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Modelling of acoustic ageing of rubberized pavements

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ABSTRACT

Tyre-road noise is the most important source of traffic noise in the mid-to-high speed range. The use of low noise road surfaces represents an ideal solution to mitigate traffic noise, because it directly affects the source, generating a widespread benefit for all the dwellings near the road and decreasing the number of people annoyed. More knowledge about long-term acoustic performance is required to promote the use of low noise road surfaces as mitigation action.

In fact, as for a traditional road surface, the acoustic properties of low noise surfaces worsen over time: only by knowing the initial noise reduction and its time evolution, public administrations can design their application and related maintenance plans.

In this work, an innovative approach was used to investigate and model acoustic ageing of some rubberized road surfaces surveyed for several years. This type of quiet pavements represents an efficient road surface technology in terms of traffic noise reduction. A new regression model was applied to estimate the acoustic ageing of the investigated pavements, considering the complex interacting system composed of three main elements: pavement type, traffic loads and climatic conditions.

1. Introduction

The acoustic properties of road surfaces worsen over time. The evolution of pavements' properties during their service life is a very complex phenomenon, which involves many processes of change and deterioration of mechanical, volumetric and surface properties. This fact implies an increase with time in tyre-road noise levels.

It is known that tyre-road noise constitutes the most important source of traffic noise in the mid-to-high speed range, from 35 km/h to 120 km/h [1].

Tyre-road noise is strongly variable, depending on tyre and pavement type [2–4], because it is generated by several mechanisms that occur simultaneously.

Rolling noise is in fact caused by a combination of airborne and structure-borne mechanisms in which tyres and pavement surfaces act as a source. Structure-borne mechanisms are due to tyre vibrations caused by the impact of the tyre against the road surface during its motion, which generate mainly low frequency noise. The noise due to airborne mechanisms affects frequencies higher than 1 kHz and it is mainly caused by the compression and expansion of the air trapped between the tyre tread and the road surface. This mechanism is known as air pumping. Moreover, many other mechanisms contribute to the generation of the tyre/road noise, such as resonances and other non-linear effects like the stick and slip mechanism [1]. A deep knowledge on the role played by the road surface on tyre-road noise generation is needed to optimise the Pavement Acoustic Design, or PAD. In particular, surface macro and mega texture, porosity and layer thickness constitute the main pavement characteristics involved in tyre-road noise [5–7], while other properties, such as microtexture and stiffness, produce minor contributions. Fig. 1 summarises all the main contributions to tyre-road noise due to road properties, which initially depend on the mix design and used materials and on work quality during the laying procedures.

The worsening of acoustic performances of a road surface over time, caused by ageing and wear phenomena due to exposition to traffic loads and climatic elements, is a very complex phenomenon related to the numerous processes of change and deterioration of the mechanical, volumetric and surface properties of the road pavement. It can be argued that these processes are the result of the interaction of three main complex elements: pavement type,

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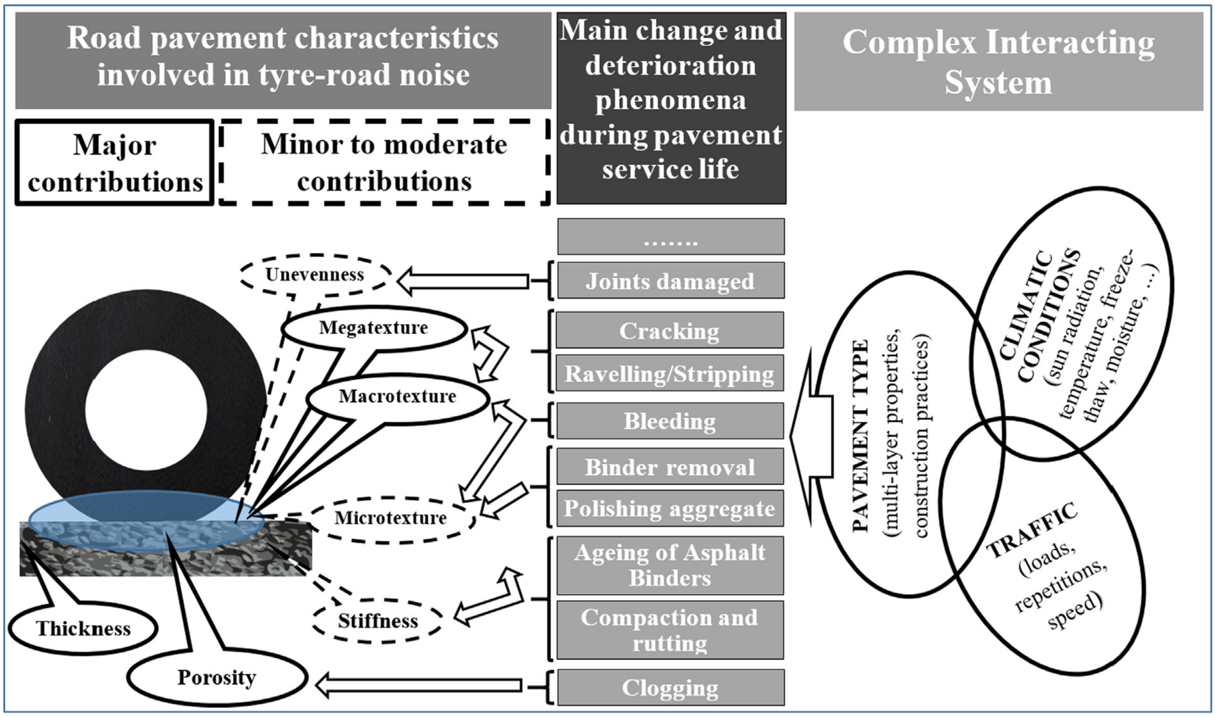

Fig. 1. Scheme of road pavement characteristics involved in tyre-road noise.

traffic loads and climatic conditions [8], as shown in Fig. 1. The complex element "pavement type" takes into account the influence of multi-layer properties and construction practices, including production errors (e.g. regarding the composition of the mixture, the mixing process, high/low mixing temperatures) and pavement construction errors (e.g. mixture transport issues, insufficient and/or unsuitable compaction processes).

Part of the change and degradation phenomena induce acoustic ageing of road surfaces, because they affect pavement characteristics involved in tyre-road noise generation. These processes may concern the clogging of the pores, in case of porous pavement, and the variation and degradation of the texture, in terms of polishing of the surface, superficial closing due to dust accumulation and post-compaction, distresses on the pavement surface such as ravelling, cracking or bleeding phenomena [9,10].

Referring to phenomena that regard changing in materials, ageing of asphalt binders includes both physical and chemical mechanisms that lead to a more brittle pavement, amplifying the risk of pavement distresses, i.e. cracking and ravelling, with consequent increase of road texture. The most important mechanism is the oxidative ageing, a chemical process caused by the oxidation of asphalt binder components [11,12].

Main change and degradation phenomena and their influence on the tyre-road noise generation are summarized in Fig. 1.

The worsening over time of acoustic performances of a road surface, due to the degradation phenomena summarised in Fig. 1, generally results in an increase with time in tyre/road noise levels, whose time trend is described in literature as a linear, exponential or logarithmic function of the pavement age. The models available in literature are summarised in Table 1, which also reports the pavements monitored, noise indicators measured and expected increase for each model.

It is possible to note that the expected increase in noise varies widely: the values range between 0 up to 5 dB per year. This great variation can be explained by the fact that acoustic ageing is a very complex phenomenon as already stated. The higher value, in fact, regarding the Scandinavian data, is strongly related to issues in mixture design, pavement construction, use of studded tyres and harder climate conditions [18].

The modelling of the worsening of the acoustical performances over time is crucial, especially for low-noise road surfaces, which represent an ideal solution for the noise mitigation action, since they directly affect the source, generating a widespread benefit for all the dwellings near the road, and decreasing the number of people annoyed.

Different types of quiet pavements have been developed and applied in the mitigation of road traffic noise, as porous asphalt, rubberized asphalt, poroelastic road surface, thin and very thin layers with texture optimisation [5,19].

Rubberized asphalt pavements, built using asphalt mixes containing crumb rubber, constitute an efficient road surface technology in terms of traffic noise reduction that ranges up to 8–10 dB(A) [20]. Two main different methods may be used to add crumb rubber into the asphalt mixtures: the wet process and the dry process.

In the wet process, the crumb rubber is blended with liquid asphalt cement (AC) before to mixing AC with the aggregates. Differently, in the dry method, rubber is blended to the hot aggregates before the addition of the asphalt cement AC.

In Italy, rubberized technologies have been introduced quite recently and some experimental installations have been acoustically studied in the last years [21].

In the present work, some experimental rubberized road surfaces, produced according to the wet process and laid on interurban roads in Italy, have been surveyed for several years, by means of the CPX method [22].

This monitoring was useful to verify the effectiveness of the noise mitigation action and to analyse the road surfaces long-term acoustic performances. The study was performed taking into account a set of different variables that describe the service life of a road surface by means of multivariate analysis.

Table 1
Models of acoustic ageing of road surfaces.

Model	Indicator/Method	Pavement type	Increase dB per year	References
Linear, Logarithmic	CPX, SPB	1L-PA, 2L-PA, DGAC, TLS	0.03–1.00	[13]
Linear, Exponential, Logarithmic	SPB	DGAC, OGAC, SMA, UTLAC	0.40–0.70	[14]
Exponential, Logarithmic	SPB, CPX	SMA, ACMR, SDA		[15]
Logarithmic	SPB, RVS, CPX	SMA, LN-SMA, 1L-PA, 2L-PA		[16]
Linear	SPB, OBSI	DGAC, OGAC, 1L-PA, RAC, UTLAC, SMA	0.10–1.30	[8]
Linear	CPX	ARFC	0.55	[17]
Linear	SPB, CPX	1L-PA, 2L-PA, TSL, SMA, DGAC	0.00–5.00	[18]

ARFC = Asphalt Rubber Friction Course; CPX = Close Proximity method; DGAC = Dense Graded Asphalt Concrete; LN-SMA = Low-noise Stone Mastic Asphalt; OBSI = On-Board Sound Intensity method; OGAC = Open Graded Asphalt Concrete; RAC = Open and Dense Graded Asphalt Concrete with rubber; RVS = RVS 04.02.11 method; SMA = Stone Mastic Asphalt; SPB = Statistical pass-by method; TSL = Thin Surface Layers; UTLAC = Ultra-thin asphalt layers; 1L-PA = Single-layer Porous asphalt; 2L-PA = Double-layer Porous Asphalt.

2. Experimental plan

2.1. Experimental sites

This work is focused on the study of the acoustic ageing of rubberized pavements built on inter-urban roads in Italy, surveyed for several years by means of the CPX method. Table 2 details each analysed pavement in terms of mix characteristics, crumb rubber recycling process, monitoring period, site and number of surveyed lanes.

As shown in Table 2, all the pavements studied were asphalt rubber friction courses (ARFCs), built using a gap-graded asphalt mix and containing crumb rubber added according to the wet method.

Three pavements out of four, called AR16-1, AR16-2 and AR16-3, share the same job mix formula (JMF). These pavements have been laid on different sites respectively identified with the numbers from 1 to 3. For these road surfaces, one lane for each direction of traffic, have been surveyed. The fourth pavement, called AR09-1, has been laid on the site 1, but according to a different job mix formula.

For each laid pavement, the following characteristics were determined from extracted cores: asphalt binder content referred to mixture weight b (%), gradation curve, bulk specific gravity G_{mb}, air voids content AV (%), layer thickness.

For all the pavements aggregate gradations are shown in Fig. 2.

2.2. Tyre/road noise measurement protocol

In this paper, the modified protocol based on the CPX method, described in [23,24], was used. Results are shown in terms of tyre/road noise levels, without strictly referring to the actual CPX indexes, but for the sake of simplicity they are hereafter named as L_{CPX} values. Since the monitoring started in 2011, the measurements protocol adopted is not compliant with the last version of ISO 11819-2, and the reference tyre used for measurement is a Michelin Energy XSE 185/65 R15 88T.

The set-up is based on the measurement system mounted on a self-powered vehicle. The modification to the official protocol regards mainly data analysis, which is based on the spatial resolution of a segment about 5.9 m long, i.e. three times the tyre circumference.

During the measurement session, acquisitions over the tested surfaces were repeated several times and at different speeds. Then, an iterative algorithm based on minimum chi-squared was used for fitting sound levels and speed data, for each segment and for each third octave band level, in order to compute the L_{CPX} values at the reference speeds using the right speed coefficient. The mean value of the results, named L_{CPX} in the following, was used to characterize the whole road surface installation.

2.3. Measurement uncertainty and spatial variability

The uncertainty related to the result, i.e. the averaged L_{CPX}, derives from three different sources of error or data variability. Firstly, segment results are obtained by means of the fitting process and then they are provided with a related uncertainty due to data dispersion around the fit. Data dispersion around the fit is mainly due to the measurement process, thus it is a clearly random source of error and it regarded as the “measurement uncertainty”. To obtain the uncertainty related to the mean value L_{CPX}, computed along the whole installation, the spatial homogeneity of the installation, i.e. the data dispersion around the mean value, has been taken into account. The last source of data variability derives from “several factors and processes, whose cause and nature of these disturbance are either known, but randomly distributed in an uncontrollable way, or are of a systematic nature, but affect the result in an unpredictable way” (as declared in Annex K of the ISO 11819-2).

In the following, only the uncertainties due to the first two sources of variability are shown, since the third source is the same for all values and showing it would not enhance the analysis with useful information.

3. Analysis and results

3.1. Preliminary analysis

During the long-term monitoring, in addition to the acquisition of L_{CPX} data, the following set of nine variables were collected for each road surface:

Table 2
Investigated pavements.

ID	Pavement type	Crumb rubber recycling process	Mix characteristics				Layer Thickness (cm)	Monitoring period (months)	Site	Surveyed lanes
			Gradation curve	b (%)	G_{mb}	AV (%)				
AR16-1	ARFC	wet	Gap graded 0/16	8.5	2.164	8.07	4.8	46	1	2
AR09-1	ARFC	wet	Gap graded 0/9	8.3	2.164	8.11	4.5	46	1	1
AR16-2	ARFC	wet	Gap graded 0/16	7.6	2.151	8.04	4.0	61	2	2
AR16-3	ARFC	wet	Gap graded 0/16	7.8	2.188	8.06	3.9	32	3	2

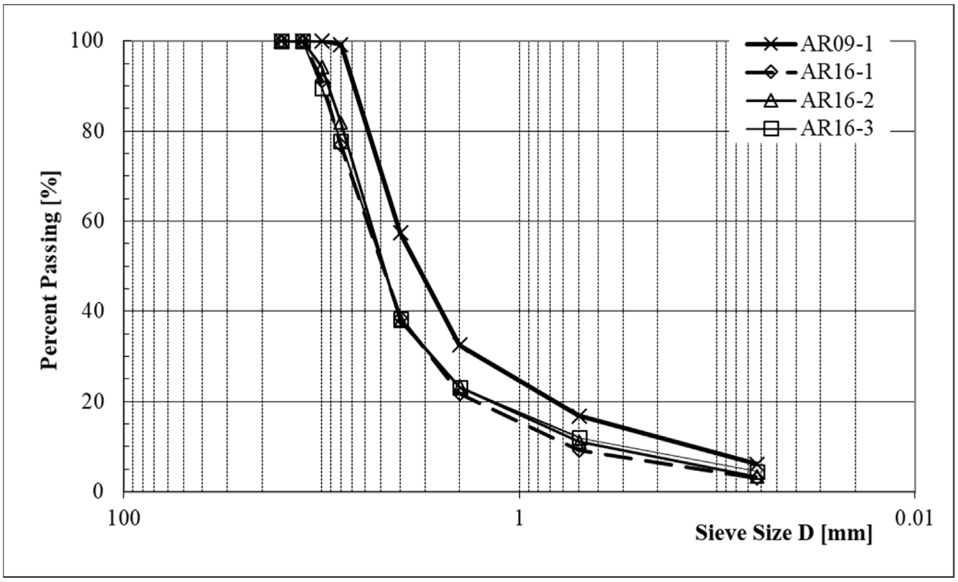

Fig. 2. Aggregate gradations for analysed pavements.

- total traffic data (TT);
- heavy traffic data (HT);
- age of pavements in months;
- total precipitations in mm;
- number of freeze–thaw cycles (F-T), i.e. the number of days in which the temperature varies between values above and below 0 °C;
- number of ice days, i.e. the number of days in which the maximum temperature stays below 0 °C;
- air temperature during the CPX measurement in °C;
- pavement temperature during the CPX measurement in °C;
- hardness of the tyre rubber in Shore A.

As required by the ISO technical standards, a temperature and hardness normalisation must be performed on L_{CPX} data in order to be able to compare data collected in different measurement sessions and to evaluate the acoustical performances of the road surfaces. In fact, it is known that both these parameters represent the most important factors that influence the measures [25–28]. The current ISO standard provides a set of parameters to use to perform this correction, however these parameters are only valid for the SRTT tyre, with no assumption about the general validity of the coefficients for other tyres. Therefore, in order to provide a more accurate normalisation, temperature and hardness data were also considered as independent variables, and regression models have been carried out applying a multivariate analysis [29].

Before carrying out the regression models for the estimation of the acoustic ageing phenomena, a principal component analysis (PCA) was performed in order to evaluate correlations among the independent variables. Tables 3 and 4 summarise the results of PCA analysis.

Since, as shown in Table 3, the first four principal components explain more than 99% of the total variance, the loadings reported in Table 4, that show the correlation between the principal components to the original variables, can be analysed only for these components.

In particular, from the values of the coefficients in bold, it appears that the third component is mainly represented by the number of ice days, while the fourth component is due to tyre rubber hardness. The second component manly refers to pavement and air temperature, since they have similar coefficients (0.609 and 0.601). The two variables, in fact show strong mutual correlation in the correlation matrix, as expected. Considering that the ISO normative requires a normalisation for air temperature, the correction for pavement temperature was deemed not significant. Lastly, the first component is mainly represented by a combination of variables related to pavement age. In fact, age, traffic data (TT and HT) and the remaining weather variables, that is to say freeze–thaw cycles and precipitation, share similar coefficients.

High correlation between age and traffic data can be explained considering the trend of traffic flow. Under the assumption of constant traffic flow, in fact, a simple linear relation can yield the number of vehicles that travel on that road between two instants.

Climatic conditions follow the same reasoning. Since the sites surveyed are share some climatic conditions, due to their relative small mutual distance, the relationship between precipitation, freeze–thaw cycles and time can be described as linear. Ice days are an exception to this rule, since they are significantly higher on site 1. This can be explained taking into account that site 1 is at a higher altitude than the other sites, despite their small linear distance.

Since the main purpose of this study was to elaborate a physical model of pavement ageing based on quantities strictly related to ageing phenomena, multivariate regression was performed taking into account the actual variables measured, and not the principal components. Anyway, the fact that temperature, hardness and age are significant in different components ensures that they also represent a quasi-orthogonal set in which variables do not show strong mutual correlation. The same can be assessed for the ice days, but not for TT, HT, FT and Precipitations.

3.2. Application of regression models for the acoustic ageing

Since a reference model that takes into account eventual influences of climatic effects on pavement ageing is still not available, the analysis started from a simplified model that describes time evolution of road traffic noise as a function of age of the road surface.

In this simplified model, variables highly correlated with age, such as traffic data, were not taken into account. Fig. 3 shows the

Table 3
PCA analysis - Importance of components.

	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8	Comp. 9
Standard deviation	2.2743275	1.3689907	1.0661238	0.8615375	0.1793006	0.16242565	0.10901208	0.052501582	0.035511114
Proportion of Variance	0.5747295	0.2082373	0.1262911	0.0824719	0.0035721	0.00293134	0.00132040	0.000306268	0.000140115
Cumulative Proportion	0.5747295	0.7829668	0.9092579	0.9917298	0.9953019	0.99823321	0.99955362	0.999859884	1.000000000

Table 4
PCA analysis – Loadings.

	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8	Comp. 9
Tair	−0.201	**0.609**	0.221	−0.187	0.631	−0.159	−0.252	−0.109	
Tpav	−0.205	**0.601**	0.216	−0.224	−0.619	0.248	0.204		
Age	**−0.431**	−0.110		0.133	0.263	0.225	0.113	0.439	0.678
Hardness	0.157	0.365		**0.916**					
TT	**−0.414**		−0.294		−0.318	−0.297	−0.524	−0.422	0.307
HT	**−0.416**		−0.290				−0.270	0.560	−0.585
F-T	**−0.421**	−0.104	0.191	0.111		−0.631	0.582		
Ice		−0.293	**0.835**	0.144	−0.143		−0.401		−0.146
Pre	**−0.424**	−0.161			0.149	0.611	0.185	−0.534	−0.261

Tair = air temperature; Tpav = pavement temperature; Age = age of pavements; Hardness = hardness of the tyre rubber; TT = total traffic data; HT = heavy traffic data; F-T = number of freeze–thaw cycles; Ice = number of ice days; Pre = total precipitations.

L_{CPX} data collected for each road surface surveyed, plotted against age.

In the first phase of the CPX data analysis, the linear and logarithmic regression models were applied to estimate the acoustic ageing of the rubberized pavements in terms of L_{CPX} as shown in Table 5. Both models, reported in Table 5, describe broadband CPX level as a function of the age A of the pavement expressed in months. The functional dependence of broadband CPX levels on the difference ΔT, between the air temperature during the CPX measurement and the reference air temperature (20 °C), and the difference ΔH, between the measured rubber hardness and the reference rubber hardness (66 Shore A) is described using the same linear dependence used by the ISO technical standard.

Parameters Y_{0i}, α, α_T and α_H are constant model coefficients. The logarithmic regression is calculated assuming as reference A_0 equal to 1 month. In both models, the intercept Y_{0i} represents the initial L_{CPX} value of the ith pavement and depends on mix type and construction practices, whereas α depends on mix susceptibility to the factors of acoustic ageing as exposure to traffic loads and to climatic conditions.

In this first phase of the analysis, the same coefficient α was used for all the rubberized pavements. Results are shown in Table 5 and Fig. 4 shows the estimated acoustic ageing trends for all the pavements studied, for both linear and logarithmic models.

If a pavement has been surveyed for the two directions of traffic flow (identified with D1 and D2), two trend lines are plotted. The graphs also report measured data. In particular, in order to show the actual effect of the multivariate analysis, empty and full points respectively represent uncorrected and corrected data for tire hardness and air temperature.

In the lights of the results in terms of RMSE values listed in Table 5, the logarithmic model seems to describe the acoustic age-

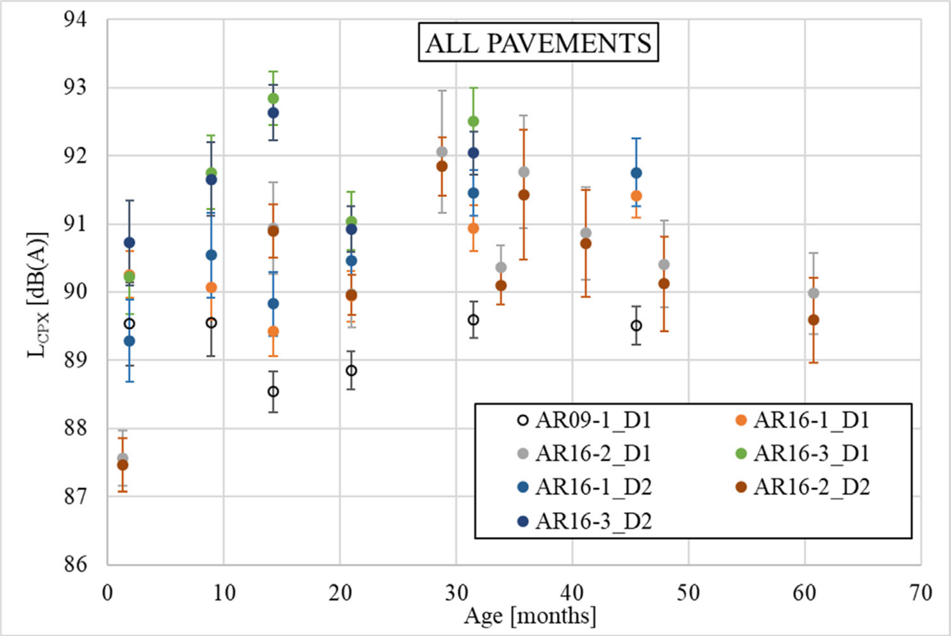

Fig. 3. L_{CPX} collected data for each road surface.

Table 5
First phase of the CPX data analysis: linear and logarithmic models.

Model	Equation	Coefficients	RMSE
Linear	$L_{CPXi} = Y_{0i} + \alpha * (A) + \alpha_T \Delta T + \alpha_H \Delta H$	α = 0.048 [dB/months] α_T = -0.057 [dB/°C]; α_H = 0.063 [dB/Shore A]	0.685
Logarithmic	$L_{CPXi} = Y_{0i} + \alpha * \ln\left(\frac{1+A}{A_0}\right) + \alpha_T \Delta T + \alpha_H \Delta H$	α = 0.940 [dB]; α_T = -0.056 [dB/°C]; α_H = 0.089 [dB/Shore A]	0.471

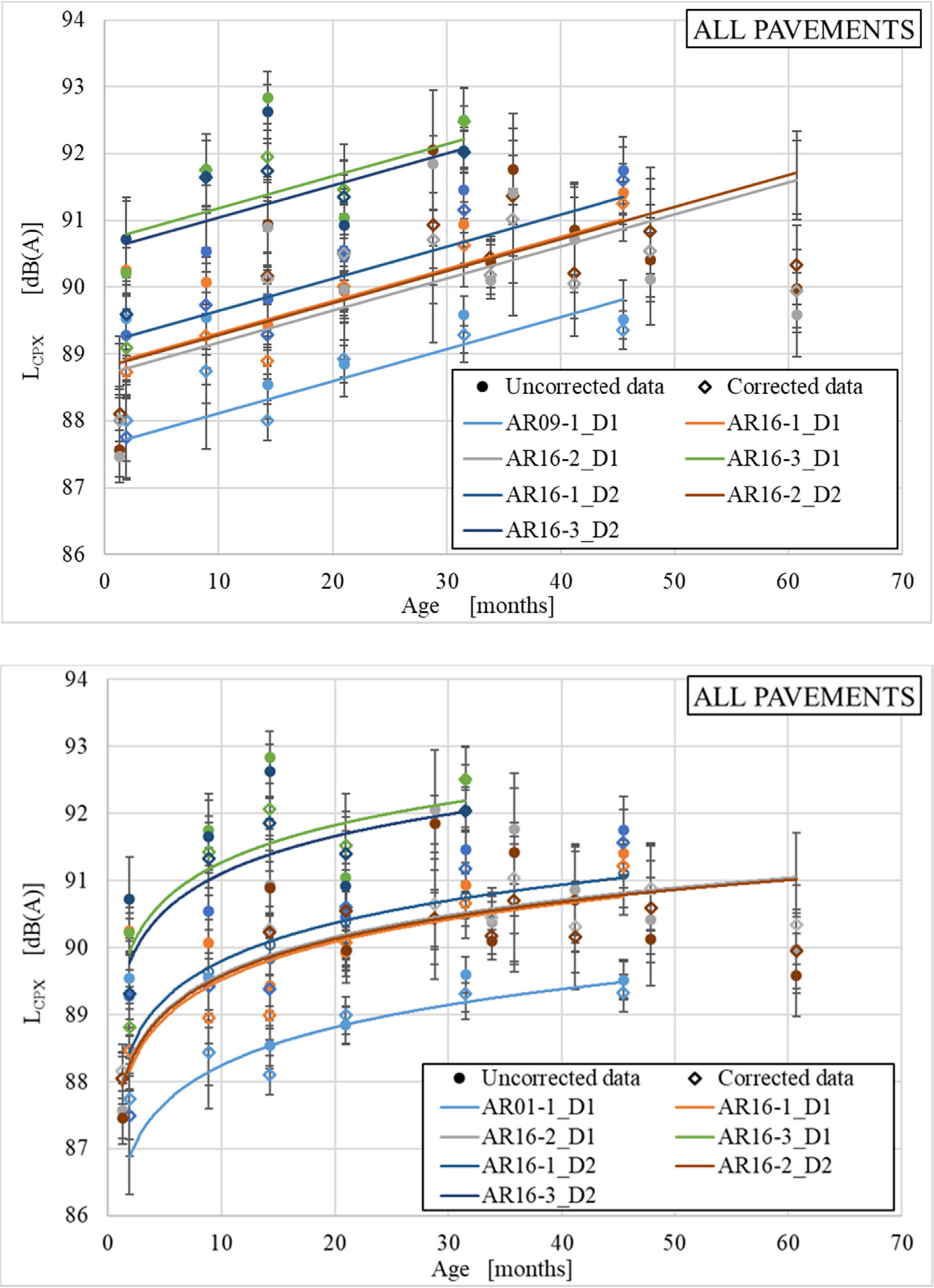

Fig. 4. Acoustic ageing trends for both linear and logarithmic models.

ing of investigated pavements better than the linear one. The better data fitting obtained by using a logarithmic model can be qualitatively explained by assuming that phenomena such as binder removal and aggregate polishing produce an asymptotic effect whose amplitude is not constant with time.

Acoustic ageing is strongly affected by interaction between complex elements, as qualitatively shown in Fig. 1, so it is reasonable to expect that a same pavement will exhibit a different susceptibility to acoustic ageing when its exposure to road traffic loads and climatic conditions varies.

For this reason, in the second phase of analysis, the logarithmic model was reapplied considering a different coefficient α_i for each pavement as in the following equation:

$$L_{CPXi} = Y_{0i} + \alpha_i * \ln\left(\frac{1+A}{A_0}\right) + \alpha_T \Delta T + \alpha_H \Delta H \tag{1}$$

where the coefficient α_i refers to a specific combination of a set of three factors: pavement type with its properties, traffic actions in terms of load magnitude and number of load repetitions, and climatic parameters.

The use of a different coefficient α_i for each case study allowed to obtain a better data fit as shown in Fig. 5, confirmed by a lower RMSE value equal to 0.341.

Although for each pavement the acoustic performances mainly deteriorate in the first phase of its service life, the increases in tyre/road noise levels appear very different, as shown by the range of α_i values, which range from 0.695 to 1.698.

3.3. Influence of traffic and climatic conditions on regression coefficients

The following step is the comparison of the various coefficients found in the previous section with traffic and climatic data.

Through the following Figs. 6 and 7, it is possible to provide an interpretation of the results based on the combination of phenomena involved in ageing. Fig. 6 compares annual total precipitation (mm), number of annual freeze–thaw cycles (oscillations of temperature above and below 0 °C) and number of annual ice days (in which the maximum temperature remains below 0 °C) on the different sites. As clearly highlighted from the number of ice days, site 1 is characterized by harder climate conditions than sites 2 and 3, which instead have similar conditions.

Moreover, in Fig. 7, the coefficients α_i are plotted as a function of traffic data, expressed as annual heavy traffic (AHT), in millions of passages/year. A clustering of data points related to climatic conditions is quite clearly visible. In particular, it is possible to identify three different areas, corresponding to the three experimental sites.

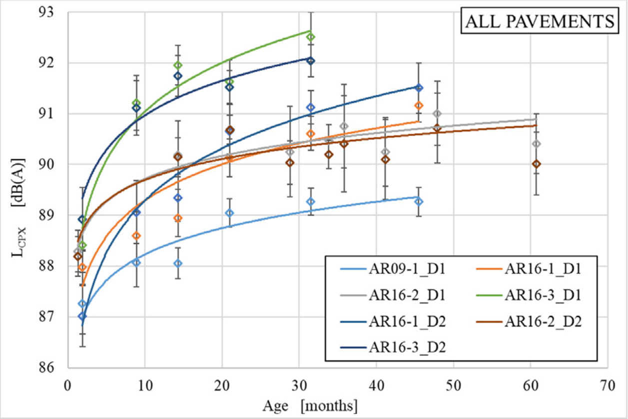

Fig. 5. Acoustic ageing trends for logarithmic model using of a different coefficient α_i for each case study.

The results show a strong impact of environmental factors on acoustic ageing, in agreement with previous studies [30]. In fact, the area delimited by the dashed red line, which encloses data relative to site 1, reports high rates of acoustic decay, due to the worse climatic conditions despite low traffic rates.

Data relative to sites 2 and 3 is encircled by dashed blue and green lines respectively. By referring only to the site 3, the two lanes unexpectedly show a different behaviour, probably due to differences occurred in paving operations. But, in a joined analysis of sites 2 and 3, characterized by very similar climatic parameters, the acoustic decay seems to increase with traffic rate as generally expected.

Limiting the analysis to site 1, it is possible to separate the different effects of the factors involved:

- the segment *ab*, in fact, refers to two pavements (previously called AR09-1_D1 and AR16-1_D1) with different mix characteristics, but subjected to same traffic loads and climate conditions. The pavement AR09-1, identified by point *a* and designed with an aggregate gradation finer than AR16-1 (point *b*), appears less susceptible to the acoustic ageing factors;
- the segment *bc* represents the same AR16-1 pavement laid on opposite lanes, and therefore exposed to identical climate parameters but subjected to different traffic levels. As reasonably expected, the higher traffic volume, the higher is the value of α_i.

Since the coefficients α_i describe the acoustic decay over time incorporating all the different effects, it should be important to quantify the single factor effect, in order to yield a deeper understanding of the phenomenon. For this reason, the coefficient α_i can be described as the product of three factors:

$$\alpha_i = \alpha_{pav} * \alpha_{met} * AHT_i \tag{2}$$

where the coefficients α_{pav} and α_{met} respectively refer to the pavement type with its characteristics and its climatic parameters, and the term AHT_i represents the annual heavy traffic rate on the *i*th pavement as millions of passages per year. The annual heavy vehicle traffic rate is obtained by dividing the cumulative number of heavy vehicles by the time elapsed since the laying of the road surface.

Applying Eq. (2) to the case studies, five coefficients were estimated by performing least chi-square regression in order to take into account data uncertainty. Results are summarised in Table 6.

Fig. 8 shows coefficients α_i and their estimated values obtained through Eq. (2). Since most of the points fall near the equality line, the model reported in Eq. (2) seems to be able to separate the different effects, describing the interaction between traffic loads, climate parameters and mix characteristics.

As expected, the values of coefficients α_{met} seem to increase when the climatic conditions get worse, as shown in Fig. 9, where α_{met} is plotted against both freeze–thaw cycles and ice days.

It is important to point out that since only few data points were available, the study provides only a qualitative information about the trend, and future research is needed in order to increase the statistics and to establish strong relationships.

Unfortunately, the set of pavements analysed does not show great variations among traffic and climate condition, and therefore other case studies are needed to accurately estimate model parameters in different conditions than those studied. However, the analysis performed in this paper shows that a plausible description of acoustic ageing can be achieved by expressing the CPX broadband level as a logarithmic function of pavement age with a regression

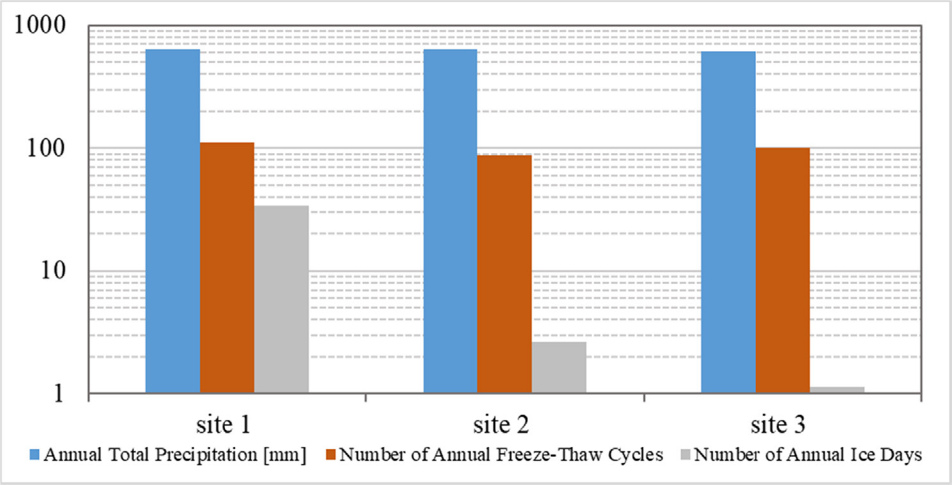

Fig. 6. Comparison between climatic parameters of the three different sites.

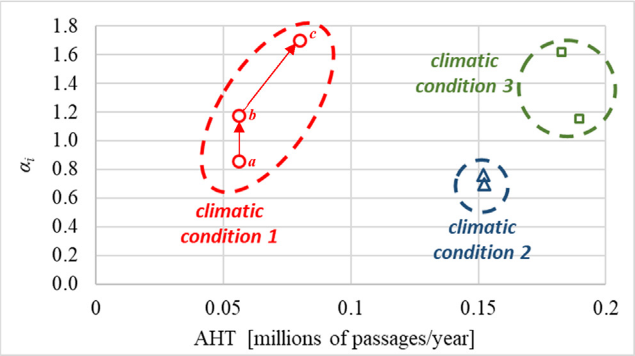

Fig. 7. Clustering of the data points related to effects of climatic conditions.

coefficient described as the product of three different factors, as given by the following equation:

$$L_{CPXi} = Y_{0i} + \alpha_{pav} * \alpha_{met} * AHT_i * \ln\left(\frac{1+A}{A_0}\right) + \alpha_T \Delta T + \alpha_H \Delta H \quad (3)$$

4. Conclusions

In this work, a new approach was used to investigate and model the acoustic ageing of several rubberized road surfaces produced according to the wet process, laid on three different sites. This type of quiet pavements represents an efficient road surface technology in terms of road traffic noise reduction, despite the scarcity of data in literature regarding the acoustic ageing process.

Linear and logarithmic regression models were applied to estimate the acoustic ageing of the rubberized pavements. In spite of the linear models commonly adopted in literature, the best model resulted to be the logarithmic one.

Although for each pavement the acoustic performances mainly deteriorate during the first phase of its service life, the increase in tyre/road noise levels in time appears very different among them.

Before carrying out the regression models to estimate the acoustic ageing phenomena, a principal component analysis (PCA) was applied in order to analyse all variables and determine a complete model, capable of taking into account traffic and climatic conditions, but based on a robust regression provided by the use of a quasi-orthonormal set of independent variables.

In particular, climatic parameters such as annual total precipitation, number of annual freeze–thaw cycles, number of annual ice days, and traffic data described in terms of heavy traffic were con-

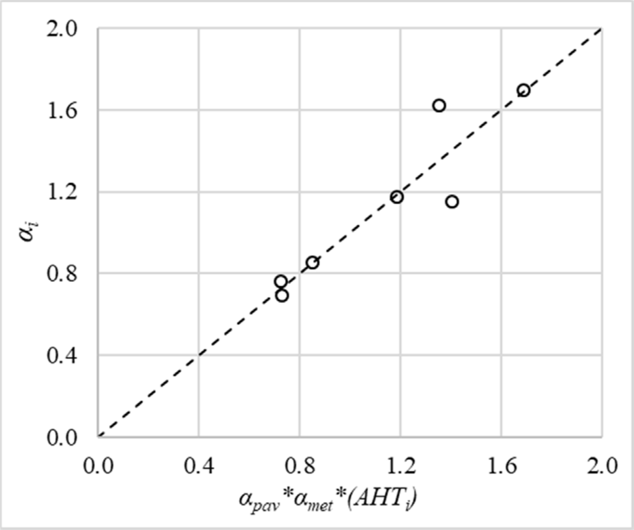

Fig. 8. Comparison between coefficients α_i and their estimated values obtained by Eq. (2).

Table 6
Coefficients related to pavement type and climate parameters.

Pavement type		Site			RMSE
AR09	AR16	1	2	3	
α_{pav1}	α_{pav2}	α_{met1}	α_{met2}	α_{met3}	
3.03	4.20	5.03	1.14	1.76	0.140

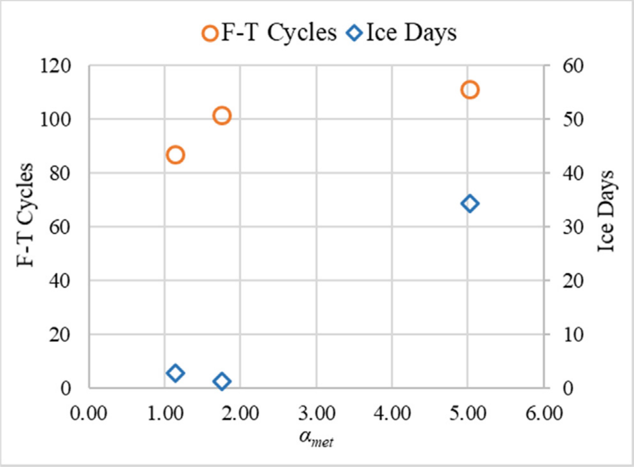

Fig. 9. α_{met} vs. freeze–thaw cycles and ice days.

sidered, in order to provide an interpretation of the results of the multivariate regression. Thus, results show a strong impact of environmental factors on acoustic ageing.

As generally expected, considering sites with very similar climatic parameters, the acoustic decay increases with increasing traffic rates. At low traffic values, but with worse climatic conditions, high rates of acoustic decay were observed.

In order to discriminate between different effects and to describe the interaction between factors involved in ageing, the coefficient α, which incorporates all the different effects, was innovatively expressed as the product of three terms, related to climate parameters (α_{met}), pavement type (α_{pav}) and traffic data.

As expected, the values of coefficients α_{met} seem to increase if the climatic conditions get worse.

In comparing the examined rubberized asphalts, the pavement designed with an aggregate gradation finer seems less susceptible to the acoustic ageing factors, but future research is needed in order to increase the number of the case studies and to confirm the relationships provided in this work.

The methodology of analysis presented in this work, extended to different classes and types of pavements, could permit to predict climatic and traffic effects on durability of acoustic pavements performances. The development of these findings could permit to address choices on pavement acoustic design for durable and effective noise mitigation actions.

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