Sound absorption by tree bark

Mengmeng Li[1]; Timothy Van Renterghem[2]; Jian Kang[1, 3, *]; Kris Verheyen[4], Dick Botteldooren[2]

[1] Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, School of Architecture, Harbin Institute of Technology, Heilongjiang, Harbin 150000, China

[2] Ghent University, Faculty of Engineering and Architecture, Department of Information Technology, WAVES research group, Belgium

[3] University College London, UCL Institute for Environmental Design and Engineering, The Bartlett, UK

[4] Ghent University, Faculty of Bioscience Engineering, Department of Forest and Water Management, Forest and Nature Lab, Belgium.

ABSTRACT

Scattering of sound waves by trunks is a main physical factor leading to sound pressure level reduction by tree belts, and it has been shown before that the absorbing properties of the trunks are relevant in this respect. However, detailed information on bark absorption is currently very scarce. Therefore, laboratory experiments were conducted with an impedance tube to measure the bark's sound absorption of various tree species, including characterizations of bark thickness, roughness, tree age and moss coverage. Preliminary measurements were made to come to a reproducible sample handling procedure. The measurements show that the absorption (at normal incidence) is generally below 0.1 for the species considered and rather frequency independent below 1 kHz. There are statistically significant differences in the averaged absorption between species. Overall, the barks of conifers absorb sound slightly better than in case of broadleaved species. The most relevant visual predictor for the sound absorption of bark is its roughness. Interestingly, moss grown barks provide a strong increase in absorption in the frequency range up to 800 Hz. Especially in dense tree belts, bark absorption might have an influence on the final noise shielding performance.

Keywords: Natural means for noise abatement, sound absorption, tree bark, impedance tube

1. Introduction

A number of researchers have shown interest on the sound pressure reduction by tree belts [1-5]. Noise reduction is a potentially interesting ecosystem service of tree belts besides, for instance, the provisioning of habitat for biodiversity increase, CO_2 uptake, rainwater interception and flood control, and microclimate regulation [6]. Scattering of sound waves by trunks and the ground effect are recognized as the dominant effects [3]. In contrast, tree crowns and leaves typically appear both above the source and receiver in typical road settings, and might give rise to a small increase in sound pressure level due to downward scattering [4]. However, this effect is limited (roughly 0.5 dBA) for road traffic noise sources [7].

In dense tree belts, the interaction between sound waves and the trunks leads to a multiple scattering process. Under such conditions, the absorbing properties of the scatters will play a role. While absorption by plants (leaves) and soil did receive quite some attention before [8-9], research on bark absorption is scarce. Although the absorption of bark might be rather low, full-wave numerical simulations reported by Van Renterghem [10] shows that even small variations can be relevant, e.g. when looking at sound propagation through tree belts. Knowledge of the variation in bark absorption between species and their influencing parameters are therefore of interest to optimize sound attenuation by tree belts.

In Reethof's pioneering work [11], the absorption coefficients of tree bark samples of six species were measured in the impedance tube. His main conclusions were that the absorption is rather frequency independent in the range of frequencies covered (from 400 Hz till 1600 Hz). Some species gave significantly higher absorption values. However, these were only exploratory measurements, and no further analysis was made to reveal what parameters could potentially predict tree stem absorption. This study reports more extensive and systematic work on this topic.

There are two main methods for measuring the sound absorption coefficient of materials: one is the reverberation chamber method, and the other one is the impedance tube method. Both have been used before to acoustically characterize plant material and growing media. Horoshenkov et al. [8] used an impedance tube to measure sound absorption at normal incidence of five different types of low growing plants with and without soil, while Ding et al. [12] measured the absorption coefficient of a single leaf on a porous substrate. Attal [13] measured the absorption of a bunch of leaves in the impedance tube. In contrast, Yang et al. [14] carried out measurements in a reverberation chamber to test random incidence absorption of plants and substrates. Similarly, Davis et al. [15], Azkorra et al [16] and Wong et al. [17] measured the absorption provided by vertical garden modules in a reverberation chamber.

Similar to Reethof's work, the impedance tube methodology is used in the current work since this is a well-established methodology, the measurement equipment is widely available and a specialized reverberation chamber is not needed. In addition, the potential problem of ending up with unphysical absorption coefficients exceeding one [18] will be avoided.

The aim of this study is to identify the dominant parameters to predict bark absorption through systematically measured impedance tube absorption coefficients of seventy-six bark samples from both broadleaved and coniferous trees. At the same time, non-acoustic characterizations were made (more precisely bark thickness, bark roughness, tree age and moss-coverage). The current paper does not aim at physically modelling the bark's acoustical absorption processes, but relies on statistical inference between the acoustical and non-acoustical parameters.

2. Methodology

2.1. Measurement equipment

In this study, a two-microphone impedance tube with a diameter of 100 mm was used to measure the absorption coefficient of the bark samples. Chung's research [19-20] showed the benefits of the "microphone swapping technique" to minimize phase errors and such procedure was followed in this work. Given the impedance tube diameter and the distance between the two microphones (i.e. 0.05 m), valid results are possible in the frequency range between 150 Hz and 1500 Hz. The data was processed to one-third octave band averaged absorption values.

2.2. Sample handling methodology

Disks of trunks were gathered in the field from freshly fallen trees. The main goal was to have a sufficient variety in species. From the trunks, cylindrical samples were taken normal to the central axis of the disk, at four locations along its circumference, as shown in Figure1. Each sample was processed to nicely fit the sample holder positioned near the end of the impedance tube.

Four locations along the same trunk cross sections' circumference **Trunk cross sections**

Fig. 1 Selection of bark samples along the trunk's circumference.

To ensure measurement accuracy and reproducibility, several steps were followed:
Step 1. Recording the lab environmental condition such as the air temperature, relative humidity and air pressure, which is important to compare the results over different days;
Step 2. Absorption of the empty tube was measured to check the performance in the low absorption range where the bark absorptions are to be expected;
Step 3. Two known absorption materials, rock wool and felt, were measured and compared to measurements from previous days;
Step 4. Using plasticine to seal bark samples ensuring no gap appeared between the

circumference of the bark samples and the holder of the standing wave tube. Leaving such gaps could lead to artificial absorption peaks in specific frequency ranges [21-22]. The absorption coefficient of the material used for sealing must be very low to avoid influencing the experimental results. Note that the total surface taken by the sealing material is in all cases very limited as the cylindrical trunk samples were tailored to the dimensions of the tube;

Step 5. Each sample was measured four times by rotating it over 90 degrees in clockwise direction. Each time, the sample was resealed, yielding information on the variability due to this potential critical sealing operation.

Step 6. At the end of a set of measurements, step 2 was repeated to ensure accuracy throughout the testing period.

2.3. Non-acoustical characterization

2.3.1. Bark thickness

"Bark" is defined as all tissues of woody stems or roots that occur outside of the cambium cell layer [23]. In this study, the largest thickness of the bark along its circumference is used to characterize bark thickness. The bark thickness for all samples is shown in Table 2.

2.3.2. Bark roughness

In this study, three methods were used to assess the roughness of the bark as summarized in table 1. The first one, R1, is the “shape index” [24-25]; the closer this value is to one, the better the bark cross section approaches a circle. A second representation of bark roughness is the so-called “radial index” (R2) [24-25], expressing the unevenness of the surface based on radius measurements. The latter is based on the thickness of the bark at 32 points, neglecting the influence of the shape of the trunk. A third approach is the one proposed by Bertrand [9] making use of seven types of visual bark textures namely “smooth”, “lenticels”, “furrows”, “ridges”, “cracks”, “scales” and “strips” (R3). The bark type of the conifers all fall in the “strips” and “scales” classes, while broadleaves tree species were mainly categorized as “lenticels” and “furrows”.

Table1 Bark roughness characterization approaches used in the current study.

	Formula	Description
Roughness 1 (R1)	$\mathrm{R1} = \frac{P}{2\sqrt{\pi \mathrm{A}}}$	P: Trunk perimeter A: Trunk area
Roughness 2 (R2)	$\mathrm{R2} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\mathrm{ri} / \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{ri} \right) * 100 - \frac{100}{\mathrm{n}}$	ri: Thickness of the bark n: The number of the radii considered (in this study, n=32)
Roughness 3 (R3)	“smooth”, “lenticels”, “furrows”, “ridges”, “cracks”, “scales” and “strips”	Visual roughness classification

2.4. Species selection and description

In this study, 76 samples of 21 trunk cross sections from 13 species were selected. Due to the unintended separation between bark and wood in some *Pinus sylvestris* samples, only a few samples could be used. Table 2 summarizes the non-acoustical characterizations of all useful samples.

Tree age varied largely from 11 to 57 years, while the trunk diameters ranged from 13.5 cm to 38.8 cm. A large variety in the R2 roughness parameter was obtained. Only the “cracks” type (R3) was not present in the dataset. The thicknesses of the different samples taken along the trunk circumference were measured separately. It can be seen from the bark samples that the thicknesses of the bark samples were mainly concentrated in two ranges, namely 0.3-0.7 cm, and 1.0-1.5 cm. Figure 2 shows an overview of the R1 characterizations, the shapes of the trunk cross sections, and a photograph of the bark surfaces.

Table 2 Non-acoustical characteristics of the 13 plant species. “Categories” refer to the sample being broadleaved (B) or coniferous (C). R2 and R3 are the roughness assessments as discussed in the text. Bark thickness is measured separately at each of the four samples taken along the trunk circumference.

	Species	Categories	Age (year)	R1	R2	R3	Thickness of bark(cm)			
							1	2	3	4
A	*Robinia pseudoacacia*	B	34	1.401	24.7214	Ridges	1.50	1.20	1.90	1.50
B	*Juglans regia*	B	20	1.016	16.4260	Furrows	1.30	1.10	1.10	1.05
C	*Prunus avium*	B	30	1.502	12.0565	Lenticels	1.50	1.20	1.40	1.60
D	*Betula pendula .*	B	32	1.390	25.4464	Lenticels	1.30	1.40	1.35	1.60
E	*Populus nigra ‘Italica’*	B	26	1.071	11.0971	Lenticels	1.40	1.50	1.40	1.20
F	*Salix alba*	B	14	1.226	11.7653	Furrows	1.30	1.10	1.10	1.00
G	*Picea abies*	C	16	1.078	23.8086	Scales	0.50	0.60	0.50	0.50
H	*Larix kaempferi*	C	57	1.096	28.0238	Strips	0.95	1.40	1.50	1.20
I	*Salix caprea*	B	27	1.195	30.0649	Ridges	0.75	0.60	0.80	0.70
J	*Populus tremula*	B	15	1.074	14.3861	Lenticels	0.55	0.60	0.65	0.75
K	*Populus tremula*	B	15	1.042	28.4958	Lenticels	0.50	0.45	0.50	0.45
L	*Populus tremula*	B	15	1.029	10.9415	Lenticels	0.35	0.30	0.30	0.35
M	*Picea abies*	C	16	1.050	23.5907	Scales	0.60	0.50	0.50	0.45
N	*Larix kaempferi*	C	57	1.115	27.1129	Strips	0.85	0.60	1.15	0.70
O	*Pinus sylvestris*	C	34	1.071	31.0416	Strips	0.50	No	No	No
P	*Pinus sylvestris*	C	34	1.100	26.5891	Strips	1.00	1.20	No	No
Q	*Fagus sylvatica*	B	31	1.028	21.4718	Smooth	0.55	0.65	0.40	0.35
R	*Prunus avium*	B	18	1.050	11.2892	Lenticels	0.65	0.60	0.60	0.55
S	*Pinus sylvestris*	C	34	1.085	No	Strips	0.75	No	No	No
T	*Alnus glutinosa*	B	11	1.323	25.8197	Furrows	0.55	0.60	0.65	0.55
U	*Salix caprea*	B	27	1.131	23.5193	Ridges	1.65	1.25	1.45	1.35

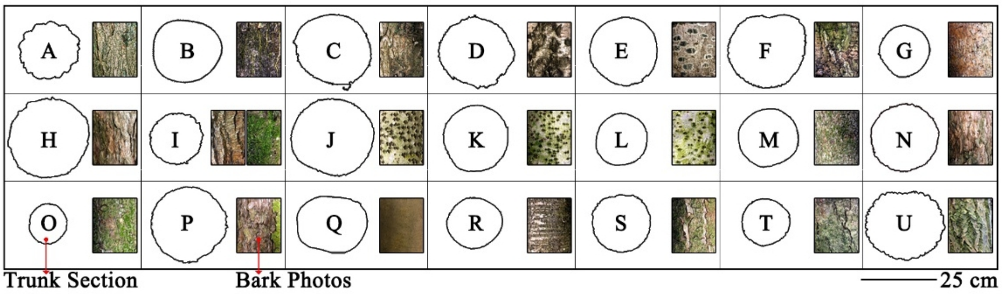

Fig. 2 Overview of the shape of all 21 trunks cross sections analysed. A photograph of the bark surfaces is shown as well.

3. Results

In this section, the findings from a number of preliminary tests are presented first, more precisely the sensitivity of the results due to sealing the samples in the impedance tube, and sensitivity due to sample age after collecting in the field. The separate effects of bark and wood were tested, and the variability in absorption along the trunk circumference, along the trunk height and between trunks of the same species were tested. Next, the influence of moss coverage was measured. Finally, the effect of species on absorption is discussed.

3.1. Reproducibility of the sealing method

To prevent the aforementioned circumferential gap problem, it has been ensured that each sample was well sealed by the use of plasticine. Without this operation, pronounced absorption peaks appear in the absorption spectra that are not linked to the bark properties, but due to the positioning of the sample in the impedance tube.

The reproducibility of this sample handling procedure was checked explicitly by putting the same sample several times in place (and each time re-sealed). Fig. 3 shows the absorption spectra as a result of four resealing operations. At some frequency bands, some variation is observed. Overall, no significant differences were found between the repetitions, which means that the sealing method is reasonably reproducible.

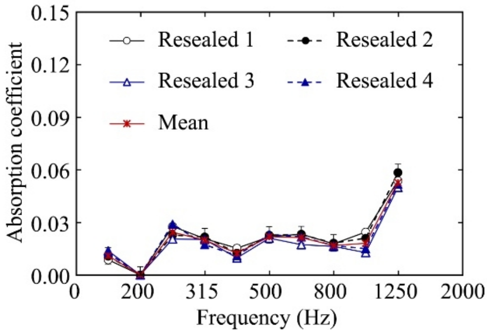

Fig. 3 Absorption coefficient spectra of resealing the same sample in the impedance tube.

3.2. *Sample age*

Figure 4 shows the absorption coefficient of bark F over time during drying in the lab after the sample collection. Fig.4a shows the absorption coefficient of bark F during the first day without changing the properties (such as bark thickness and porosity), and it is showed that bark absorption coefficient among the first 3.5h had no significant difference. Fig.4b shows the changes in the absorption coefficient over time. During the first 30 days, bark F was sealed in a plastic bag to prevent transpiration and water loss. Afterwards, the sample was dried in an unforced manner by exposure to air in the lab. The acoustic absorption of the bark seems to decrease after losing water, especially for longer dried samples. For less dried samples (between 5 and 20 days), effects are, however, minimal. Most likely, the reduced absorption of more dried samples is related to a decrease in bark thickness. To avoid this effect, the samples were always measured a few days after collecting as this will be the situation which is closest to the natural living environment, without suffering from sample aging effects.

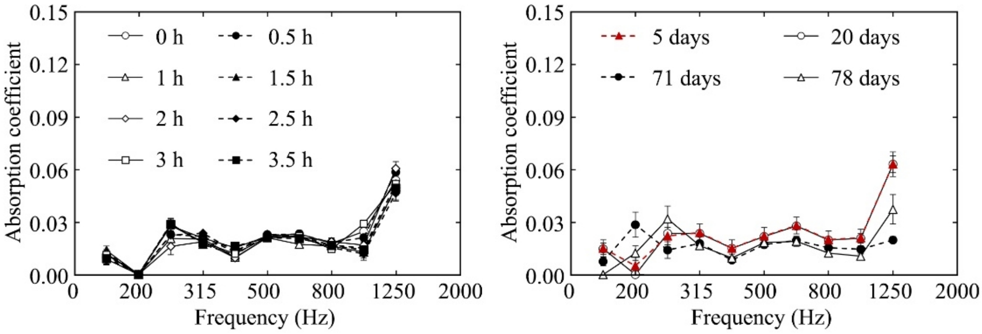

Fig. 4a For short time

Fig. 4b For long time

Fig. 4 The influence of time after collection on the absorption coefficient of bark F. The total length of the error bars are two times the standard deviation on the absorption coefficient, based on four repetitions of measuring the same sample.

3.3. *Wood and bark effects*

To discriminate between the absorption provided by either the bark or the wood behind it, a measurement was performed where the bark was separated from the wood. Fig.5 shows the comparison of the absorption coefficient of *Pinus sylvestris* with and without bark. The bark leads to a significant increase in the absorption coefficient. At frequencies below 1000 Hz, a 2% increase was observed, while at 1250 Hz the presence of the bark leads to an increase of 9%.

The sound absorption coefficient by wood, in contrast, is very limited and rather constant below 1250 Hz Only at 1.6 kHz, the absorption exceeds the one of the empty tube (which has a non-zero detection limit). The results clearly show that the bark dominates the acoustic absorption of the trunk.

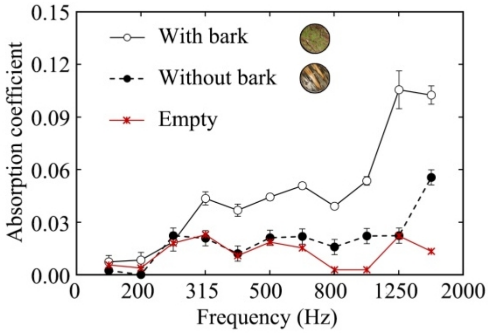

Fig.5 Comparison of absorption coefficient in presence and absence of the bark layer (*Pinus sylvestris*). The total length of the error bars are two times the standard deviation on the absorption coefficient, based on four repetitions of measuring the same sample.

3.4. Variability in absorption along the trunk circumference, along the trunk height and between trunks of the same species

3.4.1. Bark samples from a single trunk cross section

Four bark samples along the circumference of the same trunk cross section were analysed in detail. Each of these four bark samples were measured four times, including repositioning and resealing in the impedance tube (see Fig.6). The absorption coefficients of the four bark samples show no obvious differences when the frequency is below 800Hz. At higher frequencies, some clear differences were found, especially for the *Larix kaempferi* (H) sample. Variability is much smaller for the *Juglans regi*a (B) measurements.

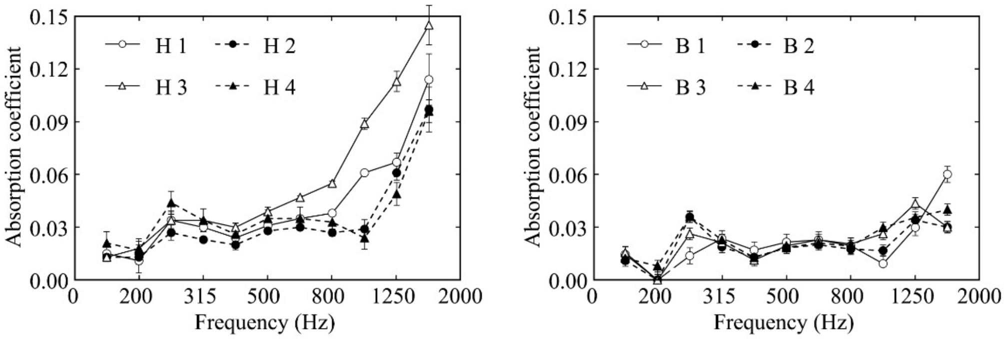

Fig. 6 The absorption coefficient of four bark samples taken at different positions along the circumference of the same trunk cross section. The total length of the error bars are two times the standard deviation on the absorption coefficient, based on four repetitions of measuring the same sample.

3.4.2. Variation in absorption along the trunk height

Samples were taken at different heights along the trunk of two trees to study the variation this might cause. With increasing height, the trunk diameter decreases, and so does the thickness of the bark and the roughness. Fig.7 shows the absorption of the bark from cross sections taken at different heights along the trunk of one *Picea abies* (conifer) and one *Populus tremula* (broadleaved tree).

Table 3 shows some non-acoustical characterizations of the trunks for the two species. For *Picea abies*, two sections of the trunk were cut and measured with a height difference of 2 m and a diameter difference of 3.76 cm, while R1 and R2 did not change significantly. For *Populus tremula*, three trunk disks were selected each time 2 m higher up, while the diameter decreased. R1 decreased slightly at greater height, while the value of R2 peaked at the diameter of 22.10 cm.

Table 3 The non-acoustical parameters of the five trunks disks considered to evaluate height differences.

	Picea abies		*Populus tremula*		
	M	G	J	K	L
Diameter (cm)	20.4	16.64	27.62	22.10	17.48
Trunk height (m)	2	4	2	4	6
R1	1.050	1.078	1.074	1.042	1.029
R2	23.5907	23.8086	14.3861	28.4958	10.9415

For both *Picea abies* and *Populus tremula* the absorption coefficient decreases above 800Hz with increasing sampling height. The effect of sampling height for *Picea abies* is more obvious than for *Populus tremula*. The distinct differences in roughness and diameter are most likely responsible for these differences. A more detailed analysis is provided further in this paper.

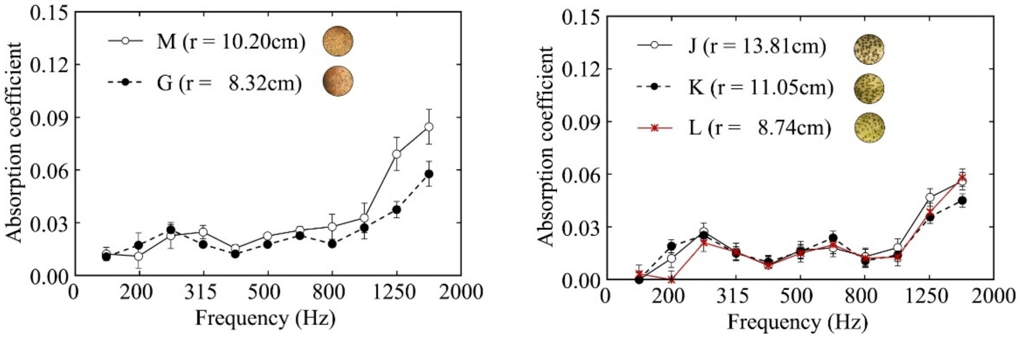

Fig. 7 The influence of trunk height on bark absorption. The total length of the error bars are two times the standard deviation on the absorption coefficient of the four bark samples combined with four positionings in the impedance tube (so in total based on 16 measurements).

3.4.3. Intra-species variability in absorption

Two trees of the same species (*Salix caprea*) were analysed. Note, however, that not all physical properties are the same. The bark of *Salix caprea* 2 (1.4cm) is two times ticker than in case of *Salix caprea* 1 (0.7cm) due to different sampling heights along the stem. Some differences in the roughness characterization might be found as well. To be more specific, the value of shape index (R1) is similar, while the values of R2 have a clear difference. For Salix caprea 1, the values are 30.0649, while the values of *Salix caprea* 2 are 23.5192. As shown in Fig.8, when looking at the shape of the absorption coefficient spectra, a rather similar behaviour is observed. There seems to be a small and more or less constant offset of 0.007 between the two samples below 630 Hz. At higher sound frequencies, no clear tendency is found anymore. For the average of absorption coefficient, variance analysis showed that the absorption of the two trees is not different at the 5 % statistical significance level. So overall, despite some differences in the non-acoustical parameters analysed, the intra-species variability seems rather limited.

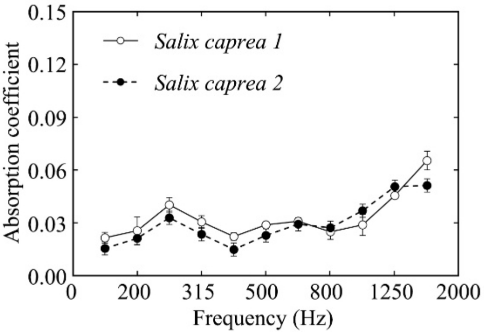

Fig. 8 The influence of species exemplars on bark absorption. The total length of the error bars are two times the standard deviation on the absorption coefficient of the four bark samples combined with four positionings in the impedance tube (based on 16 measurements).

3.5. moss grown barks

The surface of barks, especially at the base of trunks, can be grown with moss in forest stands. Samples were made from a trunk cross section where part of the circumference was grown with moss. Fig.9 shows the difference in absorption coefficient between the part with and without moss. The moss grown surface clearly provides much higher absorption at all frequencies considered, most pronounced in the low-frequency range. Such low-frequency enhancement of a covered porous material has been found before in other works where natural materials were involved [12,25,26]. Although the absorption coefficient of bark with moss significantly increases, the values stay below 0.1 at almost any frequency considered.

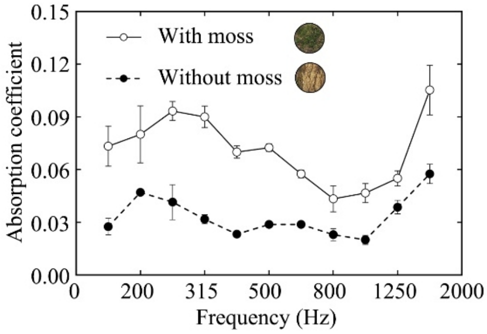

Fig. 9 The difference of absorption between bark with moss and without moss. The total length of the error bars are two times the standard deviation on the absorption coefficient, based on four repetitions of measuring the same sample.

3.6. Effect of species

Fig.10 shows the average absorption value of all bark samples from the 13 species considered. The results show that even the plant species with the highest absorption coefficient (more precisely *Larix kaempferi* in the current dataset) has still a rather low and constant absorption coefficient of about 0.04-0.05 at sound frequencies below 1000 Hz. Above 1 kHz, the absorption coefficient increases significantly but stays below 0.10.

When averaging over all broadleaved and coniferous species separately, a somewhat higher absorption coefficient of about 0.01-0.04 is found at conifers. The largest effects between these two types are again found at higher frequencies.

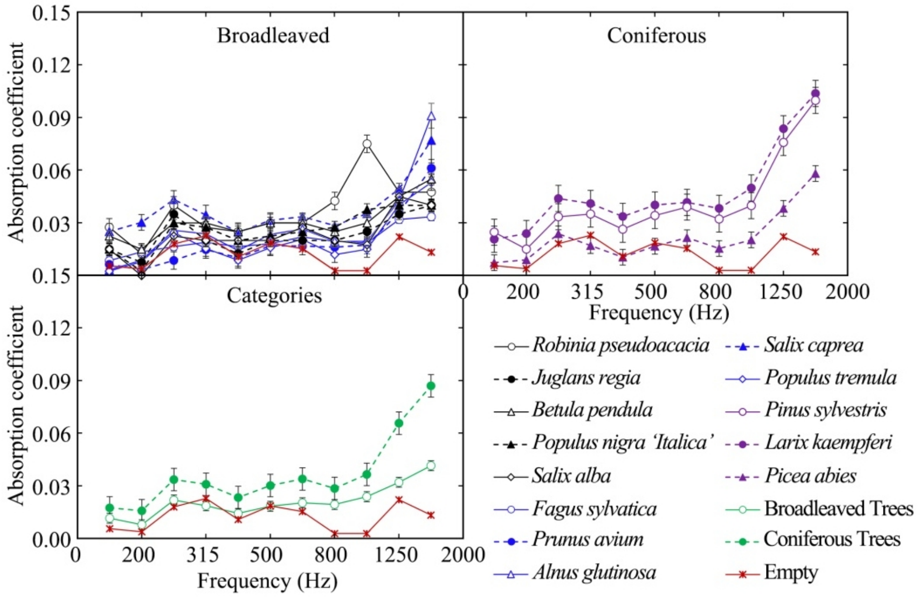

Fig. 10 Absorption coefficient spectra for all plant species. The total length of the error bars are two times the standard deviation on the absorption coefficient of the all bark samples from the same species or species type. The number of samples depends on the species (see Table 2).

4. Predicting bark absorption based on non-acoustical factors

There are potentially multiple non-acoustical factors that influence the sound absorption of barks. The currently assessed non-acoustical parameters are analysed for their predictive power in the current section. Table 4 shows the Pearson correlation coefficients between the bark properties and the absorption coefficients at individual frequency bands. At 160 Hz, and in between 400 Hz and 1000 Hz, all the five factors are statistically significantly correlated with the absorption coefficient. At the other frequency bands, this is only true for Age and R2.

Table 4 Pearson correlation coefficients between bark properties and the absorption coefficient in each 1/3 octave band. T_i is the thickness of the bark, A_i is the age of the tree, and R1 and R2 are roughness assessment factors as introduced before.

Factor	160	200	250	315	400	500	630	800	1000	1250	1600
T_i(cm)	0.357**	N	N	N	0.314**	0.267**	0.280*	0.490**	0.515**	N	N
A_i	0.403**	0.312**	0.404**	0.533**	0.591**	0.611**	0.596**	0.593**	0.566**	0.529**	0.336**
R1	0.303**	N	N	N	0.278*	0.262*	0.261*	0.401**	0.353**	N	N
R2	0.286*	0.450**	0.384**	0.402**	0.373**	0.447**	0.462**	0.253*	0.294*	0.386**	0.464**

**P < 0.01; *P < 0.05; N means P≥ 0.05 (both sides)

Table 5 shows the individual bark properties having a significant correlation with the averaged absorption coefficient, in the full frequency range considered (from 160 Hz and 1600 Hz). Significant factors are the thickness of the bark, tree age, and the two characterizations of bark roughness. All these factors are positively correlated with the absorption coefficient, and tree age and R2 are the strongest predictors. It should be noted, however, that these factors are not independent. Older barks, e.g., typically give rise to thicker and rougher barks.

The diameter of the trunk slice from which the samples were made could not be significantly correlated to the average absorption coefficient. Note that when samples come from thin trunks, a stronger curvature of the bark's surface is inevitable, and might result in an increase in the surface that could potentially absorb sound in the impedance tube. However, such effects were not found.

Table 5 Pearson correlation coefficients between bark properties and averaged absorption coefficient over the full frequency range considered.

	Ti (cm)	Age (Ai)	R1	R2
Absorption coefficien	0.264*	0.646**	0.247*	0.507**

**P < 0.01; *P < 0.05; N means P≥0.05 (both sides)

A linear mixed effect model to predict the average absorption, either based on Age or R2, is presented in Table 6. The absorption coefficients were first averaged over the four samples taken along the circumference of a single trunk disk. This led to a Gaussian distribution in the absorption coefficient (dependent variable) to be predicted all over the dataset. Species was taken as a random effect here. Using age of the tree as dependent factor gives a slightly stronger model, yielding a root-mean square error (rmse) of 0.0018 between the actual data and the predicted absorption coefficients using this model. When using R2 instead of Age, the rmse was slightly higher (namely 0.0040). The roughness characterization might however be a better visual predictor than age in a practical setting. The model performances are shown in Fig. 11.

Table 6 Generalized Linear Mixed Model statistics.

Parameter	Est.	SE	Est.	SE
Intercept	0.0095573	0.0057433	0.013481**	0.0034537
R2	0.0009365**	0.00025557		
Age			0.0006088**	0.00011773

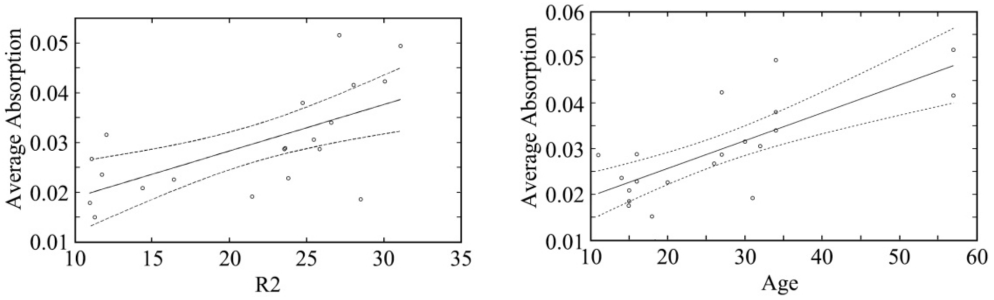

Fig. 11. Predicted average absorption coefficient in function of roughness parameter R2 and age,together with the 95 % confidence intervals on the predictions (dashed lines). The open circles represent the data points.

5. Relevance of the the bark's low absorption values

In order to study the relevance of the low absorption coefficients found in the current study, a number of simulations were made with a full wave model. The same numerical methodology and tree belt setup as defined in Ref. [3] is used. Figure 12 shows predictions of road traffic noise propagating through a 15-m deep tree belt with a trunk basal area of 1.5% (i.e. 150 m² per ha), for different values of bark absorption coefficients.

The simulations show that in this range of absorption values, the small changes that are found between species do impact the final insertion loss. So selecting for species with slightly more absorbing barks thus makes sense. Changing the absorption coefficient from 0.02 to 0.04 is predicted to increase the final shielding of the tree belt with 0.5 dBA. Although this effect is maybe small, relatively spoken, this is a relevant factor as it accounts for about 10% of the total effect. The finding that small changes in low absorption coefficient are more important than small changes in the higher absorption ranges is well known in acoustics. In case of denser tree belts, small effects in absorption coefficient would be even stronger due to the larger number of interactions between sound waves and trunks. Note, however, that the modelled trunk density is larger than would be found in a forest stand, and might need special maintenance and species selection also in a non-deep belt.

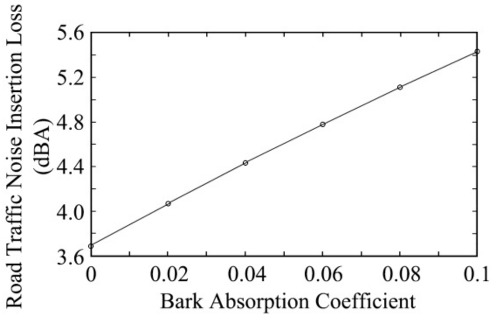

Fig. 12 The effect of the low bark absorption coefficients measured in this work. The case study as presented in Ref. [3] is considered, simulating sound propagation from a four lane road through a 15-m deep tree belt with a trunk basal area of 150 m² per ha. The road traffic noise insertion loss, relative to sound propagation over grassland, is shown here.

6. Conclusions

In this study, systematic tests were carried out using an impedance tube to measure the sound absorption coefficient at normal incidence of barks of 13 different species, together with an assessment of a number of non-acoustical parameters. Overall, the absorption coefficients are lower than 0.1 in the frequency range below 1.6 kHz. Nevertheless, statistically significant differences can be found between species. On average, the barks of conifers absorb sound slightly better than those of broadleaved trees. For most species, a rather constant (and low) absorption coefficient is measured below 1 kHz, after which a strong increase with sound frequency is seen. Moss strongly enhances the absorption at low frequencies. The tree species with the highest absorption coefficient among the tested species was *Larix kaempferi*. Bark thickness, tree age, and the two indices of bark roughness can be related to the absorption coefficient. Tree age and the radial roughness index (R2) seem the most decisive parameters.

7. Limitations and further studies

Some shortcomings in the current experiment could be mentioned. Only sound at normal incidence is studied, which is inherent to using the impedance tube. However, in a tree belt, the multiple scattering of sound in between the trunks leads to various angles of incidence on the bark's surfaces. This might lead to higher absorption values and potentially a further increase in the importance of the roughness of the bark. London's formula [27] could potentially be used to translate the absorption coefficients at normal incidence to estimated reverberant sound absorption coefficients.

The selection of species is based on random sampling of fallen trees in Flanders, the northern part of Belgium. The aim was to have some variety in species at a reasonable collection effort. However, a continued search for species with higher bark absorption could make sense, and the findings in this paper could at least indicate what kind of bark properties to look for. The measurements by Reethof [11] reported species like Mockernut hickory and *Quercus rubrn L.* having higher absorption values near 0.1 in the full low-frequency range.

In addition, a more extensive non-acoustical characterisation of the bark samples might be necessary. The statistical regression models showed fair links between either age or the radial index, but only a part of the observed variability in acoustic absorption is explained. Bark porosity, e.g., is not measured, but is expected to be a relevant predictor of the acoustical absorption, yet suggested by the differences found in between broadleaved trees and conifers [26]. Conversely, the measured absorption coefficient could be used to inversely deduce porosity and flow resistivity of the bark samples.

Acknowledgements

The authors are grateful to Kris Ceunen for helping to collect trunk sections. This study was supported by a Natural Science Foundation of China (NSFC) Grant (No. 51778169).

REFERENCES

[1] Fang CF, Ling DL. Investigation of the noise reduction provided by tree belts. Landscape and Urban Planning. 2003; 63: 187-195.
[2] Tyagi V, Kumar K, Jain VK. A study of the spectral characteristics of traffic noise attenuation by vegetation belts in Delhi. Applied Acoustics. 2006; 67: 926-935.
[3] Van Renterghem T. Guidelines for optimizing road traffic noise shielding by non-deep tree belts. Ecological Engineering. 2014; 69: 276-286.
[4] Van Renterghem T, Botteldooren D, Verheyen K. Road traffic noise shielding by vegetation belts of limited depth. Journal of Sound and Vibration. 2012; 331: 2404-2425.
[5] Pathak V, Tripathi BD, Mishra VK. Evaluation of anticipated performance index of some tree species for green belt development to mitigate traffic generated noise. Urban Forestry & Urban Greening. 2011; 10: 61-66.
[6] Brockerhoff EG, Barbaro L, Castagneyrol B, et al. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodiversity and Conservation. 2017:s10531-017-1453-2.
[7]Van Renterghem T, Botteldooren D. Effect of a row of trees behind noise barriers in wind. Acta Acustica united with Acustica. 2002.
[8] Horoshenkov KV, Khan A, Benkreira H. Acoustic properties of low growing plants. The Journal of the Acoustical Society of America. 2013; 133(5): 2554-65.
[9] Bertrand S, Cerutti G, Tougne L. Bark recognition to improve leaf-based classification in didactic tree species identification. 12th International Conference on Computer Vision Theory and Applications;27 February-1 March 2017;porto, Portugal 2017: 1-8.

[10] Van Renterghem T. Exploiting supporting poles to increase road traffic noise shielding of tree belts. Acta Acustica united with Acustica. 2016; 102(1):1-7

[11] Reethof G, Mcdaniel OH, Heisler GM. Sound absorption characteristics of tree bark and forest floor. Usda Forest Service General Technical Report Ne.1977.

[12] Ding L, Van Renterghem T, Botteldooren D, et al. Sound absorption of porous substrates covered by foliage: Experimental results and numerical predictions. The Journal of the Acoustical Society of America, 2013; 134(6):4599.

[13]Attal E, Cote N, Haw G, Pot G, Vasseur C, Shimizu T, et al. Experimental characterization of foliage and substrate samples by the three microphone two load method. Proceedings of Internoise 2016, Hamburg, Germany.

[14] Yang HS, Kang J, Cheal C. Random-incidence absorption and scattering coefficients of vegetation. Acta Acustica united with Acustica.2013; 99: 379-388.

[15] Davis MJM, Tenpierik MJ, Ramírez FR, et al. More than just a Green Facade: The sound absorption properties of a vertical garden with and without plants. Building & Environment. 2017; 116:64-72.

[16] Azkorra Z, Pérez G, Coma J, et al. Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics. 2015; 89:46-56.

[17] Wong NH, Tan AYK, Tan PY, et al. Acoustics evaluation of vertical greenery systems for building walls. Building & Environment. 2010; 45(2):411-420.

[18] Jeong CH. Converting Sabine absorption coefficients to random incidence absorption coefficients. The Journal of the Acoustical Society of America. 2013; 133(6): 3951-3962.

[19] Chung JY, Blaser DA. Transfer function method of measuring in-duct acoustic properties. l. Theory. Journal of the Acoustical Society of America. 1980; 68:3907-3913.

[20] Chung JY, Blaser DA. Transfer function method of measuring in-duct acoustic properties. II. Experiment. Journal of the Acoustical Society of America. 1998; 68(3):914-921.

[21] Reethof G , Frank LD , Mcdaniel OH . Absorption of sound by tree bark. 1976.

[22] Pilon D, Panneton R, Sgard F. Behavioral criterion quantifying the effects of circumferential air gaps on porous materials in the standing wave tube. The Journal of the Acoustical Society of America. 2004, 116(1): 344-356.

[23] Raven P H, Evert R F, Eichhorn S E. Biology of Plants. New York, N.Y. Worth Publishers. 2005:641. ISBN 0-87901-132-7, OCLC 222047616.

[24]Li H, Reynolds JF. A new contagion index to quantify spatial patterns of landscapes. Landscape Ecology. 1993; 8(3):155-162.

[25] Lovejoy S. Area-perimeter relation for rain and cloud areas. Science. 1982; 216(4542):185-187.

[26] Ilek A, Kucza J, Morkisz K. Hygroscopicity of the bark of selected forest tree species. iForest - Biogeosciences and Forestry. 2016; 10(1).

[27] A. London. The determination of reverberant sound absorption coefficients from acoustic impedance measurements. J. Acoust. Soc. Am. 1950; 22: 263-269.