ESTIMATING THE RESISTIVITY AND TORTUOSITY OF A ROAD PAVEMENT USING AN INVERSE PROBLEM APPROACH

Filippo Giammaria Praticò, Domenico Vizzari *and* Rosario Fedele

DIIES Departement, University Mediterranea of Reggio Calabria, Italy
email: filippo.pratico@unirc.it

One of the parameters commonly used for the characterization of porous road pavements is the sound absorption coefficient. This parameter can be experimentally measured (ISO 13472-1, ISO 13472-2, ISO 10354-2), or theoretically estimated. A comprehensive literature review shows that the transfer-function method (ISO 10354-2) is a quite precise experimental method. On the other hand, one of the most accurate models for the theoretical estimation of the acoustic performance of a pavement has been proposed by Stinson and Champoux (1992). This model considers the sound absorption coefficient as a function of various physical factors of pavement, i.e. thickness, porosity, resistivity, tortuosity, thermal and viscous factors.
The aim of the study described in this paper is to analyse how tortuosity and resistivity can be derived based on the remaining factors and/or based on mixture-related properties. In order to pursue this scope, the first step was the determination of the values of the two parameters in terms of an inverse problem, i.e., in terms of derivation of two model parameters (tortuosity and resistivity) based on data (starting from the absorption spectrum). The Stinson and Champoux model was used. In more detail, the input of the inverse problem were the acoustic absorption coefficient values measured, the real porosity, and the thickness (experimentally obtained). The second step was the estimation of the two parameters under investigation through models, based on mixture-related properties (e.g., real porosity and thickness). The third step was the comparison between the results of the first and the second step.
The results show that several literature models can provide a good estimate of resistivity, while tortuosity prediction can be an issue. Further studies will be carried out using values of resistivity measured in the laboratory, in order to theoretically estimate the acoustic absorption coefficient of a pavement with just one (main) unknown, i.e. the tortuosity.
Keywords: pavement, sound, absorption, resistivity, tortuosity.

1. Introduction

The surface texture and volumetrics of the friction course of a pavement are the main parameters that impact rolling noise ([1], [2], and [3]), while the overall impact of the infrastructure system on dwellers depends on noise barriers and context [4]. In turn, the volumetric properties of the bituminous mixture affect its sustainability and acoustic absorption ([5], and [6]). One of the parameters commonly used for the characterization of porous road pavements is the sound absorption coefficient. This parameter can be experimentally measured (ISO 13472-1, ISO 13472-2, and ISO 10354-2), or theoretically estimated. A comprehensive literature review shows that the transfer-function method (ISO 10354-2) is the most accurate experimental method. One of the most accurate model for the theoretical estimation of the acoustic performance of a pavement has been proposed by Stinson and Champoux (1992) [7]. This model considers the sound absorption coefficient as a function of various physical factors of pavement, i.e. thickness, porosity, resistivity, tortuosity, thermal and viscous factors. The resistivity can be derived from the airflow resistance:

$$R = \frac{\Delta p}{Q_v} \quad (1)$$

where Δp is the pressure difference across a sample and Qv is the flow rate thought the sample.

The product between R and the sample's section is the resistivity [8]; [9]. Resistivity is a crucial parameter because it refers to the acoustical properties of porous materials, to their structure, production and compaction process, and quality control ([10], [11], [12], and [13]). It can be measured according to the ISO 9053, through two experimental methods (direct airflow method and alternating airflow method). Hamet and Bérengier [14] in 1990 modelled a porous asphalt as a solid structure supposed rigid, where the dimension of pores and of particles must be small enough compared to acoustic wavelengths. In terms of resistivity the result is expressed by the following formula:

$$R_S = \mu \cdot q^2 / \left(\Omega^3 d^2\right) \quad \textit{Hamet}\ (2)$$

where μ is the dynamic viscosity [Ns/m^2], q^2 [dimensionless] is the tortuosity, Ω is the porosity of the medium [dimensionless] and d is the diameter of the pores.

In the case of a medium composed by parallel and straight cylindrical pores of radius r with their axes normal to surface [15], the resistivity can be estimated through the following algorithm:

$$R_S = 8\mu / \left(\Omega \cdot r^2\right) \quad \textit{Attenborough\_1}\ (3)$$

For a microstructure of straight parallel-sided slits, with axes normal to the surface [15], it is:

$$R_S = 3\mu / \left(\Omega \cdot b^2\right) \quad \textit{Attenborough\_2}\ (4)$$

where b is the semi-width of the slit-like pores.

If the (slit) semi-width and the grain shape are assumed to be constant, then the relationship becomes:

$$Rs = \frac{const}{\Omega^{(1+n)}} \quad \textit{Attenborough\_3}\ (5)$$

where n depends of the average shape of the grains [15] (i.e. n is 0.5 for a collection of spheres).

The expression proposed by Von Meier refers to a porous layer of granular material and it is a function of the chipping diameter (k, assumed 10 mm for a thickness around 4 cm), porosity and thickness s [16]:

$$R_{S\max} = 10^{-2} / \left(1.7 k^2 \Omega^2 s\right). \quad \textit{Von Meier}\ (6)$$

The tortuosity is the square of the ratio between pore lengths and sample length ([7], and [9]). The calculation of tortuosity is a difficult task ([17], [18], and [19]) and actually it can be measured, for example, using tomographic reconstructions [17], or through a prototype realized by the University of Ferrara [21]. The prediction of tortuosity can be carried out by using the follow theoretical models. For idealized microstructures, tortuosity depends on porosity as shown in the next equation [15]:

$$q^2 = \Omega^{-n} \quad \textit{Attenborough\_4}\ (7)$$

where n is a constant defined to the Eq. 5.

Another formula refers to a granular material composed by rigid identical spherical particles and it depends only on porosity ([22], and [23])

$$q^2 = 1 + \frac{1-\Omega}{2\Omega}.$$ *Umnova* (8)

In 2014 Praticò obtained an expression for pavement layers which depends on nominal maximum aggregate size (NMAS, which in turn may correlate with volumetrics) and thickness (TH) [9]:

$$q^2 = 1 + \frac{0.40 \cdot TH^{0.8}}{NMAS^{1.03}} + \frac{1.44 \cdot TH^{0.40}}{NMAS^{0.51}}.$$ *Praticò* (9)

Yu and Li proposed a model for media with two-dimensional square particles ([24], and [25]):

$$q^2 = \frac{1}{2}\left[1 + \frac{1}{2}\sqrt{1-\Omega} + \frac{\sqrt{\left(1-\sqrt{1-\Omega}\right)^2 + (1-\Omega/4)}}{1-\sqrt{1-\Omega}}\right].$$ *Yu & Li* (10)

Equations below refer to media composed by spherical particles ([26], [27], [28], [29], and [30]):

$$q^2 = 1 - 0.41\ln\Omega;$$ *Comiti* (11)

$$q^2 = 1 - 0.49\ln\Omega;$$ *Mauret* (12)

$$q^2 = \frac{1}{\Omega^{0.33}}.$$ *Bear* (13)

When solid objects have a low density [31], the tortuosity can be predicted by:

$$q^2 = \left[1 - 0.64(1-\Omega)\right]^{-1}.$$ *Pisani_1* (14)

In the case of high density media, the following formula is given:

$$q^2 = 1 + 0.64(1-\Omega).$$ *Pisani_2* (15)

Ahmadi obtained the tortuosity of mono-sized spherical arrays based on a volume approach [32]:

$$q^2 = \sqrt{\frac{2\Omega}{3\left[1-1.209\left(1-\Omega^{2/3}\right)\right]} + \frac{1}{3}}.$$ *Ahmadi* (16)

In 2016 Khabbazi derived the tortuosity in 2D stochastically generated porous media composed of rectangular particles, based on the aspect ratio (AR) [33]:

$$q^2 = 1.01 - 0.37 \cdot \ln(\Omega);\ \text{for AR} = 1$$ *Khabbazi_1* (17)

$$q^2 = 0.99 - 0.8 \cdot \ln(\Omega);\ \text{for AR} = 2$$ *Khabbazi_2* (18)

$$q^2 = 0.98 - 1.16 \cdot \ln(\Omega).\ \text{for AR} = 3$$ *Khabbazi_3* (19)

2. Objectives

The aim of the study described in this paper is to analyse how tortuosity and resistivity can be derived based on the remaining factors and/or mixture-related properties. In order to pursue this scope, the first step was the determination of the values of the two parameters in terms of an inverse problem, i.e., in terms of derivation of two model parameters (tortuosity and resistivity) based on data (starting from the absorption spectrum). The Stinson and Champoux model was used. In more detail, the input of the inverse problem were the acoustic absorption coefficient values measured, the real porosity, and the thickness (experimentally obtained). Subsequently, the estimation of the two parameters under investigation was carried out through models based on mixture-related properties (e.g., real porosity and thickness). Finally the comparison between the results of the steps above was carried out.

3. Results and final remarks

In the pursuit of the objectives and scopes of this study, experiments were organised as follows: i) Task 1. A preliminary analysis of the expected results was carried out; ii) Task 2. The second step was the determination of the values of the two parameters in terms of an inverse problem, i.e., in terms of derivation of two model parameters (tortuosity and resistivity) based on data. The Stinson and Champoux model was used. In more detail, the inputs of the inverse problem were the acoustic absorption coefficient values measured, the real porosity, and the thickness (experimentally obtained); iii) Task 3. The third step was the estimation of the two parameters under investigation (Rs and q^2) through literature, based on mixture-related properties (e.g., real porosity and thickness); iv) Task 4. The fourth step was the comparison between the results of the second and the third step.

Figs. 1 and 2 and Tables 1 and 2 summarise results. Table 1 refers to the range of variation of Rs and q^2 based on literature. Note that for porous European mixes (PEMs), the resistivity approximately ranges from 1,000 to 60,000 Ns/m^4, while the tortuosity usually ranges from 2.5 to 4.5.

Table 1: Reference values

Input Parameter	**Main effect on the absorption a(f) of a bituminous mixture**	**Measurability**	**Reference values based on literature**	
			DGFC	**PEM**
Thickness (t, 0.01m)	The higher the thickness is the lower the frequency of the first maximum is. Absorption tends to be lower and smoothed.	Easy to measure	2 - 4	4 - 6
Porosity (Ω, %)	The higher the porosity is, the higher the absorption coefficient is. Maximum frequency does not depend on porosity.	Quite easy to measure	4 – 8	16 - 30
Resistivity (Rs, Ns/m^4)	The higher the resistivity, the lower the maxima, the smoother the curve.	Quite difficult to measure	600,000 - 30,000,000	1,000 - 60,000
Tortuosity (q^2)	The higher the tortuosity is, the lower the frequency of maximum is. The impact on the maximum value of absorption is usually quite negligible.	Quite difficult to measure	1 – 10 (usually 2.5-4.5 for PEMs)	
Total resistance (RT=Rs×t)	For low values of RT, the higher the total resistance is, the higher the maxima are. For RT higher than about 100 Ns/m^3, the behaviour is opposite. If, Ω, RT, q^2 are constant, the "shape" is constant but the maximum frequency depends on t (the lower, the higher).	See above	See above. Note: DGFC= dense-graded friction course	

Fig. 1 (A and B, Task 1) illustrates how the models described above vary as a function of the porosity. Note that for a porosity of about 20% (0.2), R_s is expected to have values in the range 1,000-100,000 Ns/m^4, while q^2 is expected to have values between 1 and 4. These values partly comply

with the ones set up in Table 1, even if the models after Yu & Li, Umnova, and Ahmadi (dotted curves in Fig. 1B) partly differ from the remaining ones. In Task 2 (inverse method), fourteen case studies were considered. Overall the following average values were obtained: t_{ex}=52 mm; Ω_{ex}=0.20; q^2_{ex}=2.42; Rs_{ex}=77,043 Ns/m^4. Note that the subscript ex refers to the fact that q^2_{ex} and Rs_{ex} derive from the inverse application of the theoretical model, based on the experimental spectrum, and based on the experimental values of porosity (Ω_{ex}=14-26 %) and thickness (t_{ex}=41-71 mm). In more detail, Fig. 1 (C) focuses on the values of Rs_{ex} and q^2_{ex} as per the inverse method. Note that q^2 approximate range is 1-5 and Rs approximate range is 3k-177k Ns/m^4. Both of them decrease when porosity increases. Fig. 2 and Table 2 illustrate the comparison between the values of tortuosity and resistivity obtained based on models (see equations above) and the corresponding values obtained by means of the abovementioned inverse model. It is important to highlight that in the application of the models to the 14 cases mentioned above, when possible, each method was calibrated based on the given parameters. For example, in the case of the Hamet and Bérengier model (see Eq. 2 and Table 2), the value of d (diameter of the pores) was obtained based on the least square method, i.e., based on the minimization of the sum of squared residuals.

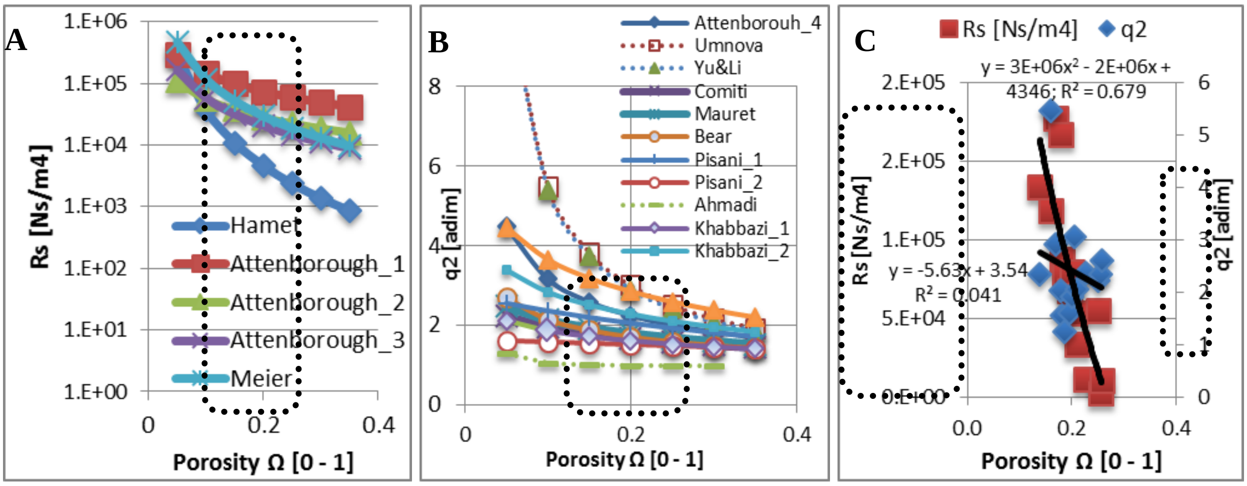

Figure 1: Expected results for Rs and q^2 based on models (A, B) and inverse problem (C).

For resistivity (see Fig. 2(A) and Table 2), least square optimization aiming at minimising the differences between inverse problem parameters (i.e., ex) and model outputs leads to the following observations: i) Hamet and Béreinger model has the lowest R-square, while Attenborough's methods (Eqs. 3, 4, and 5) and the model after Von Meier (Eq. 6) attains the best R-squares. Eq. 6 (Von Meier), which is based on chipping diameter, thickness, and porosity achieves the best fitting of the data derived based on the inverse problem. This fact points out that the porosity has the potential for affecting similarly both the solution of the inverse problem and the algorithm set up by Von Meier. Indeed, thickness influence cannot be assessed, due to its negligible variation. Similarly, chipping size, for the case under consideration has a negligible importance; ii) The lowest coefficient of variation is obtained for the models Attenborough_1 and Attenborough_2 (Eq. 3 and 4), while the highest is obtained for the model after Hamet and Bereinger. An intermediate value is obtained for the model after Attenborough_3 (Eq. 5); iii) Based on data fitting, the value of pore diameter obtained for the model of Hamet and Bereinger is about 0.3 mm. This value partly complies with Torres [34], where probability density functions centred in 0.8-1.3 mm are shown; iv) The corresponding value in Attenborough best fit is about 2 mm, where similar observations may emerge; v) By referring to Eq. 5 (Attenborough_3) it seems noteworthy to emphasize that the exponent 1+n has the potential to fit the phenomena, when the term "const" is assumed as viscosity divided the square of r (r assumed as 0.1 mm) and the term n is assumed as 0.5 (case of a medium composed by spherical grains) . This notwithstanding, it is noted that chipping size and layer thickness are not considered.

For tortuosity (see Fig. 2(B) and Table 2), based on the least square optimization, the following observations can be derived: i) Overall the R-square values are low and unsatisfactory; ii) The Hamadi model (Eq. 16) obtains the best R-square value and the lowest coefficient of variation; iii) The models after Umnova (Eq. 8) and Yu & Li (Eq. 10) correspond to the highest coefficients of variation; iv) The quite low values of tortuosity that correspond to sections 5-8 do not depend considerably on porosity. This behaviour is not reasonably predicted by any models; v) As specified in Table 2, in some cases, the equations were modified in order to optimise data fitting without impairing the rationale behind the algorithm. Consequently, in this case, best-fit parameters do not have any physical meaning (see Table 2, last column on the right).

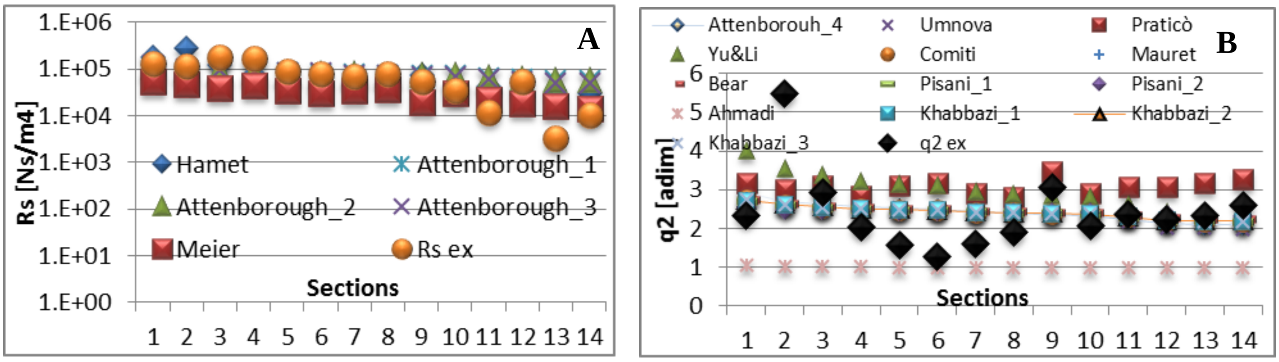

Figure 2: Comparing the values of resistivity/ tortuosity obtained for the case study through the different algorithms or based on the inverse problem method (ex), for the selected sections.

Table 2: Main statistics derived from data fitting (models) and inverse problem

Parameter	Model/Method	Average	Standard deviation	Coefficient of variation	R-square	Best-fit parameter
Rs (Ns/m^4)	Inverse (ex)	77,043	55,657	0.7	NA	NA
	Hamet	77,043	70,098	0.9	0.3	$d = 3*10^{-4}$ m
	Attenborough_1	77,043	14,220	0.2	0.7	$r = 10^{-4}$ m
	Attenborough_2	77,043	14,220	0.2	0.7	$b = 6*10^{-5}$ m
	Attenborough_3	77,043	21,502	0.3	0.6	const = 6,528 Ns/m^4
	Von Meier	31,769	12,530	0.4	0.7	NA
q^2 (dimensionless)	Inverse (ex)	2	1.0	0.4	NA	NA
	Attenborouh_4	2	0.2	0.1	0.1	n = 0.54
	Umnova	2	0.3	0.1	0.1	a = 0.68
	Yu&Li	3	0.5	0.2	0.1	NA
	Comiti	2	0.2	0.1	0.1	a = 0.87
	Mauret	2	0.2	0.1	0.1	a = 0.87
	Bear	2	0.1	0.1	0.1	a = 1.41
	Pisani_1	2	0.2	0.1	0.0	a = 0.73
	Pisani_2	2	0.1	0.0	0.0	a = 1.78
	Ahmadi	1	0.0	0.0	0.1	NA
	Khabbazi_1	2	0.2	0.1	0.1	a = 0.87
	Khabbazi_2	2	0.2	0.1	0.1	a = 0.88
	Khabbazi_3	2	0.2	0.1	0.1	a = 0.89

Summarising, data and results suggest that while the Rs estimates can be considered quite satisfactory, the estimation of the tortuosity through models and inverse methods calls for further research and study. The following points can be useful to explain the unsatisfactory results and their potential to affect acoustic spectra and therefore the predicted benefits associated to quiet surfaces: i) For the average values mentioned above for porosity and resistivity, variations of q^2 in the range

1.00-3.84 (i.e., 2.42±1.42, or simply 1-3) imply that the maximum frequency (first peak) varies in 0.7-1.2 kHz, and the maximum value of a_0 varies in 0.50-0.55. The real impact of such a change on human health is questionable and transient (because pavement properties change over time). This point calls for further investigation in terms of consequences on noise mapping and noise planning; ii) The range of variation of q^2 is 1-10 while the range of variation of Rs is 1,000-60,000 Ns/m^4 for PEMs and 600,000-30,000,000 Ns/m^4 for DGFCs [35]. This implies that there is an appreciable difference in terms of magnitude of variation and given the consequences above, a minor importance might be associated to this parameter in terms of measurement; iii) The same possibility to measure (and not to derive) the tortuosity for QA/QC applications appears quite difficult (see above). Consequently, further research is needed.

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