

# Impact of Asphalt Mixture Specification Limits: A Theoretical Analysis

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## 1 The Impact of Asphalt Mixture Specification Limits: A Theoretical Analysis

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## 22 Abstract

23 Specifications limits and tolerances are crucial in the relationships among contractor, road agency, and citizens,

because they impact profits, acceptance procedures, and pavement durability. They mainly depend on 24 25 processes involved and unfortunately their relationship with durability is mainly empirical and calls for further investigation. In the light of the above, the study described in this paper deals with assessing how durability 26 27 and pay adjustment are affected by variations of the explanatory variables (e.g., air void content) within 28 specification limits. A model was set up in order to assess the impact on the modulus of a bituminous mixture, 29 which is a crucial factor for the expected life. The model was applied to a well-known set of contract specifications, in order to check for their suitability and rationale. Results demonstrate that, usually, air void-30 31 related consequences are worse than penetration-related consequences, which, in turn, outrank aggregate gradation and asphalt content-related consequences. An exception is given by the maximum size of aggregates. 32 Furthermore, when pay adjustments build on empirical algorithms, they have to be layer-specific because the 33 same "error" implies severer consequences in deeper layers. Results can benefit both researchers and 34 35 practitioners.

## 36 Introduction

37	The dynamic modulus of a bituminous mixture (supposed to act as a linear viscoelastic material) is a complex							
38	number and is an important parameter in the design procedure because it affects the expected life of asphalt							
39	pavements (Colonna et al., 2012; Clyne et al. 2003). Its absolute value is calculated as the peak stress amplitude							
40	$(\sigma_0)$ divided by the peak amplitude of recoverable axial strain ( $\epsilon_0$ , cf. NCHRP Report 465). Stress and strain							
41	distribution depend on moduli. Importantly, the impact of modulus on expected life is multifaceted because							
42	many other parameters affect these relationships: 1) higher moduli may correspond to lower strains (Shahadan							
43	et al., 2013); 2) at the same time they may correspond to lower fatigue cracking performance; 3) furthermore,							
44	lower performance to thermal cracking is expected.							
45	Many authors have proposed algorithms to estimate the dynamic modulus based on nonlinear regressions,							
46	semi-empirical methods or rheological models. Input data are typical asphalt mixture parameters that refer to							
47	volumetric properties, aggregate gradations, test conditions (i.e. temperature and loading frequency) and							
48	asphalt binder (i.e. viscosity and percentage).							
49	Among the models in the literature, the following can be listed:							
50	i.	Nielsen Model, 1970 (Nielsen 1970, Riccardi 2017), based on mortar characteristics (fine aggregates						
51		+ bitumen);						
52	ii.	Asphalt Institute, 1982 (Asphalt Institute 1982, Giuliana et al. 2011);						
53	iii.	Witczak - NCHRP 1-40D model, 1996 (Witczak and Fonseca1996, Yu 2012, Riccardi 2017) or						
54		Witczak-ban model, where the dynamic shear modulus and the phase angle of the asphalt binder are						
55		used;						
56	iv.	Witczak 1-37A model, or Witczak-Andrei model, 1999 (Andrei et al. 1999, Yousefdoost et al. 2013,						
57		cf. eq. 1);						
58	v.	Hirsch Model, 2002 (Christensen et al. 2015, Riccardi 2017), that is based on VMA, VFA and $G_b$ ;						
59	vi.	Lee et al. 2002, based on Witczak 1-37A model;						
60	vii.	Alkhateeb Model, 2006 (Alkhateeb et al. 2006, Yousefdoost et al. 2013), that involves voids of mineral						
61		aggregates, VMA, and the shear modulus of the asphalt binder, G <sub>b</sub> ;						
62	viii.	Cho et al., 2010, where the dynamic modulus is a function similar to the one of the Witczak 1-37A						
63		model, but depends linearly on $\rho_{200}$ (Cho et al. 2010, Georgouli et al. 2016);						

64 ix. Seo et al., 2013, based on Witczak 1-37A model and FWD data;

- 45 x. Leiva-Villacorta et al. 2013, based on artificial neural networks and on Witczak 1-37A model;
- 66
- 67 Note that they basically refer to four main families: Nielsen, Asphalt Institute, Hirsch, and Witczak.
- The 1999 Witczak model (1-37A, Yu 2012) is based on nonlinear regressions, derived by analyzing 205 laboratory mixtures (171 unmodified asphalt binders and 34 modified binders), for a total of 2750 data points. The model predicts the dynamic modulus E\* (psi) of HMA mixtures based on eight main input parameters that describe loading condition, aggregate gradation, asphalt binder characteristics and interaction with aggregates.
- 72

$$\log \left| E^* \right| = 3.750063 + 0.02932 \cdot \rho_{200} - 0.001767 \cdot (\rho_{200})^2 - 0.002841 \cdot \rho_4 - 0.058097 \cdot AV + 0.00208 \cdot \left( \frac{V_{beff}}{V_{beff} + AV} \right) + \frac{3.871977 - 0.0021 \cdot \rho_4 + 0.003958 \cdot \rho_{3/8} - 0.000017 \cdot (\rho_{3/8})^2 + 0.00547 \cdot \rho_{3/4}}{1 + e^{(-0.603313 - 0.313351 \cdot \log(f) - 0.393532 \cdot \log(\eta))}}$$
(1)

74

In the equation above,  $|E^*|$  is the absolute value of the dynamic modulus [psi], (1psi = 0.0069MPa],  $\eta$  is asphalt binder viscosity [10 Poise = 1 Pas], *f* is the loading frequency [Hz], AV is the air void content [%], V<sub>beff</sub> is the effective asphalt binder content [% by volume],  $\rho_{3/4}$  is the cumulative % retained on the 19 mm (3/4 inch) sieve,  $\rho_{3/8}$  is the cumulative % retained on the 9.5 mm (3/8 inch) sieve,  $\rho_4$  is the cumulative % retained on the 4.75 mm (No. 4) sieve, and  $\rho_{200}$  is the percentage passing through the 0.075 mm (No. 200) sieve.

- For the viscosity, it can be assessed based on experiments or it can be predicted through models, such as the
  one below (Yu 2012):
- 82

83 
$$\log(\eta) = 10.5012 - 2.2501 \cdot \log(Pen) + 0.00389 \log(Pen)^2$$

- 84
- Where η is the viscosity [Poise], Pen [0.1mm] refers to the penetration of a standard needle of 100 g, which
  penetrates the asphalt binder for 5 seconds.
- Even if modulus derivation is a complex topic (Garcia and Thompson 2007, Cross at al. 2007, Esfandiarpour
  and Shalaby 2017, Praticò et al. 2016), Witczak model is an excellent solution for a given real mixture but, for
  the purpose of this paper, it is not possible to consider input parameters as "independent". Indeed, changing a

(2)

single variable implies variations on other input parameters (i.e., explanatory variables). In particular: i) aggregate gradation ( $\rho_{3/4}$ ,  $\rho_{3/8}$ ,  $\rho_4$  and  $\rho_{200}$ ) influences bulk specific gravity and apparent specific gravity of aggregates ( $G_{sb}$  and  $G_{sa}$ ); ii) asphalt content ( $P_b$ ) and asphalt binder specific gravity ( $G_b$ ) influence the percentage of absorbed asphalt ( $P_{ba}$ ), the volume of absorbed asphalt binder ( $V_{ba}$ ), the effective asphalt content ( $P_{be}$ ), and the volume of effective asphalt binder content ( $V_{beff}$ ); iii)  $P_b$  and  $G_b$  influence the maximum theoretical specific gravity of the mixture ( $G_{mm}$ ). For example, a variation of asphalt content or of the passing  $\rho_{200}$  implies a change of the air voids and consequently of the dynamic modulus.

97 Based on the above, the reciprocal relationships among the explanatory variables cannot be overlooked for a98 proper modulus estimation.

99

## 100 **Objectives**

In the light of the issues above, the study described in this paper aims at studying the effect of the variation of the main contract variables (e.g.,  $\rho_{200}$ ) within the range permitted by contract specifications and tolerances. This includes: i) assessing the effects on moduli, expected life and pay adjustment, based on the synergistic consideration of the mutual effects among the different explanatory variables which impact estimation models; ii) Proposing and applying a criterion for deriving specification limits well-grounded in logic.

106 The main tasks of this study were the following:

- Task 1: Modelling (section below). In this task, due to the interdependency among several variables
   of the algorithm for the derivation of moduli, a model was set up to derive the value of G<sub>mb</sub> based on
   a number of inputs.
- Task 2: Derivation and discussion of model outputs. In this task, the derivation of mechanistic
   properties, expected life and pay adjustment was carried out as a function of each contract variable.
   Based on the equations set up, consequences in terms of pay adjustment were inferred.
- Task 3: Conclusions and recommendations (last section). In this task, analyses were carried out and
   recommendations were derived.

## 116 Modelling

117 The Flow chart in Fig. 1 illustrates the conceptual framework to derive a layer modulus. In more detail, the 118 synergistic effect of gradation percentages and construction on volumetrics is depicted. It summarizes the path 119 towards the derivation of the modulus of a layer in terms of the Witczak model and clearly illustrates that 120 multiple phenomena of linear or non-linear correlations between couples of explanatory variables are present

- 121 (risk of multicollinearity). For example,  $P_b$  affects both  $V_{beff}$  and AV, which are inversely correlated.
- Apart from the quality characteristics of asphalt binder (Pen,  $\eta$ ) and load frequency, gradation affects  $\rho_i$ ,  $G_{sb}$ , as well as  $G_{sa}$  and  $G_{se}$ . This latter affects  $G_{mm}$  (together with  $P_b$  and  $G_b$ ).  $G_{mb}$  depends on  $G_{mm}$ , on  $P_b$ , and on compaction effort (N). From  $G_{mm}$  and  $G_{mb}$ , AV can be derived, while based on  $P_b$ ,  $G_b$ , and stone specific gravities ( $G_{sb}$ ,  $G_{se}$ ,  $G_{sa}$ ), absorbed ( $V_{ba}$ ,  $P_{ba}$ ) and effective asphalt binder ( $V_{eff}$ ,  $P_{be}$ ) can be derived.
- The main relationships among the explanatory variables of Witczak model are summarized below (symbols
  are explained in Fig. 1). Equations below refer to gradation and specific gravity (Sukirman 2010, Arifin et al.
  2015, McGennis et al. 1995):
- 129
- 130  $\rho_{3/4} = 100 P_{19mm}$
- 131  $\rho_{3/8} = 100 P_{9.5mm}$

132 
$$\rho_4 = 100 - P_{4.75mm}$$
 (5)

133 
$$G_{sb} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} \frac{P_i}{G_i}}$$
 (6)

$$134 \qquad G_{se} = G_{sb} + cf \cdot (G_{sa} - G_{sb}) \tag{7}$$

135

P<sub>s</sub>-P<sub>b</sub> volumetric parameters follow the well-known relationships (Al-Khateeb et al. 2006, California Test
Number 2010, and WAQTC TM 13 2012):

138

$$139 \qquad P_s = 1 - P_b \tag{8}$$

(3)

(4)

140 
$$G_{nnn} = \frac{1}{(\frac{P_s}{G_{se}}) + (\frac{P_b}{G_b})}$$
 (9)

141 
$$P_{ba} = \frac{G_{se} - G_{sb}}{G_{sb} \cdot G_{se}} \cdot G_b \tag{10}$$

142 
$$V_{ba} = \frac{\frac{P_{ba} \cdot P_s}{100}}{G_b \cdot G_{mb}}$$

(11)

143

144 
$$V_{ba} = \frac{100 \cdot P_s \cdot \frac{1 - G_{se}}{100}}{\frac{P_b}{100} \cdot G_b + \frac{P_s}{100} \cdot G_{se}} \cdot 100 \cdot \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right)$$
(12)  
145 
$$P_{c} = P_{c} - P_{c} \cdot P_{c}$$
(13)

145 
$$P_{be} = P_b - P_{ba} \cdot P_s$$
(13)  
146 
$$V_{beff} = \frac{P_{be} \cdot G_{mb}}{G_b}$$
(14)

147 
$$AV = \frac{G_{nun} - G_{mb}}{G_{nun}}$$
(15)

148 
$$VMA = 100 - \frac{G_{mb} - P_s}{G_{sb}}$$
 (16)

149 
$$VFA = \frac{VMA - AV}{VMA} \cdot 100$$
 (17)

150 
$$VFA = \frac{\frac{P_{be}}{G_b}}{\frac{VMA}{G_{nb}}} \cdot 100$$
 (18)

151

152 It is worth noting that equations above depend on  $G_{mb}$ . This latter should be measured on the given bituminous 153 mixture of given  $G_{se}$ ,  $G_b$ ,  $P_b$ . For  $G_{mb}$ , based on the literature, two main synergistic effects must be considered, i.e., compaction and asphalt binder content. Low  $P_b$  values do not permit a proper lubrication of particle contacts. It follows that a proper packing is hindered and  $G_{mb}$  is reduced.

157 Higher asphalt binder contents allow optimizing the packing of particles and achieving higher values of G<sub>mb</sub>.

158 If P<sub>b</sub> exceeds a given optimal content, the lubrication effect is not anymore the most relevant factor because

159 the excessive amount of asphalt binder tends to decrease the overall  $G_{mb}$  and  $G_{mm}$ , which both tend towards

160 G<sub>b</sub>.

161 At the same time, for a given asphalt content, higher compaction efforts imply higher  $G_{mb}$  and lower air voids 162 content, AV.

163 Compaction efforts (e.g., number of passes) do not increase the  $G_{mb}$  indefinitely, this latter approaching a given 164 asymptotic value.

165 Based on the above, from a predictive standpoint, the following equation is herein set up:

166

167 
$$G_{mb} = \left[ a \left( \frac{P_b}{100} \right)^2 + b \left( \frac{P_b}{100} \right) + c \right] \cdot \left[ d + (1 - d) \exp(N\% - 1) \right]$$
(19)



- Based on the synergistic derivation of the volumetric indicators, moduli were derived through eq. (1) (Cf. Fig.1, Yu 2012).
- 178 Poisson coefficients were derived based on the literature (Rojas et al. 1998, Popovics 2008, Maher and Bennert
- 179 2008, Xiao 2009, Pezzano 2009, Houben 2009, Jung et al. 2012, Ghadimi et al. 2013, Hanifa et al. 2015).

180 For the derivation of the expected life, the software KenLayer was used (Huang 2004). This software analyzes pavements based on multi-layer elastic theory under a circular loaded area. KenLayer can be applied to layered 181 182 systems under single, dual, dual-tandem, or dual-tridem wheels. To analyze pavements using KenLayer 183 software, the inputs required are section, geometry, material properties and wheel load. The main outputs are 184 stresses, deflections, and design life. Damage analysis can be made by dividing each year into a maximum of 185 12 periods, each with a different set of material properties. The geometry and moduli of the pavement are 186 reported in Fig. 3 and Table 1 and, in order to obtain an as-design life of 20 years, a traffic load of about 15 187 million TNRL (total number of load repetitions for each load group during each period) is considered.

Authors are aware of: 1) the dependence of outputs on traffic configurations, pavement structures, and local environment; 2) the dependence of moduli on the given algorithm; 3) the existence of different versions of the Witczak model, intended to adapt this latter to porous asphalt concretes (Giuliana et al. 2011, Geourgouli et al. 2016).

192 To this end, it is worth noting that the analyses carried out in this study aim at highlighting the impact of 193 specification limits on expected life under given hypotheses.

194

#### 195 *Cost Modelling*

The expected life is a key-factor in the Life Cycle Cost Analyses (LCCA or LCC) of the pavement. LCCA is 196 a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and 197 discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing 198 costs, over the life of the project segment (Walls and Smith 1998). Minimizing the pavement life cycle costs 199 will increase the sustainability of the pavement system (Praticò 2016). LCCA includes agency costs (AC), 200 201 which include initial preliminary engineering, contract administration, construction supervision and 202 construction costs, as well as future routine and preventive maintenance, resurfacing and rehabilitation costs, 203 salvage values, and sunk costs.

ACs affect the present value (PV) of agency costs (i.e. the future amount of expenses, discounted to reflect the current value, Praticò 2016). The difference between the PV referred to the rehabilitation works of the design pavement and the PV referred to the modified pavement (i.e., changing percentage of mix aggregates, percentage of asphalt binder or its penetration) is the pay adjustment (PA), which is defined as "the actual amount, either in dollars or in dollars per area/weight/volume, which is to be added or subtracted to the contractor's bid price or unit bid price" (Hughes et al. 2011).

210 For PV, the following equations were applied:

211

212 
$$PV_{REH} = C_{REH} \frac{\left(R^D - R^{EXL}\right)}{1 - R^D}$$
(20)

213 
$$PV_{RES} = C_{RES} \frac{R^0}{1 - R^D}$$
(21)

214

215 Where:

- R is the ratio between (1+i) and (1+r), where, for example, i=0.04 (inflation rate) and r=0.08 (interest

217 rate).

218 -  $C_{REH}$  refers to costs occurred in successive rehabilitations [ $\epsilon/m^2$ ].

219 - C<sub>RES</sub> refers to costs occurred in successive resurfacings [€/m<sup>2</sup>].

D is the expected life of the as-design pavement [years]. In more detail, D is the minimum expected
 life of the different layers of the pavement. D does not take into consideration the friction course (which will
 usually undergo its failure in a time that is smaller than D);

EXL=EREH is the expected life of the as-constructed pavement [years]. EXL corresponds to D (but it
 refers to the as-built pavement), in the sense that EXL does not take into consideration what happens to the
 friction course;

O=EXLFC=ERES is the expected life of the as-constructed friction course [years]. In other words, it
 is the time between two successive resurfacings (FC, typically 10 years).

In the next figures (results of the analysis), the ratios  $PA_{REH}/C_{REH}$  and  $PA_{RES}/C_{RES}$  were used. If these ratios are positive, they represent a bonus. If not, they represent a penalty. Finally, it is worth pointing out that: 1) in this case, due to the nature of the simulation (carried out on the "boundaries", specification limits), random sampling through Monte Carlo simulation was not used (Wu et al. 2017). 2) even if pay factors based on expected life are complex to apply, their use is here needed in the pursuit of objectives.

## 234 Simulations and discussion

In the pursuit of the objectives stated above, the pavement structure in Fig. 3 and Table 1 was considered (AsDesign Pavement). Additionally, in Table 1, reference moduli and thicknesses gathered from the literature are
reported.

238

#### 239 Friction Course (FC)

- This section deals with the effects deriving from the variation of the main characteristics of FC (Porous AsphaltConcrete, PAC, cf. Fig. 4 to Fig. 6).
- X-axes refer to the parameter under investigation (i.e., parameter which is supposed to vary in a certain rangebut that may undergo variations outside the specification limits).
- Y-axes refer: i) to the expected life of the pavement, EXL (i.e., by referring to rehabilitations). Usually the cement-treated base course was the cause of the pavement failure; ii) to the pay adjustment of the pavement (part referred to rehabilitations,  $PA_{REH}$ ) expressed as a percentage of the corresponding cost ( $C_{REH}$ ), i.e., PA<sub>REH</sub>/C<sub>REH</sub>, eq. (20). It is noted that for the case under investigation C<sub>REH</sub> includes the cost of friction course, binder course, base course, and cement-treated base course; iii) to the pay adjustment for resurfacing (PA<sub>RES</sub>), expressed as a percentage of the corresponding cost ( $C_{RES}$ ), i.e., PA<sub>RES</sub>/C<sub>RES</sub>, eq. (21). Note that C<sub>RES</sub> refers to the cost of the FC.
- P<sub>3/4</sub> (Fig. 4-A) refers to the passing through the 3/4-inch sieve, which corresponds to  $100-\rho_{3/4}$ , where  $\rho_{3/4}$  is the cumulative percentage retained on the 19 mm (3/4 inch) sieve (cf. eq. 1).
- Note that the default value is  $P_{3/4}=100$ , which corresponds to an EXL of 20 years and to a PA% of zero. Lower values imply higher expected lives (Fig. 4-A, left y-axis) and then positive PAs (<1%, Cf. Fig. 4-A, right yaxis).
- Fig. 4-B refers to the effects of nonconformities of  $\rho_{3/8}$  (9.5mm sieve), where the default value is  $P_{3/8}$ = 37.5% (that corresponds to a value of 62.5% for  $\rho_{38}$  and to EXL=20,  $PA_{REH}$ =0%,  $PA_{RES}$ =0%). Higher values imply a reduction of the expected life (negative  $PA_{REH}$  and  $PA_{RES}$ ), while lower values may imply an increase ( $P_{3/8}\approx13$ -20) or a relative decrease ( $P_{3/8}\approx20$ -38, approximately). Note that if  $P_{3/8}$  is higher than about 20% (and lower

- than the default value)  $PA_{REH}$  and  $PA_{RES}$  are positive (bonus), while for  $P_{3/8}$  close to 20%, both  $PA_{REH}$  and PA\_{RES} approach a maximum (optimal condition).
- Fig. 4-C focuses on  $\rho_4$  (4.76 mm sieve) with a default value of P<sub>4</sub>=18.5% (that corresponds to a cumulative %
- retained of 81.5 for  $\rho_4$ ). Higher values of P<sub>4</sub> (>18.5%) imply an increase of expected life, PA<sub>REH</sub>, and PA<sub>RES</sub>.

Instead, for lower values of  $P_4$  (< 18.5%), expected life,  $PA_{REH}$ , and  $PA_{RES}$  are reduced.

Fig. 5-A refers to the effects of nonconformities of  $\rho_{200}$  (% passing through the 0.075 mm sieve), with a default

266 value of  $P_{200} = \rho_{200} = 10\%$ .

267 Expected life, PA<sub>REH</sub> and PA<sub>RES</sub> have a "weak" parabolic behavior, with maxima corresponding to 8%. It is

interesting to note that for passing percentages higher than 18%, the expected life shows a sharp reduction,

with values of 0.1 years. This type of nonconformity corresponds to the failure of the friction course.

- Fig. 5-B refers to the effects of asphalt binder penetration, where the default value is 60 (0.1 mm).
- 271 Expected life, PA<sub>REH</sub>, and PA<sub>RES</sub> have a nonlinear behavior. In particular, for penetrations higher than 60, the

expected life is lower and PA<sub>REH</sub> and PA<sub>RES</sub> have a negative sign. On the contrary, for penetrations lower than

273 60, the expected life is higher and  $PA_{REH}$  and  $PA_{RES}$  become positive.

Fig. 5-C focuses on asphalt binder percentage and its effect on expected life (y-axis, left), PAREH% (y-axis,

right), and PA<sub>RES</sub>% (y-axis, right). Note that asphalt binder percentages higher than the default value (=4.76)

- imply higher EXL and positive PAs, and *vice versa*. Importantly, the model seems to underestimate rutting
- and plastic deformations for asphalt binder percentages which exceed 8-10%.
- Fig. 6-A illustrates the EXL and the PA compared to air voids (AV). The curves are monotonically decreasing

and higher values of AV imply lower values of EXL and of PA. In particular, for AV higher than about 22%,

pavement failure is due to the breaking of the friction course. Instead, for AV close to 7%, the failure occursin the base course.

282

#### 283 Binder Course (BIC)

284 This section deals with effects (on the pavement) caused by BIC characteristics (Figures 4-6).

285 Fig. 4-D refers to  $100-\rho_{3/4} = P_{3/4}$ .

In the case of the BIC, the default  $P_{3/4}$  is 78%. Higher values of passing (> 78%) imply a reduction of expected

287 life, of PA<sub>REH</sub>, and PA<sub>RES</sub>. Instead, for lower values (< 78%), the expected life, PA<sub>RES</sub>, and PA<sub>RES</sub> are higher.

- Fig. 4-E focuses on 9.51 mm sieve, with a default value of 57.5% (that corresponds to a cumulative % retained of 42.5 for  $\rho_{3/8}$ ). Unlike the case of the friction course, the behavior of the expected life, of PA<sub>REH</sub>, and PA<sub>RES</sub> is linear and without maxima. In particular, higher values (> 57.5%) imply a reduction of expected life, PA<sub>REH</sub>,
- and  $PA_{RES}$ . Instead, for lower values (< 57.5%), the expected life,  $PA_{RES}$ , and  $PA_{REH}$  are higher.
- Fig. 4-F focuses on  $P_4$  (4.76 mm sieve) with a default value of 42.5% (that corresponds to a cumulative %
- retained of 57.5 for  $\rho_4$ ). The linear behavior of expected life, PA<sub>REH</sub>, and PA<sub>RES</sub> is similar to the one for the
- case of the friction course, where higher values of passing (> 42.5%) imply the increase of expected life,
- 295 PA<sub>REH</sub>, and PA<sub>RES</sub>. Instead, for lower values (< 42.5%), EXL, PA<sub>RES</sub>, and PA<sub>RES</sub> decrease.
- Fig. 5-D refers to the effects of nonconformities of  $\rho_{200}$  (0.075 mm sieve), where the default value is 6 %.
- 297 Expected life, PA<sub>REH</sub> and PA<sub>RES</sub> have a parabolic behavior, with maxima corresponding to 8%. In particular,
- in the range 6-10%, EXL is higher than 20 years, and PA<sub>REH</sub> and PA<sub>RES</sub> are positive. In contrast, in 0-6% and
- 299 10-16%, EXL decreases, while PA<sub>REH</sub> and PA<sub>RES</sub> are negative.
- Fig. 5-E refers to the effects of asphalt binder penetration, where the default value is 90 (0.1 mm).
- 301 Expected life, PA<sub>REH</sub> and PA<sub>RES</sub> have a trend that is similar to the one of the friction course (Fig. 5-B).
- 302 Fig. 5-F refers to the variation of the asphalt binder percentage, with a default value of 4.5%. For a value of  $P_b$
- higher than 1.5%, the expected life varies in the range 16-21 years. Instead, for a P<sub>b</sub> lower than 1.5%, expected
- 304 life and pay adjustment have a sharp reduction.
- Regarding the binder course (see Fig. 6-B), the trend of EXL and PA with respect to the air void is similar to the one observed for the friction course, with a monotonically decreasing behavior. It is interesting to note that for values of AV higher than 18% the failure of the pavement is due to the BIC. In contrast, if AV is in the range 12.5-18%, the BAC undergoes a premature failure. Finally, if AV is lower than 12.5%, the failure is due to the cement-treated course (CT).
- 310

#### 311 Base Course (BAC)

Fig. 4-G focuses on  $\rho_{3/4}$  (100-P<sub>3/4</sub>). In the case of BAC, the default value of the percentage passing through the 19 mm sieve is 72% and the behavior is similar to the one of BIC. Fig. 4-H refers to  $P_{3/8}$  (9.51 mm sieve) with a default value of  $P_{3/8}=52.5\%$  (that corresponds to a cumulative % retained of 47.5 for  $\rho_{3/8}$ ). Like the case of the friction course, the behavior of the expected life, of  $PA_{REH}$ , and PA<sub>RES</sub> is nonlinear with maxima at 45.5%.

Fig. 4-I focuses on 4.76 mm sieve with a default value of  $P_4=40$  % (that corresponds to a cumulative % retained

318 of 60 for  $\rho_4$ ) and the linear behavior of expected life, PA<sub>REH</sub>, and PA<sub>RES</sub> is similar to the one of the friction

319 course and of the binder course.

Fig. 5-G refers to the effects of nonconformities of  $\rho_{200}$  (0.075 mm sieve), where the default value is 5.5%.

321 Expected life, PA<sub>REH</sub>, and PA<sub>RES</sub> have a parabolic tendency, with maxima corresponding to 8%.

322 Fig. 5-H focuses on the effects of asphalt binder penetration, with a default value of 90 (0.1 mm).

323 Expected life, PA<sub>REH</sub> and PA<sub>RES</sub> have a nonlinear behavior with maxima at about 70. It is interesting to note

that between 50 and 70, PA<sub>REH</sub>, and PA<sub>RES</sub> increase. In contrast, for penetrations higher than 90, expected life,

325 PA<sub>REH</sub> and PA<sub>REH</sub> decrease and the damaged layer is the CT (PA<sub>REH</sub> and PA<sub>REH</sub> are negative). For penetrations

in the range 70-90, EXL decreases but PA<sub>REH</sub> and PA<sub>RES</sub> are positive and the failure is still occurring in the
base course.

Fig. 5-I refers to the variation of the asphalt binder percentage. For a value of P<sub>b</sub> higher than 2%, the expected life varies into the range 16-21 years. In contrast, for a value of P<sub>b</sub> lower than 2%, expected life and pay adjustment have a sharp reduction.

Fig. 6-C refers to the effect of air voids on EXL and on PA. The trend shows a maximum corresponding to AV=4.5%. In particular, for AV between 1.7% and 4.5%, EXL and PA increase and the pavement failure is due to the BIC. When AV is in the range 4.5-12.2%, EXL and PA decrease and the failure occurs in the CT. Finally, if AV is higher than 12.2%, EXL and PA continue to decrease, but the pavement failure is due to the

335 BAC.

336 It seems relevant to observe that in some cases EXL has a convex behavior instead of a linear one (e.g., BIC

337 penetration). This happens, for example, when considering the consequences deriving from nonconformities

- 338 of asphalt binder penetration in BIC or in BAC (cf. Fig. 5-E and Fig. 5-H, respectively).
- 339 The rationale behind this convexity is a change in the layer that prematurely fails.

- 340 For example, Fig. 7 (A and B) illustrates how the EXL of the pavement (y-axis, which usually derives from
- the EXL of the deep layers, e.g., unbound base, CT, and BAC) varies when there is a defect of the grade of the
- 342 asphalt binder (x-axis), with respect to the as-design value (6mm for the FC, 9mm for BAC and BIC).
- 343 X-axes refer to the difference between real and as-design penetration.
- Fig. 7 (A and B) points out a different behavior for low values of penetration: linearity, in the case of the binder
- course (Fig. 7-B, BIC), versus convexity in the case of the base course (Fig. 7-A, BAC).
- 346 The rationale behind the difference above is that very low penetration values in the BAC imply a premature
- failure of BAC over CT (see Fig. 7-A). In turn, this fact implies the transition from the straight line of the CT
- to the straight line of the BAC, which implies the convexity. Importantly, this does not happen for the BIC andfor the FC.
- 350

## 351 Sensitivity analysis

- The analysis of the sensitivity of longevity and costs with respect to the variations of the primary variables is here carried out through two innovative parameters (cf. Fig. 8 and Table 2).
- To this end, note that the expected life of the pavement, EXL, varies when the given indicator (or explanatory variable, e.g., AV), varies between the upper and the lower specification limits (USL, LSL, respectively); for example:
- 357

$$358 \qquad EXL = EXL(AV)$$

359

As is well known, two types of specification limits can be pointed out: i) LSL<sub>JMF</sub> and USL<sub>JMF</sub>, i.e., lower and upper specification limit referred to the job mix formula (e.g., 4.75% and 5.25% in terms of asphalt binder percentage); ii) LSL<sub>specs</sub> and USL<sub>specs</sub>, i.e., lower and upper specification limit referred to contract requirements specifications for the given layer (e.g., 4.5% and 5.5%, in terms of asphalt binder percentage).

- 364 Usually, LSL<sub>specs</sub> and USL<sub>specs</sub> are very general and are a starting point for the job mix formula and for the
- 365 corresponding LSL<sub>JMF</sub> and USL<sub>JMF</sub>.

(22)

Table 2 refers to the consequences of the variations of the given indicator, (e.g., AV) within the specification limits, expressed through two parameters herein setup, i.e.,  $\Delta Y$  (in terms of years) and  $\Delta PA$  (in terms of pay adjustment).  $\Delta Y$  is the maximum variation of the expected life (years) of the pavement, for a given couple of specification limits (LSL, USL) of the given indicator. For example:

370

371 
$$\forall I \in (LSL, USL) \Delta Y = \max EXL - \min EXL$$
 (23)  
372  
373 Furthermore,  $\Delta PA$  is defined as follows:  
374  
375  $\Delta PA = |\max(AV) - \min(AV)|$  (24)  
376

377  $\Delta$ PA expresses the sensitivity of the ratio PA/C (where PA/C= (PA<sub>RES</sub>+PA<sub>REH</sub>)/(C<sub>RES</sub>+C<sub>REH</sub>), [%]) to possible 378 variations in the given indicator (e.g., AV). It depends on the corresponding gap in terms of expected lives.

Table 2 summarizes the results (ΔY and ΔPA) obtained by considering variations of gradation (ρ<sub>3/4</sub>, ρ<sub>3/8</sub>, ρ<sub>4</sub>,
ρ<sub>200</sub>), asphalt content (P<sub>b</sub>), asphalt binder penetration (Pen), or air voids content (AV), for each single
bituminous layer (FC, BIC, or BAC). Table 2 summarizes the results obtained for ΔPA and ΔY.

For example, if the AV of BAC varies in the range  $5.5 \pm 2.5$  %, then this implies variations lower than 1.71 years (EXL) and lower than 5.60% (PA/C).

By referring to the accepted range of variation with respect to the job mix formula (i.e., LSL<sub>JMF</sub>, USL<sub>JMF</sub>), note that negligible consequences are expected in terms of both expected life (< 1 year) and PA/C (< 3%). Indeed, for SL<sub>J</sub>, based on results in Table 2, note that: i) for nonconformities of  $\rho_{3/4}$ ,  $\rho_{3/8}$ ,  $\rho_4$  for the deepest bituminous layer, BAC,  $\Delta$ Y ranges from 0.43 to 1.10 years; ii) For  $\rho_{3/4}$ ,  $\rho_{3/8}$ ,  $\rho_4$  and for BIC,  $\Delta$ Y ranges from 0.16 to 0.36 years; iii) For  $\rho_{3/4}$ ,  $\rho_{3/8}$ ,  $\rho_4$  and for FC,  $\Delta$ Y ranges from 0.06 to 0.16 years; iv) for  $\rho_{200}$ , the sensitivity ranges from 0.11 to 0.73, as a function of the layer involved; v) P'<sub>b</sub> has similar consequences. By referring to the accepted range of variation with respect to the general contract (LSL<sub>specs</sub>, USL<sub>specs</sub>), note

that consequences may emerge greater than 4 years. In more detail: i) the sensitivity to the penetration grade

ranges from half a year to about two years (0.53 and 1.63 respectively); ii) the deeper the layer is, the higher
 the consequences are. Consequently, it is recommended to shorten the USL<sub>IMF</sub>-LSL<sub>IMF</sub> accordingly.

Importantly, for the layer FC and the indicator AV, note that: i) a range  $USL_{specs}$ - $LSL_{specs}$  = 8% is considered; ii) for AV=LSL=18%, the expected life of the pavement is 21.3 years and the expected life of the FC is much higher; iii) for AV=USL=26%, the expected life of the friction course is would appear negligible, while the expected life of the pavement is 18.9 years because of the cement-treated failure. At the same time, if the FC were replaced, the evolution of the distress of the CT would be different and a higher expected life would be expected. Consequently, the corresponding sensitivities in Table 2 (2.34 years and 23%, respectively) are

400 affected by this interpretation issue.

401 Fig. 8 summarizes the effects of  $P_b$ , gradation (AG), asphalt binder penetration (Pen), and air voids content 402 (AV), in terms of years ( $\Delta Y$ ) and penalties (%, $\Delta PA$ ). Fig. 8 highlights how the maximum value of  $\Delta PA$  is 403 11.35% for the case of BAC (varying  $\rho_{3/4}$ ).

404 The corresponding sensitivity in terms of years is 3.59 years ( $\Delta$ Y). Importantly, this fact emphasizes that the 405 specification limits in the area of the maximum aggregate size should have stricter specifications.

406

## 407 **Conclusions and summary**

Asphalt concrete contracts state that construction main variables (e.g., air voids content, AV) must comply
 with limits (contract specification limits, SL, USL<sub>specs</sub>, LSL<sub>specs</sub>). Furthermore, if a Job mix formula is approved,

410 each variable must comply with ever narrower limits (J-specification limits, USL<sub>JMF</sub>, LSL<sub>JMF</sub>).

411 The study described in this paper deals with the assessment of the effects of these permitted variations on

412 expected life and pay adjustment.

To this end, equation 19 and 22-24 were herein set up.

414 Moduli were derived through the Witczak model, the expected life of pavement by the KenPave software, and

415 pay adjustment by equations 20 and 21. For the as-design pavement (Fig. 3), based on the proper consideration

416 of material characteristics and traffic, an expected life of 20 years was obtained.

417 The method herein set up builds on mechanics even if the numerosity and complexity of interactions involves

418 the need for a careful calibration. Based on results, the following conclusions can be drawn:

- 419 i) Usually, AV-related consequences are worse than Pen-related consequences, which, in turn,
   420 outrank AG- and P<sub>b</sub>-related consequences. An exception is given by the maximum size of
   421 aggregates.
- ii) Except that for  $\rho_{3/4}$ , the variations of the aggregate gradation (AG) within the JMF-422 specification limits (where JMF stands for job mix formula) have no relevant influence on 423 expected life and on pay adjustment, which vary at most of  $\pm 0.5$  year and  $\pm 1.6\%$ , respectively. 424 425 Even extending the variations of the aggregate gradation to 3 times the specification limits, 426 the effects in terms of expected life appear irrelevant, except that for the pay adjustment of the BAC, which varies in the range [-5.2%, +4.6%] for the sieve  $\rho_{3/4}$ , in the range [-2.3%, +1.0%]427 for the sieve  $P_{3/8}$ , in the range [-5.1%, +5.0%] for the sieve  $\rho_4$ , and in the range [-5.2%, +0.9%]428 for the sieve  $\rho_{200}$ . Furthermore, the failure of the pavement is due to the CT. 429
- 430 iii) In terms of percentage of asphalt binder is it possible to observe that:
- a) A variation of the asphalt binder percentage of ±3 times the J-tolerance in FC, BIC and
  BAC implies no significant variations of EXL and PA.
- b) On the contrary, AV variations imply a sharp reduction of the EXL.
- iv) Higher values of the penetration of asphalt binder in FC, BIC and BAC imply a reduction in
  terms of expected life and pay adjustment, according to a monotonous trend. The failure of
  the pavement is always due to the breaking of cement-treated layer, except when penetration
  of BAC asphalt binder is lower than 3 times the tolerance with respect to the as-design value.
  In that case the failure of the pavement is due to the BAC.
- v) Variations of air voids in ± 3JT (where USL<sub>JMF</sub>-LSL<sub>JMF</sub>=2JT) have a strong influence on each
  layer. Values of AV, added of 3 times the tolerance, imply a great reduction of PA. The most
  critical situation occurs for the BIC, which causes the failure of the pavement in less of 2 years
  and reduces the PA of -92%.
- 443 vi) Sensitivity analysis confirms that AV is the most relevant parameter for the expected life and 444 for the pay adjustment of the pavement, with an  $\Delta Y$ , sensitivity in years, of 2.34 years and an 445  $\Delta PA$ , sensitivity in pay adjustment, of 23% for the FC.

- vii) When contract-related limits SL<sub>C</sub> (instead of SL<sub>J</sub>) are considered, it turns out that
  consequences are severer (1-3 times greater). This originates from being C-specification limits
  wider than J-specification limits.
- 449

450 Results of this study demonstrate that small variations (i.e.,  $\pm$  JT) of asphalt binder content or asphalt binder

penetration do not have a relevant impact on expected life and on pay adjustment. This statement is no more

- 452 valid if the variations concern the air void or  $\rho_{3/4}$  or if they become "high" (i.e.,  $\pm 3JT$ ). In those cases, pavement 453 could fail in a very short time.
- 454 Furthermore, it is assessed that when pay adjustments build on empirical algorithms, they have to be layer-
- 455 specific because the same "error" implies severer consequences in deeper layers.
- 456 Further research will investigate the effect on EXL and PA varying concurrently and how the results of this
- 457 investigation are affected by the design model used.

## 458 Notation list

- 459 The following symbols are used in this paper:
- 460 AG = aggregate gradation;
- 461 ANAS = ANAS contract specifications;
- AV = air void content [%];
- 463 BAC = base course;
- 464 bBAC = asphalt binder percentage for the base course;
- 465 BIC = binder course;
- $C_{REH} = costs of successive rehabilitations [<math>\notin/m^2$ ];
- $C_{RES} = costs of successive resurfacings [€/m<sup>2</sup>];$
- 468 CT = sub-base (cement-treated base course);
- D = 20, expected life of the as-design pavement [years];
- $E = E^* = dynamic modulus [MPa];$
- $|E^*| = dynamic modulus [psi], (1psi = 0.0069MPa);$
- 472 EBAC = dynamic modulus of the base course [MPa];
- 473 EXL = EREH = expected life of the as-constructed pavement [years];
- f =loading frequency [Hz];
- 475 FC = friction course (porous asphalt concrete);
- $G_b$  = asphalt binder specific gravity;
- $G_{mb}$  = bulk specific gravity of the compacted mixture;
- $G_{mm}$  = maximum theoretical specific gravity of the mixture;
- $G_{sa}$  = apparent specific gravity of the aggregate;
- $G_{sb}$  = bulk specific gravity of the aggregate;
- $G_{se} = effective specific gravity of the aggregate;$
- I = indicator;
- i = 0.04, inflation rate;
- $\Delta PA =$  sensitivity of the ratio PA/C in terms of %;
- $\Delta PA_{JMF}$  = sensitivity of the ratio PA/C in terms of % referred to the Job mix formula;

- 486  $\Delta PA_{specs}$  = sensitivity of the ratio PA/C in terms of % referred to contract requirements;
- 487  $\Delta Y =$  sensitivity of EXL in terms of years;
- 488  $\Delta Y_{JMF}$  = sensitivity of EXL in terms of years referred to the Job mix formula;
- 489  $\Delta Y_{\text{specs}}$  = sensitivity of EXL in terms of years referred to contract requirements;
- 490 JMF = Job mix formula;
- 491 JT = job mix formula tolerance;
- 492 LCCA = Life Cycle Cost Analyses of the pavement;
- 493 LSL = lower specification limit;
- 494 LSL<sub>specs</sub> = lower specification limit (contract requirements for the given layer);
- 495 LSL<sub>JMF</sub> = lower specification limit (job mix formula);
- 496 N = compaction energy expressed in terms of number of passes with respect to the "refusal" value (0 to 1);
- 497 O = EXLFC = ERES = expected time of the as-constructed friction course (FC, typically 10 years);
- 498  $P_b$  = asphalt content (percent by mass of total mix);
- 499  $P'_b$  = asphalt content (percent by mass of aggregate);
- 500  $P_{3/4}$  = passing at the 3/4-inch sieve, which corresponds to 100- $\rho_{3/4}$ ;
- 501  $P_{3/8}$  = passing at the 3/8-inch sieve;
- 502  $P_4 = passing at the 3/8-inch sieve;$
- 503 PA = pay adjustment;
- 504  $PA/C = (PA_{RES} + PA_{REH})/(C_{RES} + C_{REH}), [\%];$
- 505 PAC = Porous Asphalt Concrete;
- 506  $PA_{REH} = pay adjustment for rehabilitation;$
- 507 PA<sub>RES</sub> = pay adjustment for resurfacing;
- 508  $P_{ba}$  = percent of absorbed asphalt (by total weight of aggregate);
- 509  $P_{be} = effective asphalt content [\%];$
- 510 Pen = asphalt binder penetration [0.1mm].
- 511 PV = present value of agency costs;
- 512 R = ratio between (1+i) and (1+r);
- 513 r, i = interest rate, inflation rate;

- 514 SL<sub>specs</sub> = specification limit (contract requirements);
- $SL_{JMF}$  = specification limit (job mix formula);

516 SUB = subgrade;

t = thickness;

- 518 UB = compacted subgrade;
- 519 USL = upper specification limit;
- 520 USL<sub>specs</sub> = upper specification limit (contract requirements for the given layer);
- 521 USL<sub>JMF</sub> = upper specification limit (job mix formula);
- $V_{ba}$  = volume of absorbed asphalt binder [%];
- $V_{beff} = effective asphalt binder content [% by volume];$
- $V_{beff} = effective asphalt binder content [% by volume];$
- $\alpha$  = coefficients to calibrate;
- $\beta$  = coefficients to calibrate;
- $\gamma$  = coefficients to calibrate;
- $\eta$  = asphalt binder viscosity [10<sup>6</sup> Poise = 10<sup>5</sup> Pas];
- $\rho_{200} = passing percentage the 0.075 mm (No. 200) sieve;$
- $\rho_{3/4}$  = cumulative % retained on the 19 mm (3/4 inch) sieve;
- $\rho_{3/8}$  = cumulative % retained on the 9.5 mm (3/8 inch) sieve;
- $\rho_4$  = cumulative % retained on the 4.75 mm (No. 4) sieve;

- 536 Data Availability Statements
- 538 Data generated or analyzed during the study are available from the corresponding author by request.

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## 722 Figures



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Symbols.  $\rho_{200}$ : % Passing the 0.075 mm (No. 200) sieve;  $\rho_4$ : Cumulative % retained on the 4.75 mm (No. 4) sieve;  $\rho_{3/8}$ : Cumulative % retained on the 9.5 mm (3/8 inch) sieve;  $\rho_{3/4}$ : Cumulative % retained on the 19 mm (3/4 inch) sieve; f: Loading frequency [Hz]; Pen: asphalt binder penetration [0.1 mm]; n: asphalt binder viscosity [10<sup>6</sup> Poise]; P<sub>b</sub>: Asphalt content (percent by mass of total mix); G<sub>b</sub>: Asphalt binder specific gravity; G<sub>mb</sub>: Bulk specific gravity of the compacted mixture; G<sub>sb</sub>: Bulk specific gravity of the aggregate; G<sub>sa</sub>: Apparent specific gravity of the aggregate; G<sub>se</sub>: Effective specific gravity of the aggregate; G<sub>mm</sub>: Maximum theoretical specific gravity of the mixture; P<sub>ba</sub>: Percent of absorbed asphalt (by total weight of aggregate); Pbe: Effective asphalt content [%]; AV: Air void content [%]; Vbeff: Effective asphalt binder content [% by volume]; Vba: Volume of absorbed asphalt binder [%]; E\*: Dynamic modulus; N: compaction energy (in percentage with respect to the maximum value). 



**Fig. 2.** Example of prediction of AV and Gmb based on eq. 19 for a dense-graded mix (A) and an open-

744 graded mix (B).

745 Symbols. AV: air content; AVobs: observed values of air content, Pb: Asphalt content (percent by mass of total mix);

746 Gmb: Bulk specific gravity of the compacted mixture; Gmbobs: observed values of bulk specific gravity of the compacted

747 mixture.



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750 Fig. 3. As design pavement (scheme)

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751 Symbols. FC: friction course (porous asphalt concrete); BIC: binder course; BAC: base course; CT: sub-base (cement-
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treated base course); UB: compacted subgrade; SUB: subgrade; E: dynamic modulus; t: thickness.



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**Fig. 4**. EXL and PA vs P<sub>3/4</sub> (A, D, G), P<sub>3/8</sub> (B, E, H), P<sub>4</sub> (C, F, I) for FC, BIC, and BAC

Symbols. P<sub>3/4</sub>, P<sub>3/8</sub>, P<sub>4</sub>: percent passing to the given sieve; FC: friction course; BIC: binder course; BAC: base course;
EXL = expected life; PA<sub>REH</sub>, PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>, C<sub>RES</sub>: costs.



**Fig. 5.** EXL and PA vs  $\rho_{200}$  (A), Pen (B), P<sub>b</sub> (C) for FC, BIC, and BAC

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Symbols. ρ<sub>200</sub>: passing; Pen: penetration; P<sub>b</sub>: bitumen percentage; FC: friction course; BIC: binder course; BAC: base
course; EXL = expected life; PA<sub>REH</sub>, PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>, C<sub>RES</sub>:
costs.
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- 766 Fig. 6. EXL and PA vs AV (air voids) for FC, BIC, and BAC
- 767 Symbols. AV: air content; FC: friction course; BIC: binder course; BAC: base course; EXL = expected life; PA<sub>REH</sub>,
- 768 PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>, C<sub>RES</sub>: costs.
- 769 770





- 773 Symbols. EXLCT = expected life of sub-base (cement-treated base course); EXLBAC = expected life of base course;
- 774 Pen: penetration.



**Fig. 8.** Sensitivity of expected life ( $\Delta$ Y) and PA ( $\Delta$ PA) to variations within specification limits type JMF or

type specs

779 Symbols. EXL = expected life; PA<sub>REH</sub>, PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>,

780  $C_{RES}$ : costs;  $\Delta Y_{JMF}$  = sensitivity of EXL in terms of years referred to the Job mix formula;  $\Delta Y_{specs}$  = sensitivity

of EXL in terms of years referred to contract requirements;  $\Delta PA_{JMF}$  = sensitivity of the ratio PA/C in terms of

782 % referred to the Job mix formula;  $\Delta PA_{specs}$  = sensitivity of the ratio PA/C in terms of % referred to contract

requirements;  $P_b$  = asphalt binder content; AG: gradation; Pen = asphalt binder penetration; AV = air void

784 content.

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## 787 Table

## 788 Table 1: Layers moduli

Layer	<b>Reference value</b> E (MPa)	<b>Reference value</b> t (cm)	<b>Design value</b> E (MPa)	<b>Design value</b> t (cm)
Friction course (FC)	$448^a \div 2258^b$	-	1013	5
Binder course (BIC)	$2188^{\text{c}}\div8220^{\text{d}}$	$4^{\rm e} \div 9^{\rm e}$	4393	7
Base course (BAC)	$3085^{c}\div9418^{d}$	$7^{\rm e} \div 25^{\rm e}$	5101	15
Sub-base (CT)	$1263^{\rm f}\div 1583^{\rm g}$	-	1423	20
Compacted Subgrade (UB)	$160^{\rm h} \div 491^{\rm h,i}$	$20^{l} \div 30^{l}$	252	20
Subgrade (SUB)	$45^{\rm m} \div 242^{\rm m}$	semi-inf <sup>n</sup>	85	semi-inf

Note: FC = friction course (porous asphalt concrete); BIC = binder course; BAC = base course; CT = sub-base (cement-treated base course); UB = compacted subgrade; SUB = subgrade; E = dynamic modulus; t = thickness. <sup>a</sup>based on Cho et al. 2010. <sup>b</sup>based on Asphalt Institute 1982. <sup>c</sup>based on Leiva-Villacorta et al. 2013. <sup>d</sup>based on Witczak and Fonseca 1996. <sup>e</sup>based on reference data. <sup>f</sup>based on Gaspard 2000. <sup>g</sup>based on Giannattasio et al. 1989. <sup>i</sup>based on Giannattasio et al. 1989. <sup>i</sup>based on Bucchi et al. 2013. <sup>l</sup>based on Putri et al. 2012. <sup>m</sup>based on Putri et al. 2012.

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## **Table 2:** Sensitivity of EXL and PA/C for each parameter and layer

	Indicator $\rightarrow$	ρ <sub>3/4</sub>		$\rho_{3/8}$		ρ4		ρ <sub>200</sub>		P'b		Pen	AV
	↓ Layer ↓	SL <sub>JM</sub>	$SL_{spec}$	SL <sub>JM</sub>	$SL_{spec}$	$SL_{JM}$	$SL_{spec}$	SL <sub>JM</sub>	SL <sub>spec</sub>	SL <sub>JM</sub>	$SL_{spec}$	SL <sub>spec</sub>	$SL_{\text{spec}}$
	· · ·	F	S	F	s	F	s	F	s	F	s	s	S
Range of variation of I	FC	$0.0{\pm}3.0$	0.0±0.0	62.5±3.0	62.5±22.5	81.5±3.0	81.5±6.5	10.0±1.5	10.0±2.0	5.00±0.25	5.00±0.50	60±10	22.0±4.0
	BIC	22.0±3.0	22.0±18.5	$42.5\pm3.0$	42.5±12.5	57.5±3.0	57.5±12.5	6.0±1.5	6.0±2.0	4.50±0.25	$4.50 \pm 0.50$	90±10	5.9±2.9
	BAC	28.0±5.0	28.0±18.0	47.5±5.0	47.5±17.5	60.0±5.0	60.0±15.0	5.5±1.5	5.5±2.5	3.75±0.25	3.75±0.75	90 <u>±</u> 10	5.5±2.5
	FC	0.08	-	0.06	0.33	0.16	0.35	0.11	0.14	0.08	0.15	0.53	2.34
۸۷	BIC	0.33	-	0.16	0.63	0.36	1.48	0.32	0.44	0.21	0.43	0.87	1.60
	BAC	1.02	3.59	0.43	1.15	1.10	3.19	0.73	1.20	0.25	1.02	1.63	1.71
APA (%)	FC	0.25	-	0.19	1.05	0.51	1.11	0.35	0.44	0.25	0.48	1.68	22.62
	BIC	1.02	-	0.51	2.00	1.14	4.69	1.02	1.40	0.50	1.37	2.76	5.18
	BAC	3.24	11.35	1.36	3.69	3.49	10.11	2.32	3.80	0.80	3.27	5.16	5.60

Note:  $\Delta Y$  = sensitivity of EXL;  $\Delta PA$  = sensitivity of PA/C;  $\rho_{200}$  = passing the 0.075 mm (No. 200) sieve;  $\rho_4$  = cumulative % retained on the 4.75 mm (No. 4) sieve;  $\rho_{3/8}$  = cumulative % retained on the 9.5 mm (3/8 inch) sieve;  $\rho_{3/4}$  = cumulative % retained on the 19 mm (3/4 inch) sieve; Pen = penetration of a standard needle of 100 g, which penetrates the asphalt binder for 5 seconds (0.1 mm); P'\_b = asphalt content (percent by mass of aggregate); AV = air void content (%); FC = friction course; BIC = binder course; BAC = base course; SLspecs = specification limit referred to contract requirements, ANAS contract specifications 2000; SL<sub>JMF</sub> = specification limit referred to the job mix formula, ANAS contract specifications 2000.

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## 796 List of figure captions

- **Fig. 1.** Main variables that affect a bituminous layer modulus.
- **798** Symbols.  $\rho_{200}$ : % Passing the 0.075 mm (No. 200) sieve;  $\rho_4$ : Cumulative % retained on the 4.75 mm (No. 4) sieve;  $\rho_{3/8}$ :
- 799 Cumulative % retained on the 9.5 mm (3/8 inch) sieve;  $\rho_{3/4}$ : Cumulative % retained on the 19 mm (3/4 inch) sieve; *f*:
- **800** Loading frequency [Hz]; Pen: asphalt binder penetration [0.1 mm];  $\eta$ : asphalt binder viscosity  $[10^6 \text{ Poise}]$ ; Pb:
- 801 Asphalt content (percent by mass of total mix); G<sub>b</sub>: Asphalt binder specific gravity; G<sub>mb</sub>: Bulk specific gravity of the
- 802 compacted mixture; G<sub>sb</sub>: Bulk specific gravity of the aggregate; G<sub>sa</sub>: Apparent specific gravity of the aggregate; G<sub>se</sub>:
- 803 Effective specific gravity of the aggregate; G<sub>mm</sub>: Maximum theoretical specific gravity of the mixture; P<sub>ba</sub>: Percent of
- absorbed asphalt (by total weight of aggregate); P<sub>be</sub>: Effective asphalt content [%]; AV: Air void content [%]; V<sub>beff</sub>:
- 805 Effective asphalt binder content [% by volume]; V<sub>ba</sub>: Volume of absorbed asphalt binder [%]; E\*: Dynamic modulus;
- 806 N: compaction energy (in percentage with respect to the maximum value).
- 807

**Fig. 2.** Example of prediction of AV and Gmb based on eq. 19 for a dense-graded mix (A) and an open-

- graded mix (B)
- Symbols. AV: air content; AV exp: experimental values of air content, Pb: Asphalt content (percent by mass of total
  mix); Gmb: Bulk specific gravity of the compacted mixture; Gmb exp: experimental values of bulk specific gravity of
  the compacted mixture.
- 813
- 814 Fig. 3. As design pavement (scheme).
- Symbols. FC: friction course (porous asphalt concrete); BIC: binder course; BAC: base course; CT: sub-base (cementtreated base course); UB: compacted subgrade; SUB: subgrade; E: dynamic modulus; t: thickness.
- 817
- 818 **Fig. 4**. EXL and PA vs P<sub>3/4</sub> (A), P<sub>3/8</sub> (B), P<sub>4</sub> (C) for FC, BIC, and BAC.
- 819 Symbols. P3/4, P3/8, P4: percent passing to the given sieve; FC: friction course; BIC: binder course; BAC: base course;
- 820 EXL = expected life; PAREH, PARES: pay adjustment for rehabilitation and resurfacing, respectively. CREH, CRES:
- 821 costs.
- 822
- **Fig. 5.** EXL and PA vs  $\rho_{200}$  (A), Pen (B), P<sub>b</sub> (C) for FC, BIC, and BAC.

824 Symbols.  $\rho_{200}$ : passing; Pen: penetration; P<sub>b</sub>: bitumen percentage; FC: friction course. EXL = expected life; PA<sub>REH</sub>,

825 PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>, C<sub>RES</sub>: costs.

826

827 Fig. 6. EXL and PA vs AV (air voids) for FC, BIC, and BAC

828 Symbols. AV: air content; FC: friction course. EXL = expected life; PA<sub>REH</sub>, PA<sub>RES</sub>: pay adjustment for rehabilitation

- $\label{eq:constraint} 829 \qquad \text{and resurfacing, respectively. } C_{\text{REH}}, C_{\text{RES}}\text{: costs.}$
- 830

Fig. 7. Consequences of BAC (A) and BIC (B) nonconformity on the expected life of the pavement

832 Symbols. EXLCT = expected life of sub-base (cement-treated base course); EXLBAC = expected life of base course;
833 Pen: penetration.

834

**Fig. 8.** Sensitivity of expected life ( $\Delta$ Y) and PA ( $\Delta$ PA) to variations within specification limits type JMF or

type specs

837 Symbols. EXL = expected life; PA<sub>REH</sub>, PA<sub>RES</sub>: pay adjustment for rehabilitation and resurfacing, respectively. C<sub>REH</sub>,

- 838  $C_{RES}$ : costs;  $\Delta Y_{JMF}$  = sensitivity of EXL in terms of years referred to the Job mix formula;  $\Delta Y_{specs}$  = sensitivity of EXL
- 839 in terms of years referred to contract requirements;  $\Delta PA_{JMF}$  = sensitivity of the ratio PA/C in terms of % referred to the
- B40 Job mix formula;  $\Delta PA_{specs}$  = sensitivity of the ratio PA/C in terms of % referred to contract requirements;  $P_b$  = asphalt
- binder content; AG: gradation; Pen = asphalt binder penetration; AV = air void content.
- 842
- 843 **Table 1:** Layers moduli.
- 844 Symbols: FC = friction course (porous asphalt concrete); BIC = binder course; BAC = base course; CT = sub-base

845 (cement-treated base course); UB = compacted subgrade; SUB = subgrade; E = dynamic modulus; t = thickness.

- 846
- **Table 2:** Sensitivity EXL and PA/C for each parameter and layer.
- 848 Symbols:  $\Delta Y$  = sensitivity of EXL to I;  $\Delta PA$  = sensitivity of PA/C to I;  $\rho 200$  = passing the 0.075 mm (No. 200) sieve;
- 849  $\rho 4 =$  cumulative % retained on the 4.75 mm (No. 4) sieve;  $\rho 3/8 =$  cumulative % retained on the 9.5 mm (3/8 inch) sieve;
- 850  $\rho_{3/4}$  = cumulative % retained on the 19 mm (3/4 inch) sieve; Pen = penetration of a standard needle of 100 g, which
- 851 penetrates the asphalt binder for 5 seconds (0.1 mm); P'b = asphalt content (percent by mass of aggregate); AV = air
- void content (%); FC = friction course; BIC = binder course; BAC = base course; SLC = specification limit referred to

- 853 contract requirements, ANAS contract specifications 2000; SLJ = specification limit referred to the job mix formula,
- 854 ANAS contract specifications 2000.