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Original Research Paper

An experimental method to design porous asphalts to account for surface requirements

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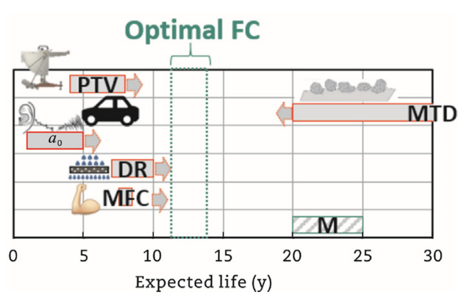
HIGHLIGHTS

- Porous asphalts, PAs, have many properties.
- A comprehensive and synergistic method to design PAs was set up and applied.
- Pavement acoustics, permeability, and surface properties were monitored.
- The actual properties of PAs may be quite far from having a similar durability.
- Optimal design involves technology choice and complex mix optimisation.

GRAPHICAL ABSTRACT



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ABSTRACT

Porous asphalts have supplementary surface and volumetric properties (e.g., acoustic absorption, drain ability, texture, and friction). These properties are linked to intrinsic factors (e.g., gradation and bitumen content) and extrinsic factors (e.g., traffic load), while their evolution over time depends on complex phenomena and processes that cause their deterioration and therefore affect safety, noise, and budget. Despite the decay of so many and complex properties over time, there is a lack of criteria to synergistically optimize the pavement system. Consequently, the objective of this study is to set up and validate a design method that synergistically addresses the most relevant properties of friction courses as a part of a pavement structure. The abovementioned method is based on in-depth analyses of the literature and on laboratory and on-site tests carried for several years in order to evaluate the decay over time of the main surface and volumetric properties.

The method was applied to a case study.

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Friction
Porous asphalt

Results show that 1) the level of fulfilment of single requirements varies over time and among the characteristics; 2) a sound optimization of the design of the mix in order to balance the different characteristics is needed; 3) further studies are needed because of uncertainty in predicting the main surface properties.

1. Objectives

The objective of the study presented in this paper is to set up and apply a method to design porous asphalts from a more comprehensive perspective, that is to say, considering traditional (e.g., crack percentage) and premium (e.g., acoustic absorption) properties.

The objectives above originate from the study of the literature (section 2), which points out the complexity of porous asphalts (because of many properties and their variation over time) and the lack of comprehensive methods to design. The literature analysis allows a better understanding of the surface properties decay over time and it helps predict how these properties evolve. This step is essential for implementing a new method. A method was set up (section 3) and an experimental investigation was then designed and carried out (section 4). Finally, conclusions were drawn (section 5).

2. Introduction and literature analysis

2.1. Introduction

The term premium friction courses refers to wearing courses that have "superior" performance, i.e., properties usually not required to common pavement surfaces. To this end it is noted that several authors and agencies have already used this term in the nineties, e.g., Technical Advisory T 5040.31, in terms of higher percent cost (premium) over standard dense graded HMAs. It is herein intended that these courses include, for example, also quiet pavement technologies and open-graded mixtures.

Porous asphalt concretes, PA, and open-graded friction courses, OGFC, are hot mix asphalts, HMA, with high air void contents, often in the range 15%–25% (Alvarez et al., 2006; Chen et al., 2015a; Gu et al., 2018; Putman, 2012).

At present, several methods are used to design porous asphalt mixtures, and some procedures are more complex than others (Huang, 2003; Putman and Kline, 2012). The Federal Highway Administration (FHWA, 1990) developed a mix design procedure based on aggregate quality that aims at providing and maintaining good frictional characteristics. The National Center for Asphalt Technology (NCAT) proposed a mixture design method consisting of the following steps (Kandhal, 2002): 1) materials selection; 2) selection of design gradation; 3) determination of optimum asphalt content; 4) evaluation for moisture susceptibility. Kline and Putman (2010) compared OGFC mix design methods that are currently used in the United States.

Vehicular loads (Chen et al., 2015a, b), thermal loads (Chen and Xu, 2009), creep phenomena (Hamzah et al., 2012), and particulate matter (Tan et al., 2003) affect a pavement actual air void content (Chen et al., 2013). To this end, note that vehicular loads carry out a further compaction of the pavement (with reduction of air voids of an additional 2%–4%), thermal loads can cause cracks and local increases of AV, while creep phenomena may imply air void changes. Finally, particular matter accumulates within the pavement structure and slowly clogs up and reduces the voids. This affects other characteristics, such as drainability (or permeability, or hydraulic conductivity) (Chen et al., 2015a; Praticò et al., 2013), noise performance (Bendtsen et al., 2010; Chu et al., 2017), friction (Khasawneh and Liang, 2016), surface texture (Ahammed and Tighe, 2012), and mechanistic performance (Alvarez et al., 2018; Garba, 2002). On the other hand, as is well-known, drainability, texture, and friction affect safety (Widyatmoko and Kingdom, 2015), while traffic noise affects health (Brown, 2015; Welch et al., 2013), and mechanistic performance affects mobility and road agency budgets (Amin and Amador-Jiménez, 2014). Unfortunately, the surface properties cited above (i.e., drainability, noise performance, friction, and surface texture) decay over time (Licitra et al., 2015) (tracking EN 12697-22) are tests commonly carried out in the laboratory to study the performance of OGFC/PA and improve their design (King et al., 2013). Field tests (e.g., visual inspection, pavement condition, and traffic surveys) may be carried out to assess their quality. The causes behind the decay of the surface properties of PAs can be mainly associated to: 1) clogging, 2) polishing, 3) ravelling, 4) aging, 5) continued pavement compaction by traffic (after the construction, about 2%–4%). Clogging is mainly due to deposition of sand and debris inside pavement pores (Pattanaik et al., 2018). Raveling is the loss of aggregate particles from the asphalt surface during the service life of pavement. The main factors that impact raveling are inadequate compaction of pavement and its air void percentage, pavement placement in wet weather, pavement mix design and aggregate gradation, binder cohesive or adhesive capacity, binder aging, and ambient condition of asphalt concretes (Massahi et al., 2018). Raveling can be faced (King et al., 2013) acting on materials, design, production, appropriate storage, hauling and placement, minimizing draindown, and avoiding the use of PAs where snow and ice accumulate.

Ageing of asphalt mixtures occurs during production and construction and continues throughout the service life of the pavement. It depends on exposure time, bitumen and aggregate properties, bitumen film thickness, air void content, and production (Gómez et al., 2013). A "self-cleaning mechanism" is observed during the lifetime of porous pavements (Bendtsen and Andersen, 2005). During the periods of rain, water is pushed at high pressure by vehicle tires. High pressures are helpful, while lower pressures and slower rotation of the vehicle's wheels are disadvantageous (urban roads) (Bendtsen and Andersen, 2005). Dedicated machines and processes can mitigate the level of clogging (Chopra et al., 2010; King et al., 2013; Schaefer et al., 2011; Winston et al., 2016). Raveling can be reduced using surface treatments (e.g., spraying bituminous emulsion on the wearing course layer using a spraying truck) and testing the effectiveness of the treatment using the rotating surface abrasion test to determine the stone loss (Zhang et al., 2016).

In summarising, there are many required properties and many failure modes, whose interference poses theoretical and practical issues. Indeed, not only each premium property (e.g., quietness) has a different design method but also these different approaches must comply with more traditional mix design methods that build on mechanistic and volumetric variables. This issue calls for setting up a synergistic (because of the interactions) and comprehensive (because of the different properties) method. Consequently, in the pursuit of the objectives mentioned above, a more comprehensive literature review was carried out. The variation over time of the following properties was studied: i) air voids content, in-lab and on-site permeability and drainability; ii) surface texture and friction (i.e., mean texture depth, MTD, and pendulum test value, PTV). Furthermore, the variation of the drainability as a function of the position on the carriageway (i.e., inside and out-site the wheel path) was included in this review.

2.2. *Permeability and drainability*

The permeability of a hot mix asphalt (HMA) is linked to a pavement's durability and its performance, providing a measure of how accessible a pavement's void structure is to its environment (air and water). It impacts wet-weather driving safety, stormwater peak load, and replenishment of groundwater supplies (Chu et al., 2018). Several test methods cover the laboratory measurement of the hydraulic conductivity (ASTM, 2001; Florida Department of Transportation, 2004). Falling head tests on water-saturated and laboratory-compacted specimens or field cores are carried out using the flexible wall permeameter. Importantly, even if the ASTM PS129 was withdrawn in 2013, many studies after 2005 were carried out using the flexible wall permeameter (Hassan et al., 2016; Hurley and Prowell, 2008; Xie and Shen, 2016; Zhong et al., 2017). In-lab and on-site permeability depends on many variables, e.g., air voids content, gradation, and nominal maximum aggregate size. Based on the saturated hydraulic conductivity of asphalt mixtures (Aboufoul and Garcia, 2017; Kanitpong et al., 2001; Mallick et al., 2003; Nataatmadja, 2010; Putman, 2012), measured using different tests (ASTM, 2010a; Florida Department of Transportation, 2004), under different conditions, and in the laboratory, increases with air void content, ranging from about 10^{-7} cm/s (AV is about 3%) (Kanitpong et al., 2001), where AV stands for air void content), to about 0.5 cm/s (AV is about 26%) (Aboufoul and Garcia, 2017). A number of models were set up for representing in-lab HMA permeability as a function of AV (Aboufoul and Garcia, 2017; Kanitpong et al., 2001; Mallick et al., 2003; Mogawer et al., 2002; Nataatmadja, 2010; Norambuena-Contreras et al., 1997; Praticò et al., 2013; Putman, 2012). On average, the proposed models provide the permeability values in Table 1 and Fig. 1 (a).

Fig. 1 illustrates the values of on-site drainability in percentage. *A* is PA wheel path, data referred to PAs (Isenring et al., 1990), *B* is PA center lane (Isenring et al., 1990), *C* is wheel path (Takahashi, 2013), *D* is non wheel path (Takahashi, 2013), *E* is PA left wheel path (Ellebjerg and Bendtsen, 2008), *F* is PA between wheel paths (Ellebjerg and Bendtsen, 2008), *G* is PA right wheel path (Ellebjerg and Bendtsen, 2008), *H* is 0/6-10/14 (Brosseaud and Anfosso-

Table 1 – Hydraulic conductivity (*K*) vs air void (AV).

Permeability	Value				
AV (%)	5	10	15–20	25	30
K (cm/s)	10^{-6}–10^{-2}	10^{-4}–10^{-2}	10^{-2}–1	10^{-4}–10^{-1}	10^{-1}–10^{5}

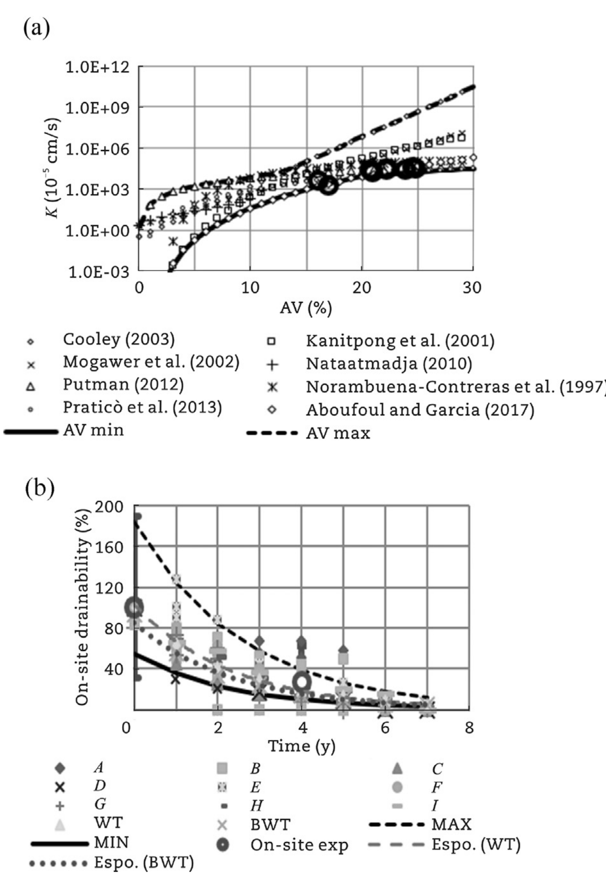

Fig. 1 – In-lab experiments on cores and on-site experiments versus literature data. (a) In-lab. (b) On-site.

Lèdèè, 2009), I is 4/6-10/14 (Brosseaud and Anfosso-Lèdèè, 2009), WT is average values on the wheel paths, BWT is average values between the wheel paths, MAX is exponential curve based on maxima, MIN is exponential curve based on minima.

On-site permeability varies over time because of several concurring phenomena (e.g., clogging and overcompation). Chen et al. (2017a, b), addressed on-site drainability versus time, with a drainability reduction per year that was on average −0.7%–3%.

Many authors studied how on-site drainability of porous asphalts decreases as a function of the age of the mix. Fig. 1 shows the on-site drainability with respect to its starting value (as-built). Note that on-site drainability tests are carried out through cylindrical field permeameters (falling head method). Fig. 1(b) illustrates the concerned results in the literature (Brosseaud and Anfosso-Lèdèè, 2009; Ellebjerg and Bendtsen, 2008; Isenring et al., 1990; Takahashi, 2013): 1) wheel track permeability is usually higher than the one obtained between the wheel paths or in the emergency lanes because of the cleaning and squeezing effect due to rolling tires; 2) after 5 years, there is an average reduction of 72%–81%, such that pavements can be considered completely clogged. For air voids over time, which is the main volumetric parameter that governs permeability, Fig. 2(a) depicts the correlation between time after construction (age of the pavement) and air voids content (Pas) (Wang et al., 2015), with an as-built AV of about 18% and an approximate loss of 1% of AV per year. Clogging greatly affects the expected life of PAs. Chu and Fwa (2018) considered two measures of percent clogging as a practical way to define the degree of clogging, i.e., CL_{AV}, based on porosity, and CL_K, based on in-lab permeability. Importantly, for permeability measurements (in-lab), Chu et al. (2017) and Chu and Fwa (2018) used the Method A of ASTM test C1754/C1754M−12 (ASTM, 2012) and the Method A of ASTM D5084-10 (ASTM, 2010a).

2.3. *Friction and surface texture*

Friction and surface texture interact. Friction depends on contact pressure, slip velocity, temperature, road surface properties (surface micro- and macro-texture, and aggregate properties), intrinsic characteristics of rubber tires, and the contamination conditions in between tire and road surface, such as water, ice, snow, or dust (Chen et al., 2017a). Based on the literature, some conclusion could be obtained as follow. 1) Friction optimization builds on aggregate characteristics. Polishing value, PSV, is a key indicator and it affects both the highest and the lowest value of friction over years (Ullidtz, 1987). 2) Friction is higher outside of the wheel paths and lower in the wheel paths (McDaniel et al., 2014; Raaberg et al., 2001; Woodward and Gunay, 2007). 3) Friction may be lower (for example) in the right wheel path than in the left wheel path, due to slope and/or other factors (Wilson, 2006). 4) There are also differences between slow and passing lane and based on alignment. According to Yu et al. (2015), for a PA with an initial AV of 22.5%, a reduction in PTV of about 18 points in five years after road construction is expected. According to Chen et al. (2017a, b), the evolution of the skid resistance of a pavement undergoes three primary stages: 1) initial roughening phase, from 6 months to 2 years after the opening to traffic; 2) polishing phase, from 3 to 6 years, the duration of this phase being dependent on the wear resistance of aggregates; 3) equilibrium phase. According to the authors' results, based on the 8-year evaluation of the Shenhai Expressway skid resistance, on average, PTV decreases of 5 units per year. Cenek et al. (1999) found that PTV reaches an equilibrium state after a phase in which the reduction is approximately 2.9 unit per year. Vaiana and Praticò (2014) found a reduction of PTV of about 9 points from month 13 to month 44, mightly as a part of a long-term phenomenon. First derivatives over time (in years) often range from about −3 to about −5 (points per year).

Experimental studies show that tire-pavement friction values are related to conditions such as pavement temperature, ambient temperature and surface characteristics of the pavement (Anupam et al., 2014). In particular, lower pavement temperatures cause higher moduli and shear resistance. Consequently, when the temperature is different from 20 °C, a correction factor is applied. According to the European Standard UNI EN 13036-4 (National Standards Authority of Ireland, 2011), the measured values are corrected through a correction factor that ranges from −5PTV (at 5 °C) to 3PTV (at 40 °C).

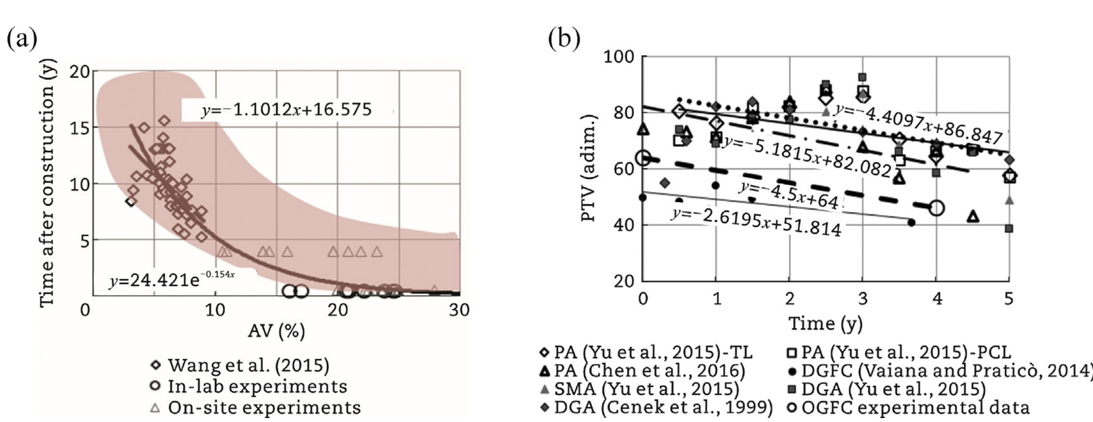

Fig. 2 – Air voids content and friction versus pavement age. (a) AV. (b) Friction (PTV).

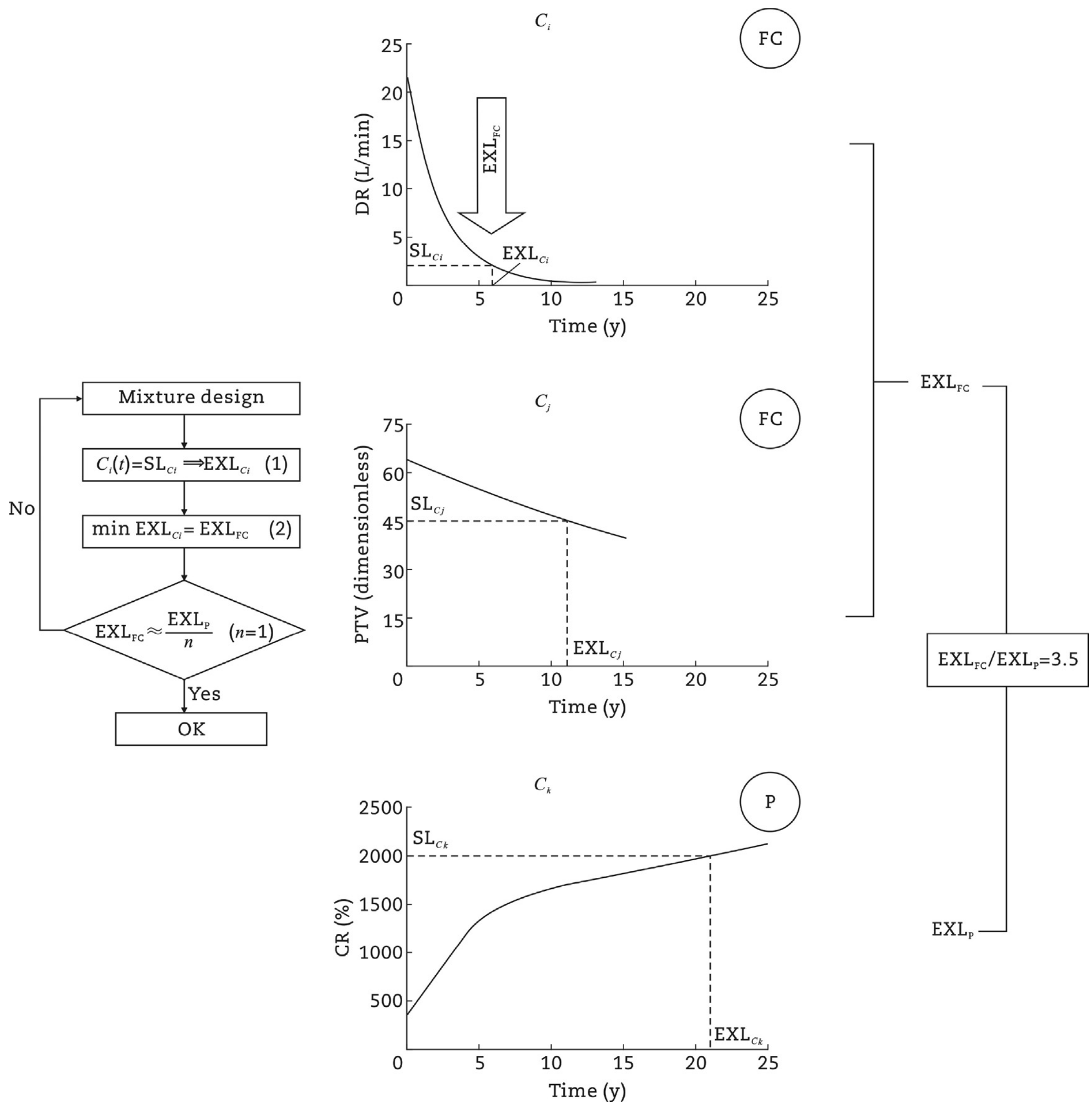

Fig. 3 – Simplified schematic of method.

Microtexture, wavelengths lower than 0.5 mm (ASTM, 2006; ISO, 2002) refers to fine-scale texture irregularities of the surface of the aggregate particles that are measured at the micron scale of harshness and are known to be mainly a function of aggregate particle mineralogy (Masad et al., 2007). It is usually supposed that microtexture can be measured using the British pendulum tester (National Standards Authority of Ireland, 2011); pendulum test value (PTV), slip speed of 10 km/h, 100% slip (Forster, 1989). Despite this, also macrotexture may have a certain influence on PTV (Pancar and Karaca, 2016).

Macrotexture refers to the coarse-scale texture irregularities that are associated with the void area between aggregate particles (wavelengths between 0.5 and 50 mm) (ASTM, 2009; ISO, 2002). From a design standpoint, macrotexture depends on the gradation (including size and shape) of coarse aggregate and on the construction practices for the surface layer (Noyce et al., 2005). Its decay depends on time, traffic, position (wheel paths) (Praticò and Vaiana, 2015; Woodward and Gunay, 2007), and alignment. Vaiana et al. (2012) monitored an average reduction of 10% per year in the first 18 months (dense-graded friction courses, with several increases in the last period) (Praticò et al., 2009), while Aavik et al. (2013) found a decrease of about 6% per year (corresponding to about 0.05 mm per year) for stone mastic asphalts. Miao et al. (2016) monitored a decrease of about 0.1 mm per million of vehicles. Macrotexture undergoes many variations and it is usually higher in the wheel paths than outside of them and differences between the two wheel paths are often observed (Buret et al., 2014; Stroup-Gardiner et al., 2001).

2.4. *Acoustic absorption and noise level*

Acoustic absorption depends on resistivity, tortuosity, thickness, and interconnected air voids. Following the ASTM E1050-10 (ASTM, 2010b) standard procedure, corresponding to ISO 10534-2 (ISO, 1998), range of frequency 100 to 2.5 kHz, PAs, Chu et al. (2017) indicated that sound absorption decreases progressively (from about 0.45 to 0.90 to about 0.15–0.3 in terms of dimensionless acoustic absorption coefficient a_0) as the percentage of clogging increases from zero up to 100%. As is well known, noise level usually increases over time (Bendtsen et al., 2010; Merska et al., 2016; Ribeiro et al., 2018). Based on the literature, for OGFCs (which are similar to PAs, even if AV is usually close to 15%), an increase of noise in the range 0.1–0.2 dB/year is expected (speed of 50 km/h). The results confirm that a natural drop in acoustic properties of this type of pavement occurs during road's lifetime. Overall, open graded friction courses are among the quietest surfaces.

3. Method

As is well known, currently, the design of a bituminous mixture (as a layer of a multi-layered system, i.e., a pavement) aims at determining the quantities and quality of the components of the mix. It mainly builds on fulfilling workability, volumetric, mechanistic, and resistance-related properties over the expected life. This latter depends on plastic deformations, thermal cracking, and fatigue cracking. Importantly, in turn, mechanistic properties depend on the quantity and quality of the components (Fig. 3). Finally, the design of the multi-layered system is even more complex and ends up with an array of expected lives (one per layer), whose minimum is the expected life of the pavement (EXL_P). The method here proposed aims at rationalizing the design of a pavement in terms of expected life and is based on the need of "intersecting" different classes of requirements. Indeed, for friction courses, surface properties (e.g., friction, surface texture, acoustic absorption, drainability) need for a concurrent design too. As a result, each property (e.g., drainability, DR) has an expected life (EXL_D) and the optimal solution is to have: a) similar expected lives (in order to minimise economic losses); b) expected lives that are not higher than the expected life of the remaining layers (same reason); c) expected lives that are possibly a natural sub multiple of the pavement expected life (EXL_P). This allows having a rehabilitation that coincides with the resurfacing. Based on the above, the given equation to comply with is Eq. (1) in Fig. 3, where $C_i(t)$ is the curve of the characteristic C_i as a function of time t, SL_{Ci} is the concerned upper or lower specification limit, and EXL_{Ci} is the corresponding abscissa of $C_i(t)$ for $C_i(t) = SL_{Ci}$, i.e., the expected life for the characteristic C_i.

In Fig. 3, $C_i(t)$ is decay curve of the ith property over time, SL_C is specification limit of C, t is time, EXL_{Ci} is expected life of C_i, EXL_{FC} is expected life of the friction course FC, EXL_P is expected life of the entire pavement P. Examples of $C_i(t)$, DR(t) is drainability; $a_0(t)$ is acoustic absorption coefficient, MTD(t) mean texture depth, PTV(t) is pendulum test value, typical values for n is 2 or 3.

Importantly, given the dependency of several surface properties on air voids content, AV, a supplementary condition should be considered for these properties, in order to have thresholds (SL_{Ci}) corresponding to a common value of air voids content (AV*), where SL_{Ci} is the specification value of the ith characteristic and C_i(AV*) is the value of C_i when the air void content approaches a common threshold of AV. This equation aims at having a consistent threshold system for the characteristics of the premium surface that have a sound dependency on AV, i.e., drainability, texture (outside the wheel path), and absorption coefficient. Indeed, this implies an economic advantage in terms of similar expected life.

In summarizing, the method is the followings. 1) Based on the mix design of the friction course, the curves $C_i(t)$ are derived, e.g., C_i = DR(t), drainability of FC; C_j = PTV(t), friction of FC; C_k = CR(t), longitudinal cracking rate (CR) of the entire pavement (Fig. 3), are derived. 2) The intersection between each curve (e.g., $C_i(t)$) and the pertaining specification limit (e.g., SL_{Ci}) is derived. This intersection is the expected life (EXL_{Ci}). 3) The minimum expected of FC life is derived (EXL_{FC}). 4) This value, EXL_{FC}, is compared to the expected life of the pavement, EXL_P. 5) If EXL_{FC} approximates a natural submultiple (e.g., $n = 2$) of EXL_P the process comes to the end. If this does not happen (e.g., the ratio is about 3.5 as depicted in Fig. 3, a new mix design is required. The need for having natural builds on the minimisation of agency and user costs, that is to say from having the rehabilitation of pavement (P) when not only the deeper layers but also the friction course (FC) are close to the end of their respective expected life.

4. Experiments and results

4.1. *Design of experiments*

In the pursuit of applying the method in Fig. 3, a suburban road located in southern Italy was investigated. The road under investigation consists of two carriageways (one each direction). Each carriageway includes two 3.75 m wide lanes and one 3.00 m wide emergency lane. The FC mixture under investigation (porous European mixture (PEM), or porous asphalt (PA)) had the following characteristics: i) passing of 100%, 90%, 25%, 12.5%, 6%, 5%, 4%, and 3% through the sieves with the size 20, 15, 10, 5, 2, 0.4, 0.18, and 0.075 mm, respectively; ii) percentage of bitumen (by weight of mixture) of 5.2% (Fig. 4). This information was derived from cores extracted from a 5-cm thick wearing course. Fig. 4 compares the concerned mix gradation with superpave control points (dense-graded) and the requirements (open-graded) of NCHRP Report 673 (NCHRP, 2011).

The factorial plan of experiments included both in-lab and on-site experiments. In more detail, on-site and in-lab tests were carried out in order to gather information on how

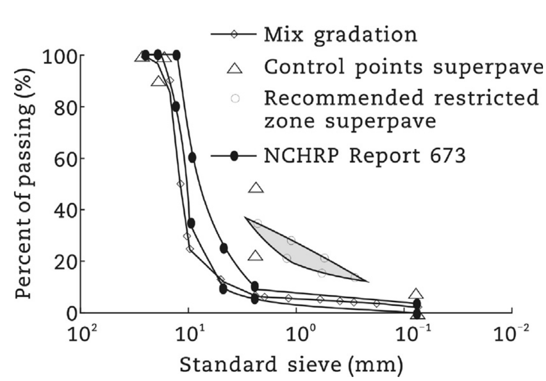

Fig. 4 – Mix gradation.

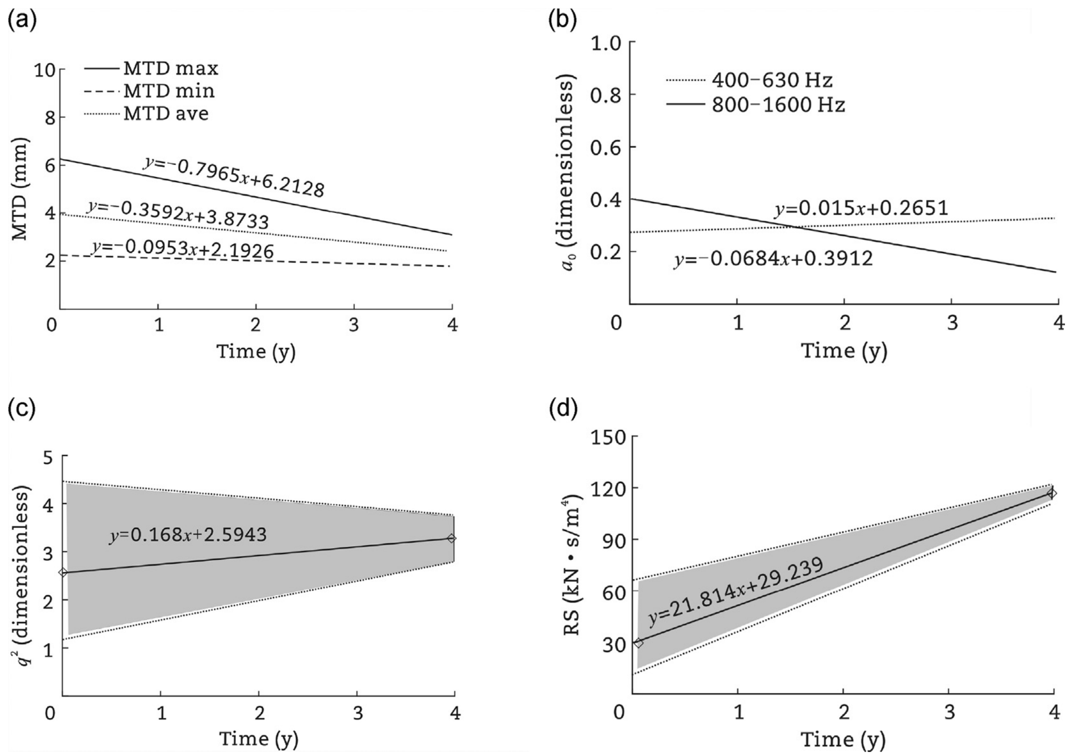

Fig. 5 – Parameter. (a) On-site MTD. (b) In-lab Kundt's tube. (c) Tortuosity. (d) Resistivity.

surface properties vary as a function of time. The same pavement sections were monitored over six years.

In-lab experiments were carried out on cores extracted from the pavement mentioned above in order to evaluate: i) permeability using the flexible-wall permeameter (K, according to ASTM PS 129-01 and Florida Test Method FM 5-565) (Florida Department of Transportation, 2004), skid-resistance (PTV) (Praticò and Astolfi, 2017); ii) acoustic sound absorption ($a_0(f)$), using Kundt's Tube (ISO, 1998); iii) volumetric properties (i.e., dimensional analysis, Gmb_{DIM}, Gmb_{COR}, Gmm, AV_{eff} (ASTM, 2018a, b). To this end, note that, even if the PS 129-01 standard has been withdrawn, many studies after 2005 on the permeability of road pavements have been carried out using the flexible wall permeameter.

The following on-site experiments were carried out: 1) extended surface method (also known as Adrienne test) (ISO, 2010); 2) drainability, DR (Autostrade, 2001); 3) macrotexture, MTD (ASTM, 2015; National Standards Authority of Ireland, 2010); 4) pendulum test, PTV (National Standards Authority of Ireland, 2011); 5) Spot method for reflective surfaces (as known as on-site Kundt's tube) (ISO, 2010). Data were reported as a function of years. Importantly, the concerned average annual daily traffic, AADT, was 10,000 vehicles per day per lane, while the traffic on the emergency lane was considered negligible.

4.2. Results

Fig. 1 illustrates how the values of permeability of the cores extracted and the corresponding air voids content match the models and the data in the literature. In more details, for the data obtained in the laboratory, K ranges from 10^{-2} to 1 cm/s and AV from 15% to 25%. They correspond to different ages and lane positions (wheel paths and between wheel paths).

Experimental (EXP) data were obtained based on the experiments carried out on-site after 0–6 years. Importantly, it is noted that while the initial drainability of the pavement does not depend on the position in the transverse section, the values after, for example, four years do depend on it and range from about 7% (outside the wheel paths – emergency lane) to about 62% (in the wheel paths). By referring to the on-site drainability out of the wheel paths, based on the experiments carried out, it is observed that there is a decrease of about 18% per year, while the standard deviation decreases from 8 to 4 and the corresponding coefficient of variation increases from 38% to 74%. Fig. 2(a) points out the values of AV obtained based on on-site experiments carried out. Importantly, they are compared with the values after Wang et al. (2015). The first derivative, which is approximately −1 for AV around 5%, ranges from about −4 for very low AV to about one hundredths of it (for AV around 30%). Fig. 2(b) shows the skid data (ASTM, 2013; National Standards Authority of Ireland, 2011) gathered from the literature. These data are compared with the experimental results related to the porous asphalt concrete under investigation (Praticò and Astolfi, 2017). Averages are reported.

Note that PTV does not have a strictly monotonic curve and varies as a function of many variables, among which lane (slow or passing) and position (wheel paths or not) and that data gathered refer to wheel paths. It is noted that: 1) the first derivative for PAs varies from −4 to −5 while the corresponding intercept varies from 60 to 90; 2) for the remaining mixes (SMA and DGA), based on the literature, the first derivative varies from −4 to −5 while the corresponding intercept varies from 60 to 90. Apart from the well-known complexity of friction evolution over time, experimental data confirm that, during the first four years, the PTV of porous asphalt concretes decreases with a slope of about 4–5 PTV points per year, standard deviation is about 5, and coefficient of variation is about 0.1. Fig. 5 illustrates how on-site MTD, acoustic absorption, a_0, tortuosity, and resistivity (RS) vary over years for the road sections investigated. For macrotexture, Fig. 5 illustrates how the on-site MTD varies over time. Note that outside the wheel paths, MTD decreases of about 0.4 mm per year, i.e., of about 9% per year. The standard deviation decreases while the coefficient of variation is constant and around 0.2. The average absorption coefficient in the selected frequency bands, 400–630 Hz and 800–1600 Hz, is plotted. Importantly, the acoustic absorption in the range 400–630 Hz increases (+6% per year) while it decreases in the range 800–1600 Hz (−22% per year). The tortuosity q^2 of a porous mix is a dimensionless parameter that varies from 1 to higher values. It describes how much the shape of the pores of the mixture differs from a straight line (Praticò, 2014). Based on the parameters known, the tortuosity was derived using an inverse problem approach (Praticò et al., 2017). Results show that there is an annual increase of about 0.2, while standard deviation (−0.13 per year) and coefficient variation decrease (−0.06 per year).

In Fig. 5, MTD max is maximum mean texture depth, MTD min is minimum mean texture depth, MTD ave is average mean texture depth.

The resistivity is the pressure drop per length divided by the mean air velocity. The derivation of resistivity was carried out through the inverse problem approach, as for q^2 (see above). Results show that the resistivity increases at a rate of about 22 kN·s/m^4 (75%) per year while its standard deviation and coefficient of variation undergo a sharp decrease (−2 kN·s/m^4 per year and −0.1 per year, respectively). This result points out that the older the pavement is, the higher the pressure drop is due to the reduced volume of voids and to the higher tortuosity of pores. At the same time, while as-built mixtures show a constitutive inhomogeneity of pores, clogging greatly affects the value of RS, reducing its variability.

4.3. *Investigating the limit conditions*

The method set up above builds on predicting the evolution of each property and its expected life based on operation-related limits (intervention level). In this study, the values reported in Table 1 were selected.

To this end, note that specifications report as-built lower and upper specification limits (LSL, USL), while they do not address usually the corresponding limits during operations (intervention level).

The intervention level of a road builds on political, and technical motivations, including the importance of the road (e.g., urban built, motorway, highway). For PAs, practical limit conditions in terms of AV, drainability, and K, can be assessed by deriving, for given AV, the corresponding K_{20} (and its time) and DR (as well as its flow time). Based on Cooley (2003) and Praticò and Moro (2007), K_{20} is about 0.000003 cm/s (and DR about 0.001 L/min) for AV close to 1%, while K_{20} tends to 0.23 cm/s (and DR to 22 L/min) when AV tends to 27%.

For DR, the SL originates from the dependence on AV, where it seems relevant to highlight that 12% is commonly considered the threshold for the technical acceptability of a dense-graded friction course and it corresponds to a 2-min on-site test (DR). Based on the above, on average, the on-site limit condition for K_{20} is supposed to be 0.014 cm/s (LSL), which corresponds to a drainability of 1.6 L/min, to a corresponding drainability time of about 2 min, and to AV is 12%. For low-frequency acoustic absorption, the (as-built) acceptance SL (0.15) and its corresponding intervention level do not have practical consequences, because, as observed above, the acoustic spectrum over time moves towards left, which implies that in this frequency range it slightly increases. In contrast, for high frequencies, for the same reason (peak shift), as-built SL (0.30) and the selected intervention limit (0.15) are critical. This latter was selected based on the average value a dense-graded friction course would have for this range of frequency. Macrotexture and friction operation-related limits were set up based on specifications and literature. In terms of lower specification limit of friction, LSL, two types of minimum skid resistance are commonly used for pavement friction management: the investigatory level and the intervention level. The investigatory level is the skid resistance at which road agency should start to monitor skid resistance and crash levels, and start planning some preventive or restorative actions. The intervention level is the skid resistance at which it is necessary to take immediate corrective action, such as a maintenance or restorative treatment. According to Fwa (2017), the intervention level is the threshold below which the driving safety risk becomes unacceptable. The lower specification limit for friction during operations varies based on: 1) indicator chosen (e.g., PTV, SCRIM, DWW or SN40R), type of level intended (e.g., investigatory level, intervention level), and author. Based on the literature (Highways Agency, 2006; Lal Das, 2011; Henry, 2000; Speir et al., 2009; Wu and King, 2012), the lower specification limit (intervention limit) corresponds to SNR40 or SNR50 of about 25–38 (ASTM, 2011), PTV of about 45 (ASTM, 2013), SFC of about 0.35–0.50 (British Standards Institution, 2006), DWW of about 38 (DWW, 1997). Note that SNR40 = 30, based on PIARC 1995 (Wambold and Henry, 1995) and Praticò (2018), corresponds to PTV = 45, under the hypothesis of having MTD = 1.4 mm (around) Importantly, this value agrees with Chen et al. (2015a, b), Ahadi and Nasirahmadi (2013), and Blake et al. (2017).

4.4. *Method implementation and discussion*

Based on the method set up above, the most critical characteristic can be derived based on the intersection between each curve above and the corresponding specification limit. Tables 2 and 3 and Figs. 6 and 7 summarize the application of method to the case study under investigation.

Linear and exponential curves were derived, and, based on the corresponding specification limits (LSL), the corresponding expected life (EXL) was derived. For DR, the equation refers to outside the wheel paths and it is EXL$_{DR}$ around 7 years (OWP) and 10 (WP). For a_0 in 800–1600 Hz, it results EXL$_{a_0}$ around 5 years (WP) and 1 year (OWP). Note that due the shift of absorption spectra towards low frequencies, for a_0 in 400–630 Hz, the expected life is theoretically infinite (NA in

Table 2 – Method implementation (SL).

Method	C_i	DR (L/min)	a_0 (400–630 Hz)	a_0 (800–1600 Hz)	MTD (mm)	PTV
SL	As-built	18 (**)–12 (*)	>0.15 (*)	>0.30 (*)	1	53-55 (**)
	Intervention limit	1.6	0.10	0.14	0.7	45

Note: SL is specification limit, * means capitolatos ANAS, ** means capitolato CIRS.

Table 3 – Method implementation (linear and non linear).

Method		DR (L/min)		a_0 (400–630 Hz)		a_0 (800–1600 Hz)		MTD (mm)		PTV	
		WP	OWP	WP	OWP	WP	OWP	WP	OWP	WP	OWP
Linear	m	−3.75	−4.409	0.029	0.006	−0.052	−0.096	−0.152	−0.279	−4.752	−2.544
	q	21.554	21.554	0.265	0.265	0.391	0.391	3.873	3.873	64.34	64.34
Non linear	a	21.554	21.554	0.265	0.265	0.391	0.391	3.673	3.673	29	29
	b	−0.272	−0.348	0.090	0.022	−0.189	−1.049	−0.046	−0.090	−0.260	−0.105
	c	0	0	0	0	0	0	0.2	0.2	35	35
	EXL (y)	10	7	NA	NA	5	1	43	22	4	10
	Ci(EXL)	1.61	1.61	0.10	0.10	0.14	0.14	0.7	0.7	45	45
	Ci(0)	21.55	21.55	0.26	0.26	0.39	0.39	3.87	3.87	64	64
	Ci(15)	0.36	0.11	1.02	0.36	0.023	0.00	2.04	1.15	36	41

Note: m and q are the coefficient of variation, and the intercept of the linear function, respectively, a, b, and c are the base, the exponent coefficient, and the constant of the exponential function, respectively, WP is in the wheel paths, OWP is outside the wheel paths, NA is not available (expected life theoretically infinite). Non linear: $y = a\exp(bT)+c$, linear: $y = mT+q$, where y is the genetic surface property (i.e., DR), and T is the time in year.

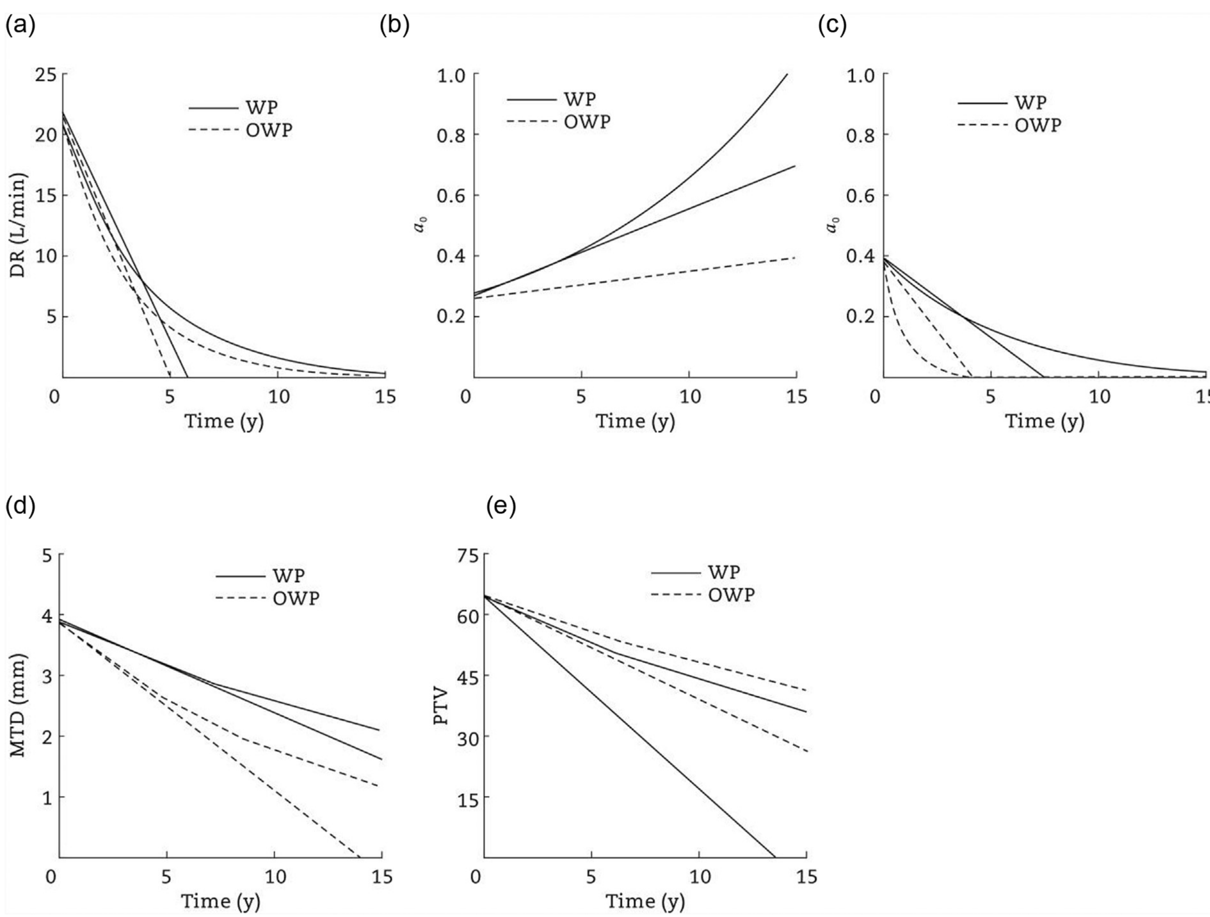

Fig. 6 – Linear and nonlinear curves for the selected characteristics. (a) DR. (b) a_0 (400–630 Hz). (c) a_0 (800–1600 Hz). (d) MTD. (e) PTV.

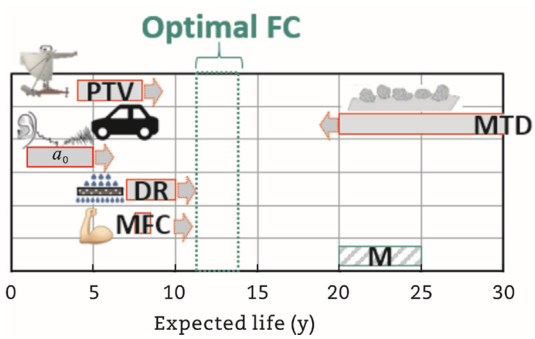

Fig. 7 – Towards optimality in functional design of PAs.

Table 2). For macrotexture, expected life is EXL_{MTD} around 43 years (WP) and 22 year (OWP). For friction, EXL_{PTV} is around 4 years (WP) and 8 year (OWP). The specification limits were 1.6 L/min (DR), 0.10–0.14 (a_0), 1.9 mm (MTD), and 45 (PTV, friction). Importantly they relate to the corresponding as-built specification limit as follows (Tables 2 and 3).

Tables 2 and 3 (EXL) point out that friction and acoustic absorption in 800–1600 Hz are the most vulnerable characteristics. This occurrence depends on the particular bituminous mixture considered. It seems relevant to highlight that while the friction characteristics over time depend on the mineralogical nature of aggregates and the addition, for example, of basalt, would improve the expected life (Do et al., 2014; Roe and Hartshorne, 1998), the acoustic absorption in 800–1600 Hz pertains to the same choice of the porous asphalt concrete as selected mixture. Another relevant point is that outside wheel paths noise-related conditions are worse and expected lives lower. This has consequences for dwellers because the outdoor noise is greatly affected by reflections and acoustic absorption along the path between sources (located in the wheel paths) and receiver (outside the carriageway) (Musolino et al., 2018). It appears relevant to observe that linear curves do not represent properly experiments carried out and literature data outside the concerned range. Consequently, they imply an expected life that is not well grounded in logic (Tables 2 and 3).

Finally, it is noteworthy noting that while functional properties fail when considering high frequency absorption and friction, the big picture is even more complex if mechanistic properties are considered (MFC and M in Fig. 7). Indeed, for the case study under investigation, the mechanistic-based EXL of the friction course (MFC) is close to 8 years. In contrast, being 20–25 years the reference target for pavement rehabilitation (M, which includes the layers underneath), the optimal duration would be about 12 years. The schematic of Fig. 7 depicts that the actual fatality succession is very different from the optimal one i.e., FC-related properties (PTV, a_0, MTD, DR, MFC) close to 12 years, in order to minimize agency cost, user costs (delays), and environmental costs (depletion of non-renewable resources). Based on case study, there is an appreciable difference between optimal and actual situation. This fact, based on the literature, is not an isolated case and may apply to many premium properties as well as porous asphalt concretes. This calls for further studies and for a sound consideration of pros and cons of the different solutions existing in the market (e.g., two-layer porous asphalt concretes). Another issue pertains to prediction (Fig. 6) uncertainty. This latter arises from uncertainty in input values (e.g., traffic and climate effect on decay curves), numerical solution (e.g., curve order), model structure (e.g., asymptote corresponding to a stationary state that refers to a physical constraint), and uncertainty propagation through the model. This issue calls for further experimental investigations aiming at investigating how much boundary conditions affect prediction and if accelerated testing are able to limit prediction uncertainty.

5. Conclusions

The surface properties of porous asphalt concretes are vital. They decay over time. Particularly, because of clogging, on-site permeability decreases over time and this phenomenon depends on many variables, among which pavement type, position in the lane, type of lane, hydrological parameters, and position of the road. In turn, clogging impacts the air void content. This latter affects the hydraulic conductivity. An in-depth literature investigation and experimental investigation was carried out. A method was set out and applied. Results demonstrate that: 1) The design of a premium friction course, such as a porous asphalt concrete, is a complex topic and involves several functional properties as well as the mechanistic point of view. 2) The actual behaviour over time of the main functional properties does not fit properly the corresponding intervention limits. Premature failures may be expected for friction and high-frequency acoustic absorption. 3) The actual evolution over time of the main functional properties is essentially governed by clogging, which affects quantity and characteristics of pores, involving both volumetric indicators (AV) and other indicators (q^2 and RS). As a result, each characteristic has a different trend over time and the level of fulfilment of requirements varies over time and among the characteristics. In practice, this implies that several characteristics fail prematurely. 4) The practical remedial to this constitutive asymmetry in decay involves many strategies. Some of them are quite intuitive, viable, and recurrent, such as the optimization of friction through the increase of aggregate intrinsic properties and consequent quality indicators (e.g., PSV for friction and bitumen type for the mechanistic expected life of the friction course). Some of them appear to be intrinsically related to the way clogging evolves in the specific type of mix, due to their gradation (e.g., nominal maximum aggregate size) and initial voids content. This implies that, based on the state-of-the-art level and actual data available, a sound optimization of the design of the mix in order to balance the different characteristics could imply simply to change the typology of mix (e.g., passing from PA to a two-layer PA). 5) Further studies are needed because of uncertainty in predicting the main surface properties. This is a reasonable starting point for building a future research program.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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