Asphalt Mixtures Modified With Basalt Fibers For Surface Courses

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ASPHALT MIXTURES MODIFIED WITH BASALT FIBRES FOR SURFACE COURSES

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Abstract. *This paper shows the results of an experimental study concerning the effect of introduction of basalt fibres in asphalt mixtures for surface course, mainly with regard to those to be used in urban areas, for dedicated bus lanes. Surface layers, where tire-pavement interactions occur, have to provide different properties such as high friction (very important for users' safety), stability, resistance to meteorological agents, and contribution to the overall pavement performances. Considering that basalt fibres provide considerable physical and mechanical properties and above all high abrasion resistance, scope of the study is to evaluate the effects of these fibres on mixtures properties, especially in terms of friction and rutting behaviour.*
For this purpose, after setting up a model to estimate the impact of fibres on asphalt film thickness and richness modulus, the mixtures produced were subjected to laboratory tests for performance evaluation in terms of rutting resistance and the surface texture.
The test results allow drawing some important conclusions about basalt fibre-modified asphalt mixtures: in particular, these mixtures show better performance with reference to permanent deformation resistance when compared with the traditional mixture; moreover, the introduction of basalt fibres involves a "flattening" of the profile texture and a lower macrotexture. Interestingly, fibres addition is likely to slightly increase the micro-texture. This point calls for further study.

1 Introduction

The modern road pavements must meet many performance requirements in order to satisfy the current needs of the transport: not only due to the increasing traffic load that requires high mechanical performance; they must also ensure the movement of vehicles securely, smooth, safe and comfortable surfaces according to qualitative levels that depend on the category of road and the expected traffic.

Road safety is related to the quality of the surface layer of the pavement. In particular, adequate friction, in tire – road interaction, must be guaranteed in all situations, to allow the vehicle to maintain the chosen trajectory and efficient braking, especially in curve.

Another functional characteristic of the surface layers - the user's comfort - involves a series of factors related to surface characteristics of the road and in particular to the absence of irregularities, such as waves and degradations of any kind [1].

Nowadays, for sustainable development, research focuses on developing new technologies for asphalt mixtures production in order to improve mechanical and functional performances and assure the same performances specified by the current Technical Specification, also thanks to the use of specific additives for achieving improved performances. Furthermore the use of specific additives such as fibres or scrap materials is considered as an interesting and effective solution to face environmental issues linked to reusing waste materials and to satisfy particular needs in road technique [2].

At present, there are two research orientations to improve pavement performance of asphalt mixture: one is to better asphalt non-deformability at high temperature, via improving aggregate gradation, which is based on asphalt structure type and design procedures; the other is to better asphalt mechanical performance and decrease temperature susceptibility, via improving asphalt property and quality [3]. For the past few years, more and more new materials have been introduced into the technology field of bituminous pavements. Thus, the third orientation to improve its performance is formed, that is to add specific additives - fibres amongst these - to asphalt to improve its physical and mechanical property.

At the moment, there mainly are three types of fibres applied in pavement project: cellulose fibres, polyester fibres and mineral fibres [4]. Taking asphalt regeneration into consideration, mineral fibres have been familiar to people, with better mechanical performance and higher work temperature [5].

Basalt fibres (especially those obtained from scoria or vesicular basalt that cannot be directly used as a construction material) can be considered environmentally friendly and non-hazardous materials. It is not a new material, but its applications are surely innovative in many industrial and economic fields, from building and construction to energy efficiency, from automotive to aeronautic, thanks to its good mechanical, chemical and thermal performances. Hence, basalt fibre has gained increasing attention as a reinforcing material especially if compared to traditional glass fibres.

The production process, even if it is very similar to the glass fibres one, does not require additives and a lower amount of energy is needed with benefits in terms of environmental impact, economics and plants' maintenance. The base cost of basalt fibres depends on the quality and the chemical composition of the raw material and this leads to have several kind of fibres with different thermal, chemical and mechanical properties [6]. Indeed, the final cost of the fibres depends, at a large scale, not only on the specific production process for the needed type of fibre, but also on the total quantities to be produced. Many scientific studies confirm the growing interest on this type of fibres [6-9].

There are so far few studies about the use of basalt fibres in the road pavement, all confirming their good properties in terms of Marshall stability, rutting stability, water stability [5, 10, 11], the possibility to have better low temperature performance, and the anti-fatigue property. Besides, at high temperatures, the stiffness of asphalt mixture can be increased and permanent deformation can be reduced [11, 12]. Thus, it is of interest to evaluate the benefit of introducing basalt fibres in surface course for urban applications, in order to offer effective maintenance and rehabilitation options for urban pavement management, as a valuable alternative to the use of polymer modified bituminous mixtures.

2 Objectives and main phases of the study

The object of this research work is to evaluate the effect of the introduction of basalt fibres in asphalt mixtures for surface courses, in terms of surface texture and permanent deformation resistance, especially for use in urban areas, for dedicated bus lanes, where vertical stresses and strain level are more severe [13], due to frequent stopping and restarting manoeuvres, both at bus stops and at traffic lights [14].

The study is organized into the following main sections: modelling, design of experiments, material characterisation and mix design, results and discussions.
A model to consider the impact of fibres on asphalt film thickness and richness modulus is set up. The consequent effect in determining the optimum binder content, as related to the binder film thickness, is then derived. The factorial plan of experiments is shortly summarized in the Design of experiments paragraph, while the Material characterization and mix design section fully provides the characterization of the materials used in this study. In the Results analysis and conclusions section key conclusions are drawn and main contributions are pointed out.

3. Modelling

In the pursuit of the above objectives, if analytical methods are used to estimate the specific surface area of aggregates [15], it is relevant to model the impact of fibres on two conceptually similar approaches to determine the optimum binder content: the asphalt film thickness (according to the Standard STP 204-19 [16]) and the richness modulus [17], fundamental to ensure mixture durability.
If the aggregates are modelled in terms of spheres (where D_A is the diameter, m) and the fibres are modelled in terms of cylinders (diameter: D_F, m, height L, m, $L/D_F \cong 800$), the specific surfaces, (SS_A, SS_F, respectively, m2/kg), are approximated as follows:

$$SS_A = \frac{6}{D_A \cdot G_{seA}} \quad (1)$$

$$SS_F = \frac{4}{D_F \cdot G_{seF}}. \quad (2)$$

where G_{se} refers to the effective specific gravity of aggregates/fibres.

Let the thickness (z, m) of the asphalt binder on the single particle be the function given by:

$$z = \frac{\alpha^* \cdot D^{0.8}}{G_{se}^{0.2}} \quad (3)$$

It follows:

$$z_A = \frac{\alpha_A^* \cdot D_A^{0.8}}{G_{seA}^{0.2}} = \frac{\alpha_A^*}{G_{seA}} \cdot \left(\frac{6}{SS_A} \right)^{0.8} \quad (4)$$

And

$$z_F = \frac{\alpha_F^* \cdot D_F^{0.8}}{G_{seF}^{0.2}} = \frac{\alpha_F^*}{G_{seF}} \cdot \left(\frac{4}{SS_F} \right)^{0.8} \quad (5)$$

If K_D is the richness modulus of the bituminous mixture, as *per* Duriez formula [17], the percentages of bitumen (by weight of aggregates) are given by:

$$b_A = \frac{\alpha_A^*}{G_{seA}} \cdot \left(\frac{6}{SS_A}\right)^{0.8} \cdot SS_A = \frac{\alpha_A^* \cdot 6^{0.8}}{G_{seD}} \cdot \frac{G_{seD}}{G_{seA}} \cdot SS_A^{0.2} = K_{DA} \cdot \alpha_A \cdot SS_F^{0.2} \quad (6)$$

$$b_F = \frac{\alpha_F^*}{G_{seF}} \cdot \left(\frac{4}{SS_F}\right)^{0.8} \cdot SS_F = \frac{\alpha_F^* \cdot 6^{0.8}}{G_{seD}} \cdot \frac{G_{seD}}{G_{seF}} \cdot \left(\frac{4}{6}\right)^{0.8} \cdot SS_F^{0.2} = K_{DF} \cdot \alpha_F \cdot \beta_F \cdot SS_F^{0.2} \quad (7)$$

Where α is the well-known coefficient that takes into account the specific Gse, while β (which pertains to the shape effects on the theoretical framework of Duriez and Arambide [17]) is herein defined based on the equations above.

It turns out that if A% and F% are the percentages of aggregates and fibres (by total weight of non-binder components) respectively (e.g., F=0.2%, A=99.8% [5, 10, 18]), the corresponding asphalt binder percentage of the mixture (B, by total weight of aggregates/fibres) is the following:

$$B = \frac{b_A \cdot A\% + b_F \cdot F\%}{A\% + F\%}. \quad (8)$$

In general terms, if $K_{DA}=K_{DF}=K_D$ (i.e., overall richness modulus according to Duriez), when the traditional Duriez formula cannot be used due to very different shape characteristics of non-binder components, the following algorithm is herein proposed:

$$B = K_D \cdot \frac{\sum_i \alpha_i \cdot \beta_i \cdot SS_i^{0.2} b_i \cdot A_i\%}{\sum_i A_i\%} \quad (9)$$

Where each SSi can be either expressed according to the given shape characteristics or in terms of known correlations:

$$SS_F = \frac{4}{G_{seF} \cdot D_F} \quad (10)$$

$$100 \cdot SS_A = 0.25 \cdot G + 2.3 \cdot S + 12 \cdot s + 135 \cdot f \quad (11)$$

where, G is the percentage of aggregate particles greater than 6.3mm, S between 0.25 and 6.3mm, s between 0.075 and 0.25mm, f less than 0.075mm [19]:

Based on STP 204-19, the following algorithm applies in order to estimate the effective film thickness (*Fbe*, μm):

$$F_{be} = \frac{981 \cdot P_{be}}{SST \cdot (100 - P_b)} \quad (12)$$

Where P_{be} (%) is the effective asphalt binder content by total mix weight (while B, %, is the asphalt binder content by weight of aggregates), SST (m^2/kg) is the total surface area of the aggregate in the mix, and Pb (%) is the (absorbed + effective) percent asphalt content by total mix basis. Note that: i) the area factors specified in the concerned standard (STP 204-19) are different from the ones specified in other standards and contexts (e.g., application of the Duriez formula [17] or Minnesota Department of transportation adjusted asphalt film thickness [20]); ii) equations 1-10 are new, while equations 11 and 12 derive from the literature. Based on the above, the relations among richness

modulus (k), binder percentage of the mixture (B%), fibres percentage (F%), and effective film thickness (Fbe) are plotted in Figure 1.

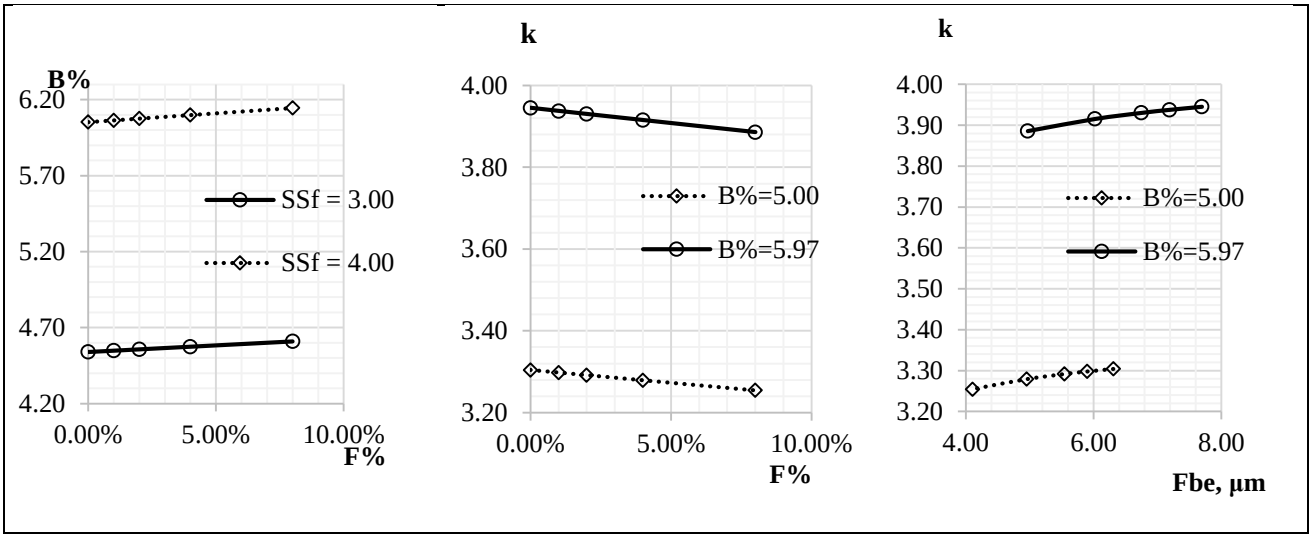

Figure 1. Relationships among bitumen content, richness modulus and effective film thickness

It may be observed that: i) The higher the percentage of fibres is, the higher the bitumen percentage that is needed, for a given richness modulus (3 or 4); ii) The higher the percentage of fibres is, the lower the richness modulus becomes, for a given bitumen percentage (5.97% or 5.00%); iii) The higher the effective film thickness is, the higher the richness modulus is, for a given bitumen percentage (5.97% or 5.00%). Indeed, both k and F_{be} refer to the concept of bitumen coverage of grains (aggregate, fibres, etc.). Note from Figure 1 that when F(%) = 0, for the selected range of SS_F, the corresponding values of k, B% and F_{be} above comply with the requirements given in literature for a durable mixture, i.e. a binder film thickness in the range of 6-8 µm [21, 22].

For B, the following supplementary requirements apply:

- B must comply with mechanistic/resistance requirements (e.g., resilient modulus, Marshall Stability and quotient, etc.);
- B must comply with volumetric requirements (e.g., air voids content, voids filled with asphalt, voids of mineral aggregates);
- B must comply with fatigue and rutting requirements;
- B must comply with workability requirements. Indeed, the use of fibres may be useful to improve the stiffness at higher temperatures and to reduce the stiffness at lower temperatures. Unfortunately, along with several advantages, several construction-related issues may emerge, which may include appropriate mixing and compaction temperatures [23] and appropriate asphalt binder content. To this end, it is noted that in terms of workability, mixtures with fibres usually require a slight increase on the optimum binder content [24].
- In case of friction courses, B must comply with functional requirements (e.g., surface macrotexture, surface microtexture, and surface permeability/drainability, see [25]).

4. Design of experiments

Table 1 summarises the factorial plan of experiments. Three sets of tests were designed and carried out, namely case 1, case 2, and case 3.

Table 1. Factorial plan of experiments

	Case 1	Case 2	Case 3
Samples dimensions	305 x 305 x 50 mm		
Fibers percentage (F%)	0.0	0.0	0.3%
Aggregates percentage (A%)	100%	100%	99.7%
Bitumen	B 50/70	B 50/70	B 50/70
Richness modulus (K_D)	3.7	3.9	3.9
Tests and analyses	Material characterization (fibres, aggregates, asphalt binder) Marshall design/tests (SM , RM, vM) Rutting tests (RD) Surface texture (Z, LT, BPN, MPD, HS, AAD, AAH)		

Notes and symbols.
SM: Marshall stability; RM: Marshall quotient; vM: Marshall air voids content; RD: ruth depth; z, LT, MPD, AAD, AAH: laser-based texture indicators (profile, texture level, mean profile depth, average asperity density, average asperity height); BPN: British pendulum number; HS: sand patch height.

5. Material characterization and mix design

5.1 Material characterization (stone aggregates)

The aggregates used in the mixtures are crushed limestone come from quarry whose composition and physical and mechanical properties are summarized in Table 2.

Table 2. Physical and mechanical characteristics of the aggregates used.

Characteristics	Fraction 15/20	Fraction 10/15	Fraction 5/10	Fraction 0/5	filler	Unit	Standard
Specific gravity (**Gse**)				2.88	2.89	-	EN 1097-6 [26]
Apparent specific gravity (**Gsa**)	2.83	2.84	2.86	2.87		-	EN 1097-6 [26]
Los Angeles abrasion (**L.A.**)	17.7	19.07	19.07			%	EN 1097-2 [27]
Micro Deval abrasion test in water (**MDU**)	8.5						ASTM D7428 – 15 [28]
Polished stone value (**PSV**)		0.40					EN 1097-8 [29]
Ridgen voids v					32,70	%	EN 1097-4 [30]
Sand equivalent (**ES**)				77		%	EN 933-8 [31]
Flakiness index (**SI**)	1.96	1.91					EN 933-3 [32]
Shape index (**SI**)	3.96	3.16				%	EN 933-4 [33]
Absorption coefficient	0.31	0.44	0.70	0.97			EN 1097-6 [26]

The available fractions as provided by the quarry were then combined according to the percentages given in Table 3, in order to comply with the typical limits [34] of a thin wearing course having layer thickness of about 3 cm (see Figure 2).

Table 3. Percentage of each aggregate fraction combined for the target mixture

	Fraction 15/20	Fraction 10/15	Fraction 5/10	Fraction 0/5	filler
(%)	0.48	0.20	0.14	0.17	1

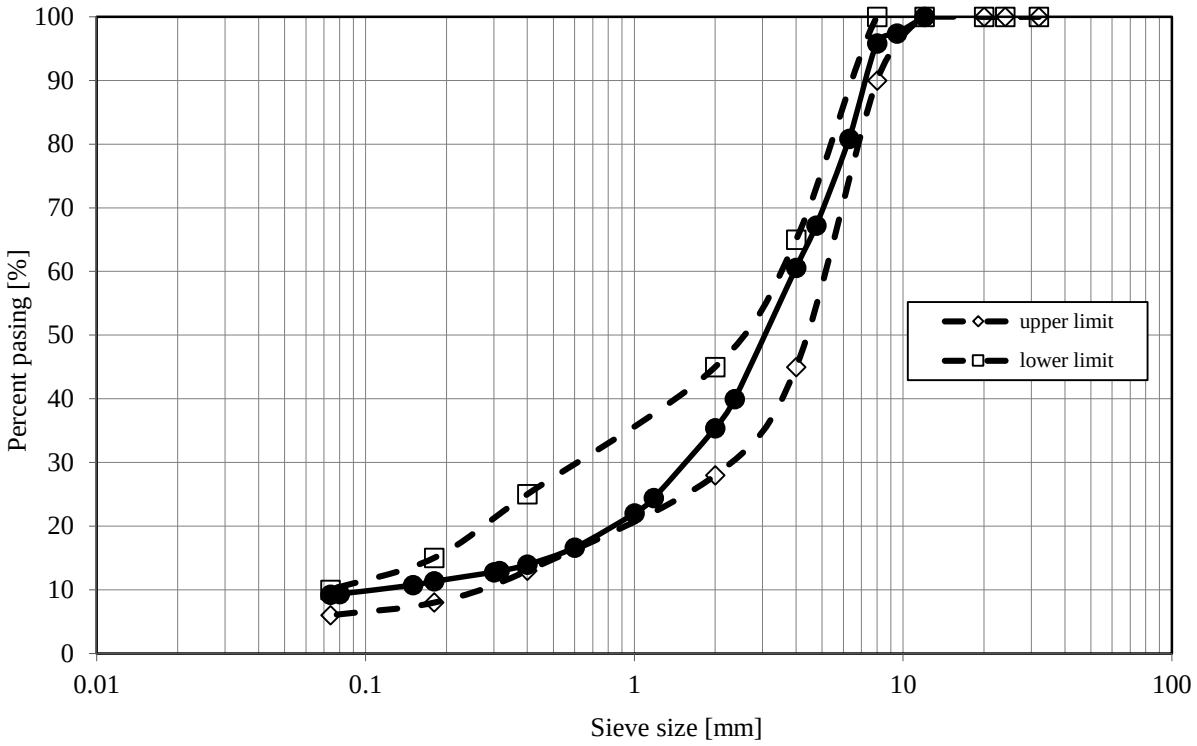

Figure 2. Mix grading curve.

5.2 Material characterization (Bitumen)

The bitumen used is a pure bitumen, and due to its penetration it ranks between the hard bitumen and semi-hard bitumen. Its characteristics are reported in Table 4.

Table 4. Characteristics of the bitumen used in the studied mixtures.

Characteristics	Unit	Values	Standard
Specific gravity at 25°C, γ	g/cm^3	1.033	ASTM D 70-76 [28]
Penetration at 25°C, pen	dmm	71	EN 1426 [35]
Softening point Ring and Ball, $T_{R\&B}$	°C	47	EN 1427 [35]
Penetration Index, PI		-1.16	EN 12591 [36]
Colloidal Instability Index		0.17	
Viscosity at 135 °C	Pa·s	0.39	EN 13302 [37]
Viscosity at 160 °C	Pa·s	0.14	EN 13302 CEN [37]
After RTFOT:			
Penetration at 25°C, pen	Dmm	50	EN 1426 [38]
Softening point Ring and Ball, $T_{R\&B}$	°C	51	EN 1427 [35]

The equiviscosity temperature is defined as the temperature corresponding to a viscosity of the binder of η = 170 ± 20 mPa·s. It refers to the mixing temperature of the bitumen with the

aggregate, during the production process. Measurements were carried out (Brookfield viscosity, AASHTO T 316 [39] and ASTM D 4402 [40]) over a range of different temperatures. The equiviscosity temperature found was Teq = 155 °C (case 1 and case 2). Note that equiviscosity does not take into account the effect on workability neither of aggregate shape and angularity on workability nor of fibres [23]. Studies carried out demonstrated that due to the presence of additives the equiviscosity may undergo an increase if fibres/modifiers are considered and asphalt binder content is not increased [41].

5.3 Material characterization (Fibres)

Basalt is a natural material that is found in volcanic rocks originated from frozen lava: it is a very common extrusion from many volcanic regions around the world. Basalt fibre is a material made from extremely fine fibres of basalt (basaltic rocks, including those with highly vesicular texture or scoria), melted under 1450-1500 °C, and then processed into a continuous fibre.

Basalt fibres have a production cycle with lower energy impact than synthetic fibres, a high chemical stability, good resistance to weather, alkaline and acids exposure, low thermal conductivity, good mechanical properties, good thermal and acoustic insulation, high fire resistance, and an absolutely competitive cost compared to synthetic fibres [6].

Indeed, the good thermal stability of the basalt fibres is beneficial for insuring their stability in asphalt mixtures, during mixing, transportation and laying of the mixture itself. Furthermore, the basalt fibres are hydrophobic, thus limiting the water damage of the asphalt mixture [42].

Typically basalt fibres are produced in the form of chopped mat, roving and unidirectional fabric. In this study, they are cut into 3-5 millimetre pieces and their characteristics are given in Table 5. The introduction of these in the mixtures took place via dry method, after the aggregate: the fibres where added to the hot aggregates, before the bitumen. Normal mixing procedure, after visual inspection, proved to guarantee a good uniformity of the fibres into the mixtures. The selected fibres content was equal to 0.3% by weight of aggregate, which complies with the literature [11]. Considering the specific gravity of the aggregate skeleton (according to the percentages of each fraction detailed in Table 4) and that of the fibres, the figure above corresponds to the 0.26% in volume (by volume of aggregate).

Table 5. Characteristics of the fibres used.

Characteristics	Unit	Values	Standard
Colour		Grey	
Specific gravity of unsized filament	g/cm^3	2.67	
Moisture content of basaltic rock	%	0.1	
Melting point	°C	1350	
Filament diameter range	µm	10÷19	ASTM D578 [43]
Elongation at break	%	2.8	ASTM D2256 [44]
Elastic modulus	GPa	84	
Continuous max temperature	°C	250° to 550 °C 1200° fire barrier	
Moisture content	wt%	≤ 0.1	ISO 3344 [45]
Ignition loss		≥ 0.3	
Combustibility	M0	Pass	NFP 92-503 [46]
UV stability		6	ISO 105-B02 [47]
Colour fastness		6	ISO 105-X12 [48]

5.4 Preliminary mix design

Marshall Test was performed in order to carry out the preliminary mix design. Furthermore, this allowed complying with the physical and mechanical characteristics typically considered in Italian/European specifications (EN 12697-34). Two target richness moduli, K_D, were selected, as *per* Table 8.

The optimal percentage was found based on mix design, carried out according to the Marshall method, for the control mixture (case 1, see Table 9). Based on the given gradation (see Figure 2), the optimal bitumen percentage (by weight of aggregate) resulted between 5 and 6%.

The results, in terms of Marshall Stability, S_M, Marshall flow, f_M, Rigidity Ratio, R_M (Marshall quotient, ratio of stability to flow), and Marshall voids, v_M, for the optimal mixture, and the corresponding voids filled with bitumen, VFB, are given in Table 6.

Table 6. Marshall test results (case 1-reference)

b [%]	S_M [kN]	f_M [mm]	R_M [KN/mm]	v_M [%]	VFB [%]
5.55	14.78	2.91	5.082	3.5	78.4

For comparison, typical requirements recommended for K_D, S_M, R_M, and v_M (commonly used French and Italian specifications) are given in Table 7.

Table 7. Marshall test requirements of Italian Specifications.

Course	Autostrade per l'Italia S.p.A. [49]	MIT [34]	ANAS [50]	SNV [51]
Surface	S_M > 11 kN R_M = 3 ÷ 4,5 kN/mm v_M = 4 ÷ 5 %	S_M > 11 kN R_M = 3 ÷ 4,5 kN/mm v_M = 3 ÷ 6 %	S_M > 10 kN R_M > 3 kN/mm v_M = 3 ÷ 6 %	K_D=3.4-4.5

Note that, based on equations (9) to (12), the following results were obtained in terms of aggregates and fibres asphalt film and richness modulus (see Table 8).

Table 8. Average volumetric properties of the selected mixes

	Case 1	Case 2	Case 3
Fibers percentage (F%)	0.0	0.0	0.3
Aggregates percentage (A%)	100	100	99.7
Bitumen, penetration grade	B 50/70	B 50/70	B 50/70
Richness modulus (K_D), design	3.7	3.9	3.9
Richness modulus (K_D), validation	3.67	3.94	3.95
B (by weight of aggregate, %)	5.55	5.97	5.97
Fbe, µm	7.10	7.52	7.70
DP (dust proportion)	1.77	1.69	1.64
Marshall air voids (%)	3.5	3.1	2.9
VFB (%)	78.4	80.3	82

No relevant effect due to fibres introduction was noticed, as proved by the quite consistent Marshall air void results for the mixtures studied (case 2 and case 3 in Table 8).

6. Results and discussions

6.1 Permanent deformation resistance

In order to evaluate the permanent deformation resistance, the following mixtures were prepared: i) Mixtures with a binder dosage corresponding to the value K_{D1} = 3.7 (optimal dosage according to Marshall tests, case 1); ii) Fibre-added mixtures with a richness modulus of 3.9 (K_{D2}) and a corresponding asphalt binder content of 5.97%; iii) Mixtures with a binder dosage corresponding to the value K_{D3} = 3.9, without fibres, for comparison purposes. It is noted that due to the slight percentage of fibres, the corresponding specific surface does not undergo a relevant

modification and consequently the richness modulus and the asphalt binder percentage of case 2 and 3 do not differ (rounding to tenths).

The wheel tracking test was carried out on slabs 305 x 305 x 50 mm in dimension, produced per each mixture to be studied at fixed residual air voids set equal to the optimum Marshall for the reference mixture (v = 3.5%), according to EN 12697-22 standard (Method B). The average values of rut depth are reported in Figure 3.

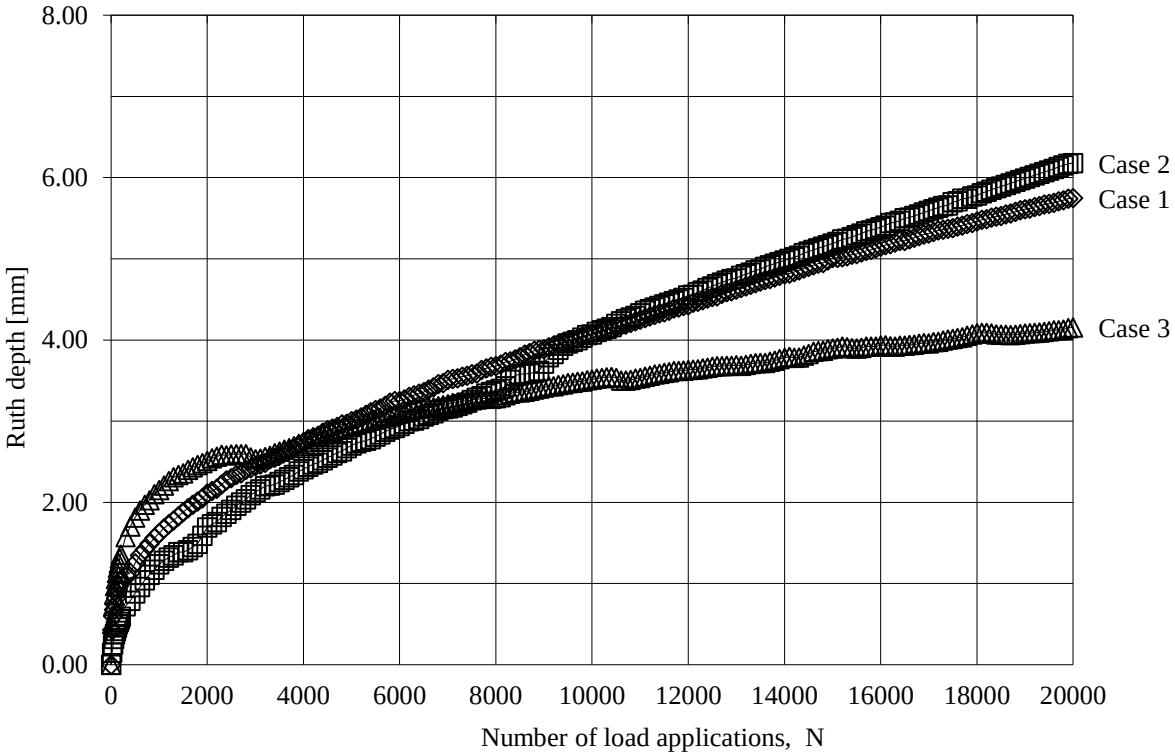

Figure 3. Trend of rut depth in the wheel-tracking test.

Note that: i) The higher the percentage of asphalt binder, the higher the rut depth after 10k-20k passages, the higher (+18%) the first derivative (case 1 vs. case 2, no fibres); ii) The presence of fibres implies lower rut depths after 10k-20k passages (-31%); iii) For the cases under investigation, fibres imply lower rut depths for a given richness modulus (cases 2 and 3) and lower rut depths, with respect to mixes with lower richness moduli, and lower asphalt film thicknesses (cases 3 and 1); iv) The addition of fibres implies an appreciable reduction of the first derivative (-53%). This effect prevails over the effects due to film thickness/richness modulus.
The considerations above suggest a potential for lanes dedicated to urban public transit [14].

6.2 Surface texture

The surface texture of a pavement refers to its deviations from a planar and smooth surface. It depends on a number of variables among which the nominal size of aggregate used and material application rates. It affects skid resistance, rolling noise, and smoothness.

The links between cause "texture" and "effects" generated are represented by "indicators" of the road surface, and these can be extrinsic or intrinsic. Among the indicators, there are HS (or MTD, measured through the sand patch test, which pertains to macrotexture, ASTM E 965:1996) and BPN (or PVT, slip/skid resistance of a surface, pendulum test, EN 13036-4:2011). Other indicators can be derived based on the analysis of profiles z(x) of the road surface (ISO 13473-2:2002), obtained

by instruments such as the "profilometers" [1]. This allows deriving mean profile depth (MPD, ISO 13473-1), texture level ($L_{tx,\ \lambda}$, ISO/TS 13473-4), average asperity density (AAD), and average asperity height (AAH).

In this study, the following indicators were derived: HS, BPN, $L_{tx,\ \lambda}$, AAD, AAH, MPD. The micro and macrotexture were evaluated by subjecting specimens to tests in order to determine the surface characteristics because texture ranges influence the grip and thus the safety. As in previous study, texture measurements were carried out on slabs produced in the laboratory using a lab-size steel roller compactor [25]. This compaction method, that uses a roll segment to compact the loose mix, is proved to be the most realistic in terms of arrangement of the aggregate, and thus it is appropriate for producing samples to be tested for both functional and mechanical performances [25, 52].

Sand patch test (macrotexture, [53]) was carried out according to ASTM E 965:1996 and the average results in terms of sand height, SH, are given in Figure 4.

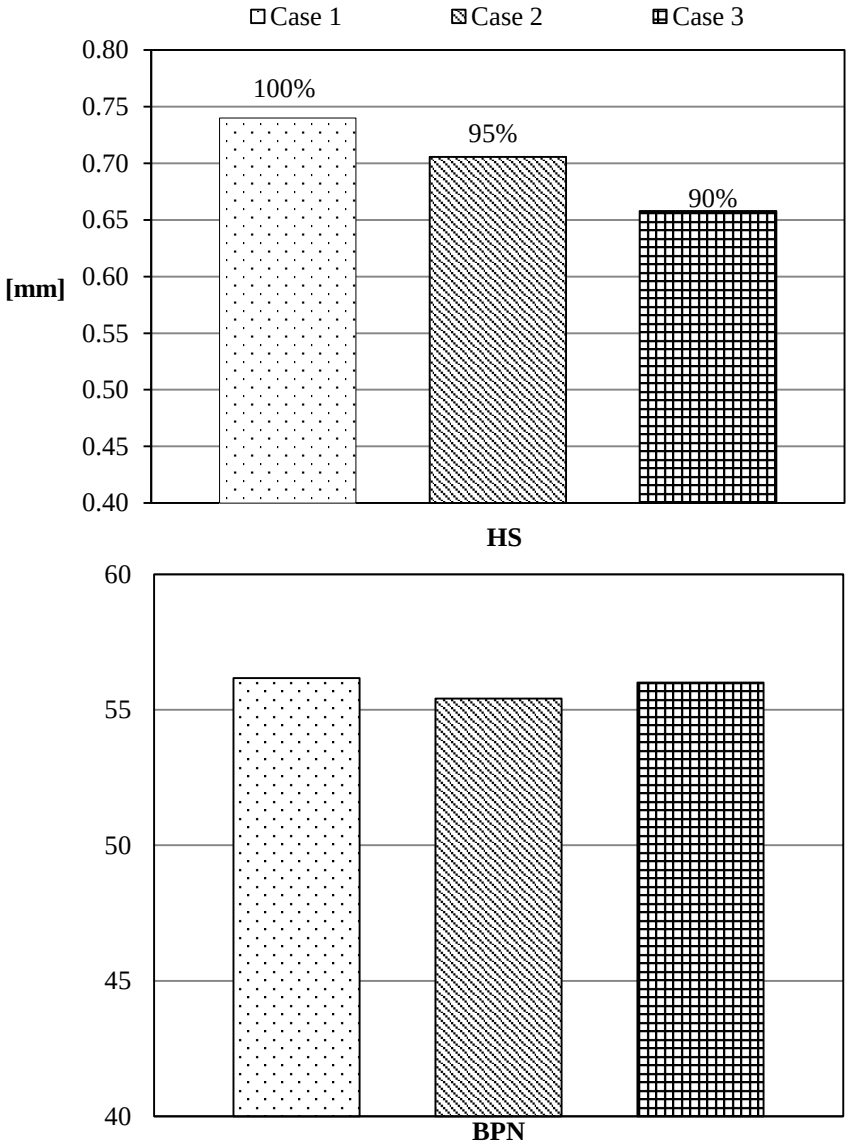

Figure 4. Sand patch test results (HS) (top) and BPN values (bottom).

It is possible to note that HS decreases when increasing bitumen content and adding fibres (fibres are a thickening agent); anyway these values comply with the minimum value required for the type of road (0.4 mm for urban and local streets).

Micro-texture values (BPN, Figure 4) are indirectly estimated in terms of pendulum test value, using low speed friction measurement devices such as the British Portable Tester British Pendulum Number (BPN) [53, 54]. Values appear to comply with Italian requirements for urban roads [34]. Due to test repeatability, to the dependence on aggregates/fibres, the low percentage of fibres, the effects of fibre/bitumen are not evident.

Additionally, a laser profilometer according to ISO/TS 13473-4 standard was used in order to obtain a characterization of the texture by direct measurements (ISO 13473-2:2002). This allowed deriving average profiles and texture level (Figure 5).

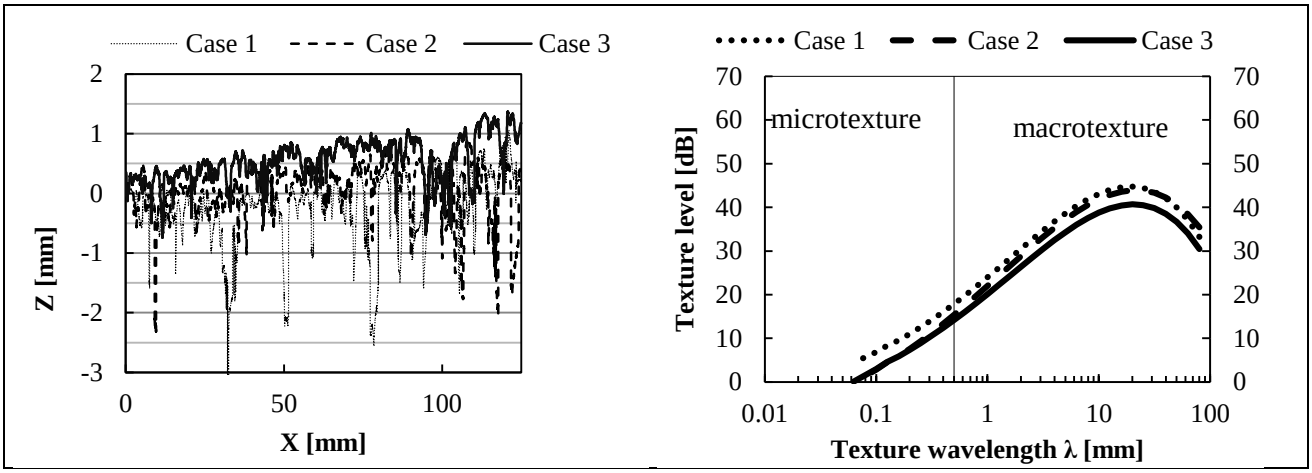

Figure 5. Profiles obtained (left) and texture spectra (right).

In Figure 5 (right), the texture profile level, $L_{tx,\lambda}$, is represented (texture level: y-axis; wavelengths: x-axis, mm). Texture level builds on the logarithmic transformation of an amplitude representation of the profile curves z(x) on the left. These latter are spectrally treated in terms root mean squares. It can be noted (Figure 5, left and right) that when increasing the bitumen content (cases 2 and 3) there is a smoothing of the surface and this is more evident in the mixture with the fibres (case 3).

When comparing BPN and MPD (Mean Profile Depth), as reported in Figure 6, it is possible to see that while MPD values change, BPN values are more or less the same for the mixtures studied.

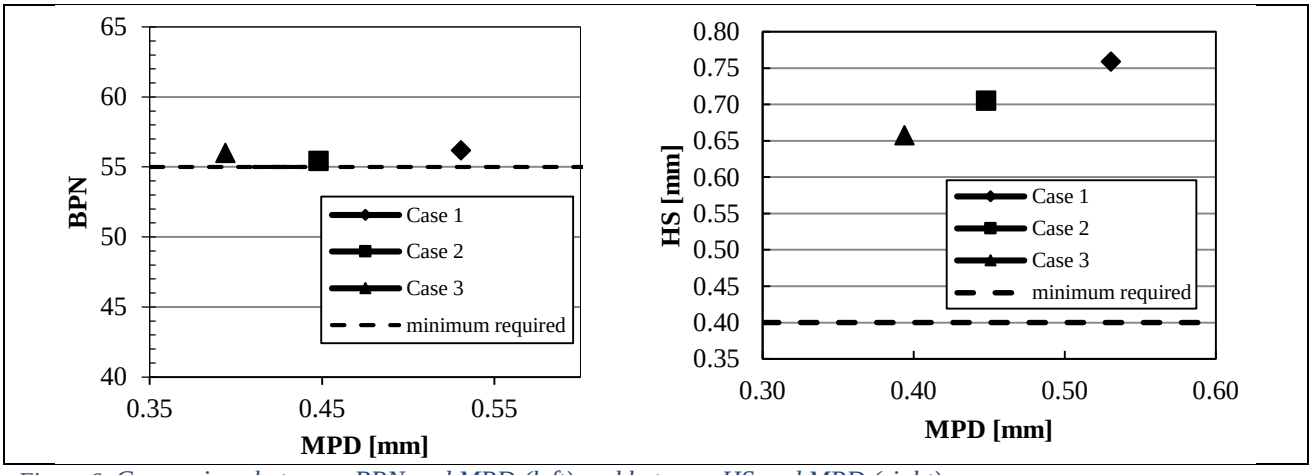

Figure 6. Comparison between BPN and MPD (left) and between HS and MPD (right).

On the other hand, when comparing HS and MPD, as can be seen (Figure 6b), it can be noted that the mixture with the lowest richness modulus provides the highest macrotexture, while the mixture with basalt fibres (and higher richness modulus) provides a lower macrotexture (a sort of flattening of the surface tested). These conclusions are in line with the results of the indicators AAD and AAH for the different mixtures studied, depicted in Figure 7.

In any case, all the mixtures prove to provide values that comply with the minimum requirements for use as wearing course, so that it is possible to conclude that all the mixture studied offer adequate friction and resistance to the inevitable wear and tear, once in service.

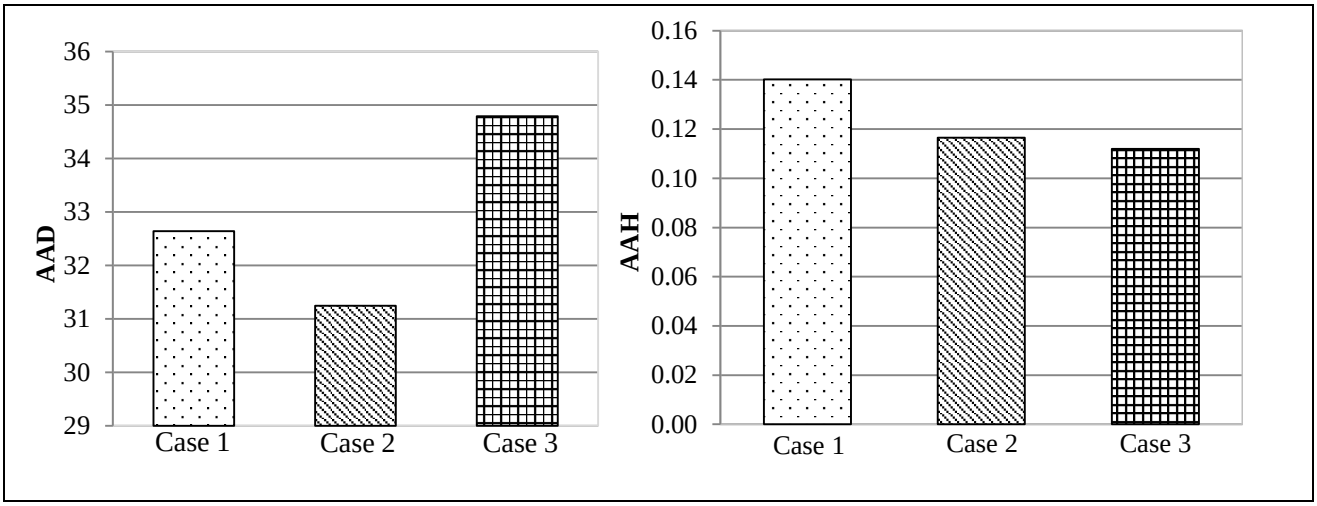

Figure 7. Average asperity density (AAD) and average asperity height (AAH)

Figure 8. Surface texture as a consequence of bitumen increase (case 2) and fibre addition (case 3)

In conclusion, based on the above, the following binary interpretation is proposed. For macrotexture (λ>0.5mm, Cf. indicators on the right in Figure 8), the increase of bitumen content usually implies the smoothing of the texture profile and this is more marked in the mixture with basalt fibres where their presence tends to fill the macro-asperities. This last effect is even more evident in terms of texture spectrum ($L_{0.5}$ to L_{70}).

For micro-texture (λ<0.5mm, Cf. indicators on the left in Figure 8), the observations above seem not to apply: mixes 2 and 3, whose richness modulus is quite comparable, differ based on

fibre content. This latter is likely to slightly increase the micro-texture. This point calls for further study as well as for the pertaining durability of texture-related effects. Indeed, there are the technological uncertainties and limits because the diameter of the laser spot interacts with the observable/ed wavelengths for the class of texture investigated [54].

5 Conclusions

The aim of this research was primarily to evaluate the effect of the introduction of basalt fibres in asphalt mixtures for surface courses especially for use in urban areas, for dedicated bus lanes, where vertical stresses and strain level are severer. Consequently, permanent deformation resistance and surface texture were primarily investigated. In the pursuit of better controlling the factors (one-factor-at-a-time), the problem was preliminary modelled and a specific algorithm was set up. Based on results, the following conclusions can be drawn:

- in terms of rutting resistance, the introduction of basalt fibres proves to be beneficial;
- with regard to surface texture, the mixtures studied prove to fulfil both BPN (skid resistance, microtexture) and HS (macrotexture) requirements for surface courses in urban contexts, thus ensuring the required level safety for functional purposes;
- the macrotexture decreases when increasing the bitumen content and adding basalt fibres. The same conclusions can be obtained by using the profilometers. In fact, when increasing the bitumen content and through the introduction of basalt fibres, a smoothing effect on the surface characteristics (asperities seem to be filled) is noted (texture spectra);
- importantly, the micro-texture seems to undergo a slight-to-negligible increase. BPN values are more or less identical for the mixtures studied and this appears reasonable because this parameter is mainly related to the characteristics of aggregates and the fibre content is quite negligible. This notwithstanding, other microtexture-related indicators seem to appreciably benefit from fibres. This point as well the durability/evolution over time of texture spectra and properties call for future investigation.

Therefore, introduction of basalt fibres from vesicular basalt or scoria may be considered an environmental-friendly and economical material for improving asphalt performance, in surface course for urban applications, in substitution of commercial polymers.

References

[1] F. Praticò, R. Vaiana, A study on volumetric versus surface properties of wearing courses, Construction and Building Materials 38 (2013) 766-775.
[2] C. Celauro, C. Bernardo, B. Gabriele, Production of innovative, recycled and high-performance asphalt for road pavements, Resources, Conservation and Recycling 54(6) (2010) 337-347.
[3] M. Ranieri, L. Costa, J.R. M. Oliveira, H.M. RD Silva, C. Celauro, Asphalt Surface Mixtures with Improved Performance Using Waste Polymers via Dry and Wet Processes, Journal of Materials in Civil Engineering 29(10) (2017) 04017169.
[4] T.R. Board, E. National Academies of Sciences, Medicine, Fiber Additives in Asphalt Mixtures, The National Academies Press, Washington, DC, 2015.
[5] N. Morova, Investigation of usability of basalt fibers in hot mix asphalt concrete, Construction and Building Materials 47(Supplement C) (2013) 175-180.
[6] V. Fiore, T. Scalici, G. Di Bella, A. Valenza, A review on basalt fibre and its composites, Composites Part B: Engineering 74(Supplement C) (2015) 74-94.
[7] V. Fiore, G. Di Bella, A. Valenza, Glass–basalt/epoxy hybrid composites for marine applications, Materials & Design 32(4) (2011) 2091-2099.
[8] V. Fiore, F. Alagna, G. Di Bella, A. Valenza, On the mechanical behavior of BFRP to aluminum AA6086 mixed joints, Composites Part B: Engineering 48(Supplement C) (2013) 79-87.

[9] G. Campione, L. La Mendola, A. Monaco, A. Valenza, V. Fiore, Behavior in compression of concrete cylinders externally wrapped with basalt fibers, Composites Part B: Engineering 69 (2015) 576-586.
[10] Y.C. Cai, Y.X. Zheng, Experiment Study of Water Stability of Fiber-Reinforced Asphalt Mixture, Advanced Materials Research, Trans Tech Publ, 2011, pp. 710-716.
[11] Y. Zheng, Y. Cai, G. Zhang, H. Fang, Fatigue property of basalt fiber-modified asphalt mixture under complicated environment, Journal of Wuhan University of Technology-Mater. Sci. Ed. 29(5) (2014) 996-1004.
[12] Y.X. Zheng, Y.C. Cai, Y.M. Zhang, Laboratory Study of Pavement Performance of Basalt Fiber-Modified Asphalt Mixture, Advanced Materials Research, Trans Tech Publ, 2011, pp. 175-179.
[13] D. Simard, F. Olard, Long-Life Overlays by Use of Highly Modified Bituminous Mixtures, in: A. Scarpas, N. Kringos, I. Al-Qadi, L. A (Eds.), 7th RILEM International Conference on Cracking in Pavements: Mechanisms, Modeling, Testing, Detection and Prevention Case Histories, Springer Netherlands, Dordrecht, 2012, pp. 837-848.
[14] E.Y. Hajj, D. Batioja-Alvarez, R. Siddharthan, Assessment of Pavement Damage from Bus Rapid Transit: Case Study for Nevada, Transportation Research Record: Journal of the Transportation Research Board (2591) (2016) 70-79.
[15] R.P. Panda, S.S. Das, P.K. Sahoo, An empirical method for estimating surface area of aggregates in hot mix asphalt, Journal of Traffic and Transportation Engineering (English Edition) 3(2) (2016) 127-136.
[16] STP, STP 204-19 Asphalt film thickness determination, Standard test procedures manual, Government of Saskatchewan Regina, Canada 2001.
[17] M. Duriez, J. Arrambide, Nouveau traité de matériaux de construction: Liants et bétons hydrocarbonés, 2e édition ed., Dunod, Paris, 1962.
[18] S. Wu, Q. Ye, N. Li, H. Yue, Effects of fibers on the dynamic properties of asphalt mixtures, Journal of Wuhan University of Technology-Mater. Sci. Ed. 22(4) (2007) 733-736.
[19] LCPC, Manuel LPC d'aide à la formulation des enrobés, Groupe de Travail RST "Formulation des enrobés". Laboratoire Central des Ponts et Chaussées LCPC. Paris, France (2007).
[20] MnDOT, Adjusted Asphalt Film Thickness (AFT) in: M.D.o. Transportation (Ed.) MnDot, St. Paul, MN 2017.
[21] B. Coree, W. Hislop, The difficult nature of minimum VMA: A historical perspective, Presented to the Annual meeting, Transportation Research Board, Washington, DC (1999).
[22] W. Campen, J. Smith, L. Erickson, L. Mertz, The relationships between voids, surface area, film thickness and stability in bituminous paving mixtures, Proceedings, AAPT, 1959.
[23] J. Gudimettla, J. L. Cooley, E. Brown, Workability of Hot-Mix Asphalt, Transportation Research Record: Journal of the Transportation Research Board 1891 (2004) 229-237.
[24] A. Mahrez, M.R. Karim, RUTTING CHARACTERISTICS OF BITUMINOUS MIXES REINFORCED WITH GLASS FIBER, Journal of the Eastern Asia Society for Transportation Studies 7 (2007) 2168-2178.
[25] F.G. Praticò, R. Vaiana, T. Iuele, Macrotexture modeling and experimental validation for pavement surface treatments, Construction and Building Materials 95 (2015) 658-666.
[26] CEN, EN 1097-6 Tests for mechanical and physical properties of aggregates-Part 6: determination of particle density and water absorption, Comité Européen de Normalisation Brussels, 2000.
[27] CEN, EN 1097-2. Tests for mechanical and physical properties of aggregates. Determination of loose bulk density and voids, Comité Européen de Normalisation, Brussels, 1998.
[28] ASTM, D 70-76. Softening point, American Society for Testing Materials, West Conshohocken, PA,, 1976.
[29] CEN, EN 1097-8 Tests for mechanical and physical properties of aggregates. Determination of the polished stone value, Comité Européen de Normalisation, Brussels, 2009.

[30] CEN, EN 1097-4 tests for mechanical and physical properties of aggregates: part 4—determination of the voids of dry compacted filler, Comité Européen de Normalisation Brussels, 1999.
[31] CEN, EN 933-8. Tests for geometrical properties of aggregates. Assessment of fines. Sand equivalent test, Comité Européen de Normalisation, Brussels, 1997.
[32] CEN, EN 933-3 Test for geometrical properties of aggregates. Part 3: Determination of particle shape. Flakiness index, Comité Européen de Normalisation, Brussels, 1997.
[33] CEN, EN 933-4. Tests for geometrical properties of aggregates. Determination of particle shape. Shape index, Comité Européen de Normalisation, Brussels, 2008.
[34] MIT, Norme Tecniche di Tipo Prestazionale per Capitolati Speciali d'Appalto - Performance based requirement for Technical Specifications for road works, Ministero delle Infrastrutture e dei Trasporti, 2001.
[35] CEN, EN 1427. Bitumen and bituminous binders - Determination of the softening point - Ring and Ball method, Comité Européen de Normalisation, Brussels, 2007.
[36] CEN, EN 12591 Bitumen and bituminous binders. Specifications for paving grade bitumens, Comité Européen de Normalisation, Brussels, 2009.
[37] CEN, EN 13302 Bitumen and bituminous binders. Determination of dynamic viscosity of bituminous binder using a rotating spindle apparatus, Comité Européen de Normalisation, Brussels, 2010.
[38] CEN, EN 1426. Methods of tests for petroleum and its products. Bitumen and bituminous binders. Determination of needle penetration, Comité Européen de Normalisation, Brussels, 2000.
[39] AASHTO, T 316 Viscosity Determination of Asphalt Binder Using Rotational Viscometer." AASHTO Standards, American Association of State Highway and Transportation Officials, Washington, DC, 2004.
[40] ASTM, ASTM D4402 / D4402M Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer, American Society for Testing Materials, West Conshohocken, PA, 2015.
[41] Y. Yildirim, M. Solaimanian, T.W. Kennedy, Mixing and compaction temperatures for hot mix asphalt concrete, Work 1250 (2000) 5.
[42] X. Gu, T. Xu, F. Ni, Rheological behavior of basalt fiber reinforced asphalt mastic, Journal of Wuhan University of Technology-Mater. Sci. Ed. 29(5) (2014) 950-955.
[43] ASTM, ASTM D578 / D578M - 05 Standard Specification for Glass Fiber Strands, American Society for Testing Materials, West Conshohocken, PA, 2011.
[44] ASTM, ASTM D2256 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method, American Society for Testing Materials, West Conshohocken, PA, 1997.
[45] E. ISO, ISO 3344 Reinforcement products -- Determination of moisture content, International Organization for Standardization, Geneva, Switzerland, 1997.
[46] AFNOR, NF P92-503 Sécurité contre l'incendie - Bâtiment - Essais de réaction au feu des matériaux - Essai au brûleur électrique applicable au matériaux souples., Association Française de Normalisation, Paris, 1995
[47] ISO, ISO 105-B02 Textiles -- Tests for colour fastness -- Part B02: Colour fastness to artificial light: Xenon arc fading lamp test, International Organization for Standardization, Geneve, Switzerland, 2013.
[48] ISO, ISO 105-X12 Textiles -- Tests for colour fastness -- Part X12: Colour fastness to rubbing, International Organization for Standardization, Geneve, Switzerland, 2016.
[49] p.l.I. Autostrade SpA, Capitolato speciale di appalto, parte seconda, opere civili - Technical specification for contractors, Part II, Civil Works, Autostrade per l'Italia SpA, Rome, Italy, 2008.
[50] Anas, Capitolato Speciale d'Appalto per lavori stradali. Norme tecniche (Standard requirements for road construction. Technical Specifications) (2009).

[51] VSS, SN 640431 – 1aNA Enrobés bitumineux compactés - Conception, exécution, exigences pour les couches en place Association suisse des professionnels de la route et des transports (VSS), Winterthur, Switzerland, 2003.
[52] C. Plati, P. Georgiou, A. Loizos, Influence of different roller compaction modes on asphalt mix performance, International Journal of Pavement Engineering 17(1) (2016) 64-70.
[53] G. Flintsch, E. de León, K. McGhee, I. AI-Qadi, Pavement surface macrotexture measurement and applications, Transportation Research Record: Journal of the Transportation Research Board (1860) (2003) 168-177.
[54] F.G. Praticò, A. Astolfi, A new and simplified approach to assess the pavement surface micro- and macrotexture, Construction and Building Materials 148(Supplement C) (2017) 476-483.