DOI: 10.61782/fa.2025.0779

SOUND ABSORPTION PREDICTION OF HIGH-DENSITY FOAM-FORMED SOFTWOOD FIBERS

Janis Heldmann[1*] **Jose Cucharero Moya**[2] **Tapio Lokki**[1]
[1] Acoustics Lab, Dept of Information and Communications Engineering, Aalto University, Finland
[2] Lumir Oy, Finland

ABSTRACT

Nowadays, porous absorption materials need to be environmentally sustainable. This concerns the sources of raw materials, low energy consumption in the manufacturing process, and options for recycling. Therefore, alternatives for mineral wools are needed and biomaterials offer an attractive solution. Some recently studied sustainable acoustic materials, such as foam-formed wood fibers, can be produced with a negative carbon footprint. However, sound absorption performance must match the less sustainable variants to ensure competitiveness. Therefore, the prediction of sound absorption is important because it supports the optimization of processes and functionality to achieve the best possible solution. In this study, foam-formed wood pulps of increasing density are produced, characterized, and modeled by semi-phenomenological and analytical models. Their density range exceeds an earlier study by choosing a non-ionic surfactant during synthesis and model accuracy across densities is evaluated against experimentally measured sound absorption. The aim is to create foam-formed fibers with maximal density and the possibility to predict sound absorption with accurate models. The results show that the JCAL model performs better than the analytical models, but the less tedious analytical models provide good approximations. The finding contributes to the optimization of foam-formed pulps by choosing feasible models for the aimed density.

Keywords: *foam-formed biomaterial, wood fibers, JCAl, analytic modeling, sound absorption*

*Corresponding author: janis.heldmann@aalto.fi.

1. INTRODUCTION

Density is a crucial factor in producing high performing acoustic absorbers. Increasing the density of a material also increases the low frequency absorption, which is often a key factor for the usability of acoustic absorbers. Usually, higher densities are related to more material per volume and therefore higher costs. However, in the light of biobased-absorbers more raw material used is a desired goal, as it allows to bind more carbon to the absorption material. This increases a negative carbon dioxide footprint, using more base material that is typically from side streams and leftovers from, e.g., the pulp and paper industry. Based on a previous study [1] that explored the prediction of foam formed wood pulp absorption with an analytical model, semi-phenomenological model, and further refined fitting, this study extends the maximum density range from 50 kg/m^3 to 64 kg/m^3. The necessary pore network stability is achieved with a non-ionic surfactant that is added during the material synthesis.

2. MATERIAL AND METHODOLOGY

Sound-absorbing foams were produced using a foam-forming process based on [2]. Pulp, water, and a non-ionic surfactant were mixed under axial agitation (3000 rpm) in a cylindrical vessel. Two pulp consistencies (3.5% and 4.5%) were used to vary foam density. The pulp was pre-soaked for one day, stirred for 10 minutes, then foamed after surfactant addition until the volume doubled.

The foam was poured into a $25 \times 25 \times 25$ cm mold with stainless steel nets for drainage and structural support. Samples were dried at 40°C for two days. Denser foams were pre-conditioned at 99% relative humidity and

20°C before compression and final drying. Circular samples (100 mm and 29 mm diameter, 40 mm thick) were cut using a bench drill, and outer layers were trimmed to ensure uniform density. The non-ionic surfactant from the group of ethoxylated alcohol replaced sodium dodecyl sulfate (SDS) from the previous study to improve foam stability and allow higher densities. The density is controlled by air content, stability of the foam and the fibre type and dimensions. The choice of surfactant affects the interaction between bubbles and fibres and therefore the foam stability.

3. MEASUREMENT

The dynamic mass density $\widetilde{\rho}$ and dynamic bulk modulus $\widetilde{K}$ were measured using the three-microphone method in a 100 mm and 29 mm diameter B&K 4206 impedance tube. A broad-spectrum random signal of 50–2000 Hz for 100 mm samples and 50-6400 Hz for 29 mm samples was emitted from a loudspeaker, with the sample placed against a rigid termination. Measurements followed ISO-10534-2 [3], and each sample was tested on both sides to account for potential non-homogeneity. Reported values are averages from the measurements of both sides.

4. CHARACTERIZATION

The characterization of the JCAL parameters was performed with the RokCell software (Matelys, France). It estimates all six JCAL parameters based on measured dynamic mass density $\widetilde{\rho}$ and dynamic bulk modulus $\widetilde{K}$ [4]. The characterization was done for each measurement individually and the final estimated JCAL parameters are averages of parameters obtained from both sides. This is done to compensate for the possible non-homogeneous properties of the samples, even though the top and bottom layers of the materials were cut off.

5. MODELING AND ANALYTICAL FIT

The non-acoustic parameters determined during characterization allow modeling $\widetilde{\rho}$ and $\widetilde{K}$ and therefore the sound absorption coefficient [5]. The analytical model consists of six submodels which predict all JCAL parameters while assuming randomly oriented parallel fibers with a symmetric radius distribution, as described in [6], making it well-suited for naturally formed bio-based materials. The submodels are only based on the effective fiber radius and mass density $\widetilde{\rho}$, calculated from the sample mass and enclosing volume (values in Table 1). The effective fiber radius a = 12.7 μm for softwood pulp was obtained earlier from Kajaani FiberLab measurements on similar foam-formed pulps [7]. Non-acoustic parameters are derived using adapted equations to match the symmetric distribution assumption. Three related analytical models were employed. First, the original model proposed in [6], secondly an adaptation in which the equations for flow resistivity and viscous characteristic length were fitted to the characterized values of flow resistivity and viscous characteristic length of the produced materials. Third, an alternative model was used to fit the flow resistivity and viscous characteristic length to the characterized values. The procedure is equivalent to the preceding study of this work and the detailed equations can be found there [1].

In the original model, airflow resistivity is calculated according to Tamayol et al. [8] using the formula:

$$\sigma = \frac{\eta}{(2a)^2} \frac{\sqrt{1-(1-\phi)}}{c_1\left(\frac{c_2}{1-\phi} - 3\sqrt{\frac{c_2}{1-\phi}} + 3 - \sqrt{\frac{1-\phi}{c_2}}\right)} \tag{1}$$

where a is the effective fiber radius and η is the viscosity of air. The fitting parameters $c_1 = 0.21$ and $c_2 = 0.71$ are validated for symmetric distributions of parallel fibers. The second model fits the parameters c_1 and c_2 to the characterized values of flow resistivity of the produced materials. The viscous characteristic length is according to the model of Umnova et al. [9]:

$$\Lambda = a\frac{(2-\phi)\phi^{c_3}}{2(1-\phi)} \tag{2}$$

with $c_3 = 2.732$ in the original model. In this study, the second analytical model fits also c_3 to the present set of values. The third model intends to further improve the modelling accuracy of the viscous characteristic length by using

$$\Lambda = b_1(1-\phi)^{-b_2}, \tag{3}$$

for the viscous characteristic length.

6. RESULTS

Table 1 presents the characterized JCAL parameters in terms of their density and sample diameter. Flow resistivity shows a typical increase with increasing density. The smallest (29 mm) samples were quite tight in the tube and it is possible that the material was a bit compressed when mounted, resulting in higher air flow resistivity than with 100 mm samples. Tortuosity grows slightly as material is denser but other parameters don't show very clear trends, however, all of them are reasonable.

Figure 1 shows the measured absorption curves across densities of 50-59 kg/m^3 for 100 mm samples and 59-64 kg/m^3 for 29 mm samples. For higher densities, the absorption curves shift towards lower frequencies. There are signs of elastic effects present such that the curves are not totally smooth. Such effects are often present when fitting in the impedance tube is tight. Figure 2 shows the comparison between JCAL, JCA, and the original and fitted analytical models. The original analytical model does not model the absorption precisely as it assumes parallel fibres resulting in lower flow resistivity and higher viscous characteristic length than in the actual randomly oriented fibre network. Fitting flow resistivity and viscous characteristic length of the analytical model improves its accuracy across densities. Unlike the results for lower densities in [1] a second step of fitting flow resistivity does not improve the accuracy further. JCAL and JCA models perform equally precisely. The elastic properties are not included in the model, therefore the curve omits the elastic modulation visible in the measured curve.

7. CONCLUSION

In this paper, the investigation of density dependent absorption and its prediction for foam-foamed fibers was extended towards higher densities by using a non-ionic surfactant instead of previously applied SDS. Sound absorption, dynamic mass density and bulk modulus were measured to characterize the JCAL parameters of the materials. An analytical model based on parallel fibres was adapted in terms of air flow resistivity and viscous characteristic length to improve its accuracy for the investigated randomly orientated fiber network. The JCAL model shows higher precision than the employed analytical models, while the analytical models give good approximations. The differences between measured and predicted sound absorption curves are due to elastic effects that appear by fitting the sample into the impedance tube, and are not included in the JCAL model.

8. ACKNOWLEDGEMENTS

This work was supported by the KAUTE foundation and by the Academy of Finland's Flagship Programme under Projects No. 318890 and 318891 (Competence Center for Materials Bioeconomy, FinnCERES)

9. REFERENCES

[1] J. Heldmann, J. Cucharero, and T. Lokki, "Characterization, modeling and prediction of foam-formed softwood fiber sound absorption," in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, (Nantes, France), pp. 8745–8756, 2024.

[2] J. Cucharero, S. Ceccherini, T. Maloney, T. Lokki, and T. Hänninen, "Sound absorption properties of wood-based pulp fibre foams," *Cellulose*, vol. 28, no. 7, 2021.

[3] ISO, "10534-2:1998 - Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer- function method.," *Ansi*, no. 1, 1998.

[4] L. Jaouen, E. Gourdon, and P. Glé, "Estimation of all six parameters of Johnson-Champoux-Allard-Lafarge model for acoustical porous materials from impedance tube measurements," *The Journal of the Acoustical Society of America*, vol. 148, no. 4, 2020.

[5] J.-F. Allard and G. Daigle, " Propagation of Sound in Porous Media: Modeling Sound Absorbing Materials," *The Journal of the Acoustical Society of America*, vol. 95, no. 5, 1994.

[6] F. Pompoli, "Acoustical Characterization and Modeling of Sustainable Posidonia Fibers," *Applied Sciences (Switzerland)*, vol. 13, no. 7, 2023.

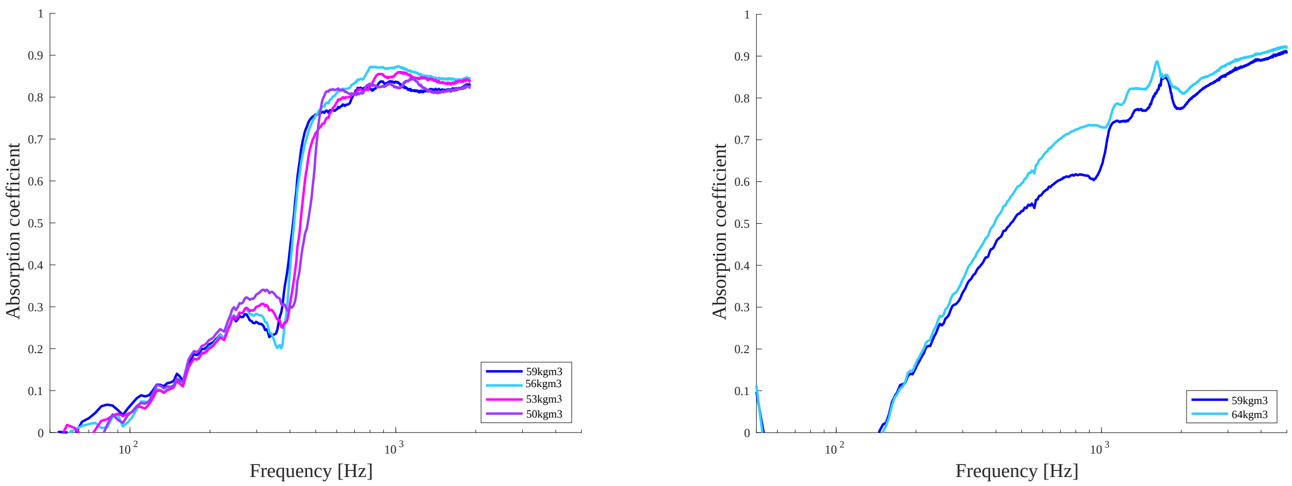
[7] J. Cucharero, S. Ceccherini, M. Awais, K. Kammiovirta, T. Maloney, L. Rautkari, T. Lokki, and T. Hänninen, "Studies on the sound absorption properties of wood-based pulp fibre foams," in *Proceedings of the International Congress on Acoustics*, 2022.

[8] A. Tamayol and M. Bahrami, "Transverse permeability of fibrous porous media," *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, vol. 83, no. 4, 2011.

[9] O. Umnova, D. Tsiklauri, and R. Venegas, "Effect of boundary slip on the acoustical properties of microfibrous materials," *The Journal of the Acoustical Society of America*, vol. 126, no. 4, 2009.

Table 1. Results for the characterization of flow resistivity, porosity, tortuosity, viscous characteristic length, thermal characteristic length, and thermal permeability of all samples in RokCell software.

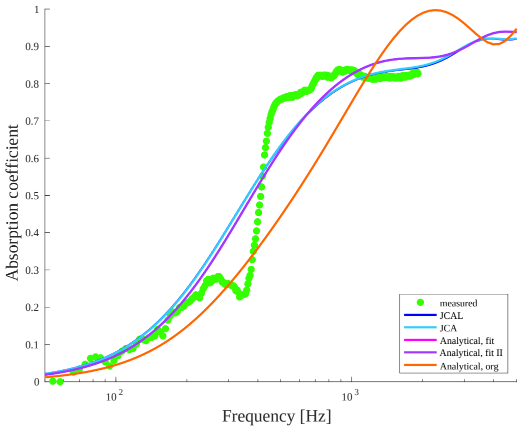
Density (kg / m^3)	σ (Nsm^{-4})	ϕ (-)	α_∞ (-)	Λ (μm)	Λ' (μm)	k'0 (1e-10 m^2)	d_s (mm)
50	33400	0.97	1.38	32	124	16	100
53	43000	0.97	1.42	29	151	18	100
56	52200	0.97	1.57	31	178	18	100
59	49800	0.97	1.58	44	116	18	100
59	63600	0.97	1.45	33	104	14	29
64	81600	0.97	1.60	61	95	12	29



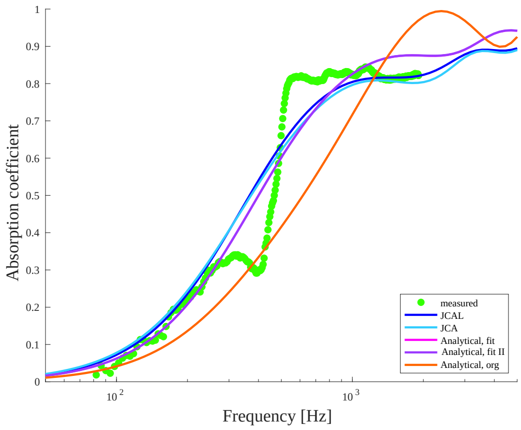
(a) Softwood, d$_s$ $= 100mm$

(b) Softwood, d$_s$ $= 29mm$

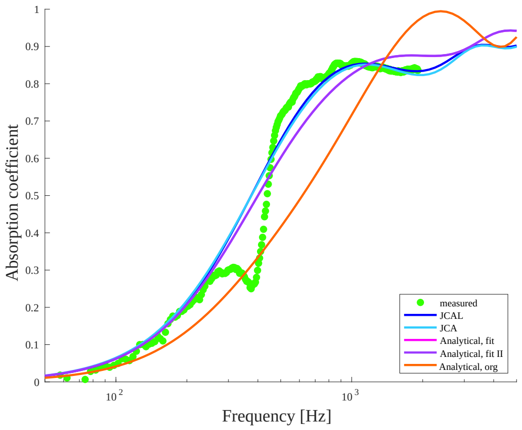
Figure 1. Measured absorption curves for foam foamed bleached softwood pulps for two sample diameters and across increasing density.



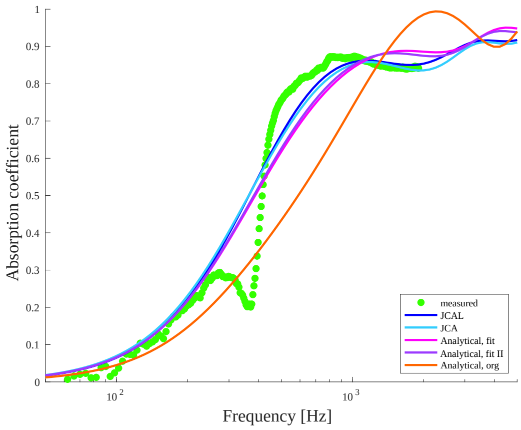
(a) $50\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 100mm



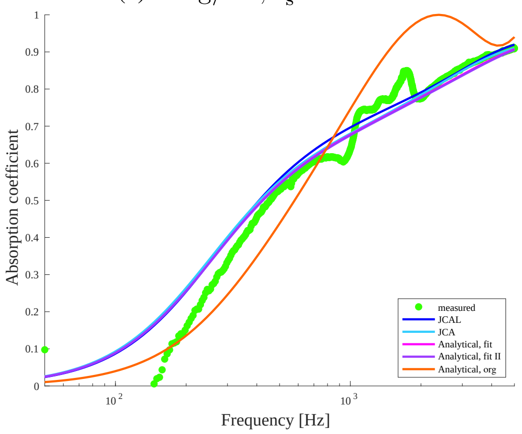
(b) $53\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 100mm



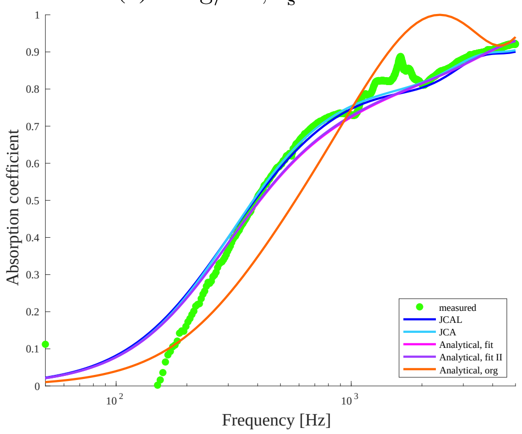
(c) $56\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 100mm



(d) $59\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 100mm



(e) $59\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 29mm



(f) $64\,\mathrm{kg/m^3}$, $\mathrm{d_s}$= 29mm

Figure 2. Sound absorption measurements and predictions at 50-5000 Hz for softwood foam-formed pulps that extend the density range from 50 - 64 kg/m^3.