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On the dependence of acoustic performance on pavement characteristics

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ABSTRACT

Acoustic-based mix design is still far from achieving a clear and accepted rationale. The three main dominions (generation, absorption, propagation) which affect pavement acoustic performance involve a number of acoustic parameters. Their relationship with pavement properties is scarcely or insufficiently known. In more detail, the parameters that define the acoustic coupling between the two phases that comprise a porous material are: porosity, resistivity, tortuosity, and viscous and thermal factors. Consequently, the spectrum of a pavement absorption coefficient depends, in particular, on tortuosity, whose relationship with HMA (hot mix asphalt) bulk properties is still an issue.

Given that, the study described in this paper aimed at: (i) assessing the effect of the tortuosity on the absorption coefficient of a pavement layer; (ii) assessing the dependence of tortuosity on mix design parameters and/or mix properties; (iii) deriving a straightforward algorithm to estimate the effect of tortuosity-related properties on the absorption coefficient.

Based on the above issues, an experimental plan was designed and carried out in order to study these relationships and set out a tentative theoretical and practical framework. The relationships between acoustic and traditional bulk properties of pavement mixtures were analysed. Acoustic models and hydraulic analogies were considered and, based on them, relationships were formalised and submitted to experimental validations. A simple relationship to derive tortuosity from nominal maximum aggregate size and thickness was derived. This relationship was used to derive the frequency of the first peak of the absorption spectrum, based on HMA properties. Nominal maximum aggregate size and lift thickness emerged as key factors in patterning peak frequency.

Future research will address a number of issues among which the following can be listed: synergetic assessment of the influence of HMA properties on the absorption coefficient over the entire spectrum, synergetic consideration of generation and absorption factors. Practical benefits and outcomes are expected for both practitioners and researchers.

Introduction

Traffic noise is one of the most important environmental problems (Freitas et al., 2012). Noise exposure can cause two main kinds of health effects: non-auditory effects and auditory effects. The first class includes cardiovascular (heart and

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blood vessels) effects, sleep disturbances, delayed language and reading skills in children, stress, related physiological and behavioural effects, and safety concerns (Berry and Flindell, 2009). Auditory effects comprise hearing impairment resulting from excessive noise exposure. In more detail the main auditory effects include: (i) acoustic trauma; (ii) tinnitus; (iii) temporary hearing loss; (iv) permanent hearing loss. The main characteristics of permanent hearing loss are the following: (a) it is a cumulative process; (b) at a given sound level, low-frequency noise (below 100 Hz) is less damaging than mid-frequencies noise (1000–3000 Hz); (c) noise-induced hearing loss occurs randomly in exposed persons; (d) initially, noise-induced hearing loss is most pronounced at 4000 Hz but, as exposure time increases, it spreads over other frequencies; (e) it usually interacts with presbycusis (age-related hearing loss); (f) time and sound levels superpose in the determination of percentage of hearing disability (ISO, 1999–1990 and American National Standard ANSI S3.44 – 1996). Note that minor corrective interventions, such as slight reductions in traffic noise level, can be sometimes insufficient to reduce noise annoyance and common mental disorder and to achieve tangible improvements in quality of life (Stansfeld et al., 2009).

Power unit and tyre-road contact (which relates to rolling noise) are the main sources of traffic noise. In the mid-to-high speed range (approximately above 40 km/h for passenger cars and 70–80 km/h for trucks) the main contributor to traffic noise is tyre/road (rolling) noise (Sandberg and Ejsmont, 2002). Pavement-tyre interaction generates acoustical pressures (Weyl–Van Der Pol's equation) which generate loudness and tyre/road noise may vary more than 15 dB (tyre and pavement type). Rolling noise depends on generation factors, problem geometry and pavement absorption properties (Praticò, 2001; Poulikakos et al., 2009; Mak et al., 2012).

Noise reduction at the source (i.e., pavement/tyre interface) can be very cost-effective (more than treatments on the buildings or on the propagation path – noise barriers). According to (Nijland et al., 2003), the cost effectiveness of "source" measures is appreciable. In more detail, as for low-noise pavements, their cost effectiveness is considerable even if it is lower than that of low-noise tires (Nijlanda et al., 2003). To this end, it is important to observe that silent pavements effectiveness could at least be improved if they were constructed on noise-sensitive spots only and that the expected life of pavement is higher than the one of tires. Note that several "silent" technologies have been set out. Porous asphalt (PA) is to date the most efficient road surface technology in terms of noise reduction. It is mostly used as a single porous layer, even if double layer porous asphalts are widespread in some countries (e.g., northern Europe). There are many types and derivations of open-graded friction courses (OGFC) and many terms are used to define them (e.g., permeable friction courses-PFC, porous European mixes-PEM, new generation open-graded friction courses-NGOGFC, porous asphalt-PA, etc.). A conventional OGFC is a layer of asphalt that incorporates a skeleton of uniform aggregate size with a minimum of sand (around 5% compared to a percentage of 25% for dense-graded friction courses). In the U.S. this material rarely exceeds 20% of voids content, while in the other countries 15–30% air voids for porous asphalt are used. The layer thickness of porous asphalt in other countries is usually between 40 and 50 mm. In the U.S.A., most open-graded friction courses are around 20 mm thick, and usually no thicker than 5 mm.

The parameters that define the acoustic coupling between the two phases that comprise a porous material are: porosity, resistivity, tortuosity, and viscous and thermal factors. Porosity refers to connected voids (Ω, dimensionless). Under several hypotheses it can be easily related to air void content (Praticò and Moro, 2007). Resistivity can be derived from the airflow resistance (R, Ns m^{-5}). This latter is the ratio between the pressure difference across a sample and the flow rate through the sample. For a sample cross-sectional area S and a thickness TH, the flow resistivity is:

$$R_s = \frac{R \cdot S}{\mathrm{TH}} \tag{1}$$

Tortuosity (which is dimensionless) refers to the square of the ratio between pore lengths and sample length (Stinson and Champoux, 1992). Two main models can be considered for deriving the acoustical absorption: the phenomenological and the microstructural one (Bereinger et al., 1997; Sandberg and Ejsmont, 2002). Under several hypotheses, the former can be considered a particular case of the latter. According to the microstructural model, six parameters are required to estimate the absorption coefficient: (i) the tortuosity (q^2, dimensionless) of a medium; (ii) the airflow resistivity of the porous structure (Rs, Ns/m^4); (iii) the porosity of air-filled connected pores (Ω, dimensionless); iv–v) the viscous and thermal pore shape factors (s_ρ and s_k, respectively, dimensionless); (vi) the thickness of the porous layer (TH, m). For bituminous mixes, their traditional values are the following: (a) R_s: (1000–4000,000) Ns/m^4; b) $q^2 \cong (1.9–7.5)$; (c) $\Omega \cong (0.04–0.30)$; $s_\rho \cong 1.00–1.14$; $s_k \cong 0.44–1.00$. If experimental data and theoretical predictions are matched (Bereinger and Hamet, 1997; Praticò et al., 2013), the following auxiliary information can be derived: (i) porous asphalt concretes have often a first peak (which is usually an absolute maximum) which has a value in the range 0.8–1.0, with a frequency in the range 0.6–1.3 kHz. For them, $R_s \cong (5000–30000)$ Ns/m^4, $q^2 \cong (2.5–7.5)$, $\Omega \cong (0.15–0.30)$, TH $\cong$ (0.04–0.08)m; (ii) dense-graded asphalt concretes have absorption spectra with values around 0.05–0.2 and their maxima points and values are less noticeable. As a consequence q^2 is often questionable, while resistivity is higher (e.g., >40,000 Ns/m^4), and $\Omega \cong (0.03–0.08)$.

The above parameters (with the exception of the thickness) affect the complex, dynamic density (ρg, N s^2 m^{-4}) and the bulk modulus (Kg, N/m^2). The dynamic density and the bulk modulus (together with the porosity of the material) determine the characteristic impedance (Zc, Ns/m^3) and the complex wave number (k, s/m). The characteristic impedance and the thickness of the porous layer determine the surface impedance (Z, Ns/m^3). In turn, the acoustic behaviour of a rigid-frame porous material (including its absorption coefficient) is completely characterised by its surface impedance and its complex wave number.

In the phenomenological model, four out of the above six parameters are required to estimate the absorption coefficient: (i) tortuosity; (ii) airflow resistivity; (iii) porosity; (iv) thickness. Tortuosity, resistivity and porosity are still but differently