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Degradation Prediction Model for Friction of Road Pavements with Natural Aggregates and Steel Slags

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Abstract: Steel production wastes (steel slags) are used more often in asphalt concrete pavements as a valuable replacement for natural aggregates, which are becoming increasingly rare. In this paper authors investigate the polishing characteristics of aggregates, and in particular of steel slags, used in bituminous road surfacing, are a major factor in determining the resistance to skidding. The main purpose of the study is the identification of a suitable degradation model, based on friction indicators, in the laboratory, as well as the comparison of in-situ pavement skid resistance with the cumulative number of passing vehicles over the years. The model predicts the expected resistance to skidding of the road surface based on the knowledge of the polished stone value (PSV) of the aggregates and the expected traffic on the road. In this study, several types of aggregates were compared: steel slag, limestone, limestone and slag mixture, diabase, Criggion stone and basalt. Using a standard PSV test, it was found that the aggregates did not reach the lower value of skid resistance (equilibrium value). The analysis of the British Portable Number (BPN) data versus polishing time allowed to empirically derive a regression model for each investigated aggregate. Hence, it appears possible to define both an investigatory level and threshold level to predict the actual residual life of the pavement from the examination of skid resistance.

Keywords: skid resistance; friction; polished stone value; road pavements; steelworks slags; BPN

1. Introduction

The by-product of steel production waste, named slag, whose chemical properties are similar to effusive rocks, is transformed into coarse aggregates and they are used for bituminous surfacing as a valuable replacement for natural aggregates, which are becoming increasingly rare. Moreover, the coarseness made by the wearing this material maintains good values of micro-texture and, therefore, friction resistance, even after prolonged exposure to the action of the traffic loads.

Several experimental studies [1] have suggested that the number of wet-pavement skid road accidents increases as skid resistance decreases and skid resistance depends on the road pavement surface characteristics: macrotexture and microtexture. Macrotexture refers to the irregularities in the road surface associated with voids between aggregate particles, which relate to the size, shape, and distribution of coarse aggregates used in pavement, as well as the construction method of the surface layer. The magnitude of macrotexture can increase or decrease during pavement service life [2–4]. Microtexture refers to roughness in the surfaces of the aggregate and is a function of aggregate mineralogy. The size of microtexture also varies over time during the pavement service life, depending on the initial roughness of the aggregate and the ability of the aggregate to maintain roughness against the polishing action of traffic and weather [5] whereas microtexture always has a decreasing trend over time.

Past studies have been dedicated to the improvement of methods aimed at predicting deterioration before pavements are constructed, in order to achieve appropriate design life and to enable advanced planning of maintenance interventions [6].

The PSV is the most widespread laboratory test, used worldwide to assess the skid resistance performance of surface aggregates; this test has, however, some limitations that affect its ability to predict the long-term performance of road surfaces. In particular, the standard PSV test uses a set polishing time of six hours, hence there is a possibility that the aggregates, in this case greywacke and melter slag, have not reached the equilibrium skid resistance by then [7].

The first research examining the effect of traffic on pavement skid resistance was carried out by TRRL report LR504 [8]. The analysis of traffic volumes and skid resistance measurements, made in the UK road network, allowed us to identify correlations between the side-force coefficient SFC, and the independent variables in traffic flow in commercial vehicles per day, or the traffic flow in total vehicles per day, and the polished stone value of some aggregates, calcined bauxite, gritstone and granite.

Diringer and Barros [9] developed a deterioration model of microtexture with cumulative polishing over time using a PSV machine for five aggregates: carbonate rock, gneiss, basalt, argillite and limestone. The laboratory-measured microtexture decay rate, as a function of the polishing hours, tends to an asymptotic value. This asymptote is referred to as 'minimum polish value' (PV) associated with a specific aggregate. The deterioration of microtexture is determined by the laboratory BPN after "t" h of polishing. However, in the model there is no correlation with traffic volume.

In the TRL report 322, Roe and Hartshorne [10] subdivided the measure sites according to the investigatory level and correlated their skid resistance (mean summer SCRIM coefficient—MSSC), with PSV and the traffic level (commercial vehicles per day, CVD). Only three types of aggregates were analyzed: basalt, gritstone and porphyry.

Haddock and O'Brien [11] correlated the on-site SN (skid number) and the BPN10 measured in the laboratory, after 10 h of polishing, with a PSV machine for two aggregates: steel slag and dolomite. In this note there is no reference to traffic.

Crisman, Ossich and Roberti [12] identified a decay curve of indicators of friction as a function of cumulative vehicle passages for a mixture of steel slags and limestone.

Siriphum et al. [13] developed a skid resistance predictive model for three types of aggregates: granite, limestone and basalt. The authors related the skid resistance value at 35° (SRV35), with the differential polishing stone value (PSV_{diff}) before and after polishing, mean texture depth (MTD) and gradation. The model does not consider the traffic volume.

Siriphum et al. [14] in relation to the same aggregates, extended the predictive model for any traffic volume for dense-graded asphalt concrete with 9.5 mm or 12.5 mm aggregate maximum size.

Although most studies show that skid resistance is related to traffic volume, an accurate skid resistance predictive model, in terms of traffic volumes and regarding many types of aggregates, has not yet been clearly defined. In particular, a relationship that links the degradation of skid resistance in the laboratory with the on-site one has not been defined.

This paper mainly discusses the skid resistance performance of various aggregates (slag, limestone, silica-limestone, mixed slag-limestone, basalt, diabase and Criggion stone), assessed with the PSV test and examines the micro-texture decay curves. In particular, the main purpose of the study is to identify a decay curve (deterioration) of the friction indicators, taking into account the number of cumulative vehicle passages over time. The aim of the research was, therefore, to assess whether the use of steel slags can replace natural aggregates by comparing the decay of skid resistance both in laboratory and on site.

2. Materials and Methods

The intention of the experimentation was to verify the deterioration of the skid resistance of a road pavement in the province of Trieste, Italy, whose wearing course was made by a mixture of aggregates that included steel slags and limestones.

The in-situ skid resistance in previous tests had shown that the surface wear of aggregates, due to the traffic polishing action, is not linear. The skid resistance, as measured by the skid tester, does not proportionally decrease with an increase in traffic levels. Therefore, the decision was made to carry out specific experiments, using an accelerated polishing machine, in an attempt to confirm these observations in the laboratory and, possibly, to find the correlation between in-situ measurements and traffic levels.

In the first part of this study, the following types of aggregates were investigated (Figure 1): slag, basalt, diabase, limestone 1 (silica-limestone), limestone 2, PSV control stone and friction tester reference stone (Criggion stone), in addition to the slag and limestone mixture at 50%, used on the wearing coarse on the investigated sites. Table 1 summarizes the main chemical composition of materials (slag and limestone) used to mix the design of wearing coarse.

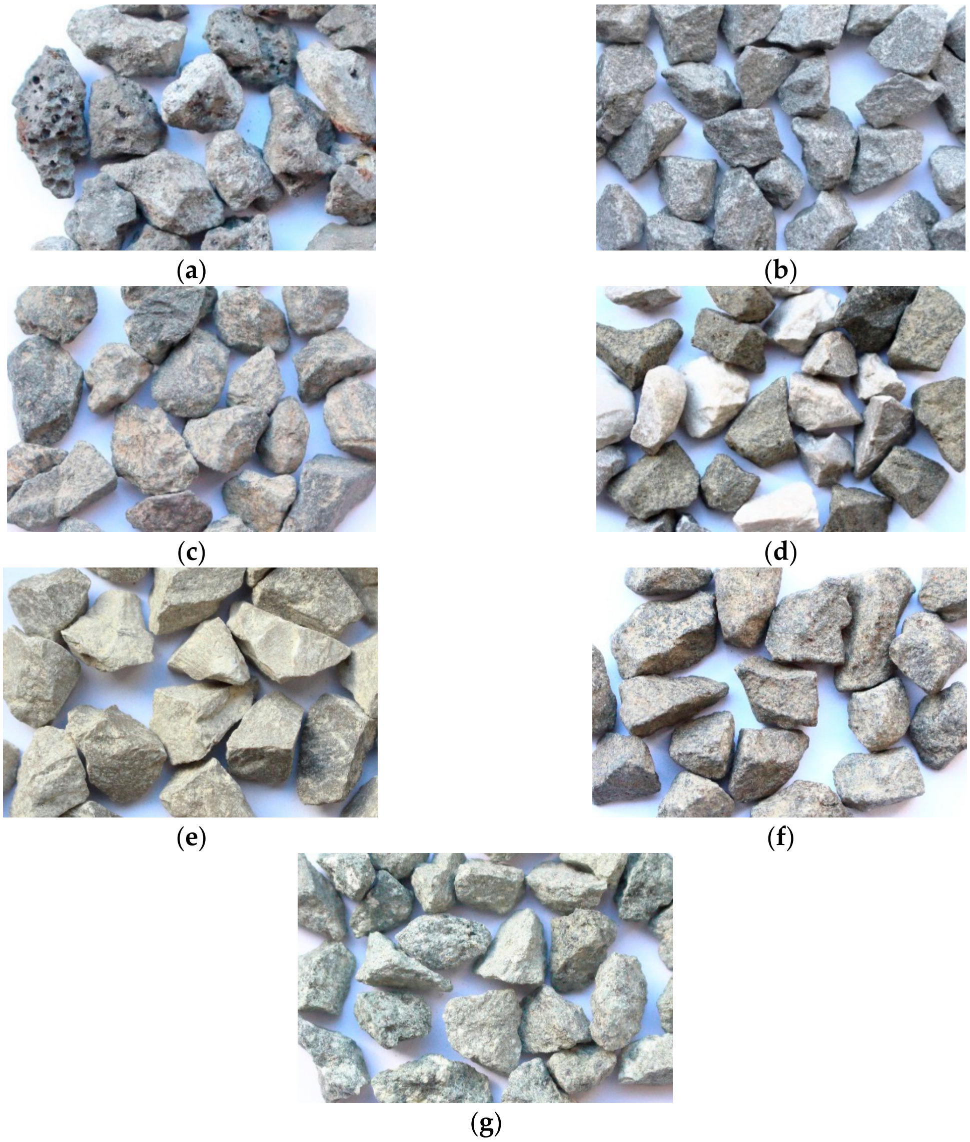

Figure 1. Tested materials: (**a**) slags; (**b**) basalt; (**c**) diabase; (**d**) silica-limestone; (**e**) limestone; (**f**) control stone and (**g**) Criggion stone.

Table 1. Main chemical composition.

Material		CaO (%)		MgO (%)		FeO (%)		Al_2O_3 (%)		SiO_2 (%)
steel slag	min	21.8		4.1		24.1		4.6		13.3
	max	29.3		8.6		43.3		11.0		19.8
		$CaCo_3$ (%)	$MgCO_3$ (%)	CaO (%)	MgO (%)	$Ca(OH)_2$ (%)	$Mg(OH)_2$ (%)	Ca (%)	Mg (%)	CO_2 (%)
limestone	min	72.6	18.3	40.7	8.7	53.7	12.6	29.1	5.3	45.5
	max	81.7	27.4	45.8	13.1	60.5	19.0	32.7	7.9	46.2

The laboratory study included several steps:

- Determination of the polished stone value (PSV) according to the standard UNI EN 1097-8 [15];
- Monitoring the same samples through an extended period of polishing;
- Determination of the skid resistance of the specimens, not only at the end of the polishing process, but also at fixed time intervals, to compare the polishing behavior in the various samples.
- Careful investigation of the first phase of the 'polished stone value' (PSV) test or initial conditioning.

To determination the PSV, according to UNI EN 1097-8, an accelerate polishing machine was used (Figure 2). The samples for the test (Figure 3) were therefore prepared with all the materials being analyzed and with the reference stone, according to the standard. The specimens have been polished through the procedure of the UNI EN 1097-8. The first three hours of testing correspond to the conditioning phase, with the main task of cleaning the surface of the specimen from any resin residues used for packaging. The next three hours of testing concern the polishing phase, as required by the standard, and, finally, the test is extended for a further three hours, to better understand long-term behavior, not required by the standard. Skid resistance was evaluated through the measurement of the British portable number (BPN) during all phases with the British pendulum skid tester (Figure 4).

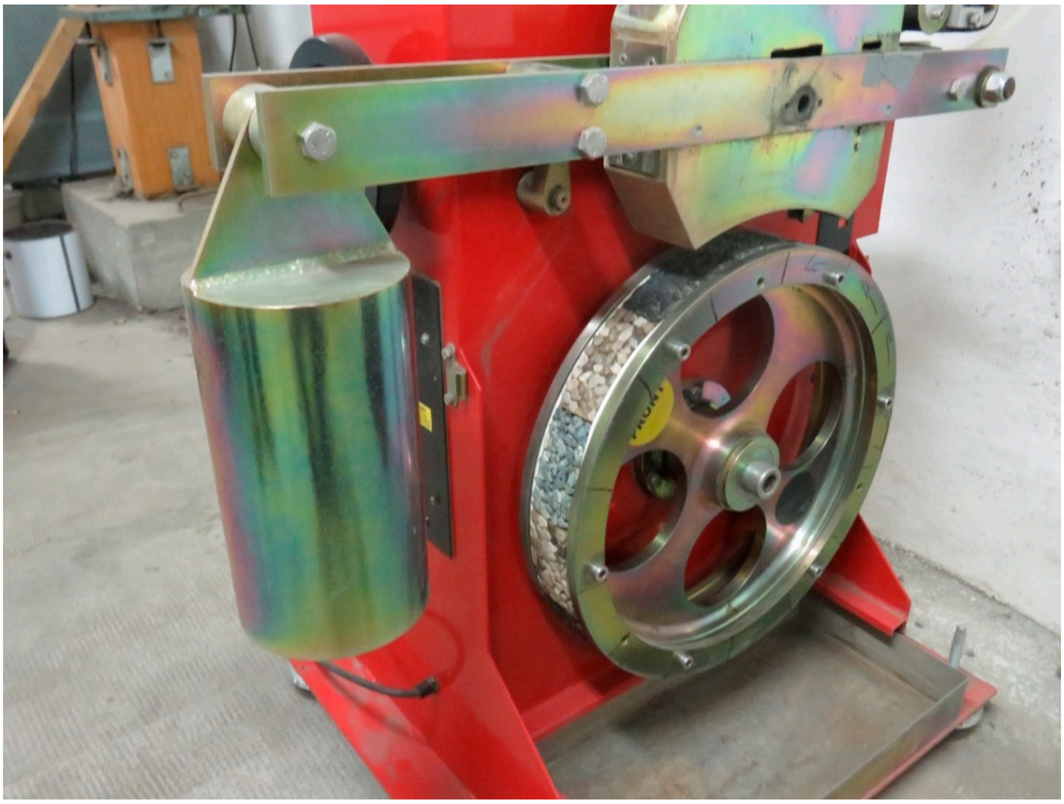

Figure 2. Accelerated polishing machine with revolving wheel and specimens.

Figure 3. Specimen example.

Figure 4. British pendulum skid tester.

During the conditioning phase (the first 3 h) the values of BPN were monitored at 10, 20, 30, 60, 120 and 180 min. During standard polishing phase (3 h after the conditioning phase) the BPN was monitored at 15, 30, 45, 60, 120 and 180 min, and the skid resistance of the specimens was measured and compared with the results from specimens made with a 'control stone' to calculate the PSV. Polishing time was further extended to 3 h in order to understand and better describe the polishing mechanism. Moreover, the other aggregates were subjected to the same test conditions.

As outlined in the introduction, the purpose of this work was to investigate the behavior of a particular kind of asphalt concrete, influenced by traffic polishing action. In order to test the behavior under field conditions, the aggregates of this asphalt concrete were subjected to a laboratory analysis, using a polishing device, and, subsequently, results were compared with on-site measurements.

All the selected sites presented suitable features to preserve homogeneity among field measurements. All the sites were part of the road network of the Province of Trieste; they were located in the road tangent and belong to two-lane rural roads. The roadway cross sections were almost the same (Table 2) and, obviously, the wearing course had been built using the same mix design (Table 3) and aggregates gradation (Figure 5), and the type of slag and limestone was the same as that used for laboratory experimentation. In addition, traffic conditions were substantially the same for each site. The heavy traffic was almost exclusively composed of local public transportation vehicles.

Table 2. Typical characteristic of road cross section.

Road Category:	Rural Road
Traffic lane:	Two-lane
Traffic lane width (L):	3.00 ÷ 3.50 (m)
Shoulder width (S):	0.20 ÷ 0.80 (m)

Table 3. Typical characteristics of wearing course mixtures analyzed.

Aggregates—slag	60 (%)
Aggregates—silica limestone 1	40 (%)
Binder content (per weight of aggregate)	5.2 (%)
Bulk density of mixture	2.9 (g/cm^3)
Aggregates density	3.2 (g/cm^3)
Air void	3.3 (%)
Maximum aggregates size	15 mm

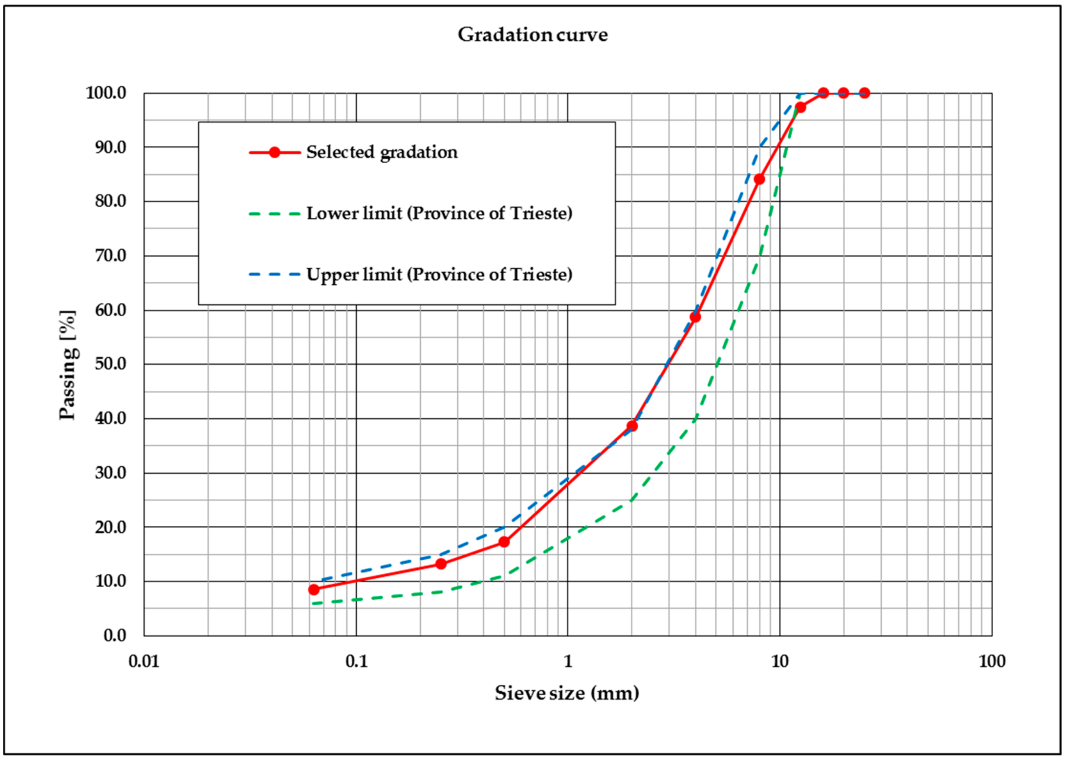

Figure 5. Aggregate gradation curve of wearing course mixtures.

The tests were carried out at the different sites during an eight-year period (Figure 6); for some of them, it was possible to perform the measurements at the same point in different time periods and, therefore, with variable values of cumulative traffic.

Figure 6. Example of in-situ measures.

Given that the type of test that allowed us to determine the value of skid resistance at a single point, a procedure that evaluates the value of BPN, according to the standard UNI EN 13036-4 [16], which can be representative of a stretch of road, had to be adopted. Before executing the measurements, the local variation in the value of the BPN was investigated in the transverse direction of the road. In particular, the distribution of the value of the BPN at several transverse points along several sections was analyzed in order to accurately identify the predominant wheel paths (Figure 7).

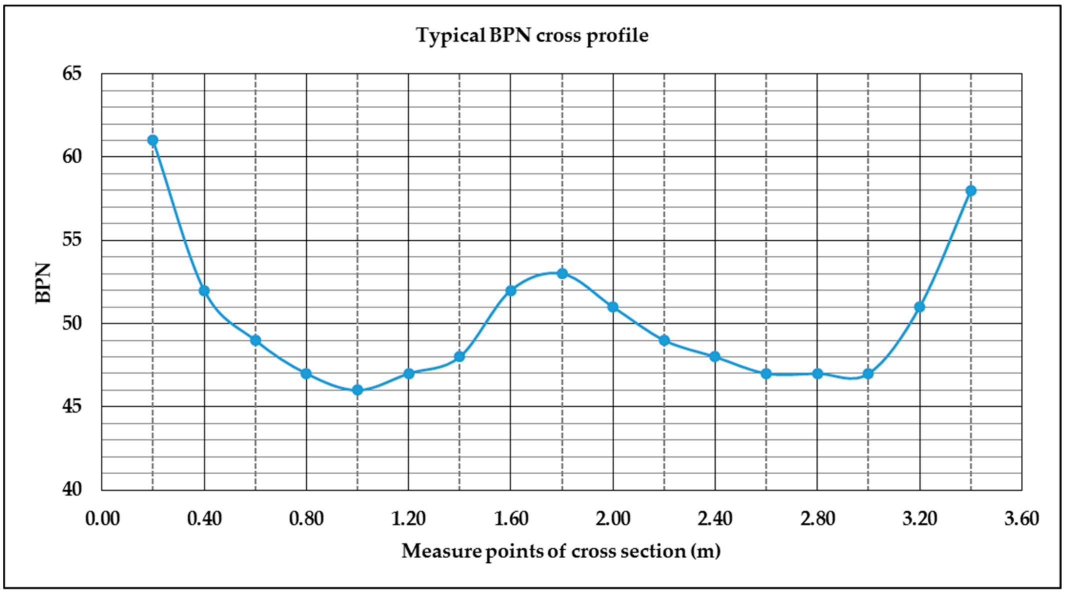

Figure 7. Example of British portable number (BPN) values in the cross section.

It was possible to exactly define the measurement points from the analysis of the experimentally derived transverse distribution of the BPN. More specifically, three points were chosen for each investigated section at different distances from the margin line (Y1 = 0.60, Y2 = 0.85 and Y3 = 1.10 m), in order to select the minimum reference value (Figure 8). In addition, for each site, measurements were carried out in correspondence with five distinct sections, arranged at a distance (X) of 10 m from one another. Ultimately, for each site the measurements were conducted at 15 distinct points.

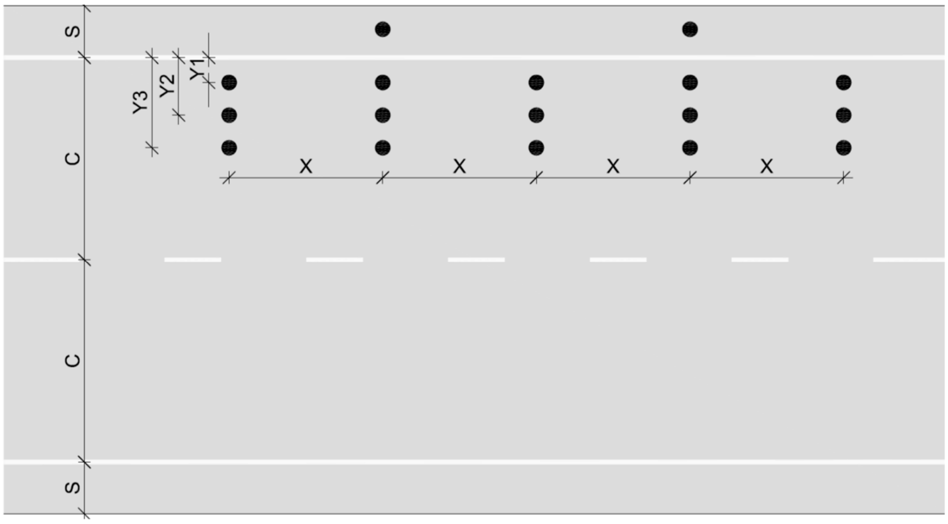

Figure 8. Plan of in-situ measures; "S" and "C" are shoulder and lane width.

The value of the BPN, representative of the site, was obtained by averaging the five minimum values of BPN among the five sections. All the values were also preliminarily corrected to consider the effect of temperature on the BPN measurements. In addition to the measurements along the predominant wheel paths, two supplementary measurements were performed along the shoulder in order to examine the BPN, which was not exposed to wearing.

3. Results and Discussion

The values reported in Table 4 are the rounded averages of the specimens for each aggregate and mixture. The conditioning phase in the polishing test showed similar trends with all types of aggregates. An initial increment of the values of BPN was followed by a subsequent slight decrement.

Table 4. Results of the laboratory test.

Aggregates	PSV	BPN at Given Times (min.), 180 min. is after Conditioning							
		180 (min.)	195	210	225	240	300	360	540
Slag	54	63	57	55	54	52	51	51	50
Silica limestone	37	53	49	43	42	40	37	36	34
Limestone	34	51	42	39	38	37	35	32	30
Basalt	53	65	61	57	55	53	51	49	45
Diabase	57	64	58	55	54	54	54	52	49
Criggion stone	60	67	63	59	58	57	56	53	53
Mixture	47	59	54	51	49	46	44	45	43

The results of the conditioning phase in the polishing test are shown in Figure 9. The BPN reported are the averages of the values of four specimens for each aggregate using the normal PSV scale for the small slider, without any correction. The trend of the values is in accordance with what normally occurs in these tests, with an initial increase, due to the removal of the residues of the resin used for the realization of the samples, followed by a decay of the values due to the initial wearing.

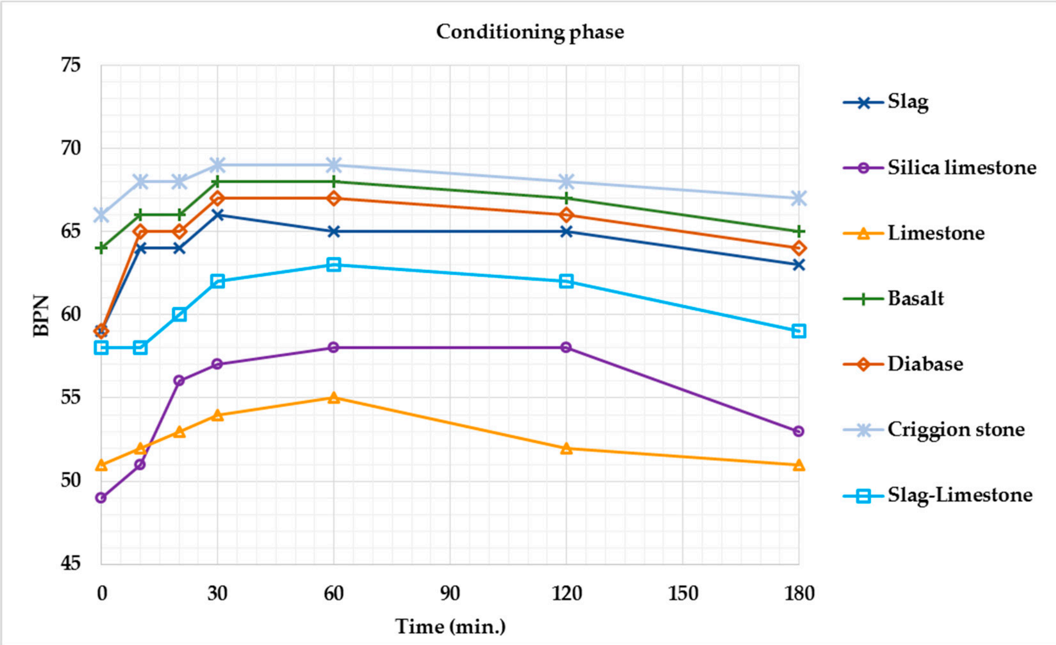

Figure 9. Conditioning phase in the polished stone value (PSV) tests.

At the beginning of the polishing phase, the highest BPN values were 67, 65, 63 and 63, respectively, for Criggion stone, basalt, diabase and slag. Limestone samples had the lowest values—53. BNP values of the control stone after the polishing activity, ranging from 47 to 50, were used to calculate the PSV.

According to the UNI EN 13036-4, the PSV was determined using the following equation:

$$\mathrm{PSV} = \mathrm{S} + 52.5 - \mathrm{D}, \tag{1}$$

where S is the mean value of skid resistance for the aggregate test specimens and D is the mean value of skid resistance for the PSV control stone specimens.

The following remarks are derived from the laboratory results shown in Table 4.

The polishing tests showed that, overall, skid resistance rapidly decreased with increased traffic conditions during initial test stages; however, as the test time was extended, the polishing slowed down or did not show observable changes.

With all the aggregates, most polishing effects occurred within the first fifteen minutes of treatment and later continued at a progressively decreasing rate.

The slag lost 17.5% of the BPN value in the first hour of polishing, while samples with limestone showed a reduction of BPN values of the order of 26–31%. The slag showed the smallest loss of BPN value throughout the entire polishing process, about 21%, against 40–45% of limestone, 33 of the basalt and 23% diabase.

The decreasing trend in BPN values during a three-hour polishing period is confirmed by previous observations in the literature, namely, that the behavior of the mixture is directly proportional to the quantity of each material. The BPN values of the samples, consisting of a 50% mixture between the two aggregates, are roughly the average of the measurements obtained for the two materials, analyzed separately. Percentage reductions of 22% were observed for the samples made with slag and limestone.

Polishing time was extended to 3 h in order to understand and better describe the polishing mechanism. Moreover, the other aggregates were subjected to the same test conditions.

The analysis of BPN data versus polishing time (t) allowed us to empirically derive a regression model of the following form:

$$\mathrm{BPN(t)} = \left(\frac{\mathrm{A}}{\mathrm{t}}\right)^4 + \mathrm{B} \cdot \mathrm{PSV}, \tag{2}$$

where A and B are two regression parameters, PSV is the value determined by the test according to EN 1097-8 and t is the time in seconds. The second term in the previous equation (B·PSV) is the minimum asymptotic polishing value and the regression coefficients of the model are presented in Table 5 for the seven types of samples analyzed.

Table 5. Laboratory model parameters.

Type of Sample	A	B	PSV	R^2
Slag	344	0.910	54	0.937
Mixture	359	0.910	47	0.932
Silica limestone	379	0.910	38	0.949
Basalt	373	0.858	48	0.808
Diabase	335	0.880	51	0.752
Limestone	372	0.890	32	0.892
Criggion stone	344	0.880	60	0.905

The fitted value of the B parameter suggests that the BPN value varied between 86% and 91% of the corresponding PSV value, at the end of the polishing process. Figure 10 shows the interpolation curves obtained using the model shown in Equation (2).

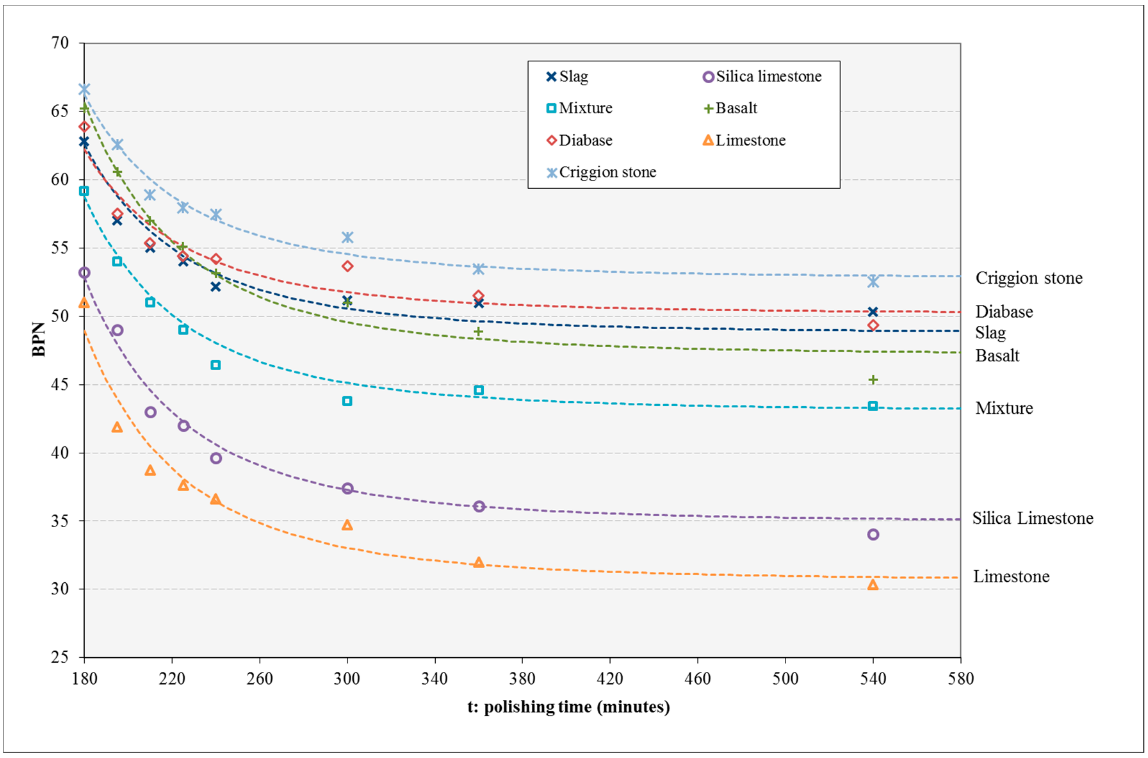

Figure 10. Laboratory polishing curves.

Table 6 summarizes the measurement results with the skid tester at various sites, where BPN is the representative value of the section, while BPN_s is the value in the shoulder in the same section, that is not subject to wearing.

Table 6. In-situ measurements.

Period between Road Rehabilitation and Test Date (Years, Months)	Road Identifier (Designation)	Location (km + m)	BPN	BPN_s	Traffic *
4 y 6 m	S.P. 1	4 + 930	46.6	67.8	5,123,000
1 y 0 m	S.P. 1	20 + 330	52.5	61.1	636,400
2 y 0 m	S.P. 1	20 + 330	50.0	71.0	1,302,200
2 y 11 m	S.P. 1	20 + 330	48.7	69.0	1,860,500
0 y 5 m	S.P. 1	20 + 450	41.7	47.5	246,200
6 y 11 m	S.P.5	1 + 260	48.0	75.4	1,713,000
7 y 11 m	S.P. 5	1 + 260	47.0	73.0	1,956,900
8 y 10 m	S.P. 5	1 + 260	46.3	72.5	2,186,000
1 y 10 m	S.P. 6	0 + 720	50.2	71.5	1,218,000
1 y 0 m	S.P. 6	0 + 720	52.8	73.4	654,500
0 y 3 m	S.P. 9	2 + 050	56.7	65.9	58,000
1 y 0 m	S.P. 10	1 + 950	50.8	73.7	1,074,300
2 y 0 m	S.P. 10	1 + 950	50.6	74.0	2,134,300
3 y 0 m	S.P. 10	1 + 950	48.2	73.1	3,103,500
1 y 0 m	S.P. 14	9 + 200	49.4	61.9	736,000
4 y 5 m	S.P. 35	4 + 320	48.6	53.1	742,600

* Cumulative traffic in equivalent passenger-cars since the last paving of wearing course.

In situ measurements of BPN, performed on homogeneous sections, according to the traffic, show the same trend as the one of the model obtained in the laboratory.

Specifically, the analyzed wearing coarse consisted of a mixture of aggregates with 60% slag and 40% limestone. Therefore, after observing a behavior directly proportional to quantities of this material, the following parameters could be found for this type of material (Table 7):

Table 7. Laboratory model parameters.

Type of Sample	A	B	PSV
Slag 60%, limestone 40%	365	0.910	48

The BPN decay curves in situ and in the laboratory can be represented by the same function. The independent variables of the two models are different: in the laboratory the polishing is linked to the number of revolutions of the PSV device wheel, on the road the polishing depends on the number of cumulative passages of equivalent cars. In order to be able to use the decay curve obtained in the laboratory to predict the behavior on site, it is necessary to determine a scale factor that links the two independent variables. The equivalent factor was determined by a non-linear regression technique using laboratory model and data measured on site. The equivalent value obtained was 2550: each minute of polishing with PSV device corresponds to 2520 passages of equivalent cars. Thus, when the type of aggregates used in situ, and degradation curves in laboratory are known, it will be possible to predict the in site behavior.

In Figure 11, the continuous line features the degradation model of the aggregate mixture used in the wearing course, identified in the laboratory (Tables 4 and 5), with the addition of a coefficient k, which takes into account the different procedures of polishing at the site. The same graph, with a change of values on the x-axis, illustrates the values of the experimentally measured BPN as a function of traffic. Using an equivalence factor between the polishing time and the traffic, according to the following expression, an adequate interpolation of the experimental data was found (Table 8):

$$t \cong \left(\frac{T}{7 \cdot v_{CLA}}\right) = \left(\frac{T}{2520}\right), \tag{3}$$

where:

- t is the polishing time expressed in minutes,
- v_{CLA} is the speed in rounds per minute (360 RPM)
- T is the total traffic (number of vehicles)

In this case, we can write Equation (2) as:

$$BPN(T) = \left(\frac{A \cdot 7 \cdot v_{CLA}}{T}\right)^4 + \frac{B \cdot PSV}{k}, \quad (4)$$

where k is a coefficient that takes into account a different behavior between the in-situ and in-laboratory test.

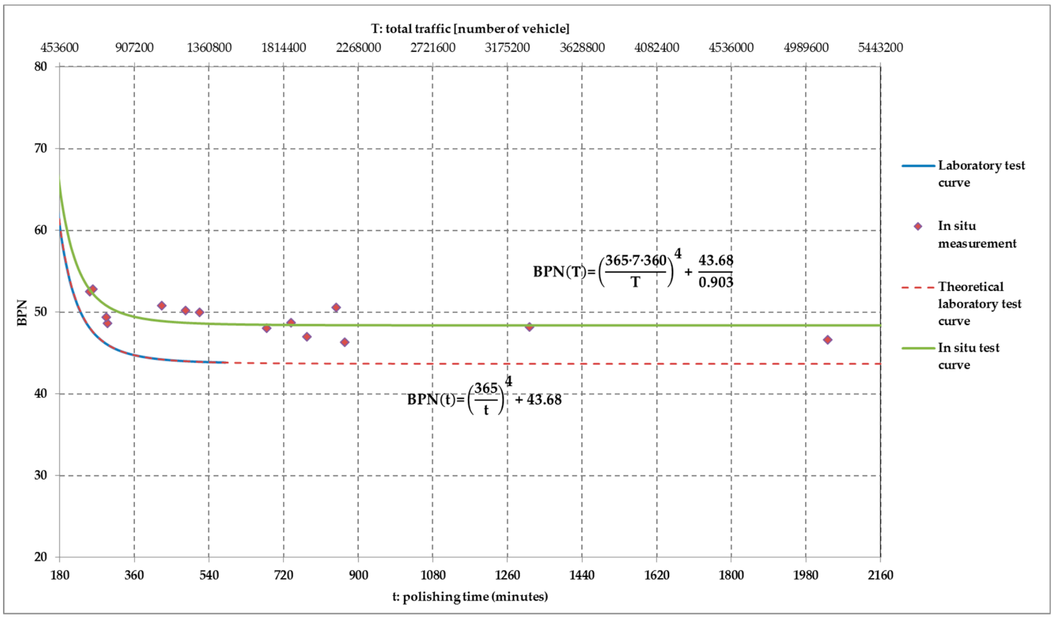

Figure 11. Comparison between degradation model in-situ and in laboratory.

Table 8. In-situ model parameters.

	A	K	B·PSV	R^2
Skid resistance BPN	365	0.903	43.68	0.460

The proposed model curve can be used to predict the decay of skid resistance of a wearing course due to traffic, calibrated with the models of the aggregates used. It will also be possible to compare the performance of different aggregates, evaluate the cost and provide assistance to maintenance operations.

This result is valid for the road network covered by the measures, which is affected by the typical traffic level of a rural road of modest importance. The R2 value in Table 8, although obtained from a small sample size, was higher than that of similar in-situ experimentations. A variation in the traffic spectrum will not affect the shape of the monotonically decreasing curve, even though the time scale (the x-axis) will be modified. Obviously, decay will manifest more quickly for the same cumulative traffic in the curves. To complete this work, it will be necessary to establish the correspondence between the number of steps in the tangents and the curved road segments that produce the same degradation in terms of BPN reduction. The equivalence factor will depend on the radius of the curve.

The measurements, which were carried out along the shoulder to examine the relative BPN differences in a road area unaffected by wearing, and performed at different times of the road rehabilitation, showed an increment of BPN values with time. This observation can be explained by the loss of binder from the surface of the aggregates.

4. Conclusions

This study evaluated the relation between the in-service performance of road pavement skid resistance (measured as BPN) and polishing resistance (measured in the PSV laboratory test).

In this study, seven types of aggregates were compared: steel slag, two kinds of limestone, basalt, diabase, Criggion and one mixture of slag and limestone.

The main findings were:

(1) Steel slag has a good resistance in term of polishing—our data confirmed results obtained by previous research. Although slags had an initial BPN value slightly lower than basalt, the ultimate BPN values were higher;
(2) The frictional resistance of a blend of slag and limestone was directly proportional to blend percentages;
(3) In the standard PSV test, the aggregates did not reach the equilibrium skid resistance. The "Terminal BPN" (equilibrium) for the seven aggregates was between 86% and 91% of the BPN values, through which the PSV was calculated;
(4) The BPN progressively decayed and approached an asymptotic value that was referred to as a "minimum polishing value" associated with a specific aggregate. A mathematical expression (decay model) was obtained from laboratory tests, employing the PSV as a performance indicator;
(5) A good correlation was found between in-service performance of road pavement skid resistance, measured as BPN, and polishing resistance, measured in the PSV test. One minute of the PSV test approximately corresponded to about 2520 equivalent passenger cars, both for the investigated aggregates and the considered sites and traffic conditions;
(6) Additional aggregate specimens and test results were required to answer the research question of how the PSV test could give a better prediction of the long-term in-situ skid resistance performance;
(7) A survey carried out on the same road network with the same spectrum of traffic and examining road sections in bends with a variable curvature radius would allow us to identify an equivalence factor among the number of vehicle passages in the bend and the ones that produce the same damage as in the tangent section;
(8) The use of a by-product (steel slags) to replace raw materials, such as limestone or basalt, is a valid example of the application of the circular economy.
(9) In the future, other pavement types additional in situ tests will be considered.

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References

1. Peter, C. *Skid Resistance and Crashes: A Review of Literature, Reserch report ARR 311*; TRB: Washington, DC, USA, 1997.
2. Miao, Y.; Li, J.; Zheng, X.; Wang, L. Field investigation of skid resistance degradation of asphalt pavement during early service skid resistance degradation of asphalt pavement. *Int. J. Pavement Res. Technol.* **2016**, *9*, 313–320. [CrossRef]
3. Susanna, A.; Crispino, M.; Giustozzi, F.; Toraldo, E. Deterioration trends of asphalt pavement friction and roughness from medium-term surveys on major Italian roads. *Int. J. Pavement Res. Technol.* **2017**, *10*, 421–433. [CrossRef]

4. Plati, C.; Pomoni, M. Impact of traffic volume on pavement macrotexture and skid resistance long-term performance. *Transp. Res. Rec.* **2019**, *2673*, 314–322. [CrossRef]
5. Noyce, D.A.; Bahia, H.U.; Yambó, J.M.; Kim, G. Incorporating road safety into pavement management: Maximizing asphalt pavement surface friction for road safety improvements. In *Draft Literature Review and State Surveys, Midwest Regional University Transportation Center*; UMTRI: Ann Arbor, MI, USA, 2005.
6. Kane, M.; Zhao, D.; Do, M.T.; Chailleux, E.; De-Lalarrard, F. Exploring the ageing effect of binder on skid resistance evolution of asphalt pavement. *Road Mater. Pavement Des.* **2010**, *11* (Suppl. 1), 543–557. [CrossRef]
7. Wilson, D.J.; Black, P.M. Comparison of skid resistance performance between greywacke and melter slag aggregates in New Zealand. In Proceedings of the International Safer Roads Conference: Managing Roads and Runway Surfaces to Improve Safety, Cheltenham, UK, 11–14 May 2008; Available online: https://saferroadsconference.com/wp-content/uploads/2016/05/Douglas-Wilson-Comparison-of-Skid-Resistance-Performance-between-Greywackes-and-Melter-Slag-Aggregates-in-New-Zealand.pdf (accessed on 30 September 2019).
8. Szatkowski, W.S.; Hosking, J.R. *Effect of Traffic and Aggregate on the Skidding Resistance of Bituminous Surfacings*; Laboratory Report LR 504; Trasport and Road Research Laboratory: Crowthorne, UK, 1972.
9. Diringer, K.T.; Barros, R.T. Predicting the skid resistance of bituminous pavements through accelerated laboratory testing of aggregates. In *Surface Characteristics of Roadways: International Research and Technologies*; ASTM International: West Conshohocken, PA, USA, 1990. [CrossRef]
10. Roe, P.G.; Hartshorne, S.A. The Polished Stone Value of Aggregates and in-Service Skidding Resistance, Wokingham. 1998. Available online: https://trl.co.uk/sites/default/files/TRL322.pdf (accessed on 30 September 2019).
11. Haddock, J.E.; O'brien, J.P. Hot-mix asphalt pavement frictional resistance as a function of aggregate physical properties. *Road Mater. Pavement Des.* **2013**, *14* (Suppl. 2), 35–56. [CrossRef]
12. Crisman, B.; Ossich, G.; Roberti, R. Durability of wearing courses made with steelworks slag. In Proceedings of the Eighth International Conference on Maintenance and Rehabilitation of Pavements, Singapore, 27–29 July 2016. [CrossRef]
13. Siriphun, S.; Chotisakul, S.; Horpibulsuk, S. Skid resistance of asphalt concrete at the construction stage based on thai aggregates. *J. Mater. Civ. Eng.* **2016**, *28*, 04016145. [CrossRef]
14. Siriphun, S.; Horpibulsuk, S.; Chotisakul, S.; Suddeepong, A.; Chinkulkijniwat, A.; Arulrajah, A. Effect of cumulative traffic and statistical predictive modelling of field skid resistance. *Road Mater. Pavement Des.* **2019**, *20*, 426–439. [CrossRef]
15. UNI, UNI EN 1097-8. *Tests for Mechanical and Physical Properties of Aggregates—Part 8: Determination of the Polished Stone Value*; UNI: Milano, Italy, 2009.
16. UNI, UNI EN 13036-4. *Road and airfield Surface Characteristics—Test Methods—Part 4: Method for Measurement of Slip/Skid Resistance of a Surface—The Pendulum Test*; UNI: Milano, Italy, 2011.