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Evaluation of the Effect of Aggregates Mineralogy and Geometry on Asphalt Mixture Friction

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Abstract

Road pavement friction is a main physical phenomenon of interaction between tires and the road surface; it provides skid resistance during accelerations and decelerations. The paper focuses on the effects, at laboratory scale, of geometry (in terms of fine aggregates - minimum/maximum size of 0.063/2 mm - content), mineralogy (basalt or metamorphic - minimum/maximum size of 8/16 mm) and shape (in terms on Flakiness and Shape index) on friction performance of asphalt wearing courses for road pavements, in terms of British Pendulum Number and Mean Texture Depth. Laboratory results were statistically treated and used to define predictive formulas which correlate friction characteristics and the explanatory variables considered by the study. The amount of fine particles in the mix and the shape of coarse aggregates demonstrated to affect friction properties and macro texture.

Keywords: Asphalt; Friction; Macro-texture; Mean texture depth; Micro-texture; Skid resistance; Road pavement

Introduction

Road and airport pavements should guarantee high performance in terms of friction and bearing capacity to allow safety movements of vehicles and aircrafts; it is well-known that several accidents are indeed caused by a lack of friction. Road engineers commonly distinguish among four variables of the pavement surface depending on deviations from a planar surface: micro-texture, macro-texture, mega-texture, and irregularity [1]. Micro and macro-texture are particularly investigated due to their great influence on pavement friction. Micro-texture is provided by the roughness of the individual aggregate particle; it is measured with wavelengths smaller than 0.5 mm and it is mainly connected to the aggregate mineralogy.

Macro-texture, usually between 0.5 mm and 50 mm, is mainly attributed to the size, shape, angularity and distribution of the aggregates on the surface; inadequate macro-texture reduces water drainage effectiveness and, consequently, pavement friction, particularly at high speeds, while increases splash & spray and tire-pavement noise. Surface texture is strictly connected to skid resistance, which is divided in two major components: adhesion and hysteresis [2]. Adhesion, which is proportional to aggregates micro-texture, is computed by multiplying the interface shear strength, developed between tire and pavement surface, and the actual contact area.

When the tire and the asphalt pavement come into contact, molecular bonds, which need some energy to get broken, are thus established: the energy involved in the breakage is the adhesion force. On the other hand, hysteresis is connected to macro-texture: the energy produced by the deformation of the rubber of the tire, alternately compressed and expanded when it rolls over the pavement asperities, accentuates the grip and creates the hysteresis component. Gunaratne et al. [3] defined a correlation between wet and dry friction coefficients and the texture properties; they found a stronger dependency of the dry friction coefficient on adhesion (due to micro-texture), while the wet friction coefficient depended mostly on hysteresis force (related to macro-texture).

The friction of a road pavement is mainly affected by the following factors: void content, surface wear, polishing of surface aggregates, rutting due to post-compaction effects or lateral distortions, bleeding and flushing of the asphalt binder to the surface, contamination, and type of aggregate. Petrographic and mineralogical nature of the different type of aggregates and their relative percentage within the mix represent two essential parameters to define micro and macro-texture of the pavement. The present paper focuses on the effects, at laboratory scale, of geometry (in terms of fine aggregates - minimum/maximum size of 0.063/2 mm - content), mineralogy (basalt or metamorphic - minimum/maximum size of 8/16 mm) and shape (in terms on Flakiness and Shaped index) on the friction performance of slab-shaped asphalt samples, in terms of British Pendulum Number and Mean Texture Depth.

Literature Review

Several studies evaluated the tire-pavement interaction in terms of BPN and MTD depending on aggregate characteristics, polishing, surface texture, and temperature. Choo [4] used the BPN to analyze granite and steel slag aggregates and the effect of aggregate gap width on the frictional resistance; it was found that the skid resistance was positively related to the magnitude of the sliding contact surface and the number of gaps within the sliding area. Other authors tried to establish a relationship between aggregate characteristics and friction: Kanitpong [5] considered the aggregate type as a significant factor which influenced the micro-texture and the macro-texture. Results from multiple linear regression analysis showed that the Polished Stone Value (PSV) affected the BPN, while fineness modulus influenced MTD values; furthermore, both the values were correlated with angularity and texture.

Shah et al. [6] evaluated the effect of the aggregate shape: angular aggregates showed greater skid resistance, followed by elongated and flaky aggregates, which exhibited the worst BPN. Davis [7] found a relationship between the Nominal Maximum Size (NMS) of aggregate and Mean Profile Depth (MPD), which can be correlated with the MTD too [8,9] and voids in the mixture and Skid Number: he found an increasing in Skid Number when voids in the mixture increase (more voids in the mixture result in more surface voids, which would allow

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water to flow from the tire-pavement interface), and an increasing in MPD when NMS increases.

In a research led by Sengoz [10] basaltic aggregate exhibited higher angularity values compared to limestone aggregate: this was probably due to the mineral grain. During testing, the slabs prepared by using basaltic aggregate showed greater MTD and MPD values compared to limestone slabs. Also, dynamic friction tester provided greater friction values for basaltic. Several authors tried to predict friction evolution over time due to texture deterioration.

Eyad [11] did not find any significant difference in MTD values before and after the polishing of the slabs of asphalt mixture (some values increased, while other decreased), but mixes with different aggregates provided different MTD values according to the following principle: the smaller nominal aggregate size provided a reduced macro-texture and BPN values showed a decreasing trend with an increasing in the polishing.

Vaiana [8] monitored an experimental road section for 2 years and analyzed four different dense graded wearing courses (100% limestone aggregate, 85% limestone aggregate and 15% basaltic aggregate, 70% limestone aggregate and 30% basaltic aggregate, 82% limestone aggregate and 8% expanded clay); results indicated that aggregates with smaller PSV values – e.g.; limestone – had a lower resistance to stripping and became more exposed to traffic deterioration. Macro-texture analysis pointed out an initial reduction due to the migration phenomenon of the asphalt binder inside the voids of the mix, while, after 6 months, the migrated binder was removed by the traffic and MTD began to increase.

Chen et al. [12] evaluated the evolution of the aggregate-surface texture during polishing processes: the Wehner/Schulze polishing machine was adopted to analyze three types of aggregate (basaltic aggregate, greywacke aggregate, and gabbro aggregate). It was found that a) the basaltic aggregate provided the worst resistance to polishing if compared with gabbro and greywacke – which exhibited the best skid resistance, power spectral density curves confirmed the global height reduction, and b) the evolution of aggregate friction was governed by micro-texture changes due to differential removal of mineral components.

Significant contributions about the texture-friction relationship were made by Tsohos [13] who identified a correlation between skid resistance of a pavement surface and its fractal dimension; a pavement with a rough fractal interpolation function exhibited a greater skid value than a pavement with a smooth fractal interpolation function.

Empirical Mode Decomposition analysis, which is part of Hilbert-Huang Transformation, was used by Kane [14] to set basic profiles, called Intrinsic Mode Funtions (IMFs). Base Intrinsic Mode Functions (BIMFs), which are the sum of four IMFs, were then introduced, and they were characterized by the density and sharpness of the peaks. The correlation between texture and friction was analyzed through the Dynamic Friction Texter (DFT) and the Circular Texture Meter (CTM) to find a strong correlation between BIMFs, expressed by density per sharpness, and the measured friction: the increasing of BIMF pointed out an increasing of DFT (which was measured at three different speeds – 20 km/h, 40 km/h and 60 km/h).

Bogardi [15] applied the International Friction Index (IFI) to connect skid resistance and surface macro-texture in a probabilistic pavement performance modeling framework; IFI is useful to convert the device-specific friction and macro-texture measurements into an international scale and it was used to define threshold values to assess the adequacy of pavement friction.

Gunaratne [3] predicted tire wear rate and tire-pavement friction on smooth concrete pavements by using Fourier Transform technique and constructing power spectral density plots of texture: he found a good correlation among the dry friction coefficient, mostly based on adhesion, and pavement micro-texture; furthermore, it was seen that whenever the macro-texture increased, the contact between the tire and individual aggregate particles was reduced and, on the other hand, when micro-texture increased, the surface became rougher owing to the increased contact between the tire and individual elements.

Bazlamit [16] and Voussough [17] investigated the effect of temperature on friction properties. They found a strong dependence among the two elements: skid resistance decreased when the temperature increased following a linear relationship; for this reason, compensations should be made to account for temperature effects, as reported in the European standard EN 13036.

Objective and Experimental Plan

The main objective of the study was to define, at laboratory scale, how friction performance of asphalt pavements, in terms of micro and macro texture, is influenced by:

– mineralogy, geometry and shape of lithic aggregates;

– Volumetric characteristics of the mixtures.

To this end, six types of aggregates currently used in Italy were selected to produce laboratory slab-shaped asphalt samples and measure their volumetric characteristics (void contents) and friction performance in terms of micro texture, by means the British Pendulum Number (BPN); macro texture was instead determined by the Mean Texture Depth (MTD).

Results were firstly treated by using the Cook's distance to identify and remove the outliers.

Then, Analysis of Variance (ANOVA) was used to validate laboratory results, and the possible correlations among the explanatory variables (mineralogy, geometry and shape of the aggregates and volumetric characteristics of the asphalt slabs) and friction performance of the corresponding slabs were computed with the Bravais-Pearson linear correlation method. Finally, prediction formulas according to the least square method and multiple linear regressions were identified.

A detailed flow-chart of the experimental plan is shown in Figure 1.

Experimentation: Materials and Test Results

The aggregates considered in this study were, in terms of mineralogy (and geometry): crushed metamorphic (8/16 mm; Los Angeles Index - LA of 15%; Polished Stone Value - PSV of 42.8%), crushed basalt (8/16 mm; LA of 16%, PSV of 43.4%), crushed limestone (8/16 mm; LA of 14%; PSV of 51.4% - 4/8 mm; LA of 15%; PSV of 51.4%), sand (2/4 mm), fine aggregate (0.063/2 mm). Although some PSV values could be considered too low for some countries, they are perfectly suitable for the current Italian standards.

As far as the shape of the aggregates, flaky and elongated shapes were considered in terms of Shape Index (SI, EN 933-4) and Flakiness Index (FI, EN 933-3), as reported in Table 1.

Aggregates were then used to produce eighteen asphalt mixtures, including the reference mix, which was also adopted as wearing course for a newly constructed highway in the North of Italy.

50/70 pen bitumen (6% by weight of the total aggregates) and filler (11%) contents were maintained constant for all the mixtures.

The investigated mixtures were divided into two groups:

– Mix 1 to 9, Mix Z, Mix ZZ and reference mixture were obtained by modifying the amount of fine and basaltic aggregates (Table 2);

– Mix 10 to Mix 15 were manufactured with a specific sieve size distribution but varying particles geometry (SI and FI index), as shown in Table 3.

For each mixture, the groups of aggregate were mixed together to reestablish the same gradation of the reference mix and, in any case, within the dotted-line limit of the sieve size distribution shown in Figure 2.

Laboratory sample production included asphalt mixture preparation, using a common laboratory mixer (T_{mix} = 160°C ± 5°C), and compaction (T_{comp} = 150°C ± 5°C) using a roller compactor (EN 12697-33, Procedure C), obtaining two slabs for each mixture. The void content of the slabs (Figure 3) was computed according to EN 12697-8: bulk density of the slabs was measured (EN 12697-6 Procedure B) and the Maximum Theoretical Density (EN 12697-5) was determined on the corresponding loose mixes. For each mix it was computed the average value between six measures.

As mentioned above, friction-related characteristics of the slabs were evaluated by both the BPN according to EN 13036-4, which is an indicator of the micro-texture of a wearing course, and the MTD obtained by the Sand Patch Method Test (EN 13036-1), currently used to determine the macro-texture of a surface mixture. BPN was measured on each slab according to 5 alignments (Figures 4a and 4b) in order to obtain a satisfactory number of test results and avoid possible influence of edge effects and compaction methodology: three alignments in the longitudinal direction (equal to the compaction direction) and two in the transversal direction. Six measures were conducted on each alignment therefore resulting in 30 measurement points on each slab. The average friction value for each asphalt mixture was evaluated according to the measurements on two slabs (30 + 30 measurements on each mix). As reported in Figure 4c, only one measure of MTD was taken on each slab (1 + 1 measurements on each mixture).

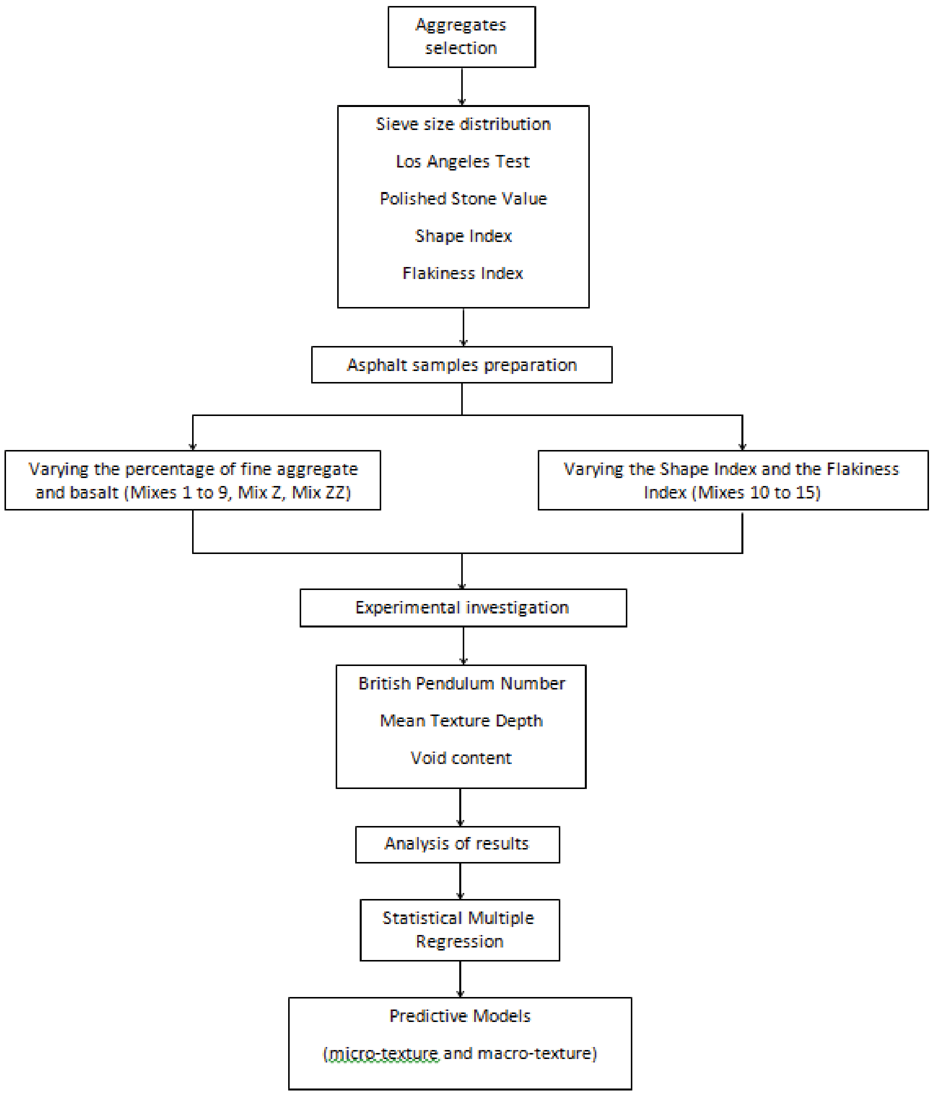

Figure 1: Experimental program.

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Type of aggregate	SI [%]	FI [%]
Metamorphic 8/16 mm	7.9	8.9
Basaltic 8/16 mm	11.4	13.0
Limestone 8/16 mm	6.5	16.6
Limestone 4/8 mm	8.0	9.9

Table 1: Shape index and flakiness index of the aggregates.

	Fine aggregate 7.1 %			Fine aggregate 11.9 %			Fine aggregate 14.2 %			Fine aggregate 16.6 %		
Basaltic aggregate 0%	-			-			Reference mix			-		
							sand	2/4 mm	3.80%			
							Limestone aggregate	4/8 mm	29%			
								8/16 mm	30%			
							Metamorphic Aggregate	8/16 mm	12%			
Basaltic aggregate 9%	-			-			Mix Z			-		
							sand	2/4 mm	3.80%			
							Limestone aggregate	4/8 mm	25%			
								8/16 mm	37%			
Basaltic aggregate 19%	-			Mix 1			Mix 2			Mix 3		
				sand	2/4 mm	3.10%	sand	2/4 mm	3.80%	sand	2/4 mm	4.40%
				Limestone aggregate	4/8 mm	34%	Limestone aggregate	4/8 mm	28%	Limestone aggregate	4/8 mm	26%
					8/16 mm	21%		8/16 mm	24%		8/16 mm	23%
Basaltic aggregate 26%	Mix ZZ			Mix 4			Mix 5			Mix 6		
	sand	2/4 mm	1.90%	sand	2/4 mm	3.10%	sand	2/4 mm	3.80%	sand	2/4 mm	4.40%
	Limestone aggregate	4/8 mm	28%	Limestone aggregate	4/8 mm	28%	Limestone aggregate	4/8 mm	32%	Limestone aggregate	4/8 mm	29%
		8/16 mm	26%		8/16 mm	20%		8/16 mm	13%		8/16 mm	13%
Basaltic aggregate 34%	-			Mix 7			Mix 8			Mix 9		
				sand	2/4 mm	3.10%	sand	2/4 mm	3.80%	sand	2/4 mm	4.40%
				Limestone aggregate	4/8 mm	32%	Limestone aggregate	4/8 mm	31%	Limestone aggregate	4/8 mm	28%
					8/16 mm	8%		8/16 mm	6%		8/16 mm	6%

Table 2: Mix 1 to 9, mix Z, and mix ZZ.

	SI = 8%	SI = 12%	SI = 17%
FI = 8%	mix 10	-	-
FI = 12%	mix 11	mix 12	-
FI = 17%	mix 13	mix 14	mix 15

Table 3: Shape index and flakiness index matrix, mix 10 to 15.

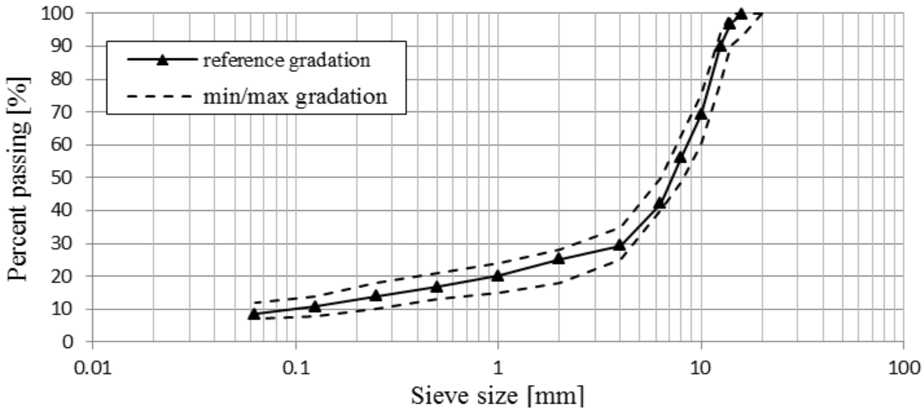

Figure 2: Sieve size gradation of the reference mix.

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Texture characteristics of the mixtures are given in Figure 5, in which maximum and minimum results are shown as error bars.

Analysis and Discussion of the Results

Linear regression

The first step of the analysis was performed taking into account the effects of mineralogy (content of coarse basaltic aggregate), dimension (fine aggregate content) and shape (Flakiness and Shape index) of lithic particles on the friction performance (BPN and MTD) of asphalt mixes. To this end, a regression analysis was used. Prior to that, the Cook's Distance statistical method was used to identify and remove outliers from the friction results.

Graphs in Figures 6 and 7 show the correlation between friction performance (BPN and MTD) and both mineralogy (Figure 6) and dimension (Figure 7) of the aggregates (mixtures 1-9, Z, ZZ, and Reference mix). Volumetric characteristics (in terms of void content) were also considered, as shown in Figure 8.

Analyzing the results in Graphs A-C of Figures 6 and, a general increase of BPN (Figures 6 and 7) can be observed according to both fine and basaltic aggregates content. A slight decrease was instead detected for MTD values (Graphs D, E and F of Figures 6 and 7).

Considering the coefficient of determination (R^2), which define the quality of a correlation from a statistical point of view, results revealed that BPN (microtexture) had a good correlation with the investigated

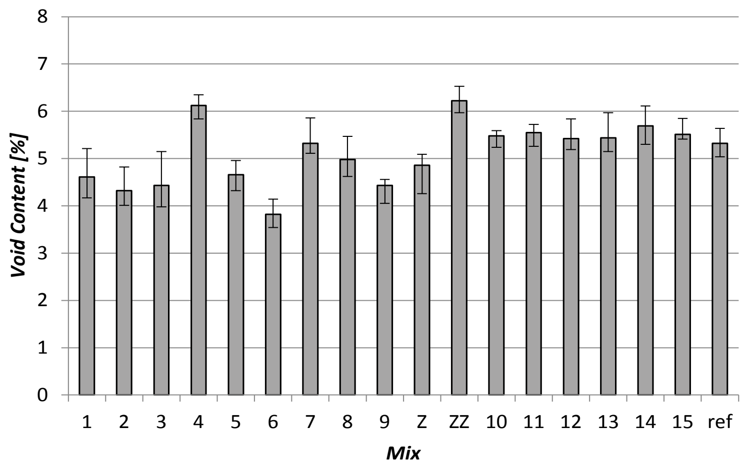

Figure 3: Average void content into the asphalt slabs.

Figure 4: (a) and (b): BPN alignments; (c) Sand patch method tests.

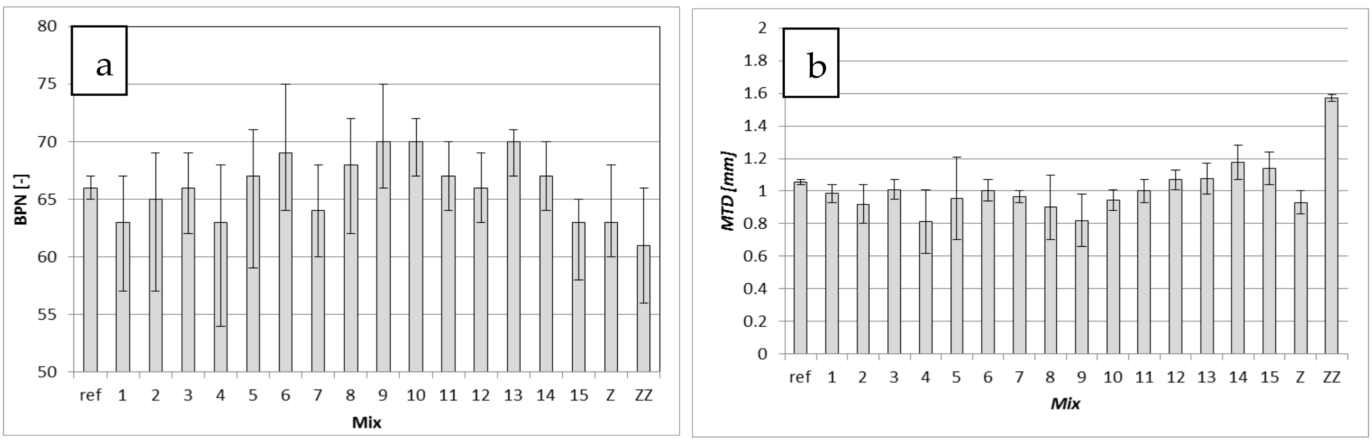

Figure 5: (a) Mix versus BPN (B) Mix versus MTD.

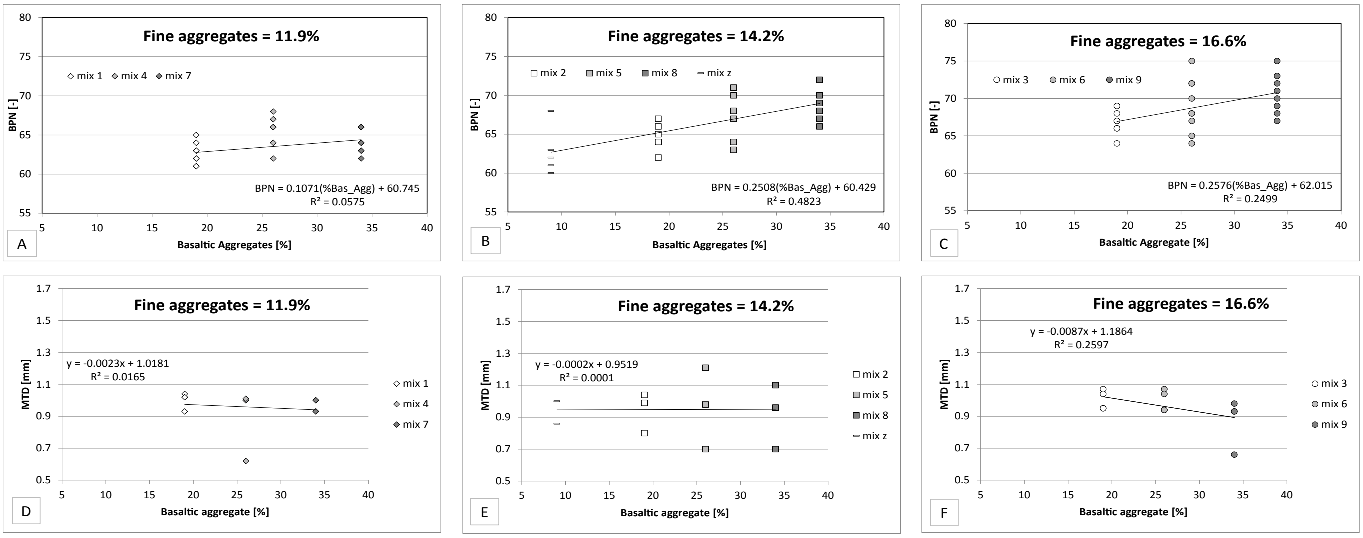

Figure 6: Basaltic coarse aggregate contents versus friction (BPN and MTD) results (Mixtures 1-9 Z, ZZ and Ref).

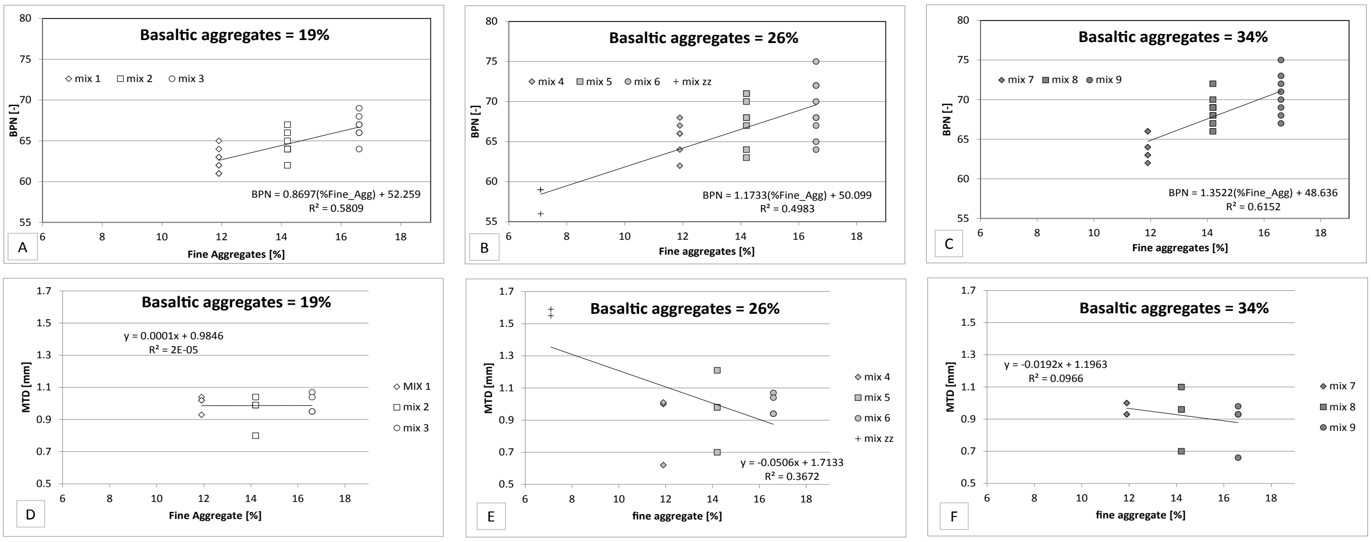

Figure 7: Fine aggregate contents versus friction (BPN and MTD) results (Mixtures 1-9 Z, ZZ and Ref).

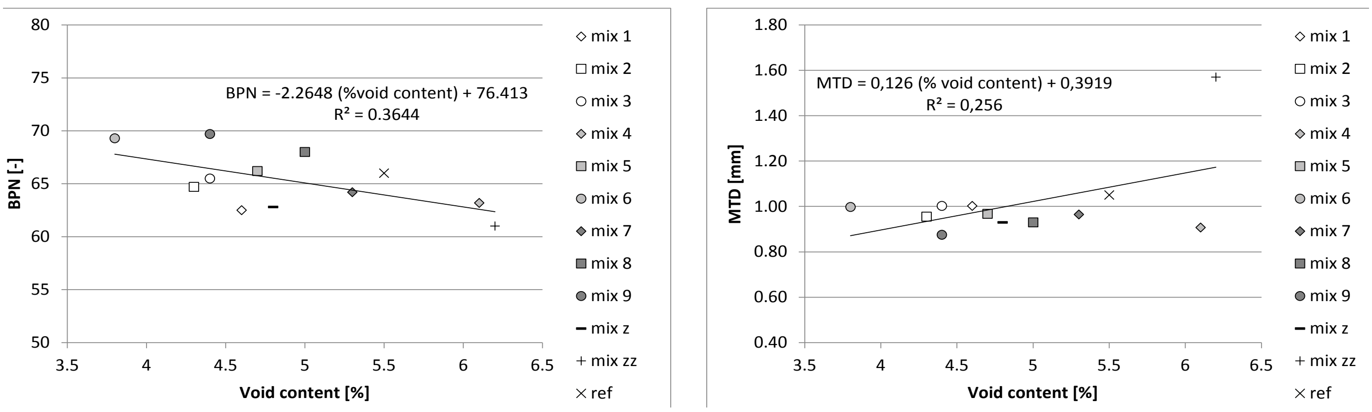

Figure 8: Void content versus friction (BPN and MTD) results (Mixtures 1-9, Z, ZZ and Ref).

variables, in particular when fine aggregate-mixes were investigated. On the contrary, unsatisfactory results were obtained in terms of macrotexture (MTD). As far as the compaction effects, results in Figure 8 indicate that BPN increases and MTD decreases for reduced void content. Thus, BPN decreases because the number of asperities per unit of surface decreases, diminishing the ability of the pavement to brake the pendulum during the tests. On the contrary, the same decrease of asperities increases the number of surface voids that manages the ability of the sand to penetrate into the surface during the Sand Patch test. Finally, the coefficient of determination (R^2) was found to be lower.

Graphs in Figure 9, shows the correlation between friction results (BPN and MTD) and shape of the aggregates (SI and FI), mixture 10 to 15. The comparison between friction parameters and volumetric characteristics was not performed since the asphalt slabs were compacted at the same content of voids (5.5%). Graphs A, B and C of Figure 9 indicate that BPN is more sensible to SI than to FI. In particular, a decrease of this friction parameter can be observed due to the increase of SI index. On the contrary, an increasing of MTD according to FI and SI was observed. However, in both cases the determination coefficient (R^2) is not very high, except for BPN versus SI (Graph A), and for both friction measures on slabs with SI=FI.

Statistical validation of the results

For validation purposes, correlations discussed in the previous paragraph were computed with the Bravais-Pearson linear correlation method, which is an index defined as the covariance of two statistical variables divided by the product of the standard deviations [18]. The correlation index evaluates the relationship between two statistical variables and ranges between +1 and -1: if the coefficient is approximately +/- 1 it means that there is a strong direct/inverse correlation, while if it is close to 0 there is no correlation between the considered variables.

The Bravais-Pearson correlation indexes for mixes 1-9, Z, ZZ and Reference mix are given in Table 4. Table 5 reports the same indexes for mixes 10-15. Given the complexity of the goals, it is more useful to discuss the Bravais-Pearson indexes considering three ranges. Particularly, the range between 0 and ±0.3 can be defined as a poor level of correlation, the ranges +0.3/+0.7 and -0.3/- 0.7 can be defined as good, and finally over ±0.7 the level of correlation is high. As far as data given in Table 4, it is possible to claim that dimension of the aggregates are more important to their mineralogy; actually both coarse and fine aggregates have a good Bravias-Pearson Index with the surface texture parameters (BPN and MTD); on the contrary, basalt appears not to affect the above-mentioned parameters. Finally, as expected, voids content affects the surface characteristic of a wearing course; in particular, if void content increases, micro-texture is reduced, thus the BPN value decreases and the macro-texture is increased and, consequently, the MTD values rise.

Referring to the shape of the aggregates, results in Table 5 identify the Shape Index (SI) as the parameter that mainly influences the surface characteristics of an asphalt wearing course, especially in terms of micro-texture (BPN), even if also the FI index shows a good

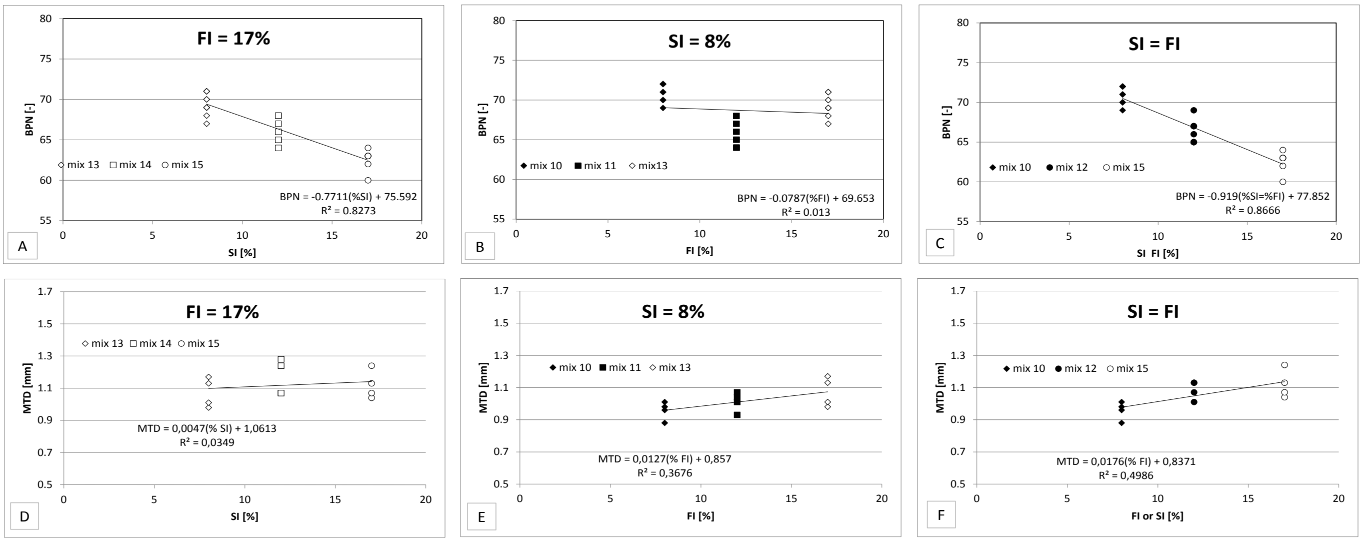

Figure 9: Shape of coarse aggregates versus friction (BPN and MTD) results (Mixtures 10-15).

	BPN [-]	MTD [mm]
Fine aggregate (0.0063/2 mm) [%]	0.46	-0.40
Coarse Aggregate (8/16 mm) [%]	-0.37	0.43
Basaltic aggregate (8/16 mm) [%]	0.19	-0.21
Voids content [%]	-0.35	0.45

Table 4: Bravais-Pearson correlation indexes for mixes 1-9, Z and ZZ.

	BPN [-]	MTD [mm]
SI [%]	-0.71	0.30
FI [%]	-0.34	0.22

Table 5: correlation coefficients between friction properties, volumetric features, and mix design (mixes 10 to 15).

correlation. On the contrary, MTD appeared not to be significantly affected by both aggregate shape indexes.

Finally, the Bravais-Pearson correlation index confirms the trend obtained using the linear regression method discussed in the paragraph 5.1.

Pavement friction predictive formulas

The analysis of variance (ANOVA) was conducted to identify predictive formulas able to define the multiple linear relations (regression) among the friction characteristics (BPN and MTD) of the investigated asphalt wearing courses and the explanatory variables considered in the study. For this reason, six predictive formulas were identified as reported in Table 6, in which PF-1-BPN and PF-1-MTD are related to dimensions and mineralogy of the aggregates, PF-2-BPN and PF-2-MTD are associated to the shape of the aggregates (SI and FI), PF-3-BPN and PF-3-MTD describe the relation with the volumetric characteristics of the asphalt mixtures (void content).

The multiple linear regression allowed to estimate the two descriptive variables, BPN and MTD, using the least-square method and determining R^2 adjusted, which confirmed if the relationship between the dependent variables and the set of explanatory variables was significant (higher than 0.50) or not (less than 0.50). Moreover, a t-Student test was performed in order to define the t-Student values for each explanatory variable in the predictive formulas, which is to be compared with the t-Student critical value (equal to 1.66) as a test to validate the significance of the variable in the formulas.

Both coefficients of the predictive formulas and their t-Student achieved values are given in Table 7.

As a first general consideration, Table 7 suggests that BPN values are more sensible to the considered explanatory variables than MTD, at laboratory scale.

In fact, considering MTD predictive formulas, t-Student values were smaller than the critical ltl value (equal to 1.66) except for t-Student tests of Flakiness Index in PF-2-MTD and Voids content in PF-3-MTD, even if in both cases the predictive coefficients were close to zero. This showed that MTD is not affected by the investigated explanatory variables. Obviously, this is not believed to be true in general but the findings suggested that it is unlikely to study the effects of aggregates (mineralogy, dimension, and shape) on the macro-texture of a road wearing course using laboratory-produced asphalt slabs. This is mainly due to laboratory compaction procedures which are not able to correctly simulate the macro-texture obtained in the field by using asphalt pavers and rollers.

More interesting are instead the results deriving from the predictive formulas of BPN.

As far as the effects of aggregates dimension and mineralogy on BPN

Dependent Variables	BPN	MTD
Predictive Formulas	PF-1-BPN	PF-1-MTD
Explanatory variables	Fine aggregates	
	Coarse aggregates	
	Basaltic aggregates	
Predictive Formulas	PF-2-BPN	PF-2-MTD
Explanatory variables	Shape Index	
	Flakiness Index	
Predictive Formulas	PF-3-BPN	PF-3-MTD
Explanatory variables	Void content	

Table 6: Variables considered into the predictive formulas.

Explanatory variables	PF-1-BPN		PF-1-MTD	
	Coefficient	t-Student value	Coefficient	t-Student value
Intercept	58.69	9.12	0.68	1.02
Fine aggregates	0.76	5.64	-0.02	-1.56
Coarse aggregates	-0.20	-1.75	0.02	1.35
Basaltic aggregates	0.18	5.04	0.00	-0.11
R^2_{adj}	0.57		0.23	
Explanatory variables	**PF-2-BPN**		**PF-2-MTD**	
	Coefficient	t-Student value	Coefficient	t-Student value
Intercept	73.98	74.72	0.80	11.14
Shape Index	-0.72	-10.11	0.01	1.20
Flakiness Index	0.06	0.92	0.01	2.48
R^2_{adj}	0.71		0.34	
Explanatory variables	**PF-3-BPN**		**PF-3-MTD**	
	Coefficient	t-Student value	Coefficient	t-Student value
Intercept	78.99	27.06	0.65	7.16
Voids content	-2.66	4.57	0.07	4.09
R^2_{adj}	0.20		0.20	

Table 7: Multiple linear regression - coefficients of predictive formulas and t-student.

(PF-1-BPN predictive formula), the ltl values of the coefficients were greater than the critical value, meaning that the accidental probability of correlation between dependent and explanatory variables was lower than 5%, which represented the actual critical value. In particular, the contribution of the coarse aggregate percentage was not as considerable as the other two coefficients (fine and basaltic aggregate) because of its smaller t-Student value. R^2adj for PF-1-BPN was equal to 0.57; this predictive formula therefore demonstrated to be adequately reliable and it well described the correlation between fine aggregate, coarse aggregate, basaltic aggregate and BPN.

PF-2-BPN aimed to define BPN values as a function of SI and FI. Unfortunately, t-Student value for FI coefficient (equal to 0.92) was smaller than the critical ltl value (equal to 1.66). Moreover, the prediction formula showed ltl value for SI coefficient equal to 10.11, largely greater than the critical ltl value. This result confirmed the trend already obtained in Figure 9a and the negative coefficient revealed that the Shape Index significantly affected the BPN values, which means that a decrease of BPN can be expected as a consequence of the increase of the quantity of elongated aggregates in the asphalt wearing course. Actually, elongated aggregates, usually lacking of well-defined surface asperities, cannot generate great micro-texture. Finally, it can be highlighted that the computed R^2adj obtained in PF-2-BPN was significant, thus SI variation is strictly correlated with BPN.

Coefficient of PF-3-BPN formula indicates that friction resistance (BPN) is negatively related to void content. Moreover, the value of t-Student for the void content coefficient is 4.57, considerably greater than the critical value (1.66). However, R^2adj was only equal to 0.20, which means the prediction formula did not show enough reliability and further analysis is necessary.

Conclusions

The present study aimed at evaluating the friction properties of asphalt slab laboratory-prepared samples by changing mineralogy, dimension and shape of the aggregates, and considering the volumetric characteristics of the corresponding asphalt slabs. The experimental results were statistically analyzed to identify possible correlations between the variables. Results highlighted the followings.

- Mineralogy and geometry. Geometry, in terms of fine aggregate (nominally, 0.063-2 mm) content, appears to be the most significant parameter that influences microtexture; actually, an increase up to 10% of BPN was observed according to fine aggregate content. An increase of BPN was also observed according to the increase of basalt, even if less evident if compared to the effect of fine aggregate. On the contrary, MTD decreases according to fine and basalt content.
- Shape. The increase of non-polyhedral particles into the mixtures appears to be detrimental in terms of microtexture (BPN results) and plays a positive role in raising the macro texture (MTD). Even if in this last case, the correlation was small from a statistical point of view.
- Volumetric characteristics. Compaction characteristics (void contents) produce a general BPN increase and MTD decrease. This was possibly due to the increase of voids that reduces the number of asperities on the surface slowing down the pendulum during the BPN tests, and consequently increases the number of surface voids that govern the ability of the sand to penetrate into the surface.

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