Characterization of pressure-dependent sound absorption in perforated rigid-frame porous materials

SAPEM 2023 – Sorrento, Italy

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Empa Materials Science and Technology

Sorrento SAPEM'23 常熟

Context

Classical open-pores foams

- Are commonly used for **sound absorption**

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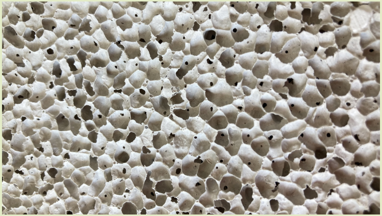
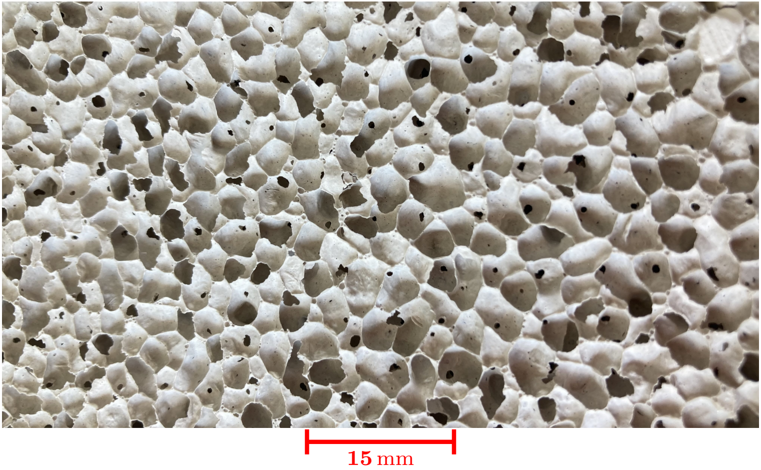
Perforated closed-pores mineral foams

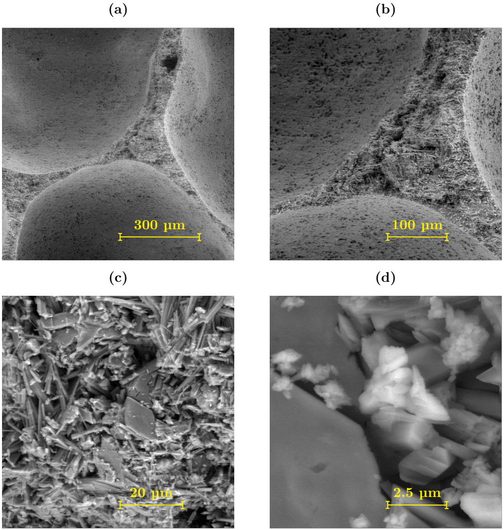


- Made of gypsum, cement, or ceramics
- Controlled porosity and wall thickness – patented by *de Cavis AG*
- Good thermal insulation/resilience properties

Context

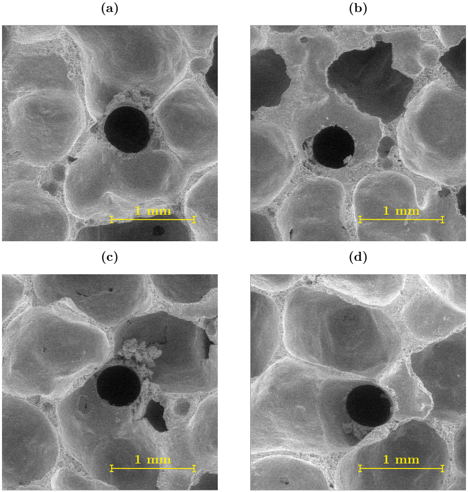


Porosities at multiple scales



- Skeleton is assumed rigid
- Homogenisation theory is applicable
- Bulk modulus and mass density are complex

Perforation in the pores



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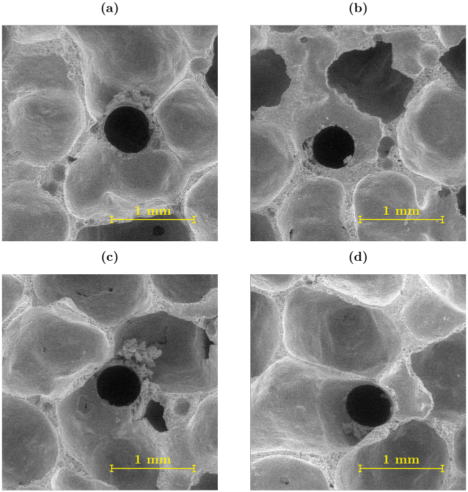
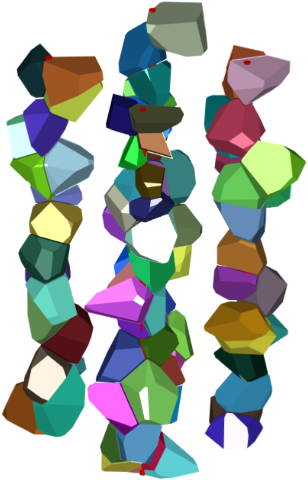
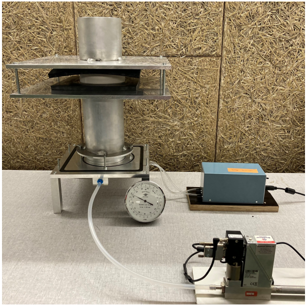




Tunable flow resistivity



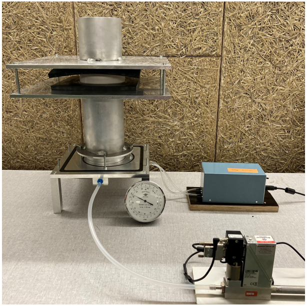
Measuring σ

- According to ISO 9053-1
- Measured on both sides
- Multiple *identical* samples tested

Darcy's law: $\langle \mathbf{v} \rangle = -\frac{\mathbf{K_0}}{\eta} \boldsymbol{\nabla} p$

Flow resistivity: $\sigma = \frac{\eta}{K_0}$

Tunable flow resistivity



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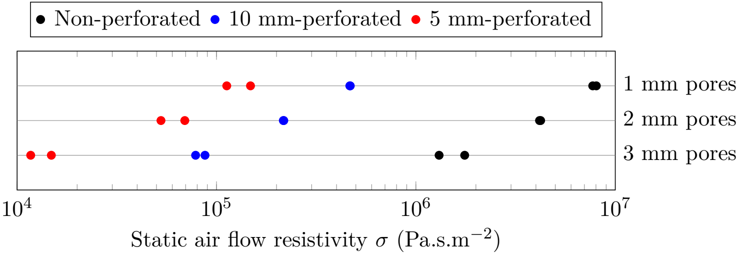

Sub-wavelength absorption

Measuring acoustic absorption

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- White noise excitation up to 1.6 kHz

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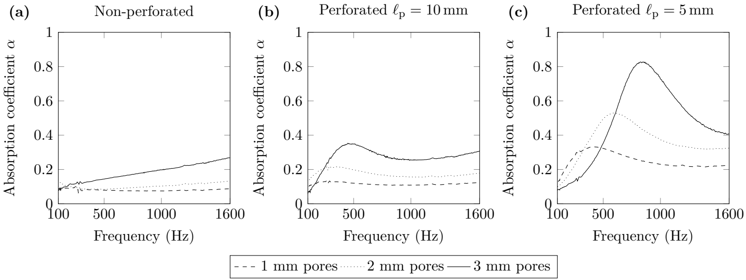
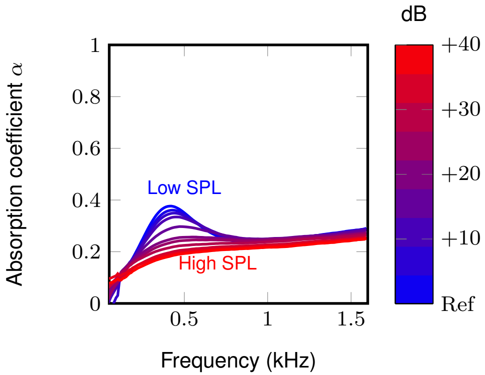


Emergence of non-linearities at high SPL

Perforated structure are known to exhibit non-linearities



- Thickness: 22 mm
- Pore size: 3 mm
- Perforation dist.: 10 mm

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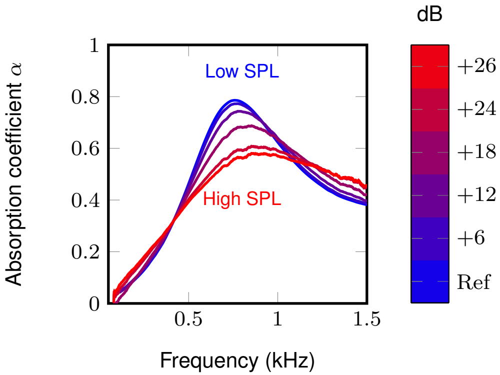
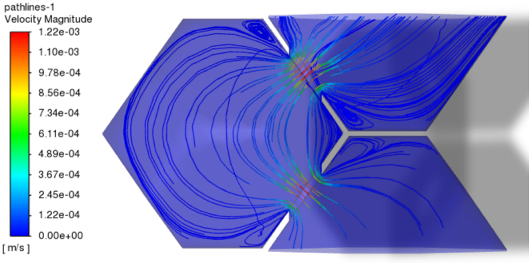


- Thickness: 25 mm
- Pore size: 3 mm
- Perforation dist.: 5 mm

Static regime

Increase of flow resistivity σ with pressure drop ∇p



Velocity magnitude and pathlines at $\Delta p = 1\,\mathrm{mPa}$ and $\langle \mathbf{v} \cdot \mathbf{e}_z \rangle = 1.95 \times 10^{-5}\,\mathrm{m.s}^{-1}$.

Static regime

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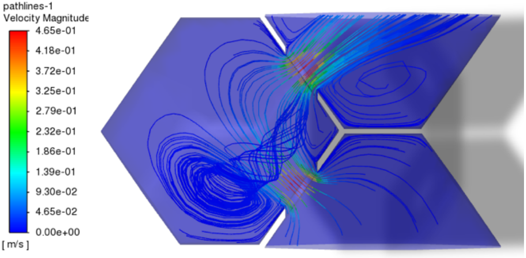
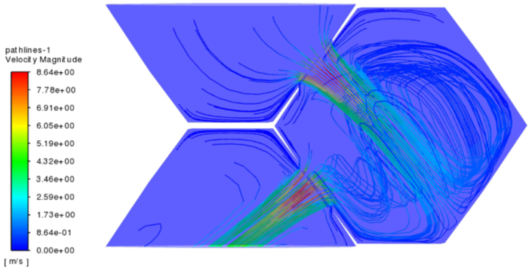


Velocity magnitude and pathlines at $\Delta p = 0.5\,\mathrm{Pa}$ and $\langle \mathbf{v} \cdot \mathbf{e}_z \rangle = 7.5 \times 10^{-3}\,\mathrm{m.s}^{-1}$.

Static regime

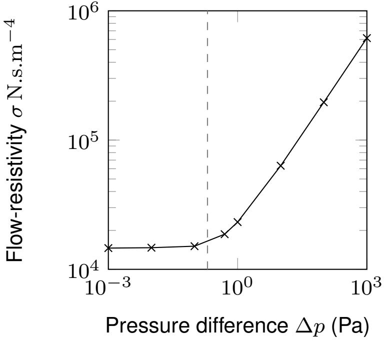
Increase of flow resistivity σ with pressure drop ∇p



Velocity magnitude and pathlines at $\Delta p = 100\,\mathrm{Pa}$ and $\langle \mathbf{v} \cdot \mathbf{e}_z \rangle = 0.14\,\mathrm{m.s}^{-1}$.

Static regime

Increase of flow resistivity σ with pressure drop ∇p



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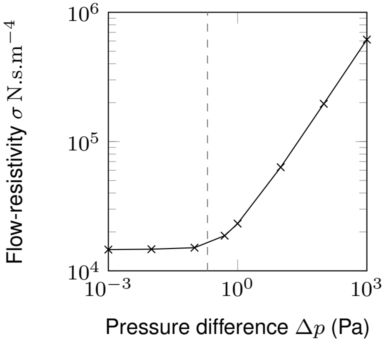
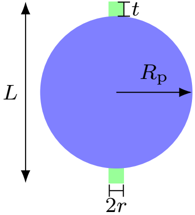


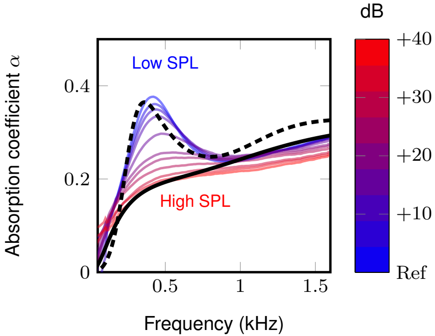


Vol. flow: $Q_{\text{vol}} = \dfrac{\pi \Delta p r^4}{16 \mu t}$

Resistivity: $\sigma = 4\mu \dfrac{d^2}{\pi r^4} \dfrac{t}{R_p}$

Accounting for SPL-dependent flow resistivity

Assuming increasing flow-resistivity $\sigma \rightarrow 10 \times \sigma$



This is observed numerically and described in the scientific literature

- Forchheimer empirical description of flow-resistivity
  - Low $\mathrm{Re} \rightarrow \sigma = f(\mathrm{Re}^2)$ and high $\mathrm{Re} \rightarrow \sigma = f(\mathrm{Re})$
- Non-linear corrections to Darcy's law

Conclusions and perspectives

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- Perforated closed-pores foams are **efficient for low-frequency absorption**
- Non-linearities are **present at high SPL**
- The perforated foams can be **adapted for extreme environments**

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Perspectives:

- Perform **transmission measurements** on samples
- Investigate **Reynold's number** in the perforations
- **Link geometric parameters** to absorption performances
- Model linear and non-linear **resistance and reactance**

Thank you for attending!

J. F. Allard and N. Atalla. *Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials*. Wiley, 1 edition, Oct. 2009.

Y. Aurégan and M. Pachebat. Measurement of the nonlinear behavior of acoustical rigid porous materials. *Physics of Fluids*, 11(6):1342–1345, June 1999.

D. Lafarge, P. Lemarinier, J. F. Allard, and V. Tarnow. Dynamic compressibility of air in porous structures at audible frequencies. *The Journal of the Acoustical Society of America*, 102(4):1995–2006, Oct. 1997.

J. D. McIntosh and R. F. Lambert. Nonlinear wave propagation through rigid porous materials. I: Nonlinear parametrization and numerical solutions. *The Journal of the Acoustical Society of America*, 88(4):1939–1949, Oct. 1990.

E. Sanchez-Palencia. *Non-homogeneous media and vibration theory*. Number 127 in Lecture notes in physics. Springer, Berlin, 1980.

B. Van Damme, A. Goetz, G. Hannema, A. Zemp, C. T. Nguyen, and C. Perrot. Acoustic absorption properties of perforated gypsum foams. In *Forum Acusticum*, pages 2887–2888, 2020.

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