driver, especially when he applies the brakes and on curved sections. It is known that, 70% of collisions in wet weather can be reduced, by improving the surface texture or the degree of friction in the pavement [3].

A viable alternative to the problem is to use permeable rigid pavements on roads, particularly in their curved sections, in order to achieve greater resistance to vehicular slip, since it reduces rainwater on the pavement surface. On the other hand, permeable pavement slabs have higher British pendulum number values than conventional rigid pavement slabs [4]. In this sense, friction increases with lower air void contents, and a 100% impermeable surface does not provide enough friction when there is rain [5]. This study emphasizes the importance of permeability within the characterization of the pavement, as well as, the properties, dosage and qualities of the materials in the mix design. In addition to this, the morphological characteristics of coarse aggregates influence slip resistance, since the macrotexture provides a drainage system so that water on the pavement surface does not accumulate [6]. Therefore, the slip resistance performance depends on different characteristic factors of texture and macrotexture [7].

On the other hand, friction has a greater influence on wet pavements, and vehicular collisions result 15% more in wet conditions compared to dry conditions [8]. For this reason, insufficient slip resistance is a negative factor in the pavement, where both microtexture and macrotexture play an important role within its anti-slip characteristic, turning the pavement into a more stable surface [9,10]. Definitely, it is distinguished that vehicular slip is influenced by different factors. Indeed, the most critical scenario is when wet conditions occur on the pavement surface, especially when the driver wants to apply the brakes. Therefore, the adhesion between tire and pavement is lost due to the existence of water on the road surface. In this sense, various methodologies are identified that contribute to reducing the problem. However, the one that proves to be most efficient is the design of a permeable rigid pavement.

Given the lack of research on slip resistance in rigid road pavements in Peru, this work evaluates the friction between a permeable rigid pavement and the tire of a vehicle in different conditions: new, semi-new and worn. In this sense, it is analyzed how much a permeable rigid pavement improves the low slip resistance in curved sections with the presence of moisture. Likewise, through the permeability of the wearing course the total impact of the pavement is prevented by the surface runoff generated by the rains that characterize places with high precipitation. In short, the research contributes the moisture is not a factor that impairs road performance. If it rains, functionality decreases little and an optimal condition prevails.

III. METHODOLOGY

The project consists of an experimental investigation, since laboratory tests are developed through a group of knowledge in order to reach a conclusion. In this case, it includes the evaluation of slip resistance through the International Friction Index (IFI). Therefore, the tests are carried out on 2 prototypes of the wearing course: a conventional rigid pavement and a permeable rigid pavement, both with resistance f'c=350 kg/cm2, so that the tire-pavement friction is evaluated. Fig. 1 indicates the research methodology.

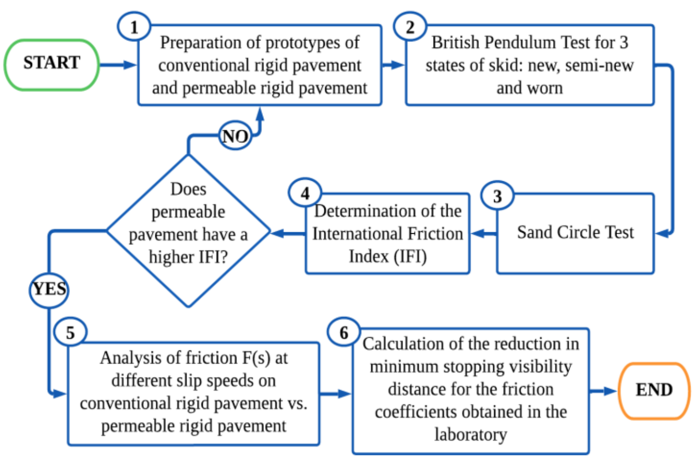

Fig. 1 Investigation methodology

IV. MATERIALS AND TOOLS

The tools that allow the evaluation of the friction of conventional rigid pavement and permeable rigid pavement prototypes are:

A. British pendulum

The Transport Research Laboratory Pendulum (TRRD) is an equipment used to measure slip resistance in pavements (See Fig. 2). In this sense, with the use of this instrument the coefficient of slip resistance (CDR) can be obtained. It should be added that, the specifications of the MTC-E1004 (British Pendulum Test) are considered.

Fig. 2 British Pendulum Test

B. Sand Circle

The sand circle test is applied according to ASTM E965 - 15 (2019) to the pavement prototypes of both wearing course. In this sense, it seeks to obtain the measure of the depth presented by the surface macrotexture of the pavement through the volumetric method. In effect, the procedure consists of spreading a certain amount of fine sand on the surface (See Fig. 3). Next, it is distributed and leveled using a certain instrument. It should be noted that the result of the sand circle test is essential for the calculation of the International Friction Index (IFI).

Fig. 3 Sand Circle Test

V. DEVELOPMENT

The procedure for creating the prototypes is developed considering a formwork of 0.70 m x 0.70 m x 0.10 m for the prototype of conventional pavement and permeable concrete pavement. Likewise, the British pendulum test is developed for both prototypes with tests in 3 skid conditions, as seen in Fig. 4. In addition to the above, the sand circle test is also developed for each type of prototype.

Fig. 4 Conditions or states of skid: new, semi-new and worn

A. Prototyping

The conventional pavement is made with concrete with a resistance of f'c=350 kg/cm2, which is subsequently poured into the formwork. Likewise, texturing is developed with a spacing of ¾" (See Fig. 5).

Fig. 5 Conventional rigid pavement prototype

The prototype of the wearing course of a permeable rigid pavement with f`c = 350 kg/cm2 is developed (See Fig. 6). Regarding the mixture design, fiberglass, micro silica, accelerator additive and superplasticizer additive are incorporated, so that the required compressive resistance is achieved.

Fig. 6 Permeable rigid pavement prototype

V. Results

A. Slip Resistance Coefficient (CRD)

Table 1 shows the CRD values obtained from the British Pendulum test on the conventional rigid pavement prototype. Similarly, in Table 2, the CRD results of the permeable rigid pavement are observed. In addition to this, the Average CRD for both prototypes is displayed, data that is used in the calculation of the friction coefficient f(s).

TABLE I
Slip Resistance Test Results on the Conventional Rigid Pavement Prototype

Skid condition	Results					Average CRD	Temperature Environment (ºC)	Temperature Surface ºC)	CRD Corrected
	1	2	3	4	5				
Worn	85	86	85	85	86	0.85	21.90	22.30	0.85
Semi-New	75	76	76	75	75	0.75	22.00	22.20	0.75
New	68	67	67	65	65	0.66	21.90	22.30	0.66
Average CRD									0.75

TABLE II
Slip Resistance Test Results on the Permeable Pavement Prototype

Skid condition	Results					Average CRD	Temperature Environment (ºC)	Temperature Surface (ºC)	CRD Corrected
	1	2	3	4	5				
Worn	91	90	90	90	91	0.90	21.20	21.80	0.90
Semi-New	78	79	80	80	80	0.79	21.60	22.00	0.79
New	69	70	70	70	69	0.70	21.30	21.80	0.69
Average CRD									0.79

B. Texture depth

From the development of the Sand Circle Test on the elaborated prototypes, the Texture Depth (PT) is determined. In this sense, the results are presented in Table 3, of the hydraulic concrete prototype, as well as, in Table 4, the values obtained from the permeable concrete prototype.

TABLE III
Sand Circle Test Results Prototype of Conventional Rigid Pavement

Nº of Test	Cylinder volume (mm3)	Sand Circle Diameter (mm)				Average (mm)	MTD (mm)
		Rdg. 01	Rdg. 02	Rdg. 03	Rdg. 04		
1	9987.00	115	112	113	112	113.00	0.996
2	9987.00	121	122	119	121	120.75	0.872
3	9987.00	115	120	117	120	118.00	0.913
4	9987.00	121	120	123	119	120.75	0.872
Average PT							0.913

TABLE IV
Sand Circle Test Results Permeable Pavement Prototype

Nº of Test	Cylinder volume (mm3)	Sand Circle Diameter (mm)				Average (mm)	MTD (mm) (PT)
		Rdg. 01	Rdg. 02	Rdg. 03	Rdg. 04		
1	25371.80	120	112	112	118	115.5	2.42
2	25371.80	125	109	108	100	110.5	2.65
3	25371.80	98	118	105	97	104.5	2.96
4	25371.80	115	98	95	100	102.0	3.10
Average PT						108.1	2.78

C. International Friction Index (IFI)

In the IFI calculation, the average CRD and PT values of each prototype are considered, so that the IFI is evaluated for each skid condition. Then, based on said data, a calculation procedure is developed for several parameters: the speed constant (Sp), the friction at 60 km/h without harmonized (FR60) and harmonized (F60), and finally obtaining the friction coefficient (F(s)). Table 5 and Table 6 show the results of F(s) at different speeds for conventional rigid pavement and permeable rigid pavement respectively. Therefore, the procedure for calculating the International Friction Index (IFI) is shown:

1) Speed constant

The values of a and b are calibration constants that are used depending on the type of equipment with which the tests are carried out. In this sense, these values are taken from PIARC table 24 for the calculation of the speed constant. In this case, the corresponding values are a= -11.66 and b=113.63, which are used in (1). Likewise, the PT is the value of the macrotexture that the surface of each pavement presents.

$$S_p = a + (b \cdot PT) \qquad (1)$$

2) Calculation of FR60

Friction is calculated at 60 km/h without harmonization, as shown in (2), where a slip speed of the rubber skid of S = 10Km/h is considered.

$$FR60 = CRD \cdot e^{\frac{S-60}{Sp}} \qquad (2)$$

3) Calculation of F60

In equation (3) the friction is calculated at 60 km/h harmonized.

$$F60 = A + (B \cdot FR_{60}) \qquad (3)$$

4) Calculation of friction coefficient at a certain speed "S".

Calculations are carried out for each skid condition according to the prototype wearing course of conventional rigid pavement and permeable rigid pavement. Likewise, based on these calculations, the friction coefficients at different speeds are determined as indicated in (4).

$$F(S) = F60 \cdot e^{\frac{S-60}{Sp}} \qquad (4)$$

D. Skid new condition

TABLE V
FRICTION COEFFICIENTS OF RIGID PAVEMENT ACCORDING TO SPEEDS IN SKID NEW CONDITION

	Rigid Pavement			Permeable Rigid Pavement		
	Nº Test: 1	IFI (F60,Sp)		Nº Test: 1	IFI (F60,Sp)	
	FR60	Sp (Km/h)	F60	FR60	Sp (Km/h)	F60
	38.36	92.12	0.36	58.55	304.528	0.52
Speeds, Km/h	Values F (s)			Values F (s)		
0	0.70			0.64		
10	0.62			0.62		
20	0.56			0.60		
30	0.50			0.58		
40	0.45			0.56		
45	0.43			0.55		
60	0.36			0.52		
80	0.29			0.49		
100	0.24			0.46		

E. Skid Semi-new condition

TABLE VI
FRICTION COEFFICIENTS OF RIGID PAVEMENT ACCORDING TO SPEEDS IN SKID SEMI-NEW CONDITION

	Rigid Pavement			Permeable Rigid Pavement		
	Nº Test:2	IFI (F60,Sp)		Nº Test:2	IFI (F60,Sp)	
	FR60	Sp (Km/h)	F60	FR60	Sp (Km/h)	F60
	43.59	92.12	0.40	67.04	304.53	0.59
Speeds, Km/h	Values F (s)			Values F (s)		
0	0.78			0.72		
10	0.70			0.70		
20	0.62			0.68		
30	0.56			0.65		
40	0.50			0.63		
45	0.48			0.62		
60	0.40			0.59		
80	0.33			0.55		
100	0.26			0.52		

F. Skid worn condition

TABLE VII
FRICTION COEFFICIENTS OF RIGID PAVEMENT ACCORDING TO SPEEDS IN SKID WORN CONDITION

	Rigid Pavement			Permeable Rigid Pavement		
	Nº Test: 3	IFI (F60,Sp)		Nº Test: 3	IFI (F60,Sp)	
	FR60	Sp (Km/h)	F60	FR60	Sp (Km/h)	F60
	49.40	92.12	0.45	76.37	304.53	0.67
Speeds, Km/h	Values F (s)			Values F (s)		
0	0.87			0.81		
10	0.78			0.79		
20	0.70			0.76		
30	0.62			0.74		
40	0.56			0.71		
45	0.53			0.70		
60	0.45			0.67		
80	0.36			0.62		
100	0.26			0.52		

IV. ANALYSIS OF RESULTS

According to the results obtained from each indicator, the following is analyzed:

A. Slip Resistance Coefficient (CRD)

As shown in Figure 7, there is a 5% variation between the average CRD results in the different skid conditions in both prototypes. Likewise, it is evident that the permeable rigid pavement prototype has a higher slip resistance coefficient than the conventional rigid pavement prototype.

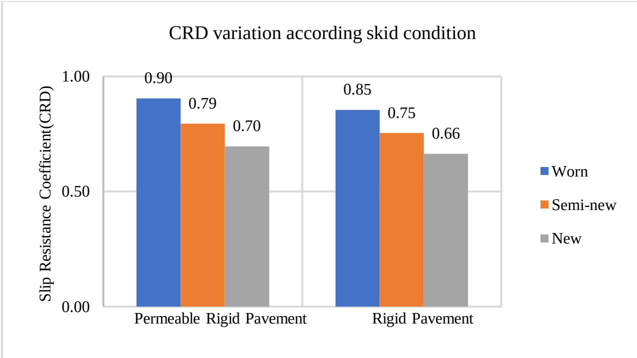

Fig. 7 Variation of the Slip Resistance Coefficient according to the condition of the British Pendulum skid

In accordance with the established in the Peruvian Highway Manual, the minimum CRD for rigid pavement corresponds to a value of 0.45. In fact, based on the results, both prototypes meet the requirement, with the permeable rigid pavement being superior to that of the conventional rigid pavement.

B. Texture Depth (PT)

In Figure 8, a considerable PT variation of approximately more than 200% of the permeable pavement compared to the conventional rigid pavement is observed. This difference is due to the texture of the permeable pavement, that is, its porous structure causes smaller diameters to be obtained in the sand circle test readings. On the other hand, within the minimum PT values specified in the Peruvian Highway Manual, although permeable concrete as such is not found, a comparison can be made with the minimum value requested for a "Porous Asphalt Mixture". Therefore, when indicating a porous characteristic, a minimum PT of 1.5 can be considered, a requirement that is met with a value of 2.78. Likewise, with respect to conventional rigid pavement, the standard states that, for hydraulic concrete pavements, the minimum PT must be 0.80, also guaranteeing compliance with said condition, since there is a PT value of 0.90.

C. International Friction Index (IFI)

In figures 8, 9 and 10 it can be seen that the permeable rigid pavement outperforms the conventional rigid pavement in the 3 established conditions. In this way, the permeable rigid pavement presents a reduction in the friction coefficient as slip speeds greater than 10 km/h increase. However, in all cases it presents values higher than those of conventional rigid pavement. On the other hand, the most critical condition corresponds when the skid is new, given that, as seen in Figure 8, the friction coefficients are much lower compared to the other skid conditions. Therefore, there is a greater susceptibility to vehicular slips when the tire is new.

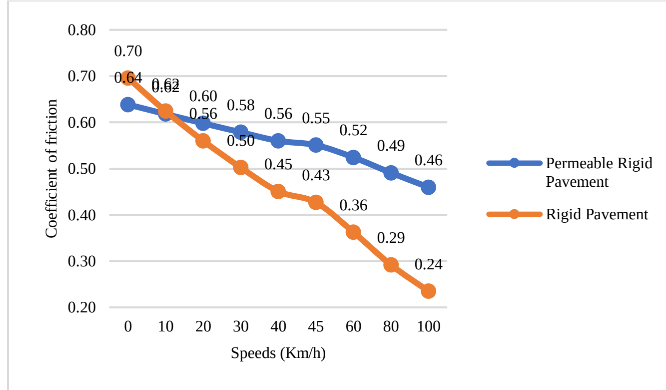

Fig. 8 Variation of the friction coefficient at different new tire speeds

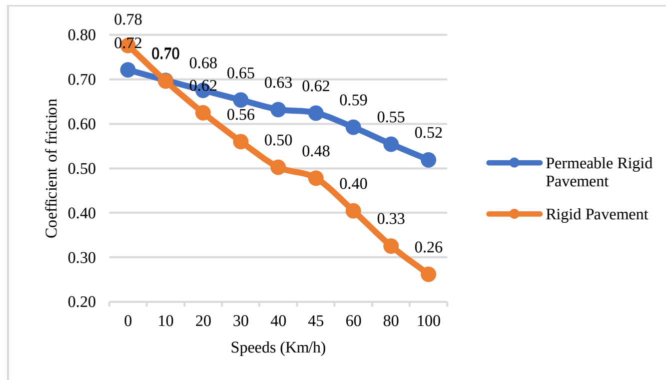

Fig. 9 Variation of the friction coefficient at different semi-new tire speeds

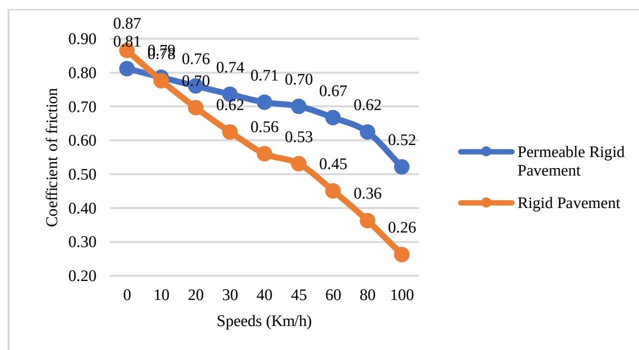

Fig. 10 Variation of the friction coefficient at different worn tire speeds

Likewise, the following 3 tables show the percentage variation that exists between the friction coefficients of both prototypes as the slip speed increases. Among the results, it stands out that at a slip speed of 40 km/h, the permeable rigid pavement maintains a higher friction coefficient of 24%, 26% and 27% in the new, semi-new and worn skid conditions respectively.

TABLE VIII
VARIATION OF THE FRICTION COEFFICIENT BETWEEN BOTH PROTOTYPES AT DIFFERENT SPEEDS

Speeds, Km/h	New Skid Condition	Semi-New Skid Condition	Worn Skid Condition
	Variation (%)	Variation (%)	Variation (%)
0	8.2%	7.1%	6.1%
10	1.0%	0.2%	1.2%
20	6.8%	8.1%	9.2%
30	15.2%	16.6%	17.8%
40	24.2%	25.8%	27.1%
45	29.0%	30.6%	32.0%
60	44.5%	46.4%	47.8%
80	68.2%	70.3%	72.0%
100	95.7%	98.1%	98.1%

As seen in the tables, as speed increases, the coefficient of friction in conventional rigid pavement decreases in a greater proportion compared to permeable rigid pavement. In this sense, the permeable rigid pavement prototype demonstrates better behavior with respect to tire-pavement friction.

D. Minimum stopping visibility distance (Dp)

According to the results obtained from the friction coefficient of the new condition of the skid, the minimum stopping visibility distance (Dp) is calculated as in (5).

$$D_p = \frac{V_0 * t_{pr}}{3.6} + \frac{V^2}{254(f \mp i)} \quad (5)$$

It should be noted that, for the calculations of both pavements, a perception-reaction time (tpr) equal to 2.5 seconds is considered. Likewise, the longitudinal slope is 1%. In this sense, the following table shows the values obtained in the most critical condition of both prototypes.

TABLE IX
MINIMUM STOPPING VISIBILITY DISTANCE CALCULATIONS FOR NEW SKID CONDITION

Minimum stopping visibility distance for new skid condition						
V_0 (km/h)	Longitudinal slope (+i)			Longitudinal slope (-i)		
	Dp Conventional Pavement (m)	Dp Permeable Pavement (m)	% Variation Dp	Dp Variation (m)	Dp Permeable Pavement (m)	% Variation Dp
30	28	27	-3.6%	29	28	-3.5%
40	42	39	-7.1%	43	40	-7.0%
60	80	69	-13.8%	83	70	-15.7%
80	140	106	-24.3%	146	109	-25.3%

In the most critical condition, the permeable rigid pavement has a lower minimum stopping visibility distance compared to conventional rigid pavement. In fact, if the driver of a vehicle travels at a design speed of 40 km/h, he or she requires at least 42 meters to stop completely if he or she sees an obstacle on a conventional rigid pavement road. On the other hand, a rigid permeable pavement road requires a minimum distance of 39 meters, that is, 7.1% less distance compared to conventional pavement.

IV. CONCLUSIONS

The most critical condition according to the analysis carried out corresponds when a vehicle is presented with new tires. In this sense, the IFI values of permeable pavement exceed conventional pavement by 44.5%. In fact, it is determined that as the vehicle increases its speed when traveling on a permeable rigid pavement, the coefficient of friction does not decrease significantly unlike when it is on a conventional rigid pavement.

The calculation of Stopping Visibility Distance for the prototypes shows that there is variability in both cases. That is, if a driver travels on a permeable pavement at a design speed of 60 km/h, he or she requires 13.8% less stopping visibility distance compared to conventional pavement. In effect, this scenario represents a greater collision risk for conventional pavement by requiring greater stopping visibility distance.

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