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Exploring the sound absorption potential of open-cell ceramic foams fabricated via Viscous Thread Printing

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Abstract

The advancement of 3D printing of ceramic materials has opened several research lines regarding the fabrication of acoustic porous building materials for a range of applications. To this end, this paper presents a first proof-of-concept experimental characterization of sound-absorbing panels produced via Viscous Thread Printing (VTP), a previously unexplored fabrication method for room acoustic applications. VTP is an extrusion 3D printing process in which the induced filament instability spontaneously generates an open-cell structure without requiring an explicit toolpath design. We evaluated the sound absorption of three typologies of ceramic panels and of resulting layered configurations, addressing the impact of design parameters such as thread diameter and associated pore size, panel thickness, and layering order. The acoustic measurements were conducted in the Small scale Reverberation Room (SSRR) of Politecnico di Torino. Measurements on cylindrical samples of the base ceramic material were performed with an Impedance Tube to gain initial insight into the contribution of the three-dimensional foam structure. Experimental results show, at greater thicknesses and in layered configurations, panels with absorption coefficients in the range 0.3 to 0.65 in the mid-high frequency spectrum, framing VTP as a fabrication method with potential for further research in the field.

Keywords: *Viscous Thread Printing, Sound Absorption, Open-cell Ceramics, Small Scale Reverberation Room, Impedance Tube*

1. Introduction

It is well known that foam-like structures with open porosity are optimal for sound absorbing applications. In the last two decades additive manufacturing technologies expanded the field of sound control by offering the possibility of manufacturing fully customizable objects with complex geometries, and highly intricate porous, fibrous, or cellular structures with a large plethora of available materials [1,2,3], including open-cell porous ceramics [4]. From the acoustic performance point of view, a metrological approach has been pursued to analyze the reproducibility of additive manufacturing technologies [5]. In recent years Viscous Thread Printing (VTP) was investigated as an efficient alternative for producing 3D foams. Using standard fused Deposition Modelling (FDM) or Direct Ink Writing (DIW) 3D printing setups, the pattern-formation effects of Viscous Thread Instability (VTI) [6] can be extended to the third dimension to produce porous 3D structures [7]. Besides the rheological properties of the chosen material, the following control parameters are responsible for the pattern generation process: nozzle height (H), nozzle velocity (v_n), flow velocity (v_f), and thread diameter (d). Toolpath-related parameters such as horizontal spacing (s) and layer height (h) extend the VTI patterns to 2D and 3D configurations (Figure 1). Compared to other 3D printing methods VTP has several design and fabrication advantages: complex structures are formed implicitly from simple linear toolpath geometries; the chaotic non-linear behavior of VTI intrinsically generates locally stochastic patterns [8]; the object's pore size is approximately one order of

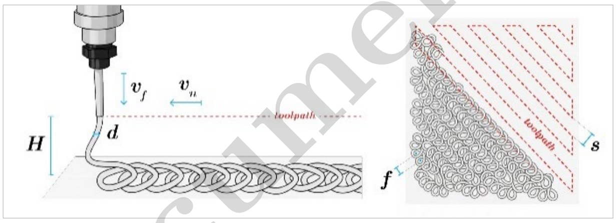

Figure 1. Left: schematics of VTP and main process control parameters: nozzle height (H), nozzle velocity (v_n), material flow velocity (v_f), thread diameter (d). Right: schematics of toolpath-related parameters: horizontal spacing (s) and coiling frequency (f). Low v_n/v_f values translate to lower f values, denser patterns, lower pore size and lower transparency.

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magnitude smaller than the printer resolution [7]; the process is scale-independent and material-agnostic in the viscoelastic regime [9]; multiple patterns and pore sizes can be embedded into a single functionally graded object [10]. The main drawback of VTP is a lower mechanical performance compared to standard 3D printing methods, due to a point-wise inter-layer bonding. Yet, VTP can outperform standard FDM or DIW methods in terms of production time for comparably complex cellular structures, due to potentially very high pattern formation speeds. To the best of our knowledge, the acoustic potential of VTP is still unexplored, as well as studies addressing its use at the architectural scale. This work provides a first proof-of-concept work for applications of Viscous Thread Printing as a viable method for the design and fabrication of sound-absorbing panels, produced with construction-grade materials, methods, and at the architectural scale.

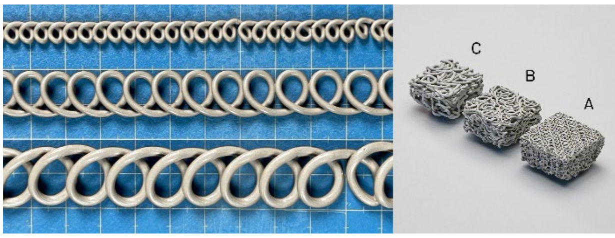

Figure 2. Left: detail of the selected base pattern (Translated Coils) scaled according to nozzle sizes of 1,2,3 mm, printed on a 10x10 mm grid. Right: fabricated samples of the resulting 3D foam types A,B,C (sample size 52x52x26 mm).

2. Methods

This section provides a description of the design, fabrication, and acoustic measurement methods used to evaluate the three typologies of bisque fired ceramic panels produced using VTP.

2.1 Panels design and fabrication

One distinctive feature of VTP is that design and fabrication methods are tightly entangled and interdependent (mainly due to a lack of easily accessible simulation tools). To ensure an efficient experimental workflow, we used a custom-made parametric design-to-fabrication pipeline that directly links a 3D CAD environment to a robotic 3D printing setup.

Table 1. Design and Fabrication Parameters per panel typology (P). Thread Diameter (d), Nozzle Height (H), Horizontal Spacing (s), Layer Height (h), Layer Count (n), Nozzle Velocity (vn), Flow Velocity (vf). The thickness of each panel type is 15 mm.

P	**d** mm	H mm	s mm	h mm	n -	v_n mm/s	v_f mm/s
A	1	10	4.9	2	6	40	62.5
B	2	20	8.8	4	4	15	39.5
C	3	30	14.1	6	3	7.5	15.6

2.1.1 Panel Design

Three sample panel typologies are designed to be fabricated using three different nozzle sizes, resulting in threads with diameters of size 1, 2, 3 mm (panel types A, B, C) and variable pore size. A single panel, sized 600x600 mm, is produced as a 3x3 grid of 200x200 mm tiles of 15 mm thickness.

2.1.2 Pattern Design

The Translated Coils base pattern is selected (with ca. 10% overlap between consecutive coils) to maximize pores density and inter-layer bonding. In our experiment the pattern coiling frequency (f) is designed to scale proportionally to each thread diameter value and to preserve shape features across the three pattern scales (Figure 2, left). These design choices result in A, B, C having comparable density (0.00089, 0.00086, 0.00089 g/mm^3) and porosity (48%, 50%, 48%), yet variable pore size (Figure 2, right). Even if pore size has not been thoroughly characterized, a ballpark estimation returns the following ranges for the three samples: 0.2-2 mm (A), 0.65-6.5 mm (B), 0.8-8 mm (C).

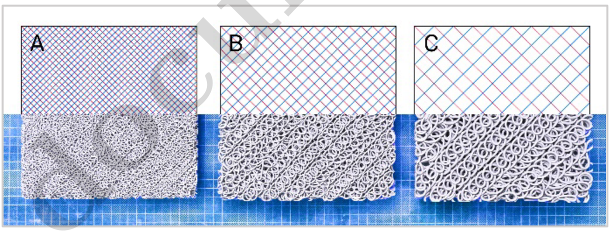

Figure 3. Top: horizontal projection of the digital toolpaths - blue and pink lines represent the two toolpath directions in alternating layers. Bottom: photos of the fabricated results of the 200x200 mm tiles (background grid measures 10x10 mm).

2.1.3 Toolpath Design

The toolpath describes the 3D coordinates followed by the extruding nozzle during fabrication. To achieve the desired pattern features in the three panels, we designed three linear and uniform serpentine toolpaths with different values of horizontal spacing (s), layer height (h), and nozzle height (H) (Figure 3) (Table 1). The toolpath direction rotates 90° every second layer, to increase pore isotropy and inter-layer bonding, and resulting in a cross-ply-like layered arrangement.

2.1.4 Fabrication

Nozzle Velocity (v_n) is the linear speed at which the printing nozzle moves along the toolpath, and Flow Velocity (v_f) is the speed at which the material flows through the nozzle. At constant material viscosity, low velocity ratio (v_n/v_f) values contribute to small coiling frequencies (f), which translates to higher panel density and lower pore size. In our experiments, v_n and v_f are calibrated to achieve the same desired pattern features across the three panel scales (see 2.1.2). Their values are described in Table 1. All panels are printed with a silica-rich industrially manufactured clay with 0% grog

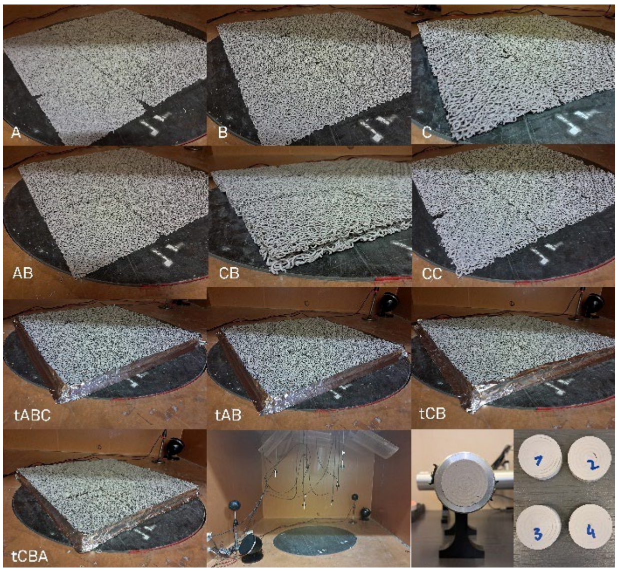

Figure 4. Images of the measured samples in different configurations. In the bottom-center, the SSRR setup. In the bottom-right, the Impedance Tube and the ceramic samples.

(quality nr. 166, Witgert GmbH & Co. KG), hand-mixed and hydrated at 0.4 water-to-clay ratio, resulting in a dynamic viscosity of 2500 Pa s.
The printing process is performed with a six DOF industrial robotic arm (model Racer-3-0.63, Comau S.p.A) equipped with a numerically controlled electro-pneumatic extruder (Lutum Dual, VormVrij3D) mounting disposable 17, 12, and 9 gauge luer-lock nozzles with circular cross-section (1.067, 2.159, 2.997 mm inner diameters). After printing, the fresh clay panels are air-dried and bisque fired at 940°C with a NC electric kiln (model P470, Nabertherm GmbH). The full fabrication process took place in the v_2_R Lab and in the Gypsum Room of the Institute of Art and Design (Research Unit of Three-dimensional Design and Model-Making) at the Vienna University of Technology.

2.2 Sound absorption measurement

Two sound absorption measurements are performed. Large panels with open-cell structure (600x600 mm) are tested in a Small-scale Reverberation Room (SSRR), and plain small cylindrical samples are measured in an impedance tube with a diameter of 35 mm.

2.2.1 Small Scale Reverberation Room

Random-incidence sound absorption coefficients were measured in SSRR located at the Department of Energy (DENERG) of Politecnico di Torino, following the general framework of ISO 354:2003. The room has been previously validated for this application and permits the use of sample areas considerably smaller than the 10–12 m² specified in the standard while preserving diffuse field conditions [11]. Known limitations of the method include reduced field diffusivity at low-to-mid frequencies and edge diffraction effects arising from the finite sample

Table 2. Summary of the measured samples and configurations of the panel typologies. Panels have been tested individually and in configurations of multiple layers, with (x) and without (o) taped edges (t).

Samples	Thickness mm	Tape
A, B, C	15	o
AB, CB, CC	30	o
tAB, tCB	30	x
tABC, tCBA	45	x

dimensions. Acoustic excitation was provided by two omnidirectional dodecahedral loudspeakers driven by an exponential sweep spanning 100 to 25000 Hz. Spatial averaging was achieved through six microphone positions, yielding a total of 12 impulse response measurements per configuration. The measurement chain comprised six ¼'' BSWA Tech MPA451 microphones, two ITA High-Frequency Dodecahedron Loudspeakers with dedicated power amplifiers, and a Roland Octa-Capture UA-1010 audio interface. Post-processing was performed in MATLAB using the ITA-Toolbox. All SSRR samples are made of the same ceramic material, they have a surface area of 0.36 m², and they are tested on the room floor without any mounting hardware.

2.2.2 Impedance Tube

Normal-incidence sound absorption coefficient was determined from averaging 4 identical ceramics samples using a two-microphone impedance tube setup following ISO 10534-2. Measurements were carried out at the Applied Acoustics Laboratory (Department of Energy, Politecnico di Torino) using an HW-ACT-TUBE device with an internal diameter of 35 mm, equipped with two flush-mounted ¼'' GRAS 46BD microphones. The setup enabled reliable sound pressure amplitude and phase measurements across the frequency range of interest, 100–5000 Hz.

2.2.3 Sample Configurations

As summarized in Table 2 and Figure 4, the panels are tested individually as single 15 mm thick layers and in different layered configurations of thickness 30 and 45 mm. Given the increase of the thickness for the 30 and 45 mm multilayer samples, the edges are covered by aluminum tape to reduce the edge effect, i.e. the tests have been performed with or without edge covering. The nomenclature of the samples assumes that a combination of two or more letters is a layered panel configuration, the first letter representing the lower-most panel (e.g. sample AB is composed of 2 stacked panels, A being in the lower position).

3. Results

The absorption measurements are shown in Figure 5, illustrating the SSRR response of the panels in different configurations. The samples are clustered according to: a) thread size (single layer), b) thickness (single vs double layer), c) grading (double layer), d) grading

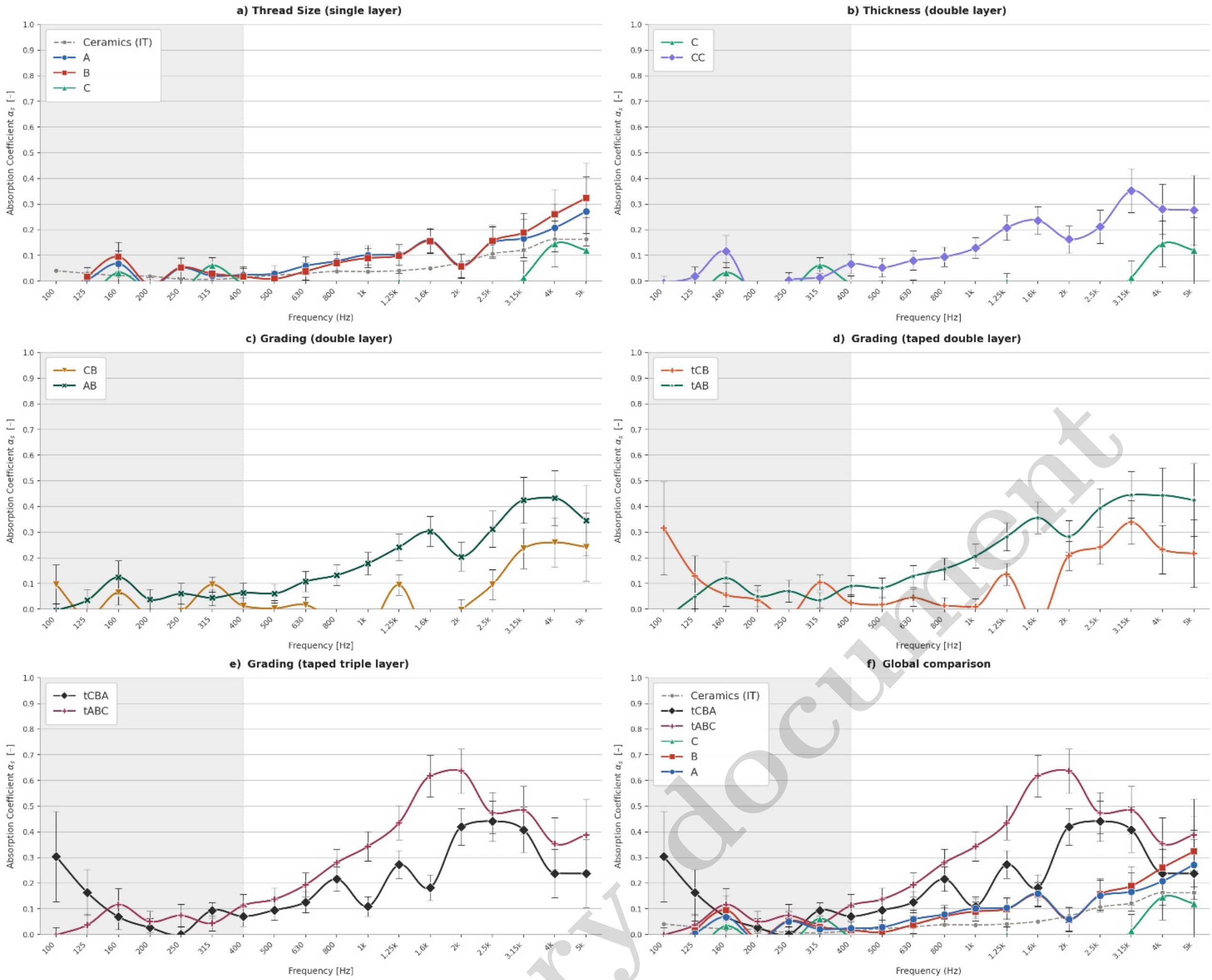

Figure 5. Absorption measurements performed in a 1:5 scaled SSRR of panel samples A,B,C tested in different configurations. The panels were tested individually and in stacks of multiple layers, addressing the impact of thread diameter and associated pore size (**a**), panel thickness (**b,f**), layering order (**c,e**), and edge covering (**d,e**).

(taped double layer), e) grading (taped triple layer), f) global comparison. Measurements from the impedance tube show that the baseline ceramic material is highly reflective, i.e. sound absorption coefficient results <0.1 at frequencies <20kHz. Its non-zero absorption derives from the residual porosity from the low-temperature bisque firing process.

a) Thread Size (single layer): compared to the baseline ceramic material, a panel thickness of 15 mm only slightly improves the absorption coefficients in samples A and B, which, regardless of their different thread and pore size, show an almost identical response. Large pore size and small tortuosity of sample C result in very low sound absorption, leading to lower reverberation times with the panel relative to the empty room condition, i.e. this translates in negative coefficients, and results in a mostly reflective behavior.

b) Thickness (double layer): doubling panel thickness from 15 to 30 mm significantly improves the response of sample C. The supposed higher pore tortuosity of sample CC, has the effect of approximately doubling coefficients above 1000 Hz, with a 3.5x effect in the 3150 Hz band. The peak seems consistent with the frequency of maximum absorption of 2858 Hz, which falls in the 3150 Hz band.

c) Grading (double layer): stacking sample B on sample C greatly reduces absorption, while stacking sample B on sample A results in a significantly improved performance, inverting the CB minimum at 1600 Hz, and reinforcing the positive trend above 2000 Hz. The panel sample with finer pores in backing position (A) and similar acoustic performance as the sample B, clearly outperforms the behavior of the panel with coarser pores (C) in the same position.

d) Grading (taped double layer) : the same experiment as the above (c) was performed with taped panels edges to compensate edge diffraction effects. The performance of sample tAB is largely unaffected if compared to AB, which might be due to more homogeneous characteristics of the two layers and edges, while tCB shows a 3x improvement in the 100 Hz band, and new peaks at 2000 and 3150 Hz if compared to sample CB. The profiles of AB and tAB seem to closely match the one of sample CC, with peaks at 3150 Hz (in line with maximum absorption frequency) and valleys at 2000 Hz. Even if with lower coefficients, the same features are visible in sample tCB.

e) Grading (taped triple layer): in a 3-layer configuration the sample with finer pores/threads in the backing position (tABC) outperforms the sample with coarser geometry in the backing position (tCBA). tABC shows a behavior which can resemble that of a multilayer microperforated panel (MPP) [12]. It is supposed that in this case, the thickness of the panel allows for a higher tortuosity of the pore network, which still allows for some absorption at higher frequencies. Indeed, the microperforated panel sound absorption model presented by Maa [13] has been used in several studies to describe the effects of different gradations of concrete mix designs. This has been highlighted also in [14]. The 45 mm thickness improves the overall performance and is likely responsible for the 2000 Hz peaks of both profiles due to maximum absorption frequency at 1905 Hz. The edge tape effect at the low frequencies is consistent with the previously analyzed tAB and tCB samples.

f) Global comparison: results show a neat performance improvement between 15 mm thick single layer samples (A,B,C) and graded 45 mm thick configuration with taped edges (tABC, tCBA), with tABC showing absorption peaks of 0.65 at 2000 Hz. The contribution of the 3D open-cell geometry is clear if compared to the baseline ceramic material profile measured with the IT (thickness ~15 mm).

4. Conclusions

The scope of this work is to provide a first insight into the sound absorbing properties of ceramic materials with a specific three-dimensional open-pore structure, produced via Viscous Thread Printing. To assess the possibilities offered by this specific 3D printing method, we tested large-scale sample panels (600x600 mm) produced with different thread diameters (1, 2, 3 mm). The open-cell porous structures emerge from 3D printing the same base pattern at 3 different scales, resulting in panels with comparable porosity (49%) but different pore size (0.2 to 8 mm). Each sample panel was tested individually (as single 15 mm thick layer) and in different stacked configurations (30 mm thick double layer, and 45 mm thick triple layer), with and without edge covering to address edge diffraction effects. The panels were tested in the 1:5 scaled Small-scale Reverberation Room (SSRR) of Politecnico di Torino against a diffuse field, and the base ceramic material was measured in an Impedance Tube against incident normal field.

The experimental results generally demonstrate that the geometry of the open-cell porous structures produced by VTP can positively contribute to sound absorption, expanding the scope of non-absorbing materials like fired ceramics to architectural applications. The best performing sample shows a total thickness of 45 mm, a graded pore size ranging from ca. 0.2 to 8 mm, with smaller pore size in proximity of the backing surface, and taped edges. Its absorption coefficients are within the range 0.3-0.65 in the mid-high frequency spectrum, and show a mid-low frequency response comparable to other graded cellular materials [14]. Future work should include a more detailed characterization of porosity and pore tortuosity of the measured samples, to offer a deeper perspective on the measured results, as well as impedance tube measurements of the ceramic foam samples. An evaluation of possible mounting strategies and/or material couplings could offer opportunities to improve the behavior of our sample panels in the mid-low frequency range.

Given the absence of other studies addressing VTP for acoustic applications, the potential of further work in this research direction is wide and deep, from a more detailed mapping of the large design space offered by VTP and its base patterns design (e.g. pore size, coiling frequency, toolpath spacing, panel thickness), to a thorough investigation of possible spatial grading strategies (vertical, horizontal, mixed). The range of available extrudable materials is also very rich, from standard construction-grade to new bio-materials. A consequent next step that builds on the presented work would imply characterizing the ceramic panels after high-temperature firing, which would complete the ceramic material evaluation, and open new aesthetic and architectural possibilities.

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References

[1] F. Setaki, M. Tenpierik, M. Turrin, and A. van Timmeren, "Acoustic absorbers by additive manufacturing", *Building and Environment*, vol. 72, pp. 188–200, 2014.

[2] J. Bauer, S. Hengsbach, I. Tesari, R. Schwaiger, and O. Kraft, "High-strength cellular ceramic composites with 3D microarchitecture", *Proceedings*

of the National Academy of Sciences, vol. 111, no. 7, pp. 2453–2458, 2014.

[3] W. Johnston and B. Sharma, "Additive manufacturing of fibrous sound absorbers", *Additive Manufacturing*, vol. 41, p. 101984, 2021.

[4] C. Minas, D. Carnelli, E. Tervoort, and A. R. Studart, "3D printing of emulsions and foams into hierarchical porous ceramics," *Advanced Materials*, vol. 28, no. 45, pp. 9993–9999, 2016

[5] T. G. Zieliński, K. C. Opiela, P. Pawłowski, N. Dauchez, T. Boutin, J. Kennedy, D. Trimble, H. Rice, B. Van Damme, G. Hannema, and R. Wróbel, "Reproducibility of sound-absorbing periodic porous materials using additive manufacturing technologies: Round robin study," *Additive Manufacturing*, vol. 36, p. 101564, 2020.

[6] P.-T. Brun, B. Audoly, N. M. Ribe, T. S. Eaves, and J. R. Lister, "Liquid ropes: a geometrical model for thin viscous jet instabilities", *Physical Review Letters*, vol. 114, no. 17, p. 174501, 2015.

[7] J. I. Lipton and H. Lipson, "3D printing variable stiffness foams using viscous thread instability", *Scientific Reports*, vol. 6, p. 29996, 2016.

[8] S. W. Morris, J. H. P. Dawes, N. M. Ribe, and J. R. Lister, "Meandering instability of a viscous thread", *Physical Review E*, vol. 77, no. 6, p. 066218, 2008.

[9] P.-T. Brun, "Fluid-mediated fabrication of complex assemblies", *JACS Au*, vol. 2, no. 11, pp. 2417–2425, 2022.

[10] M. Palma, "Grading threads: exploiting viscous thread instability for the additive fabrication of functionally graded structures via sensor-adaptive robotic control", *Architecture, Structures and Construction*, vol. 3, pp. 171–191, 2023.

[11] L. Shtrepi and A. Prato, "Towards a sustainable approach for sound absorption assessment of building materials: validation of small-scale reverberation room measurements", *Applied Acoustics*, vol. 165, p. 107304, 2020.

[12] Z. Liu, J. Zhan, M. Fard, and J. L. Davy, "Acoustic properties of multilayer sound absorbers with a 3D printed micro-perforated panel," *Applied Acoustics*, vol. 121, pp. 25–32, 2017.

[13] H. K. Kim and H. K. Lee, "Acoustic absorption modeling of porous concrete considering the gradation and shape of aggregates and void ratio," *Journal of Sound and Vibration*, vol. 329, no. 7, pp. 866–879, 2010.

[14] L. Shtrepi, A. Astolfi, E. Badino, G. Volpatti, and D. Zampini, "More than just concrete: acoustically efficient porous concrete with different aggregate shape and gradation," *Applied Sciences*, vol. 11, no. 11, p. 4835, 2021.