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(Article begins on next page)

1 A study on the relationship between Mean Texture Depth and Mean 2 Profile Depth of asphalt pavements

3

4 **F.G. Praticò^a and R. Vaiana^b**

5 ^a DIIES Department, University Mediterranea of Reggio Calabria, via Graziella Feo di Vito, Italy Tel/fax +39
6 0965 875230 – 875471 e-mail: filippo.pratico@unirc.it

7 ^b Department of Civil Engineering, University of Calabria, Arcavacata Campus of Rende, Cosenza, Italy,
8 tel/fax +39 0984 496786, e-mail vaiana@unical.it

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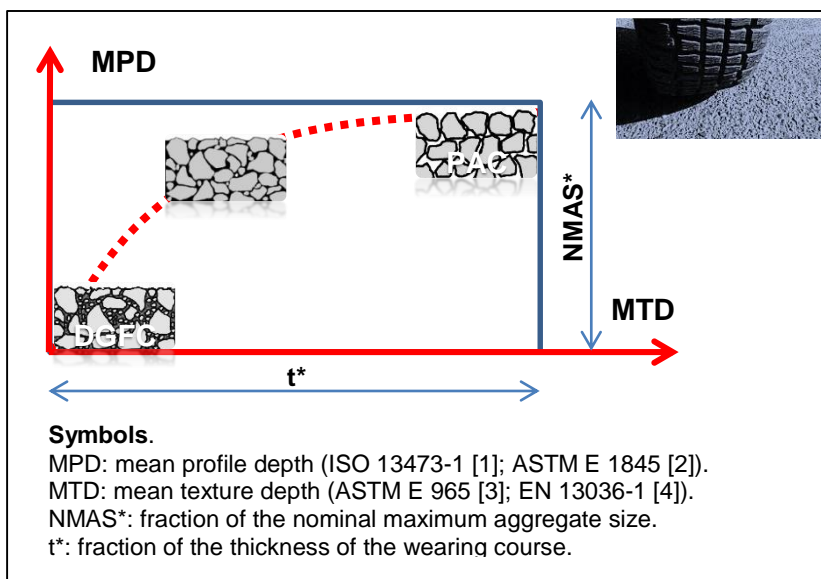
10 **Keywords:** pavement macrotexture; MPD mean profile depth; MTD mean texture depth; laser profilometer.

11 Abstract

12 Safety, skid resistance and noise of roads highly depend on the characteristics of pavement
13 surface texture, for both porous and dense-graded wearing courses.

14 In the light of the above facts, the objective of the study was to model the relationship between
15 laser-based and volumetric-type measurements of the surface macro-texture of a pavement. In
16 more detail, the study focused on the mean profile depth (MPD, as *per* ISO 13473-1 [1] and ASTM
17 E 1845 [2]) and on the mean texture depth (MTD, as known as sand patch texture, as *per* ASTM E
18 965 [3] and EN 13036-1 [4]). Different types of surface textures were considered: dense-graded
19 friction courses (DGFC), spittmastic asphalts (SMA), open-graded friction courses (OGFC), porous
20 European mixes (PEM).

21 A generalized simple model has been set up, calibrated and validated. The proposed model fits the
22 data of many types of wearing courses without neglecting the basic achievements which refer to
23 the curves previously derived.



24

25

Graphical abstract

26 **1. Background**

27 Surface texture has an outstanding importance in terms of road and airport safety (Noyce et al,
28 2005 [5]). It affects as well pavement performance (Freitas et Al., 2008 [6]): i) tyre/road friction,
29 (NCHRP 291, 2000 [7]; Do et Al., 2004 [8]; Kim et al, 2013 [9]); ii) noise emission (SILVIA, 2006
30 [10]; Lu and Harvey, 2011 [11]; Praticò et al., 2013 [12]; Praticò et al., 2014 [13]) driving comfort
31 (Delanne and Daburon, 1999 [14]); iii) rolling resistance (Bendtsen 2004 [15]; Sohaney and
32 Rasmussen, 2013 [16]); iv) wear of tyres (Nordströdm and Andersson, 1996 [17]; Domenichini and
33 Martinelli, 2004 [18]); v) particulate matter emission from paved roads (China and James, 2012
34 [19]; Amato et al., 2013 [20]); vi) operating costs (Bendtsen, 2004 [15]); vii) greenhouse gas
35 emissions. (Wang et al, 2014 [21]) focused on macrotexture (MPD, MTD) impact on life cycle GHG
36 (greenhouse gas) emissions. Indeed, macrotexture refers to the primary wavelengths that excite
37 shock absorbers in vehicle suspension systems, cause deformation of tire sidewalls for a moving
38 vehicle, affect energy dissipation, waste heat, and rolling resistance by vehicles.

39 Surface macrotexture (wavelengths between 0.5 and 50mm) can be assessed through intrinsic
40 and extrinsic indicators (Boscaino and Pratico, 2001 [22]). In more detail, the following main
41 methods apply: volumetric methods (ASTM E965 [3] procedure, with glass spheres; EN 13036-1
42 [4], with glass spheres), laser-based methods (ASTM E 1845 [2]; ISO 13473-1 [1]; Abe et Al., 2001
43 [23]; Aktaş et Al., 2011 [24]; Blanchard and Holloway, 2013 [25]; China and James, 2012 [26];
44 Sengoz et al., 2012 [27]), and permeability-related methods (ASTM STP 583 [28], Cooley, 1999
45 [29]). Note that volumetric methods and indicators (e.g., MTD) are based on the ratio between a
46 volume and a surface area, while laser-based methods and indicators (e.g., MPD) rely on the ratio
47 between a surface area and a length. (Yaacob et al, 2014 [30]) assessed pavement texture with
48 variety of test methods, including sand patch test and multi laser profiler. They concluded that
49 there were weak correlations between the results of these two measurement techniques.
50 (Rodriguez et al., 2014 [31]) advised the use of 3D texturometer laser, as a method of measuring
51 the surface macrotexture and MPD (Mean Profile Depth) in order to estimate indicators derived by
52 Sand and Grease Patch tests. Surface texture depends on mix components and construction
53 process (Stroup-Gardiner and Brown, 2000 [32]; Davis, 2001 [33]; Flintsch et al, 2003 [34]; Hanson
54 and Prowell, 2004 [35]; Sullivan, 2005 [36]; Goodman et al, 2006 [37]; Praticò et al, 2010 [38];
55 D'apuzzo et al, 2012 [39]).

56 The sand patch method (see ASTM E 965 [3], EN 13036-1 [4] and previous standards in which
57 sand was used instead of glass spheres) is suitable for bituminous surface courses and concrete
58 pavement surfaces with texture depth greater than about 0.25 mm and is affected by the surface
59 and inner structure of the mixture (air voids distribution, shape, tortuosity). Sand patch method
60 depends on dense granular (glass beads) flows. It is size-dependent and a complicated set of flow
61 properties are involved, which differentiate them from ordinary fluids (Henann and Kamrin, 2013
62 [40]) .

63 Laser-type measurements (see ASTM E 1845 [2] and ISO 13473-1 [1]) are affected by the
64 complex shape of a pavement surface but they do not depend on what the laser cannot "see" from
65 its position. In more detail, even when conoscopic holography is used (which presents several
66 advantages), a laser beam is projected onto the surface and then the immediate reflection along
67 the same ray-path are put through a conoscopic crystal and projected onto a CCD (charge-coupled
68 device for the movement of electrical charge). The result is a diffraction pattern. This pattern is
69 frequency analysed and the distance to the measured surface (pavement surface) is consequently
70 derived. The main advantage with conoscopic holography is that only a single ray-path is needed
71 for measuring, thus giving an opportunity to measure very deep pavement "valleys". Criticalities (as

72 for all the laser-based techniques) relate to beam dimensions and to the fact that beams describe a
73 family of straight lines, without any possibility to investigate pores properties outside the above
74 plane.

75 Accurate sand patch testing on/and laser based testing cannot be carried out when road surface is
76 sticky or wet. The equipment of the sand patch method costs around 0.1k€ while the equipment of
77 a laser-based texture equipment costs around 10-100k€. The duration of the two tests ranges from
78 less than one second (high-speed laser measurement), to a couple of minutes (sand patch
79 method), to several minutes (high-precision, laboratory-type lasers).

80 Pavement Macrotexture Depth (herein termed MTD, ASTM E 965 [3], EN 13036-1 [4]) and Mean
81 profile depth (MPD, ASTM E 1845 [2] and ISO 13473-1 [1]) are indicators which refer to
82 macrotexture domain (wavelengths between 0.5 and 50 mm). Two main domains can be
83 approximately observed with reference to macrotexture studies and analyses (Meegoda et al, 2002
84 [41]): low macrotextures (MPD lower than about 1.5 mm) and high macrotextures (MPD higher
85 than about 1.5mm).

86 In the first dominion many linear relationships MTD(MPD) have been derived. The slope of the
87 equation used to obtain MTD from MPD measurements takes values from about 0.5 to 1.2. In
88 particular, values of 0.5-0.6 were found by (Vaiana et al, 2012 [42]; Kim et al, 2013 [9]), whereas
89 (Freitas et al, 2008 [6]) found a slope value of 0.7. According to (Wambold et al, 1995 [43]; ASTM
90 E-1845 [2]; ISO 13473-1 [1]; Wang et al, 2011 [44]; Losa et al, 2007 [45]; De Fortier and Waller,
91 2007 [46]; Mackey 2005 [47]; Flintsch et al, 2007 [48]) the range of slope was 0.8-1. Finally,
92 Sengoz et al. 2012 [27] and Fisco and Sezen, 2013 [49] found slope values of 1.1 and 1.2,
93 respectively.

94 The intercepts range from about -0.3 (Flintsch et al, 2002 [50]), to 0.0 (Hanson and Prowell, 2004
95 [35]), to 0.2 (Wambold et al, 1995 [43]; ASTM E-1845 [2]; ISO 13473-1 [1]; Wang et al, 2011 [44];
96 Vaiana et al, 2012 [42]), to 0.3 (Kim et al, 2013 [9]), to 1 (Xiao et al, 2011 [51], MPD based on
97 microscopy evaluation).

98 It is noted that several lasers, due to their characteristics, yield other linear relationship (ASTM
99 E2157-2005 [52]). For example, for the CTMeter, the slope is about 0.95 and the intercepts is
100 about 0.07 (Fisco and Sezen, 2013 [49]).

101
102 In the second dominion (higher values of macrotexture) many authors have found results which do
103 not comply with the previous equations (e.g., Hanson and Prowell, 2004 [35]).
104 According to ISO 13473-1 [1], experience has shown that the sand patch texture may be not
105 reliable if used in porous surfaces because some material may pour down into the pores (Freitas et
106 al, 2008 [6]).

107 According to (Noyce et al, 2005 [5]), the prediction of MTD (mean texture depth, volumetric
108 method) from MPD (Mean profile depth, ASTM E 1845 [2]) is not valid for highly porous surfaces,
109 as the glass spheres or sand flows into the pores, producing high values for MTD. Furthermore, at
110 the same time, (Noyce et al, 2005 [5]) found that the prediction of OFT (ASTM STP 583 [28],
111 outflow time) from MTD was very good also for highly porous surfaces. Note that the existence of a
112 different relationship between MPD and MTD for porous asphalt concretes (PAC) or similar
113 surfaces (open-graded friction courses, OGFC, porous European mixes, PEM; etc.) has been
114 pointed out by many other authors (Other data. Hanson and Prowell, 2004 [35]; Nicholls 1997 [53],
115 Hanson and Prowell, 2004 [35]; Flintsch et al, 2002 [50]).

116 (Vilaça et al, 2010 [54]) developed a scanning prototype to derive ETD and results obtained
117 showed a certain difference between the predicted and the actual value of texture for “rough”
118 porous asphalt concretes.

119 (Praticò and Vaiana, 2013 [55]) studied the variability of MPD-related and ETD-related
120 measurements for porous asphalt concrete. Their standard deviation and coefficient of variation
121 resulted comparable.

122 Note that when comparing CTMeter and sand patch method, (Hanson and Prowell, 2004 [35];
123 Prowell and Hanson, 2005 [56]) found that the offset between the CTMeter and sand patch test
124 results was insignificant when open-graded mixtures were excluded.

125 (Freitas et al, 2014 [57]) focused on the variability of the mean profile depth and pointed out the
126 necessity to further investigate the effect of the type of surface on data variability.
127 Finally, note that the inherent proportionality between MPD and the NMAS (nominal maximum
128 aggregate size) has been partly proved by (Henault et al., 2011 [58]). In contrast, this fact didn't
129 happen when comparing MTD and NMAS. Note that Superpave defines NMAS as “one sieve size
130 larger than the first sieve to retain more than 10 percent of the material” (Roberts et al., 1996 [59]).

131 **2.Objectives**

132 Safety, skid resistance and noise of roads highly depend on the characteristics of pavement
133 texture, for both porous and dense-graded wearing courses.

134 Consequently, there is a strong need to develop methods and algorithms to quickly estimate the
135 characteristics of road surface textures, without traffic interruptions, over a wider range of
136 pavement types. To this end, assessing relationships which are valid for different types of friction
137 courses can have an appreciable impact, in a context in which porous asphalt concretes and other
138 innovative wearing courses are widely used.

139 In the light of the above facts, the objective of the study was to model the relationship between
140 laser-based and volumetric-type measurements of the surface macro-texture of a pavement. In
141 more detail, the study focused on the mean profile depth (ISO 13473-1 [1] and ASTM E 1845 [2])
142 and on the mean texture depth (ASTM E 965 [3] and EN 13036-1 [4]). Different types of surface
143 textures were considered: dense-graded friction courses (DGFC), spittmastic asphalts (SMA),
144 open-graded friction courses (OGFC), porous European mixes (PEM). Modelling was followed by
145 calibration and validation.

146 The remaining part of the paper is organised into section 3, in which the model building, calibration
147 and validation is described, and section 4, in which conclusion are drawn.

148 **3. Model and experimental validation**

149 The methodology for building and validating the model is below summarized in terms of three main
150 tasks.

151 Task 1. Model building. During this phase the model was set up, based on literature study and
152 analysis (see above), data analysis, modelling of the boundary conditions (conditions in extreme
153 points of the range of variation of the two main variables (MTD, MPD).

154 Task 2. Model calibration. In order to check whether the model fits experimental measurements or
155 other empirical data, these latter were split into two disjoint subsets: training data and verification

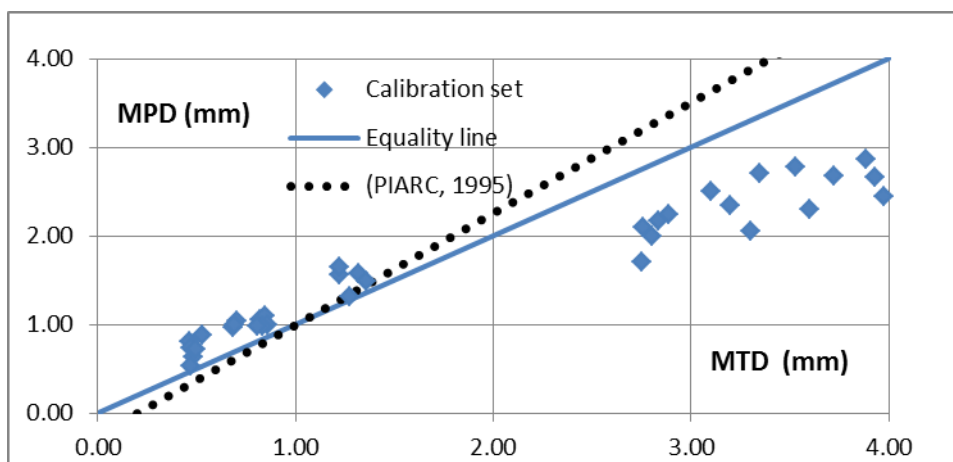
156 data. Many types of surface courses were considered for the dataset building (see Table 1): two
 157 Stone Mastic Asphalts (S1 and S2); two Porous European Mixes (P1 and P2); a porous asphalt
 158 concrete (P3) for which data were derived from a literature review; a dense graded friction course
 159 (D1), see table 1.

160 Task 3. Model verification. The verification data were derived from an experimental plan, *ad hoc*
 161 designed and carried out. In this case, a Porous European Mix (P4) and a Dense Graded Friction
 162 Course (D2) were considered.

163

164 **3.1 Model building**

165 The set of data used for analysis and calibration is shown in Figure 1. In the same picture the
 166 equality line (solid line) and the PIARC 1995 equation (dotted line, Wambold et al. 1995 [43]) are
 167 represented.
 168



169
 170 *Figure 1. Data analysis and calibration*
 171

172 It is possible to observe what follows.
 173 In the range below about 1.5 mm, a linear equation seems to represent well the data. As is well
 174 known, the intercept around 0.2mm (dotted line, Wambold et al. 1995 [43]) can be associated to
 175 the diameter of the spheres (beads or sand) when the surface tends to be flat.
 176

177 In other terms, in the case of very dense surfaces, the lowest MTD is associated with a cylinder
 178 0.2mm –thick. In turn, in the case of very dense surfaces, MPD tends to a minimum value which is
 179 zero, being based on a laser measurement of differences from the peak, as per the EN standard.

180 In the range above about 1.5mm, there is a clear divergence of data from the abovementioned
 181 linear relationships which refer to low macrottexture domain.

182 Higher MPDs yield higher MTD, but the slope MTD/MPD (the change in MTD divided by the
 183 change in MPD) varies and tends to increase ($MTD \gg MPD$). *Vice versa*, the slope MPD/MTD (see
 184 Figure 1 tends to decrease and to reach a value close to zero.

185 On average, considering only data above 1.5mm, the slope is about one fourth of the slope of
 186 PIARC 1995 equation while the intercept is almost ten times higher than the one in PIARC
 187 equation. Consequently, intercept loses its physical meaning of diameter of the spheres.

188 In the limit condition (very permeable hot mix asphalt), for the current thickness of the surface
 189 layer, the MTD can be ideally associated with a cylinder having the height which equals a fraction
 190 of the thickness of the layer ($MTD = t^*$, where $t^* < t$, and t = thickness of the friction layer).

191 In contrast, as for MPD, its maximum value (very porous asphalt concretes) depends on the
 192 nominal maximum aggregate size (NMAS, see also Henault et al., 2011 [58]).

193 Based on the above two models were set up.

194 The first model is below shown, where α , β , and χ are positive coefficients to calibrate:

$$195 \quad MPD = \frac{\left(\frac{MTD}{0.8} - \frac{0.2}{0.8}\right)}{e^{\alpha \cdot MTD}} + \left(1 - e^{\beta \cdot (-MTD + 0.2)}\right) \cdot \chi \cdot NMAAS \quad (1)$$

196 Note that: i) when MTD tends to 0.2, then MPD tends to zero; ii) when MTD tends to increase, then
197 MPD tends to a fraction of the NMAAS.

198 More in general, the following equation can be written:

$$200 \quad MPD = \frac{\left(\frac{MTD - q}{m}\right)}{e^{\alpha \cdot MTD}} + \left(1 - e^{\beta \cdot (-MTD + q)}\right) \cdot \chi \cdot NMAAS \quad (2)$$

201

202 Where m and q, together with α , β , and χ are positive coefficients to calibrate.

203 The same concepts can be used to derive a different, simpler, second algorithm.

204 Indeed, based on the above, as far as low values of MTD and MPD are considered, the curve
205 MPD(MTD) needs to satisfy the following conditions:

- 206 a) Low values dominion (see Figure 1, left). When close to the origin, the curve must have a
207 first derivative ($\partial MPD / \partial MTD$) around $1/m$ (where $m \cong 0.8$, as per PIARC 1995 experiment
208 see Wambold et al, 1995 [43]).
- 209 b) Low values dominion (see Figure 1, left). The curve must pass for the point $MTD \cong q$,
210 $MPD \cong 0$, where $q \cong 0.2$ mm, as per PIARC 1995 experiment.
- 211 c) High values dominion (see Figure 1, right). the curve must have a first derivative close to
212 zero, when it approaches (from left) the point $MPD \cong NMAAS^*$, $MTD \cong t^*$, where $NMAAS^*$ is a
213 linear function of the nominal maximum aggregate size and t^* is a linear function of the
214 thickness t of the permeable layer.

215 Based on the above, in the case of a parabolic curve, the following equation can be derived:

216

$$217 \quad MPD = -\frac{1}{2mt^*} \cdot MTD^2 + \frac{1}{m} \cdot MTD - \frac{q}{m} \quad (3)$$

218

219 Note that the above m and q refer to the well-known (PIARC, 1995) curve:

220

$$221 \quad MTD = m \cdot MPD + q \quad (4)$$

222

223 Where $m \cong 0.8$ and $q \cong 0.2$ mm.

224

225

226 Note that for regression purposes, the above equation can be simply rewritten as:

227

$$228 \quad MPD = d \cdot MTD^2 + e \cdot MTD - f \quad (5)$$

229

230 Note that the above equations (3) and (4) are defined for values of MTD lower than t^* .

231 Note that equation (3) can be considered as a reference equation. It derives from the modelling of
232 the two extreme areas (low and high values, DGFCs, PACs, and PEMs) and permits to overcome
233 the existence of a maximum for an abscissa lower than t^* (equations 1-2). Indeed, based on the
234 data available to date, the existence of such a maximum of the curve MPD(MTD), which is
235 theoretically possible in equations 1-2, is not well-grounded on data analysis.

236

237 **3.2 Model calibration**

238 Table 1 illustrates the main characteristics of the data set used to analyse, calibrate and validate
 239 the model.

240
 241 *Table 1. Data used for calibrate and validate the model*
 242

Acronym of pavement surface	S1	S2	P1	P2	P3	D1	P4	D2	
Type	SMA	SMA	PEM	PEM	PAC	DGFC	PEM	DGFC	
Data from	Survey (*)	Survey (*)	Survey (*)	Survey (*)	Flintsch et al, 2003 [34]	Survey (*)	Exp (**)	Exp (**)	
Type of analysis	CAL	CAL	CAL	CAL	CAL	CAL	VAL	VAL	
Average MPD (mm)	1.01	1.56	2.70	2.53	2.14	0.72	2.62	0.72	
Average MTD (mm)	0.77	1.14	3.63	3.58	3.07	0.49	4.30	0.51	
NMAS (mm)	8	14	15	15	12.5	10	15	10	
Aggregate gradation passing	5/NMAS mm (***)	10%	66%	78%	75%	86	53	77	55
	2/5 mm	50	15	6	15	11	17	12	15
	0.075/2 mm	32	10	9	4	1	24	5.5	23
	<0.075 mm	8	9	7	6	1	6	6.5	7
bitumen content (%)	6	5.5	4.7	5.3	5.5	5.7	5.0	5.9	
Legend. NMAS: nominal maximum aggregate size (mm) derived from aggregate gradation as the dimension corresponding to one sieve size larger than the first sieve to retain more than 10 percent of the material. DGFC: dense-graded friction course. PAC: porous asphalt concrete. PEM: porous European mixes; SMA: Stone Mastic Asphalt. MPD: mean profile depth (ISO 13473-1 [1] and ASTM E 1845 [2], mm); MTD: mean texture depth (ASTM E 965 [3] and EN 13036-1 [4], mm). (*): Surveys carried out in the past by the same authors. (**): New experiments carried out in this study (see Figure 3). (***): percentage passing the sieve NMAS and retained on 5mm sieve. CAL: Calibration; VAL: validation									

243
 244 Based on the calibration of the model (equation 5), the following results were obtained for the
 245 parameters d, e, f:

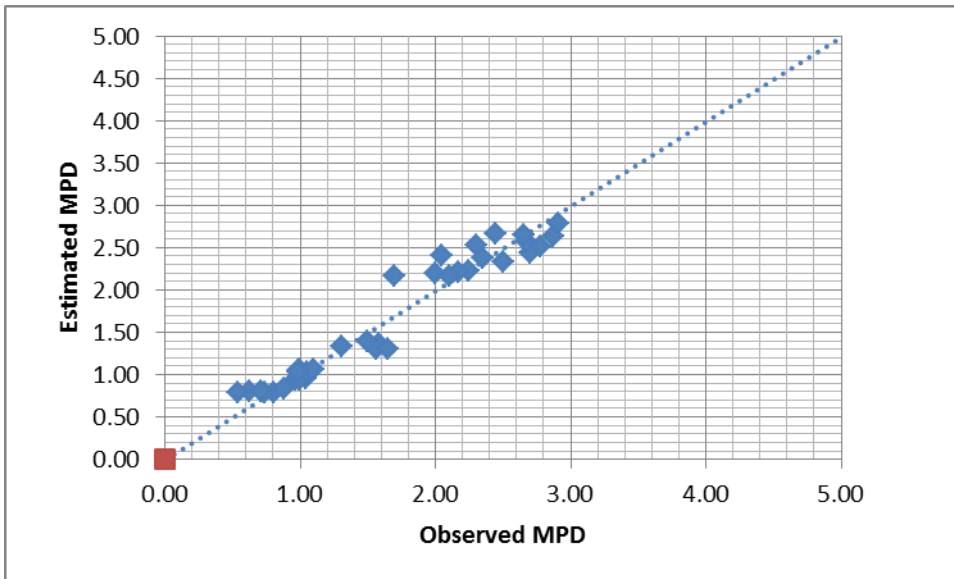
246 $d=-0.05 \text{ mm}^{-1}$; $e=0.78 \text{ mm}^0$; $f=0.43\text{mm}$; $R^2=0.94$, $p=0.000$.

247 Note that the parameter f, even if close to zero, is very different from the one which was
 248 theoretically predicted (-0.25, see equation 3). This implies that the above curve doesn't pass for
 249 the point MTD=0.2mm, MPD=0mm, which is not satisfactory from a theoretical standpoint, even if
 250 this fact has a negligible practical importance for real DGFCs.

251 The parameter e is very different from the one which was theoretically predicted (1.250, see
 252 equation 3). This value of the first derivative in the origin of the axes (very dense hot mix asphalts)
 253 is lower than 1.250 and this fact depends on the necessity to fit both open and dense-graded
 254 mixes with a so simple (second-order) polynomial.

255 Under the abovementioned hypotheses (first derivative approaches zero when MTD approaches
 256 t^*), it comes that $d=-e/(2t^*)$ and then $t^*=7.1\text{mm}$. If simple computations are carried out ($MPD(t^*)$),
 257 this means that the extreme configuration (i.e, for PACs, often termed porous asphalts) entails
 258 MPDs and MTDs which are around the 10-20% of the correspondent NMAS and thickness. This
 259 occurrence derives from the experiments and simulations carried out on a quite copious data set. It
 260 implies that the model takes into account the physical meaning of MTD (*versus* t , thickness of the
 261 wearing course) and MPD (*versus* NMAS, nominal maximum aggregate size), achieving a viable
 262 and reasonable compromise between simplicity, physical configuration and numerical fitting.

263



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Figure 2. Observed (x-axis) versus estimated values of MPD

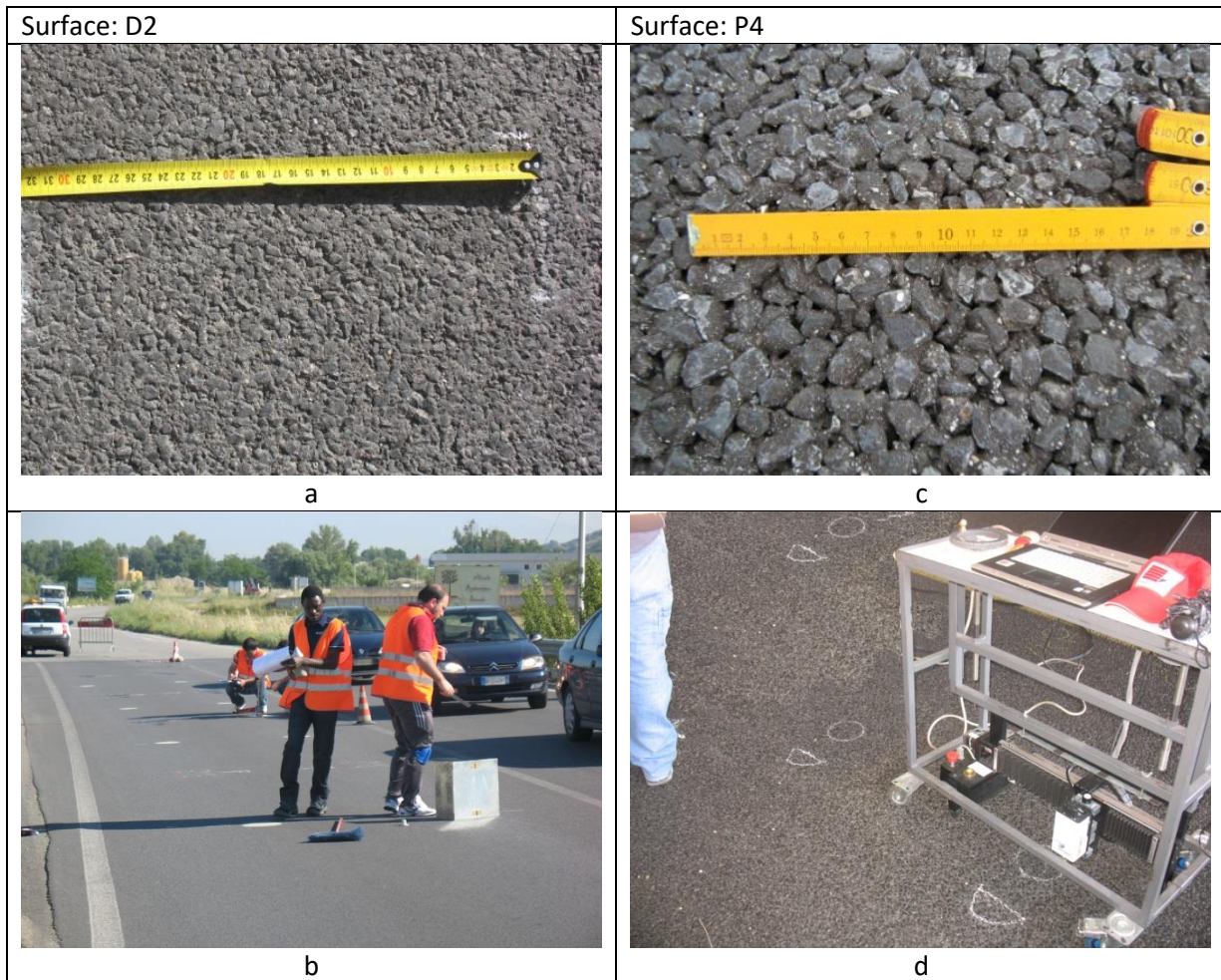
269 3.3 Experiments and Verification

270 An experimental plan was designed and carried out in the pursuit of obtaining new observations
 271 (data) for the dependent (MTD) and independent (MPD) variable (see Figures 3-7 and table 2).
 272 Experiments were carried out in Southern Italy (Figures 3 and 4). They were carried out as *per* the
 273 abovementioned standards for MPD (ISO 13473-1:1997 [1]) and sand patch texture (ASTM E965
 274 [3]; EN 13036-1 [4]).

275 Two main types of wearing courses were investigated:

- 276 - dense-graded friction courses (D2) see Table 1 and Figure 3 (left);
- 277 - porous European mixes (P4), see Table 1 and Figure 3 (right).

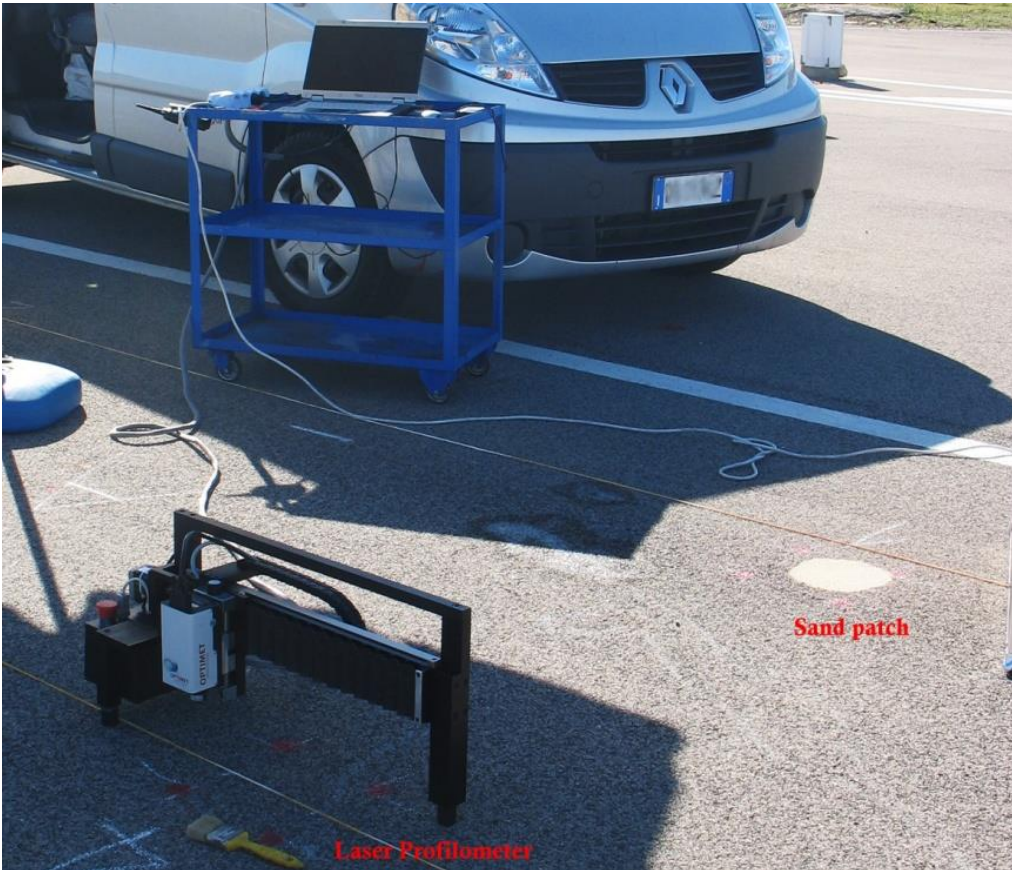
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288 *Figure 3. Experiments carried out. Left: friction course (D2, a and b). Right: PEM (P4, c and d)*
 289

290 In particular, laser profilometer scanning was carried out in terms of (x,z) coordinates, where z
 291 represents profile depths. A laser profilometer based on conoscopic holography was used (see
 292 Figure 4). The device has the following characteristics (ISO 13473-3 [60]): i) Mobility: Stationary,
 293 Slow (time on lane per single measurement equal or higher than 1 minute, according to ISO
 294 13473-3 [6]); ii) Texture wavelength range: Range covered BD class 0.20÷50mm; iii) Pavement
 295 contact: Contactless devices; iv) Principle of operation: Laser profilometer; v) Objective Focal
 296 Length: 100mm; vi) Max Vertical measuring range: 35mm; vii) Vertical resolution for class
 297 0.003÷0.03 mm: 0.012mm; viii) Stand-off distance: 90mm; ix) Minimum horizontal resolution Δx
 298 (sampling interval) BD for class 0.05÷1 mm: 0.01mm; x) Angle coverage: 170° (Praticò et al., 2013
 299 [12]).

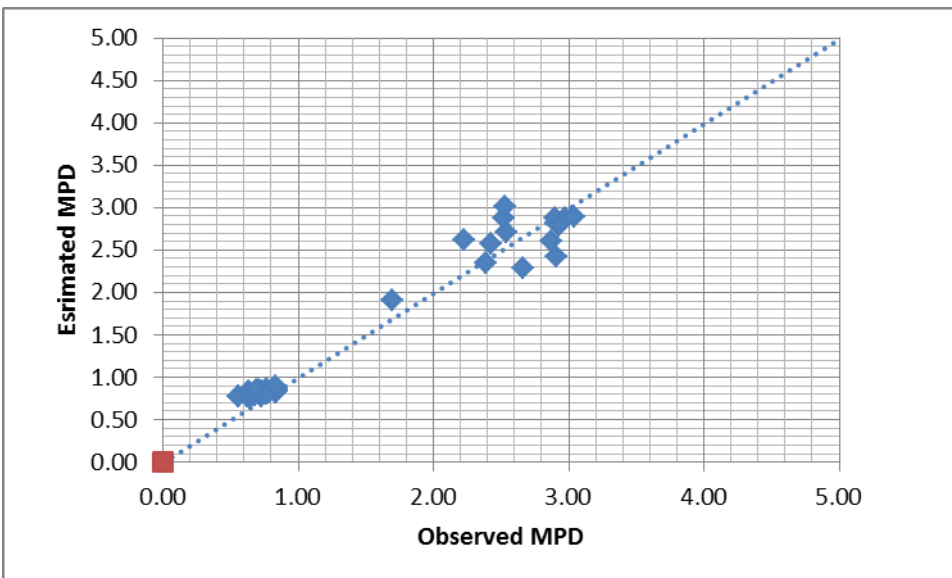
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301
302 *Figure 4. Sand patch (right) and laser (left) measurements for surface S2 (see table 1).*
303

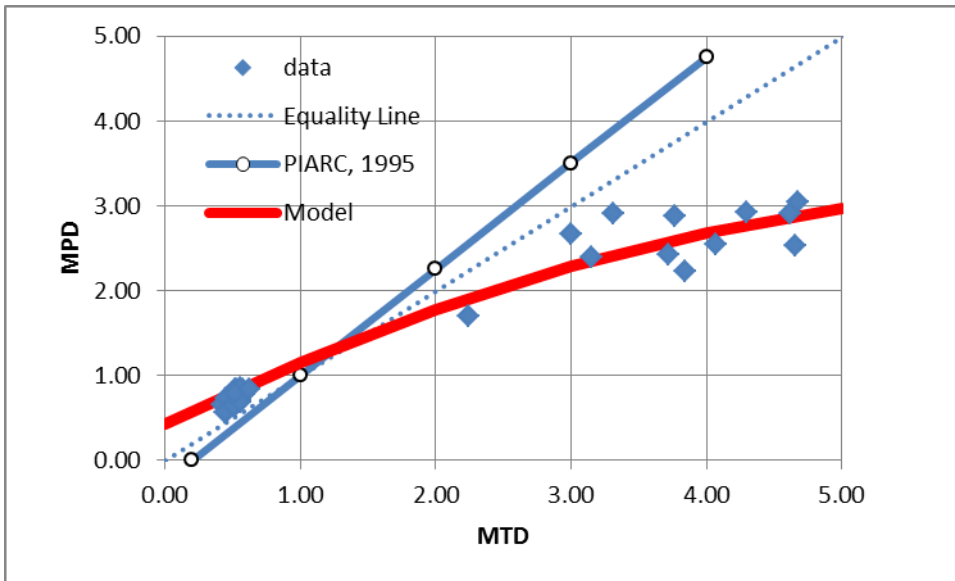
304 Model input-output transformations (input data versus macrotexture prediction) were compared to
305 corresponding input-output transformations for the data derived through the new experiments,
306 herein carried out.

307 Figure 5 and 6 illustrate how the curve formerly calibrated fits the new data.



308
309 *Figure 5. Observed versus estimated MPDs for the validation data set (see table 1).*
310

311



312
313
314

Figure 6. Validation data set and fitting curve (see table 1).

315 Table 2 and Figure 7 summarise experiments and analyses. They summarise all the data and
316 information gathered in the literature and through the experiments and how obtained results related
317 to them.

318 As for the three coefficients of the polynomial, note that d ranges from -0.11 to -0.05, e ranges from
319 0.75 to 1.25, and f ranges from -0.25 to 0.43. Importantly, these dominions are affected by the
320 theoretical predictions more than by data fitting, being -0.11, 1.25 and -0.25 values obtained in the
321 aim of obtaining a good consistency with PIARC, 1995 experiment (in which dense-graded mixes
322 were used).

323 As for MPD and MTD averages (1.4-1.7mm versus 1.8-2.0 mm) and standard deviations (0.7-
324 0.9mm versus 1.3-2.1mm) they appear to be quite consistent and reasonable and able to assure a
325 consistent process of model building, calibration and validation.

326 By referring to the significance of the correlations (four cases in Table 2), note that:

- 327 i) R^2 is the R-square value: the higher it is, the higher the significance is; 0.05 and 0.01
328 are the significance levels commonly used;
- 329 ii) N is the number of data used (sample size): the higher N, the higher is the significance;
- 330 iii) the p-value reported in table 2 represents the probability of making the “wrong
331 decision”, i.e. a decision to reject the null hypothesis (the two variables are not
332 correlated) when the null hypothesis is actually true (Type I error, or “false positive
333 determination”). The smaller the p-value is, the more significant the result is said to be;
- 334 iv) being $p < 0.01$, it is confirmed that the correlations are significant at a 1% level of
335 significance.

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340 Table 2. Summary of experiments and analysis

	Unit	Overall	Calibration	Validation	Simplified model
d	mm ⁻¹	-0.05	-0.05	-0.05	-0.109
e	-	0.76	0.78	0.78	1.250
f	mm	0.39	0.43	0.43	-0.250
R ²	-	0.95	0.94	0.96	0.93
N	-	76	35	40	76
t* derived	mm	7.2	7.1	7.1	5.7
Average MPD	mm	1.5	1.7	1.4	1.5
Standard deviation of MPD	mm	0.9	0.7	0.9	0.9
Average MTD	mm	1.9	2.0	1.8	1.9
Standard deviation of MTD	mm	1.8	1.3	2.1	1.8
Significance (p-value)	-	8.9E-51	6.3E-23	6.6E-30	3.35E-44

Legend. Overall: results obtained using all the data in Table 1. Calibration: results obtained using calibration data in Table 1. Validation: results obtained using validation data in Table 1. Simplified model: equation 3. d, e, f: coefficients in equation 5. R²: coefficient of determination (indicates how well data fit the model); N: number of data used. t*: fraction of the thickness obtaining from $2dt^*+e=0$. Average MPD, MTD, Standard deviation of MPD, MTD: position and dispersion characteristics of the data set in Table 1. Significance: p-value, which is the probability of observing the effect given that the null hypothesis is true (results have occurred by chance alone). If $p<0.05$, then the result is statistically significant.

341

342 Figure 7 shows the impact of parameters adjustment on the second-order polynomial.

343 It is important to observe that the simplified model in Table 2 and Figure 7 refers to the polynomial
 344 based on PIARC 1995 (Wambold et al. 1995 [43]) straight line ($MTD=q+m \cdot MPD$, with $m=0.8$;
 345 $q=0.2$; $e=m/0.8$; $f=q=-0.2/0.8$), and was set up in order to carry out comparative analyses,
 346 considering both PIARC 1995 straight line ($MTD=0.2+0.8MPD$) and purely statistical studies.

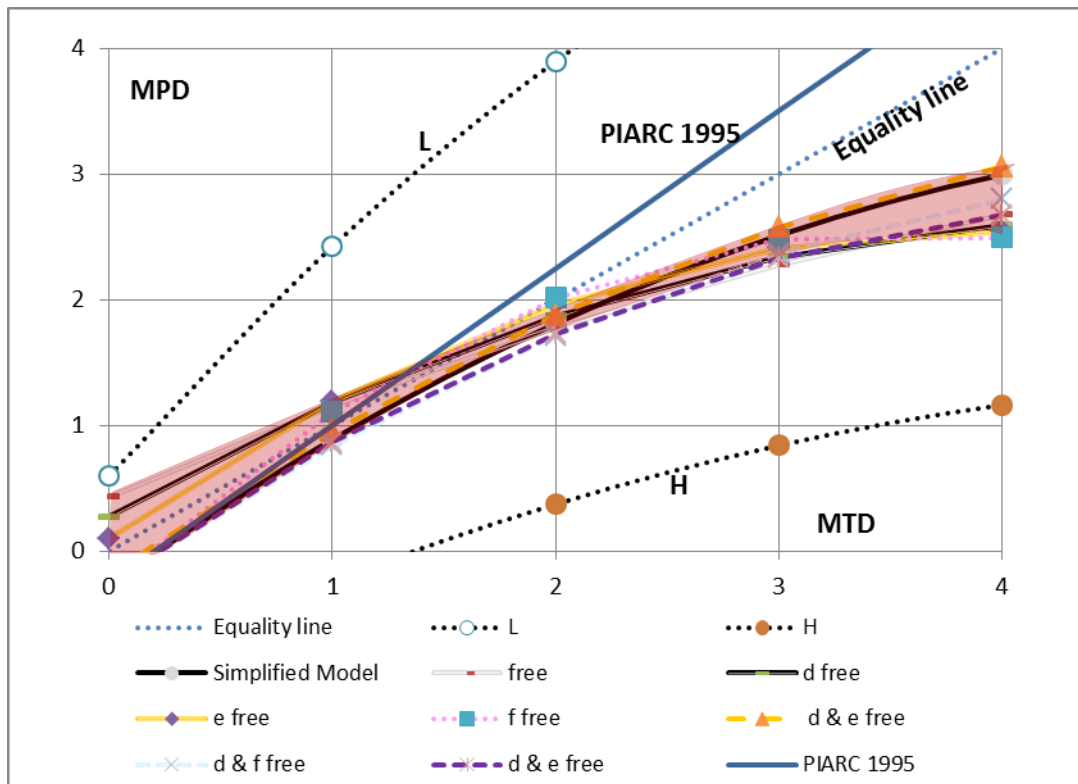
347 To this end, in Figure 7, the following twelve curves are considered: i) equality line; ii and iii)
 348 polynomials based on the lowest (L) and highest (H) m and q in the literature (based on equation 4,
 349 in this case no optimization was carried out; see curves L and H); iv) simplified model as *per*
 350 equation 3; v) polynomials in which the adjustable parameters d, e, f were adjusted in order to
 351 "best" fit the data through the least squares method (d, e, f "free", see equation 5); vi) polynomials
 352 in which the adjustable parameter d was set free and remaining parameters were fixed based on
 353 PIARC 1995 (Wambold et al. 1995 [43]) straight line (i.e., $e=1/0.8$; $f=0.2/0.8$); vii) e free (and
 354 remaining parameters constrained, based on PIARC 1995); viii) f free (and remaining fixed based
 355 on PIARC 1995); ix) d & e free (and remaining fixed based on PIARC 1995); x) d & f free (and
 356 remaining fixed based on PIARC 1995); xi) d & e free (and remaining fixed based on PIARC 1995);
 357 xii) PIARC 1995 straight line.

358 In summarising in Figure 7 there are two types of curves: four reference curves (Curves H, L,
 359 Equality line, PIARC 1995) and eight curves derived in this paper (the remaining ones).

360 Results in Figure 7 confirm that all the above (seven) solutions (each one obtained by adjusting the
 361 parameters of equation 5 to best fit the same data set) resulted in curves close to the case

362 “Simplified model” (equation 3). This fact means that the new algorithm has a good level of
 363 consistency with the previous literature and extends to the dominion of innovative and more open
 364 mixes the relationship between volumetric-based and laser-based indicators.

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Figure7. Impact of parameters adjustment on the second-order polynomial

368 **4. Conclusions**

369 It is well known that pavement texture impacts surface performance, tyre-vehicle interaction and
 370 road safety.

371

372 Texture in the range of wavelengths between 0.5 and 50mm is termed macrotexture and can be
 373 assessed in terms of MPD (2D derivation, based on ISO 13473-1 [1] and ASTM E 1845 [2]) and
 374 MTD (3D – derivation, based on ASTM E965 [3] or EN 13036-1 [4]).

375 Based on the model set up and on the experiments and studies carried out it is possible to
 376 conclude that:

- 377 • There is an evident divergence from linearity when open-graded mixtures are
 378 considered. MPD and sand patch texture measure different properties and linear
 379 correlations seem not to represent effectively this complexity and dissimilarity.
- 380 • There is a reasonable consistency of the majority of the studies conducted in the past
 381 when only DGFCs are considered.
- 382 • The divergence between laser-based and volumetric-based macrotexture indicators
 383 (when open-graded wearing courses are considered) has quite simple explanations and
 384 physical reasons. It originates from the fact that the laser works in a two-dimensional

- 385 scenario, while the sand patch method has rational behind which is three-dimensional
386 and more complex.
- 387 • A generalised and simple model has been set up and validated. It fits the data of a wide
388 spectrum of wearing course types without neglecting the fundamental achievements
389 which refer to the curves derived in the past.

390 Future research will focus on the following main issues: a) considering other advanced materials
391 such as Porous Elastic Road Surfaces, which imply higher values of air voids content and surface
392 macrotexture; b) considering other types of wearing courses in the area of intermediate
393 macrotexture (bituminous surface treatments, etc.); c) investigating in more detail the possible
394 relationship between the overall model (MPD versus MTD) and the advanced modelling of granular
395 flows and water flows.

396 Further investigations will be also needed in the area close to the origin of the axes (ideally
397 compact HMAs, very low values of MTD and MPD), where procedures and equipment precision
398 can greatly affect the studies.

399 It is supposed that results outcomes of this research can benefit both researchers and
400 practitioners.

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