3D PRINTED ARCHITECTURAL COMPONENTS TO ENHANCE INDOOR ENVIRONMENTAL QUALITY

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3D PRINTED ARCHITECTURAL COMPONENTS TO ENHANCE INDOOR ENVIRONMENTAL QUALITY

Juan D. Vargas [1]
Giorgia Autretto [1]
Vincenzo Gentile [1]
Louena Shtrepi [1]
Stefano Fantucci [1]

[1] Politecnico di Torino – Department of Energy | Italy
Corresponding author: stefano.fantucci@polito.it

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Abstract

The improvement of *Indoor Environmental Quality (IEQ)* represents nowadays a crucial factor for the occupant's health and comfort. For this reason, the development of passive strategies to control indoor humidity and noise levels is of particular interest for research purposes. The presented study aims to develop an indoor cladding 3D printed panel deployable for the improvement of the *IEQ*. Moreover, a workflow integrating *computational design* and *optimization processes* assisted in the definition of the panel's geometry and manufacturing parameters. The panel was primarily developed to exploit moisture buffering. Nevertheless, considering its geometrical complexity and internal void tortuosity, its capability to absorb sound was also assessed.

The research methodology was based on an experimental approach defined to design, develop, and manufacture a component with complex geometry by following a parametric approach, using *Grasshopper for Rhinoceros*. Furthermore, some of its geometrical features have been optimized using the multi-objective evolutionary engine *Wallacei*. At the fabrication stage, several samples with geometrical variations have been manufactured with *a Liquid Deposition Modelling (LDM)* 3D printer. After being manufactured, the component's moisture buffering and sound absorption performances were assessed. First, the samples' *Practical Moisture Buffer Value* was calculated according to the NORDTEST protocol. Successively, the sound absorption properties were tested using the *reverberation chamber* method. Finally, the analysis of the results showed further insights into how an optimized geometrical structure with a maximized exposed surface and reduced use of material, could potentially affect moisture buffering and sound absorption.

1. INTRODUCTION

Passively enhancing *Indoor Environmental Quality (IEQ)* is a highly relevant factor when talking about people's well-being and energy efficiency goals. *IEQ* refers to a variety of physical phenomena and factors that act on buildings' internal spaces. According to [1] *Thermal Comfort, Indoor Air Quality; Visual Comfort, and Acoustic Comfort* are among the main factors that can influence *IEQ.* There are some others, however, they are not easily assessed due to several variables which are not quantifiable, therefore, subjective. Recent studies show that in Europe and the USA, people spend around 90% of their time indoors [2]. This number can increase depending on the season. There are even some places such as the United Arab Emirates where due to the extreme weather conditions, people are estimated to spend over 99.9% of their time indoors. Consequently, *IEQ* phenomena are known to also have a significant impact on the occupant's health, productivity, and comfort [1], especially in overcrowded spaces. Additionally, *IEQ* is normally enhanced with the use of active systems, therefore, it has a significant incidence on the overall energy consumption in buildings. For example "*In tropical climates, the energy consumed by heating, ventilation, and air-conditioning (HVAC) can exceed 50% of the total energy consumption of a building*" [3]. In general, all the factors affecting *IEQ* are highly influenced by design and construction choices.

Day by day there are new examples of how 3D printing can bring huge benefits to the building sector such as more efficient use of construction materials; a reduction of buildings' environmental impact; the increase of occupants' comfort; the nonconventional use of traditional and locally extracted materials (e.g. clay). For example in [4] the 3D printing approach has been used to produce wall components with a complex external and internal geometry enhancing the passive wall heat rejection, with a consequent improvement in *Thermal Comfort* and the reduction of active cooling systems usage.

The case study presented in this investigation is a bio-inspired interior wall cladding solution designed to passively improve *indoor Environmental Quality* in buildings. The panel was primarily developed to target *moisture buffering* in spaces such as offices and meeting rooms, where humidity levels may increase rapidly during the occupied schedules, affecting the occupants' experience. Nevertheless, considering the achieved geometrical complexity and internal void tortuosity, its *sound absorption* capabilities, were also assessed. Furthermore, the research exploited *3D Printing* capabilities to design and manufacture the component. Implementing state-of-the-art technology enabled to develop a component with intricated geometrical features that uses materials more efficiently when compared with traditional manufacturing methods.

1.1. MOISTURE BUFFERING

Moisture buffering can be understood as a way to mitigate the fluctuations of humidity levels in indoor spaces. Given the role of relative humidity on indoor environmental quality, *moisture buffering* becomes a highly relevant factor given its incidence on *thermal comfort* and *indoor air quality.* Therefore, it can be considered to significantly impact the buildings occupant's overall well-being. On one hand, excessive humidity levels (over 60% RH), for short periods can produce discomfort. In contrast, for long periods can generate the perfect conditions for the growth of harmful microorganisms, which can lead to respiratory problems and other health issues [5]. On the other hand, low levels of *relative humidity* (below 40%) can determine dry skin and dry throat and a potential accumulation of hazardous chemicals in the air [6]. Consistently, according to the ASHRAE [7], *relative humidity* should be maintained between the ranges of 40 to 60 % during summer and 30 to 60 % during winter.

The *practical moisture buffer value* is a measure of a material's ability to absorb and release moisture in tested real-world conditions. It considers boundary conditions such as the alternation of humid/dry cycles typical of real environments. Specifically, the $MBV_{practical}$ is intended as a key performance indicator which *"indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the* $MBV_{practical}$*. The unit for* $MBV_{practical}$ *is* $kg/(m^2 \cdot \% RH)$*"* [8].

1.2. SOUND ABSORPTION

Sound absorption properties could be designed to control the performance at different frequencies. In particular, mid-high frequencies are absorbed from porous materials. This is achieved by sound energy being dissipated due to viscous and thermal effects within the material itself. The absorption of sound within porous materials occurs as sound waves propagate through a network of interconnected pores, leading to the energy being dissipated due to friction with the pore walls and changes in flow as the sound moves through the irregular pores. To be effective, porous absorbent materials must have a high tortuosity or an open pore structure with interconnected air paths [9]. Furthermore, some of the most common materials with *sound-absorbing* properties are carpets, acoustic tiles, acoustic foams, curtains, cushions, cotton, and mineral wools like fiberglass. However, there are also 3D printed innovative solutions. For example in [10], a 3D printed panel has been developed to reduce noise in internal spaces. This component is made of a sound absorptive foam, and it has a complex geometry that maximizes its performance. Other investigations on Additive Manufacturing and Computational Design application for 3D printed acoustic material are presented in [11] A research that focuses on designing, fabricating, and testing acoustic panels with locally diffusive geometry and a 3D sound distribution testing method, for correlation of geometry and sound scattering in architectural acoustics. Also in [12] This research explores the additive manufacture of customized ceramic elements via paste-based extrusion, offering precise control of part design and generating manufacturing parameters such as toolpath geometry and machine code.

2. METHODOLOGY

The research methodology consisted of following an experimental approach in which it was necessary to structure a multidisciplinary and multiscale workflow that integrated *Biomimicry, Computational Design, Additive Manufacturing,* and *laboratory tests.* It was divided in four main processes: *design & optimization, manufacturing,* and *assessment.* Figure 1 shows the workflow, and the different processes and tools implemented.

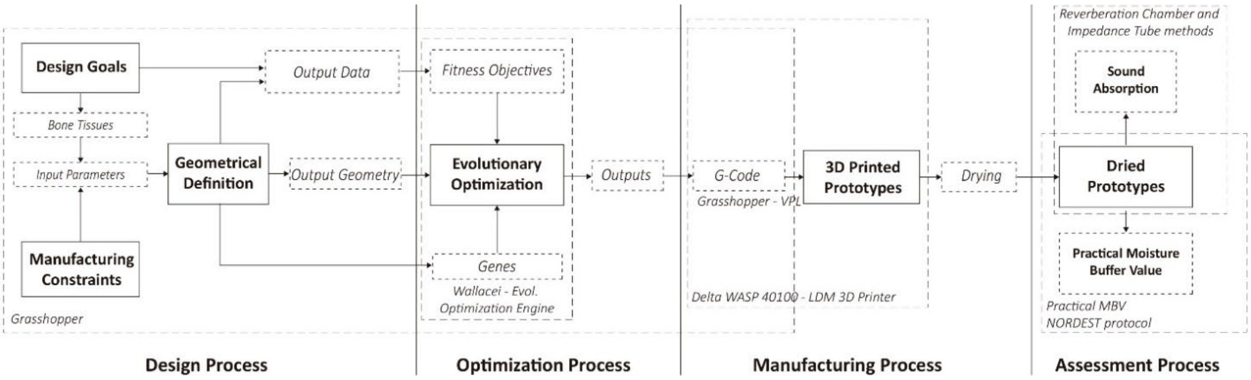

Figure 1. Multiscale workflow that integrates Biomimicry, Computational Design, and Additive Manufacturing using Grasshopper.

[13] Is research that implements a similar workflow to manufacture optimized 3D printed clay bricks that require 50% less materials, compared to a similar component fabricated with traditional methods. For developing such component, the authors coupled *computational design* and *additive manufacturing,* following a *biomimetical approach.*
To assess the *moisture buffering capabilities,* the *Practical Moisture Buffer Value* was determined following the *NORDEST* protocol [8]. Additionally, to assess the sound absorption properties of the devices developed during this research, there were two methods used. The *impedance tube* and the *reverberation chamber,* which according to [9] are two of the most common methods for understanding the *incidence absorption coefficient* of materials and components.

2.1. DESIGN & OPTIMIZATION

The main objectives of the design and optimization processes are related to the design and manufacturing approaches applied to a lightweight, resistant, and cost-efficient panel that passively buffers moisture and absorbs sound while simultaneously using materials efficiently. As a first step, the design is inspired on biomimicry, which involves emulating nature-based functional processes to solve a given design problem. This approach was chosen based on evidence related to the fact that building efficient structures have always been one of the main challenges for architects and engineers. According to [14] "*Since organisms have spent millions of years having their structures developed towards the greatest economy it seems rational that engineers with their questions about materials, structures, and even mechanisms, should look to nature for an exposition of some energy-efficient answers to similar problems raised by technology*".
The panel's structure works as a 3D scaffolding that allows air to flow through it in different directions and it was designed taking inspiration from bone tissues. These natural structures have evolved to become extremely efficient. They work as a porous interconnected system of semi-hollow tubes arranged to generate a *"match between the density of bone filaments and the concentration of stresses; where there is high stress, there is a proliferation of material and elsewhere there is a void"* [15]. Therefore, bones are lightweight materials with a high specific strength, capable to withstand great mechanical strains. Even though, the panel is not meant to perform as a structural component and the loads it would be subjected are simply related to its own weight, bones' porosity, was considered to be a property that could become advantageous for improving the panel's performance. However, in this case, differently to the trabecular tissues, porosity would be applied on the panel's macro-structure to enhance its capacity to buffer moisture and absorb sound with the following features: *air permeability and exposure, lightweight structure, geometrical complexity.*

One of the main reasons for choosing Grasshopper as the main tool to develop the research was the Parametric Approach. This enabled to structure a design process based on quantifiable Key Performance Indicators (KPIs). Furthermore, designing the device from parametric inputs enabled to easily modify the panel's geometrical features and to generate multiple alternatives to compare against each other. Considering that the panel's main purpose was to absorb moisture from air using materials efficiently, three main KPIs were stablished. Figure 2 displays the relation between *Volume [cm^3] and Exposed area [cm^2].* While the benchmark (B0) had low *Exposed Area and* high *Mass,* the 3D printed samples can be manufactured with lower *Volume* and higher *Exposed Area.* Furthermore, for this phase, there were six samples assessed. Five of them were 3D printed while the sixth was the benchmark (B0). The benchmark represents a prototype manufactured with traditional methods. Hence, it is a solid clay parallelepiped with similar gross dimensions to the 3D printed samples. Figure 4 displays the two types of samples.

- *Exposed area [cm^2]:* The panel's *Exposed Area* is the portion of the total surface that can potentially interact with the air. This area is a key-factor in determining the panel's moisture-buffering capabilities. The goal was to maximize this parameter to improve the panel's performance.
- *Volume [cm^3]:* The *volume* refers to the estimated amount of material used to create the 3D-printed structure. One of the main goals of the panel was to use materials efficiently. Therefore, the aim was to minimize its *Volume* as it would represent less use of materials and a reduction of the panel's *weight.*
- *Exposed area / Volume [cm^2/ cm^3]:* This ratio is a key indicator of the panel's overall geometrical efficiency as it shows the relationship between the *exposed surfaces* and the *printed volume*. This parameter is important as it determines an effective distribution of material, and the goal is to maximize the exposed surfaces while minimizing *Mass.*

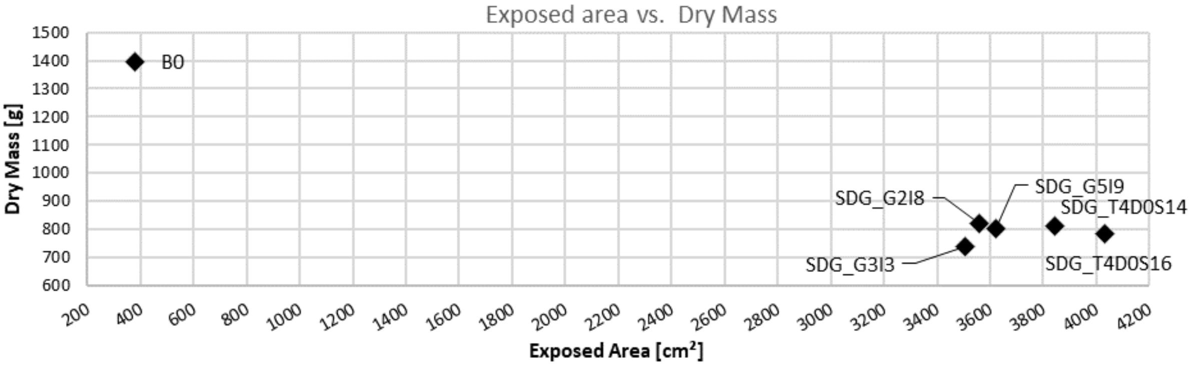

Figure 2. Exposed area versus Dry Mass. B0 is a reference sample made of solid clay, while SDG are different design alternatives of the 3D printed clay panels.

The *Optimization Process* was performed following a *generative design* approach. It consisted of using the *Grasshopper* plugin *Wallacei* to perform an *evolutionary optimization* on the prototypes' geometrical features, with the *Non dominated Sorting Genetic Algorithm 2 (NSGA-2)* [16]. This approach allowed to generate, in a systematic way, a population of potential solutions, to evaluate their performance based on a set of defined *Fitness Objectives (Parameters)* and to choose the best-performing *individuals* to act as parents for generating offspring. The process was repeated generation after generation, creating better-performing and more evolved batches of individuals. From the optimization process, five *individuals* were chosen to be manufactured and posteriorly tested. Given that the main focus of this paper is to provide the data related to the samples' performance, the information related to the evolutionary optimization process included in this paper represents a brief description and it does not include details for the sake of brevity.

2.2. MANUFACTURING PROCESS

The *Manufacturing Process* was carried out using the *Liquid Deposition Modelling (LDM)* 3D printer *Delta WASP 40100.* It can manufacture samples with maximum gross dimensions of 40 cm diameter x 100 cm of height. For this phase of the research all the prototypes were manufactured using pure clay. After being printed, they were dried at ambient temperature for more than 48 hours. Posteriorly, in an oven with a temperature ramp from 30 °C to 100 °C in one hour. Furthermore, an important highlight from the in manufacturing process was that it benefited from an innovative workflow (explained by [17]) that allowed to generate the *G-code* directly from the *Grasshopper* interface. This workflow enabled to have a higher accuracy level over the samples since the geometry didn't have to be exported to a *slicing* software.

The manufacturing parameters that constrained the prototypes' features are the nozzle diameter was 4mm, and the printing speed was of 1800 mm/m. Additionally, the samples' gross (wet) dimensions were set at 137 x 137 x 50 mm. However, after the drying process, due to clay's shrinkage, the components' dimensions became 125 x 125 x 45 mm. Furthermore, for the sound absorption tests, the components were manufactured using two types of clay (gray and white). This difference was generated with the objective of exploring the potential differences in sound absorption properties between the two types of clay. The Figure 3 displays the manufacturing process (beginning and end) of one of the panel samples.

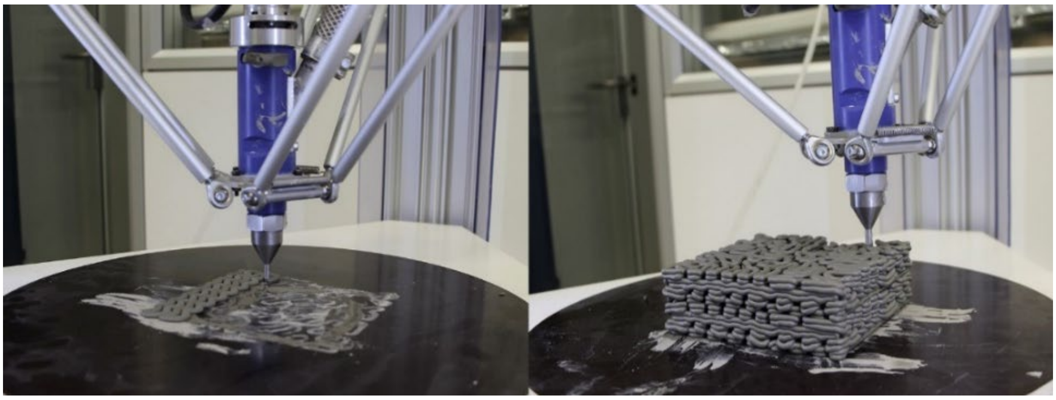

Figure 3. Manufacturing process with clay using the Delta WASP 40100.

2.3. PRACTICAL MOISTURE BUFFER VALUE

The Practical Moisture Buffer values were assessed within the Department of Energy (Politecnico di Torino). The main goal with this test was to assess the possible impact of using 3D printing on the samples capability to absorb moisture. Six samples were tested, five of them were 3D printed while one was a solid clay block, used as a benchmark. Table 1 contains the geometrical features of the tested prototypes. Figure 4 displays two of the tested samples.

Table 1. Samples characterization - KPIs and geometrical information.

CODE	Tot. Exposed Area [cm^2]	Tot. Exp. Area / Dry Mass [cm^2/g]	Net Dry Mass [g]
B0	381.25	0.27	1398.00
SDG_T4D0S16	4033.18	5.16	782.00
SDG_T4D0S14	3843.48	4.73	812.50
SDG_G5I9	3619.47	4.51	803.00
SDG_G2I8	3557.99	4.33	821.00
SDG_G3I3	3506.89	4.75	738.50

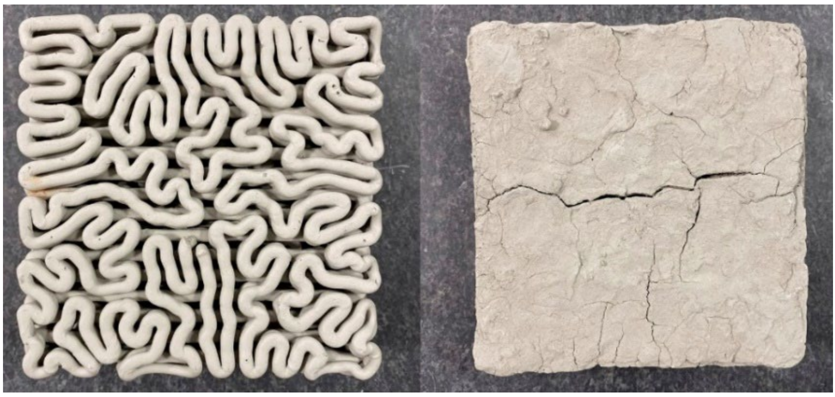

Figure 4. 3D Printed sample (SDG_T4D0S16) / Benchmark (B0).

To assess the *practical Moisture Buffer Value,* the samples were exposed to five dry/humid cycles of 24 hours. The environmental conditions were composed by intervals of low and high *relative humidity,* with a constant *dry bulb* temperature of 23°C (Figure 5). Each cycle consisted of an interval of low exposure at 33% RH for 16 hours followed by an interval of high exposure at 75% RH for 8 hours [8]. The test setup consisted of a climatic chamber, used to control the environmental conditions, and a scale with a resolution of 0.05 g, used to measure the samples' mass *[g]* after each cycle.

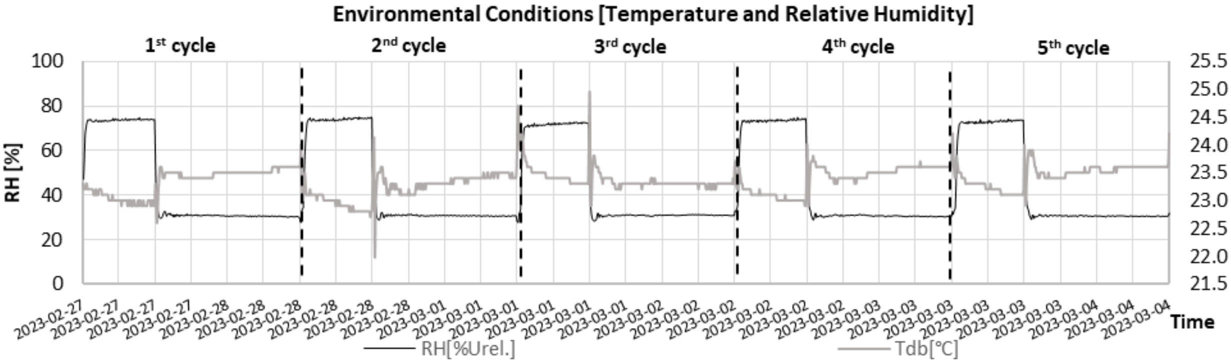

Figure 5. Climatic chamber environmental conditions during MBV test. Relative Humidity (RH[%]) & Dry Bulb Temperature (T_{db}[°C])

2.4. SOUND ABSORPTION TESTS

The aim of this experiment was to assess the *panels* overall *sound absorption* capabilities. To have a complete spectrum, tests were performed at two scales: the material scale and at the component scale. Therefore, the *impedance tube* and *the reverberation chamber* methods were used to assess the frequency-dependent sound absorption coefficients. The first enabled to assess clay material absorptive properties, while the second method was used to assess the 3D panel overall absorption capability.

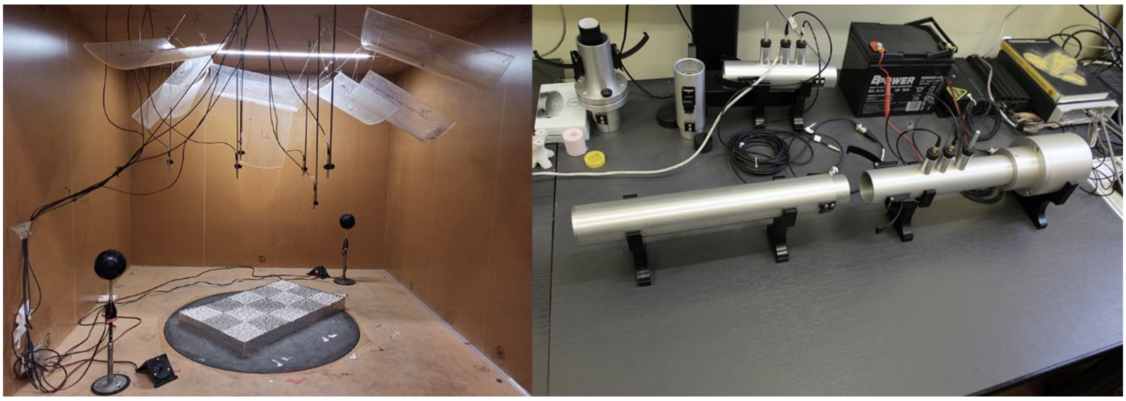

Figure 6. Left) Reverberation Chamber; Right) Impedance Tube.

The impedance tube measurements have been performed in accordance with ISO 10534-2 [18]. The advantages of this method rely on the possibility to obtain measurements using small samples. An impedance tube HW-ACT-TUBE (Figure 6) has been used at the Applied Acoustics Laboratory (Department of Energy, Politecnico di Torino). It has an internal diameter of 35 mm and is equipped with two ¼'' flush mounted GRAS 46BD. The method allows to have accurate sound pressure amplitude and phase measurements in the whole frequency range of interest, i.e., 100-5000 Hz [44] using a 29mm microphone spacing.

The measurements of the normal-incidence absorption coefficient (α_0) have been performed for each clay typology (white clay and gray clay) used in the manufacturing process.

According to [19] the small-scale reverberation room (Figure 6) is a 1:5 scale reproduction of a reverberation room from the acoustics laboratory (Department of Energy, Politecnico di Torino). It is an oblique angled room with pairs of nonparallel walls. The floor area is about 2.38 m^2 and the height in the range 1–1.2 m, which lead to a maximum volume of 2.86 m^3 and a total area of 12.12 m^2. Additionally, the room is raised from the ground on a wooden scaffold and damping layers have been used to seal the *joints* and openings. The chamber was built with lightweight partitions of MDF (Medium Density Fibreboard) with a thickness of 3.8 cm. The MDF has an internal finishing layer of *adhesive film* that maximizes sound reflection. The acceptability of the small-scale reverberation room test results in the frequency range of interest (00-5000 Hz) has been clarified in [19].

3. RESULTS AND DISCUSSION

3.1. MOISTURE BUFFERING

The Figure 7 shows the MBV results obtained by the six prototypes. The benchmark (B0) reached an MBV of 3.8 g/(m² %RH), while the 3D printed samples reached a $MBV_{practical}$ between 14 and 16 [g/(m² %RH) @8/16h], with an average *standard variation* of 0.6 g/(m² %RH).

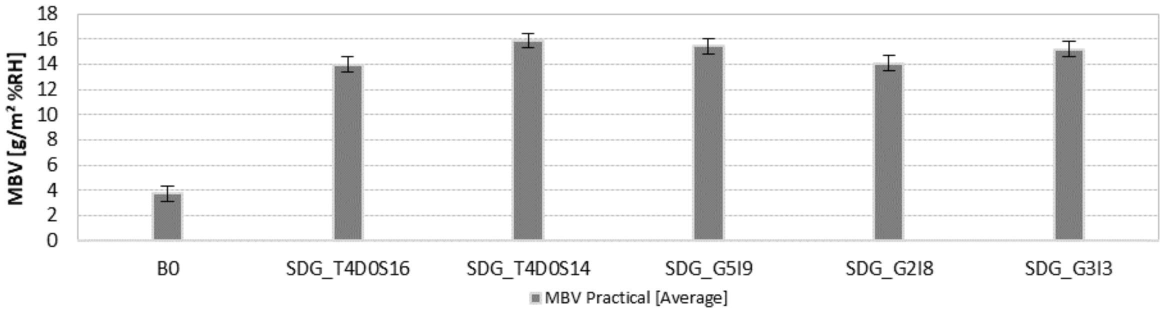

Figure 7. MBV Practical results

For understanding the performance gap between the samples, it was necessary to analyse the prototypes' MBVs and KPIs. The Figure 8, displays the MBV as a function of the MBV/Net Dry Mass, which represents how efficiently is the material being used in the components. When comparing the results, it was noticed that the *Exposed Area* may have a direct incidence on the MBV. While the benchmark had an exposed area of 420 cm^2 and an MBV of 3.8 g/(m² %RH), the 3D printed prototypes had an average exposed area of 3712 cm^2 (about 9 times higher) and reached MBVs 3.5 – 4 times higher and using almost half of the material (see table 1).

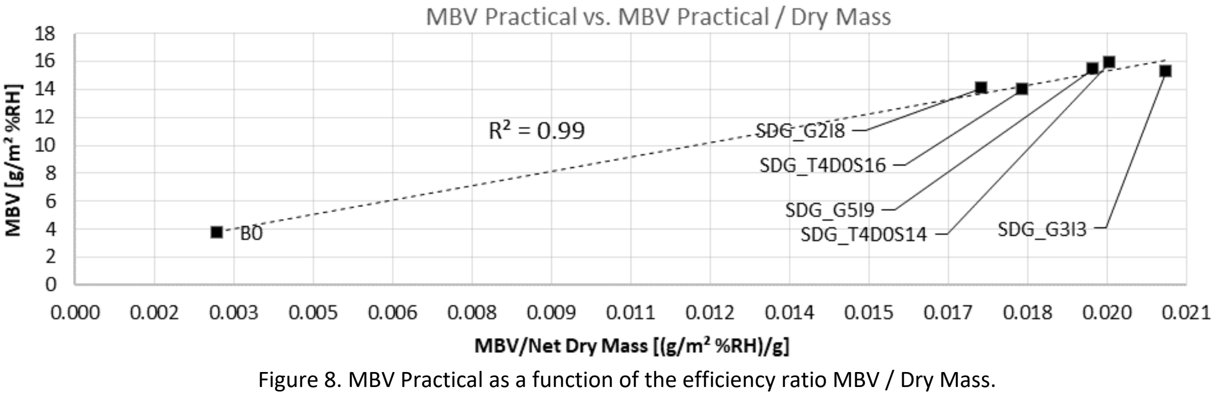

Figure 8. MBV Practical as a function of the efficiency ratio MBV / Dry Mass.

According to the *NORDEST* $MBV_{practical}$ classification [8], a device or material reaches an excellent $MBV_{practical}$ after 2.0 [g/(m² %RH) @8/16h]. Hence, the results obtained during the tests are promising given that the 3D printed samples significantly overtake this threshold value of about 12-14 [g/(m² %RH)]. Furthermore, the benchmark (B0), reached as well an excellent MBV of 3.8 g/(m² %RH). However, there was a significant difference, almost an order of magnitude, between the 3D printed samples and the solid block.

The results proof that the 3D printed individuals reached a significantly higher efficiency in the use of clay. They were on average 43% lighter than the benchmark. While the 3D printed panels had an average dry mass of less than 800 g, the B0 had a mass of about 1400 g. The Figure 8 displays the relationship between the MBV and the ratio between *MBV and Dry Mass [(g/m² %RH)/g].* This relationship was helpful to normalize the *moisture buffering* capacity per gram of material used.

3.2. SOUND ABSORPTION

The *Impedance Tube Test* results showed that clay can be considered a highly reflective material, reaching a maximum value of 0.1 (Figure 9). Additionally, given that both clay samples presented similar *absorption* values, it was concluded that using panels with different clays does not affect significantly the *Reverberation Chamber* measurement results. The clay samples *average absorption coefficient* was of 0.04.

The *Reverberation Chamber* test results evidenced that the *3D panel sound absorption* capabilities could be improved due to the geometrical complexity. This is mainly evident between 1000-2500 Hz which are relevant frequencies for speech. However, they do not exceed values above 0.5 throughout the 100-4000 frequency range. These results could be attributed to clay reflective nature as a ceramic material with a very low porosity. Therefore, further variations of the design of the complexity of the macro geometry and the use of a more porous mix-design that would have a higher sound absorption coefficient could drastically improve the acoustic performance of the 3D panel.

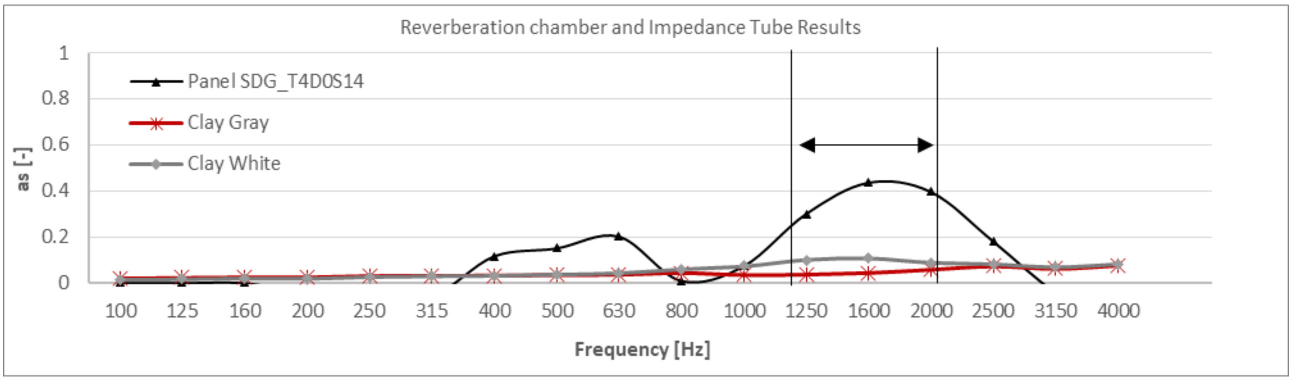

Figure 9. Sound absorption measured in two scales: material scale and component scale. White and gray clay sound absorption measured in the impedance tube and the panels sound absorption measured in the reverberation chamber.

4. CONCLUSIONS

In conclusion, this paper has presented the IEQ Control Panel, a 3D printed bio-inspired interior wall cladding solution designed to enhance indoor environmental quality in buildings. The panel has been shown to effectively target moisture buffering and sound absorption, two factors that significantly impact occupants' comfort, health, and well-being. Additionally, by exploiting the capabilities of 3D printing technology, the panel was developed with intricate geometrical features that enabled it to use materials more efficiently and to have a better performance than a similar component manufactured with traditional methods (simpler geometries). Finally, the results of this study highlight the potential of 3D printing in the construction industry to help passively enhance IEQ, reduce energy consumption, and improve occupants' comfort and health. In particular, it can be highlighted that the *IEQ Control Panel,* is proof of how 3D printing enables the creation of innovative devices, with complex geometrical features, using traditional materials as clay. The component evidenced to have the potential of passively enhancing *Indoor Environmental Quality*, despite the sound absorption capabilities might be even improved with further research. The results obtained during the moisture absorption tests may represent a significative milestone in how to design and manufacture architectural components that enhance the occupants' experience by passively regulating humidity levels.

The *MBV tests* showed that the *IEQ Control Panel* reached *excellent moisture absorption* capabilities, according to [8]. All the 3D printed devices manufactured with clay, reached practical MBV values between 14 to 16 *(g/m² %RH).*

Results proved how 3D printing enabled a more effective use of clay, given that even though the reference sample *B0,* reached values considered as excellent 3.7 *(g/m² %RH)*, its ratio between *performance* and *mass* was several times lower.

The acoustic tests showed that the device's *sound absorption capabilities* require further optimisation to reach a higher performance. However, with the tests performed, it can be said that the complex panel's geometrical features allowed to reach semi-absorbing properties within a specific range of frequencies, despite using a sound-reflective material such as clay.

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