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Significance and reliability of absorption spectra of quiet pavements

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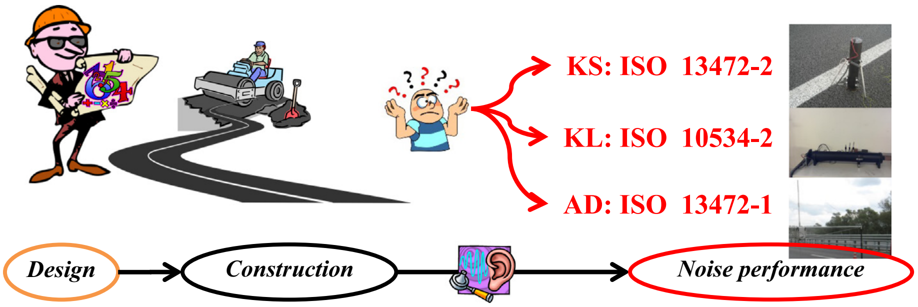
HIGHLIGHTS

- Three methods for assessing the acoustic absorption of a pavement were compared.
- New objective functions to fit observed data and model were set up.
- Boundary conditions were attentively investigated and experimental data were used.
- The precision and the accuracy of each device were studied.

GRAPHICAL ABSTRACT



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ABSTRACT

The objectives and scope of the study described into this paper were to compare different methods to assess (measure or predict) the acoustic properties of a pavement in order to derive information about use in practical applications. To this end, in-lab Kundt tube, on-site Kundt tube, Adrienne device and theoretical modelling were used. Based on measurements, absorption spectra were derived. Analyses and results focused also on composite indicators, first-pick frequencies and objective functions.

Based on results, when fitting experimental data through theoretical models the least square method is unsatisfactory and alternative algorithms are proposed. The on-site Adrienne method provides a good estimate of thickness, tortuosity, resistivity and maximum, while in-lab impedance tube, even if quite time consuming, seems to achieve the best accuracy. The on-site Kundt tube provides a satisfactory estimate of porosity and further investigations and analyses are recommended to investigate its use also for porous surfaces. Future research will address two competing needs which emerged from the study: i) the need for simplifying the procedures/methods; ii) the need for improving the quantity of information gathered (e.g., texture), through the same device.

1. Introduction

As is well known, traffic noise is one of the most important environmental problems in Europe (see [1–5]). Power unit and tyre-road contact are the key sources, and in the mid-to-high speed range (above 40 km/h-80 km/h) rolling noise prevails [6]. Based on the Weyl-Van Der Pol's equation these phenomena generate acoustical pressures, which, in turn, generate loudness ([7–10]). Tyre/road noise may vary >15 dB, based on tyre and pavement type. To this end, noise reduction at the source can be more cost-effective than treatments on the buildings or on the propagation path (e.g., noise barriers). Generation factors (pavement texture, tyre type, see [11] and [12]) and acoustic absorption govern rolling noise ([13,14]). Pavement characteristics (volumetric and surface proprieties) affect generation, absorption and propagation ([8,15–19]).

Based on the above, road agencies require a satisfactory level of acoustic absorption, which can be assessed through in-lab (ISO 10534-2; [20]) and/or on-site (ISO 13472-1; ISO 13472-2) tests.

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Furthermore, other relevant tests were set up in order to provide accurate and high-speed methods and procedures in terms of absorption properties ([21]). These tests have an outstanding importance in worldwide quality assurance/quality control (QA/QC, see [22–25]) because of noise-related health issues, because of the growing diffusion of quiet pavements ([22,26–28]), and because pavement acceptance procedures include adjusted payment schedules ([22]). This notwithstanding, it may be observed that: i) there is no common agreement on the best measurement method; ii) different methods and devices can be used and each one implies different issues, time consumption, traffic restrictions, and results. In more detail, it is stated the inapplicability of the ISO 13472-2 to porous asphalts and there is a certain lack of attention on "true" values, i.e., about variability (precision) and trueness (accuracy); iii) in both design and acceptance plans, the consistency and dependency between material properties (e.g., air voids content) and acoustic performance (as per measurements) is a key-factor but is often neglected due to the complexity of the involved relationships and algorithms and to the diverse cultural backgrounds involved (acoustics *versus* civil engineering).

The facts above imply potential biases and uncertainties from a practical and scientific standpoint.

2. Objectives

Based on the above, the objectives and scope of the study described into this paper were the following:

1. to match and analyse three methods for measuring the acoustic absorption of a pavement (Adrienne, ISO 13472-1, AD; in-lab Kundt tube, ISO 10534-2, KL; on-site Kundt tube, ISO13472-2, KS).
2. to compare measurements and expected results based on theoretical modelling. This implies: i) To study the objective (error) function that allows better comparing experimental and theoretical spectra (least square method versus new recipes for optimisation), for the three different methods; ii) To fit the theoretical model to the experimental data, without boundary conditions (i.e., deriving tortuosity and resistivity, thickness, and porosity without imposing ranges they belong to) or with boundary conditions (using as input the real thickness and the effective porosity and deriving the remaining two parameters); iii) To study the relationships among the actual value of thickness and porosity (i.e., based on experiments on cores) and the corresponding values obtained from the optimisation above; iv) consequently, to ascertain which method (out of the three ones involved in the experiments) best fits the theoretical results in terms of sound absorption spectra (accuracy).

3. Design of experiments

Fig. 1 illustrates the flow chart of the experimental investigation.

Task 1 focused on field investigations according to ISO 13472-1 and ISO 13472-2. A motorway, located in Southern Italy was investigated. Measurements were carried out on the hard shoulder lane and on the inside lane, but not on the outside (overtaking) lane. The surface layer main characteristics were the following: nominal maximum aggregate size: 16 mm; asphalt binder content, percent by total weight of mixture: 4.7%; air voids content: 20%; clogging not noticed. For each device, operating time and performance were analysed.

In Task 2, after core extraction (in the sections corresponding to the quoted on-site measurements), cores were labelled and transported to the laboratory. There, each core was preliminary cleaned, swept and controlled (for imperfections in the lower face). Afterwards it underwent the nondestructive tests (KS, ISO 10534-2; effective porosity ASTM D6752-11; thickness EN 12697-36:2003).

Task 3 focused on data analysis (absorption spectra).

Finally, in Task 4 experimental spectra (from Tasks 1 and 2) were compared with the ones derived from the theoretical model (Task 3).

4. Modelling, implementation and preliminary analyses

As mentioned above, Task 1 and Task 2 provided experimental data to Tasks 3 and 4.

In terms of theoretical modelling, note that the sound pressure level depends on the acoustic absorption coefficient based on the Van der Pol formula [8]. For the absorption coefficient, note that the main parameters that define the acoustic coupling between the two phases that comprise a porous material (i.e., porous asphalt concrete) are: porosity (Ω, dimensionless), resistivity (Rs, Ns/m^4), tortuosity (q^2, dimensionless), thickness (t, e.g., m), and viscous and thermal factors. Porosity refers to connected voids (Ω, dimensionless). Under several hypotheses it can be easily related to air voids content. Resistivity can be derived from the airflow resistance (R, $Ns \cdot m^{-5}$). This latter is the ratio between the pressure difference across a sample and the flow rate through the sample. Tortuosity (which is dimensionless) refers to the square of the ratio between pore lengths and sample length [31]. The parameters above (with the exception of the thickness) affect the complex, dynamic density (ρg, $N \cdot s^2 \cdot m^{-4}$) 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). In turn, the characteristic impedance and the thickness of the porous layer determine the surface impedance (Z, Ns/m^3). The acoustic behaviour of a rigid-frame porous material (including its absorption coefficient) is completely characterized by its surface impedance and its complex wave number:

$$a_0 = 1 - \frac{|Z - \rho c|^2}{|Z + \rho c|^2} \tag{1}$$

where ρ is the air density and c is the speed of sound in air.

For the four most relevant parameters which impact the absorption, note that (Table 1):

- Thickness (t) is easy to measure. The higher the thickness is the lower the frequency of the first maximum is. Absorption tends to be lower and smoothed ([32]);
- Porosity (Ω) is quite easy to measure (in the laboratory). The higher the porosity is, the higher the absorption coefficient is. Maximum frequency does not depend on porosity ([32]);
- Resistivity (Rs) is quite difficult to measure. The higher the resistivity, the lower the maxima, the smoother the curve ([32]);
- Tortuosity (q^2) is difficult to measure ([33–37]). The higher the tortuosity is, the lower the frequency of maximum is. The impact on the maximum value of absorption is usually quite negligible ([32,38]).

Finally, note that, for the total resistance (Rt = Rs*t), the higher the total resistance is, the higher the maxima are when Rt is lower than about 100 Ns/m^3. For Rt higher than about 100 Ns/m^3, the behaviour is opposite.

From a theoretical and computational standpoint, apart from the overall complexity of models, it is very relevant to "confine" both expected spectra and input values (Ω, q^2, t, Rs). In this regard, Porous European mixes (PEMs) and dense-graded friction courses