EXPLORING NOVEL, HARD, ACOUSTICALLY ABSORBENT, MATERIALS

by

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DEDICATION

I give my sincere thanks for all those especially my wife and parents who endlessly encouraged and supported me through this pursuit. I also highly appreciate the help and guidance extended by my college friends, faculty, and advisors. Your support and mentorship often provided the inspiration to persevere.

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ABSTRACT

At the turn of the 20th century two contemporaries in their respective fields teamed up to develop a solution to an acoustic problem with the hard-surfaced vaulted ceilings being installed in many large spanning rooms being built at the time. In the spirit of their ingenuity, this research explores a 21st century solution to a similar problem in contemporary buildings; the desire for a durable, hard surface wall or ceiling material treatment that is more sound absorbent than other common surface treatments. To find a material answer to this desire an impedance tube was used to analyze the mid-frequency octave band absorption coefficients of various re-purposed existing materials and tiles created utilizing 3D print technology and Helmholtz resonators. Additionally, an empirical study of Helmholtz resonator geometry was performed by analyzing the sound absorption of resonant cavity shape changes. Finally, plots of the absorption coefficients for each material tested were created to provide a visual comparison against two common surface treatment materials, tectum and gypsum wall board.

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INTRODUCTION

Guastavino Vaults

This research of acoustically absorbent materials began with the architectural study of vaulting without centering. Centering is the process of creating a vault or dome by first building a temporary frame for the structural building material to be rest upon until the keystone, the very center element, is placed holding the structure together through gravity. One building type that heavily relies on this method of construction is the gothic cathedral. Vaulting without centering does not rely on gravity to hold the structure together but rather a type of mortar as the building is constructed. This style of vault found its way to Europe and was studied extensively by Catalan architects and builders. One of these builders to study this form of construction was Rafael Guastavino in 1861 at the Escola Especial de Mestres d'Obres, or Special School of Masters of Works. (1) After a few commissions in Spain, he and his youngest son, Rafael III, moved to New York in 1881. There were many advantages to this vaulting technology, he termed cohesive construction in his 1887 US patent, which allowed Guastavino to succeed in business once he

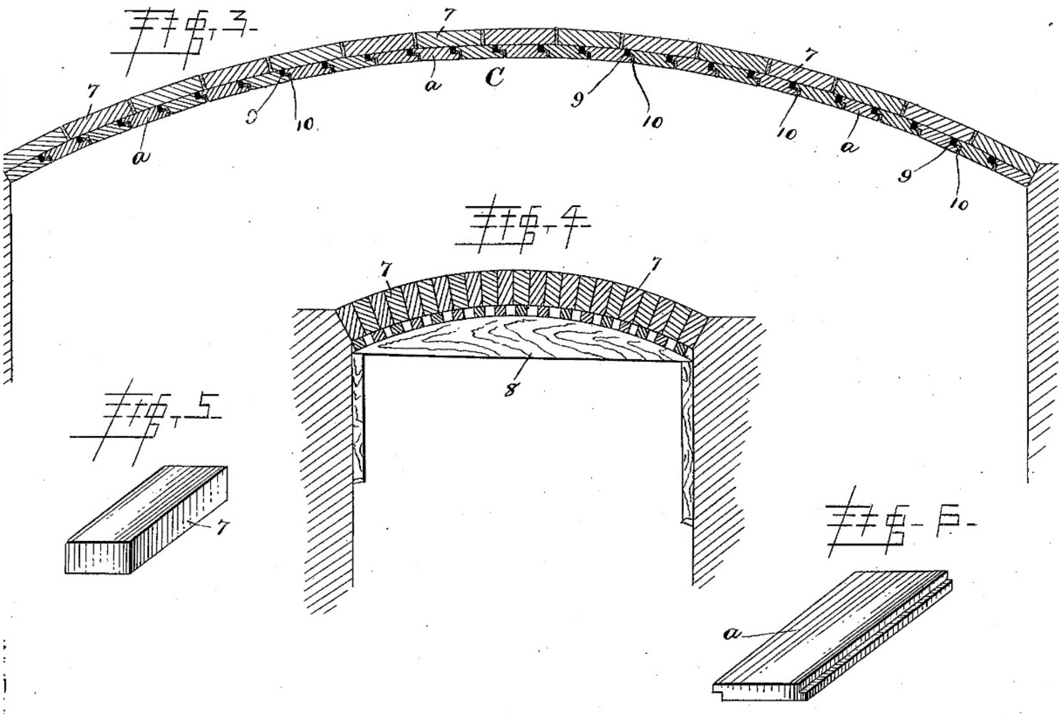

Image 1: Centered Vaulting ("Fig 4") vs Cohesive Construction ("Fig 3"), drawn by R. Guastavino, US Patent No 464562 "Construction of Buildings", Dec. 8, 1891, p.2

moved to the United States. (2) The cohesive construction method utilizes a minimum of 2-3 layers of tiles to be adhered together using Plaster of Paris in a crossing herring bone pattern creating a low vault. This mortar was chosen for its fast setting time and strong integrity once dried.

Guastavino's first major project in the United States was the Boston Public Library designed by architects McKim, Mead, and White completed in 1895. (1) The ceilings are still visible in the exhibition spaces, now carrying the name of Guastavino. This method of construction became highly sought after as a fire-proof, low material, and high load capacity way of construction. The early 1900's were some of the most prolific years for the Guastavino Company with a great number of their commissions coming from New York City. By 1910, Rafael III had become integral to the family business as he began taking over certain responsibilities from his father. One of the challenges he faced was overcoming the acoustic defects caused by the concave surfaces of a vaulted ceiling constructed of acoustically reflective materials. To solve these problems he sought help from the professor of physics at Harvard who was pioneering the field of architectural acoustics, Wallace C. Sabine. (1; 3)

Sabine's Solution

Wallace Sabine began as a physicist studying electricity at Harvard in the 1890's where he joined the faculty as an associate professor after graduating. It was here he was presented with the task of developing a mathematical solution to fix the reverberation time of the lecture hall in the newly built Fogg Art Museum. It wasn't until he was brought on to provide acoustics advice for Symphony Hall that he devolved the formula defining the relationship between reverberation and absorption. Within a short time Symphony Hall was deemed an acoustic success leading to many architects and product manufactures approaching him for acoustic consultation. (3)

Sabine found it challenging to work with manufactures as he wanted to present his findings freely with the public no matter the findings, whereas, manufactures wanted to only publish marketable data. It was with an introduction by architect firm Cram, Goodhue, and Ferguson that Raphael Guastavino was able to speak to Sabine about developing an acoustically absorbent ceramic tile. (1) Cram, an architect practiced in Neo-Gothic architecture, wanted a material that provided sound absorption and also had stone-like appearance to be used in the cathedrals he was designing. The two men agreed to work together utilizing Guastavino's knowledge of ceramics and Sabine's expertise of porous absorbers and testing methods.

Guastavino experimented, firing tiles with different proportions of organic material as a way to increase the tiles porosity. Although this method of firing wasn't new, it was a challenge to find the ideal combination of components to achieve the desired tensile strength, porosity, and thickness. The first product to be patented by Guastavino and Sabine was the Rumford tile. The Rumford tile was 25% clay, 10% feldspar, and 65% "vegetable bearing earth or peat" and, according to Sabine's measurements, absorbs 29% of the incident sound energy compared to the 3% of a standard Guastavino tile. They were able to achieve this porosity through interconnected channels "irregular in form, expanding and contracting in cross-section so that their action will be like the muffling action of a muffler on an engine exhaust." (4)

Even with the success of the Rumford tile they decided to continue to experiment to find a product that would yield even higher acoustic absorption. Guastavino began experimenting with Portland cement as means to have the tiles be more consistent and stone-like in their appearance. The Akoustolith tile achieved this goal with 38% absorption, and with the base component of Portland cement they were able to create more than tiles using molds to create ornamentation decorative tiles. Throughout the 1920s until the Guastavino Company's closure in the 1960's Akoustolith was a common product used for ceilings in Churches, Universities, and Public Buildings.

With the closure of the Guastavino Company we also lost the knowledge to create these unique building elements. This study uses insight gained from the works of these pioneers to attempt a recreation of their building materials, explore the possibilities of novel materials, and new technologies to create material absorbers.

BACKGROUND

Absorption – Terminology And The Sabine Equation

Sound absorption is the process by which sound energy is diminished in passing through a medium or in striking a surface. (5) It was the relationship between this striking of a surface and reverberation that Wallace Sabine developed into a formula. By plotting the data he collected from his experiments he was able to recognize a regular hyperbola, a basic mathematical equation written as: $x * y = k$ where k is a constant. (3) With the equation's outline he was able to rework the formula to replace the hyperbola constant as a proportional relationship to Volume in meters cubed ($0.164*V = k$), and the summation of each product between the surface area of a material in meters squared (s_n) and the absorption coefficient of a material (a_n), where a material 100% absorptive is 1. (3)

$$t = \frac{0.164*V}{\sum s_n a_n} \qquad 1$$

Helmholtz Resonator – Sound As A Spring

A Helmholtz resonator is an acoustic tool to cancel sound waves using a rigid-wall chamber with an orifice or tube considerably smaller than the soundwave. (6) Together the air mass in the neck and chamber act as a "mass" attached to a "spring". When a force presses on the mass of air in the neck it compresses the air inside the cavity building pressure limited by the cavity's size. As the pressure wants to return to equilibrium the air in the chamber presses back against the mass of air in the neck causing oscillation. If this mass of air is oscillating at the same cycles per second, or frequency, as the soundwave striking the neck the soundwave's corresponding frequency will be reduced in intensity through wave addition. A Helmholtz resonator can be tuned by solving for the resonant frequency using the classic Helmholtz formula described later in this study. While an effective tool, it is limited in that each Helmholtz resonator can be tuned to only one frequency.

EXPERIMENTS

Helmholtz Resonator Cavities

Hypothesis

This study uses modern technology, 3D printing, to create Helmholtz resonators and control the geometry of the cavities. The challenge with using a 3D printer to print an absorptive tile is that it requires a fully defined object to print, including the interconnected pores with random cross-sections similar to those in Guastavino's acoustic tiles. An initial attempt to do this was created as discussed in the next section of this research, however, another way of removing sound by impacting a surface is to use a Helmholtz resonator. The equation derived by the research performed by Helmholtz, Rayleigh, Soundhauss, and Werheim to create a Helmholtz resonator is:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{V_O(L_N + 0.3D)}} \qquad 2$$

Where:

f: frequency

c: speed of sound in a gas (approx. 343m/second)

A: cross-sectional area of the neck

V_O: Volume of cavity

L_N: Neck length from opening to cavity

D: Diameter of the neck opening

Using this equation it became apparent the geometry of the neck was critical to the frequency, however, the geometry of the volume behind the neck didn't appear to have an effect on the resonant frequency. Based on a paper by M. Alster suggesting the equation needed to be modified to account for the geometry of the resonator volume, this study examined several resonator geometries with the same volume to seek empirical proof to this theory. (7)

Materials and Methods

Image 2: Powder based 3D printed cube Helmholtz resonator

The physical tiles containing the Helmholtz resonators were printed using a Z-corp 450 with a plaster powder base. This printer was chosen for its speed and higher resolution than those of the plastic filament extrusion printers commonly used in 3D printing. The platonic solids and sphere were chosen as the cavity geometries to study because of their regularity and derived equations for volume and surface area. However, before beginning a check was made to make sure that while volume remains constant the surface area will change for each solid. This was done using the formulas for a cube and tetrahedron.

Volume of a cube

$$V_C = {a_C}^3 \tag{3}$$

Surface Area of a cube

$$SA_C = 6{a_C}^2 \tag{4}$$

Volume of a tetrahedron

$$V_T = \frac{{a_T}^3}{6\sqrt{2}} \tag{5}$$

Surface Area of a tetrahedron

$$SA_T = \sqrt{3}{a_T}^2 \tag{6}$$

A proof was then worked out to verify the mathematical statement, if $V_C = V_T$ then $SA_C \neq SA_T$. Once this basic concept was proven the following formulas were rearranged from their volume equations to solve for length or radius "a" for each solid. This variable was then used in a 3D modeling software to generate the desired solids.

Tetrahedron

$$a_T = \left(6V\sqrt{2}\right)^{\frac{1}{3}} \tag{7}$$

Cube

$$a_c = V^{\frac{1}{3}} \tag{8}$$

Octahedron

$$a_o = (\frac{3V}{\sqrt{2}})^{\frac{1}{3}} \tag{9}$$

Dodecahedron

$$a_d = (4\frac{V}{15+7\sqrt{5}})^{\frac{1}{3}} \tag{10}$$

Icosahedron

$$a_i = (\frac{12V}{5\left(3+\sqrt{5}\right)})^{\frac{1}{3}} \tag{11}$$

Sphere

$$a_s = (\frac{3V}{4\pi})^{\frac{1}{3}} \tag{12}$$

With multiple variables to the Helmholtz equation [**Error! Reference source not found.**], a parametric solver was utilized to visualize the ratio of the resonant cavity plus neck's height to their corresponding resonant frequency. This study utilized a regular cylindrical neck, proportionally adjusting the cross sectional area and height to achieve the targeted frequency.

Knowing that the samples would be tested in a 100mm diameter B&K impedance tube the only factor would be the thickness at which the sample tile would need to be made. Once a reasonable height of 38.1mm was determined using the parametric modeler, the cavity and neck were joined into a single solid then subtracted from the sample that was to be 3D printed. To clearly see results from the impedance tube the subtracted solid was copied using an x and y axis array where the distance between each solid was the radius of the widest geometry, the tetrahedron.

Results

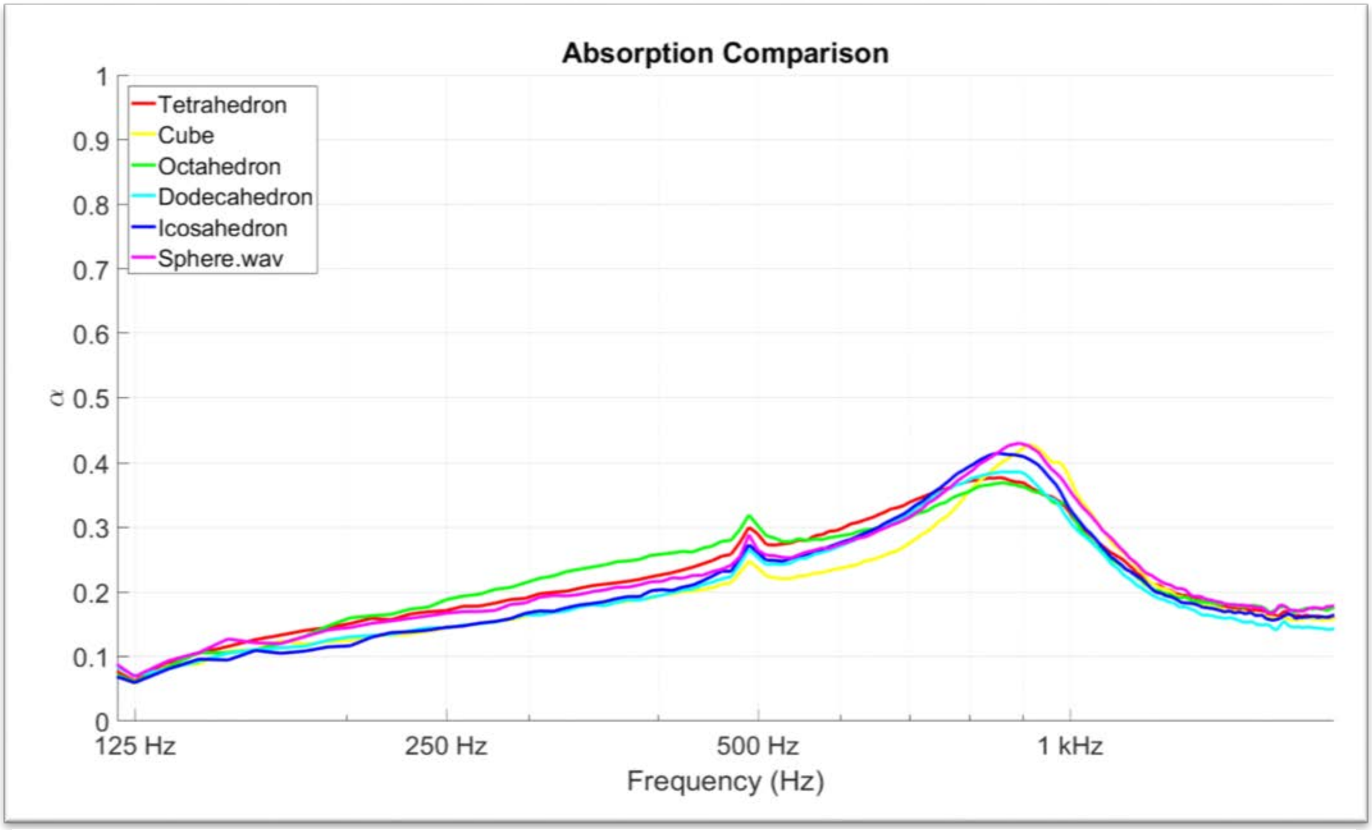

Figure 1: Plot of absorption for platonic solid resonant cavities with the same volume.

From the plotted graph in **Error! Reference source not found.**, it is clear by the way all the curves maintain the same general intensity, that the cavity's geometry has little effect as was originally described by the classic Helmholtz equation. This would suggest that the classic equation does not need to be modified, as hypothesized, for more general applications such as surface treatments. However, for applications where precision could be of great consequence, using the modified equation may be critical. Finally, it should be noted that each tile's resonator produced a peak sound reduction close to the targeted 900Hz. By achieving the targeted frequency with the precision and speed of the powder jet printing, these tiles could be quickly tuned in a software program and printed to provide frequency-accurate acoustic absorption building modules. Once these prints go through a hardening process, they would be fairly durable and provide targeted frequency "absorption".

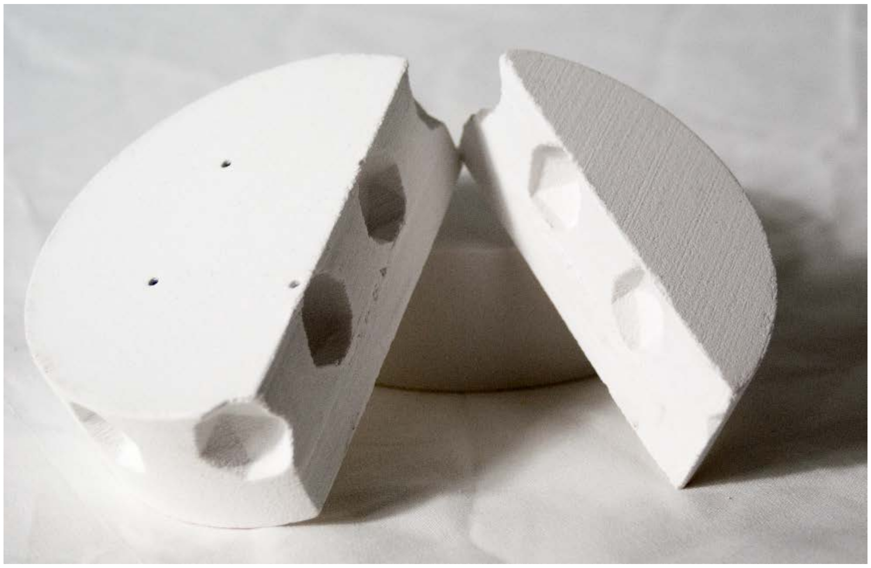

Image 3: Section cut of icosahedron Helmholtz resonator

Acoustic Absorption

Hypothesis

The primary focus of this experiment was to find modern materials that acoustically performed comparable to the Guastavino-Sabine tiles using materials that offered acoustic absorption through interconnected pores. Several manufactured products in use have such pores but are used in situations where acoustic absorption is not the intended application. Additionally, an attempt was made to 3D print tiles with “randomized” interconnected pores to test their effectiveness.

Materials and Methods

The materials tested for acoustic porosity in this study are two clay bodies, Portland cement, kiln brick, packaged ramen noodles, and PLA filament for 3D fusion printing.

Clay

With the closing of the Guastavino Company in the 1960’s, much of the knowledge associated with manufacturing their absorptive tile was lost. What remains were collected by professor and art historian George Collins and archived at Columbia University containing several office drawings, samples of their later products, and copies of the United States patents.

The first material study in this experiment was to re-create the Guastavino acoustically absorbent ceramic tile. As a means to accurately reproduce the ceramic tiles, the researcher visited Asheville, North Carolina to source clay from the mountains near where the Guastavino Company sourced its clay. (1) Two particular clay bodies were chosen because of their range of firing temperatures, cone 06 (1828-1855 F) to cone 5 (2167-2205 F). The use of clay is particularly challenging as firing causes the object being fired to shrink. Once the shrinkage rate were found for the clay bodies at cone 06 and cone 5 a new tile was cut from the clay body to be fired that would fit within the impedance tube’s 4 inch diameter.

Finally, with a base line absorption defined for the two clay bodies at each firing temperature, organic aggregate was to be added to the clay bodies to experiment with the porosity of tiles.

Portland Cement

The second material tested in this experiment was based on the more successful Guastavino-Sabine tile, Akoustolith. Portland cement is made by combining cement, aggregate such as sand, and water. This study experimented with the ratios between the cement and aggregate while maintaining the ratio of cement to water. In addition a high strength pre-mixed concrete was compared to the Portland cement.

Image 4: Portland cement tile with 1 part cement to 3 parts sand

Packaged Ramen Noodles

In addition to experimenting with clay and cement this research sought other porous products that are not traditionally used by architects or acousticians. One of the products tested was a direct result from discussing Tectum, a product commonly specified by architects and acousticians. The manufacture describes Tectum as, “composed of aspen wood fibers, bonded with an exclusive inorganic hydraulic cement binder and formed in a continuous process under heat and pressure.” (8) This product is versatile in its application by either being hung in space by cables defined as E-mounting, or as a direct mount product, A-mounting. If directly mounted to a surface it performs generally well at mid frequencies.

Image 5: Three packaged ramen noodle products cut to fit inside the B&K impedance tube

After looking at a sample of Tectum with several colleagues, it was noted how similar to Ramen Noodles it resembled. This observation led to acoustic absorption testing on several types of packaged noodles in an impedance tube. Using a LaserCAMM, the 4 inch square packaged noodles were cut to fit inside the impedance tube to determine the absorption coefficients. Several brands were tested to determine a range of absorption based on manufacture.

Kiln Brick

This study also tested a ¾" soft kiln brick. These bricks are placed in kilns as shelves for clay to be placed on during the firing process. One property these bricks did not have that this research was investigating was the products durability. While the brick is rigid, it has a dried sponge-like quality to its texture allowing for small abrasions to cause damage to the surface. With the use of a band saw it was easy to cut the product to fit in the impedance tube.

Image 6: Kiln brick cut to the 4" diameter need to be placed in the impedance tube

3D Fusion Print

With the advancement of technology, 3D printing has become more readily available and inexpensive to solution to print large quantities of a repetitive module. This experiment utilized an Anet A8 fusion printer to print two models of a tile designed with interconnected pores of irregular geometry in a tile with a thickness of 1” and diameter of 4” to fit in the impedance tube. In addition to the two sizes of interconnected pores, each version was printed with two types of filament for a total of four samples. The filaments used were polylactic acid (PLA) filament and a wood fiber infused PLA filament. The primary difference between the prints of the same file was the change in density from the two types of filaments.

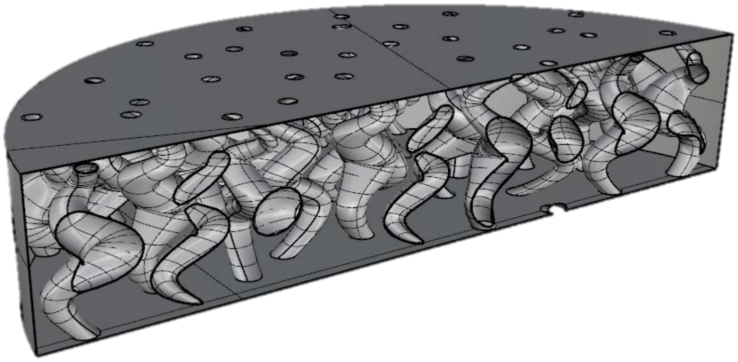

Image 7: Model section cut through 3D print

Results

The following results are all compared to two existing building materials commonly used in construction, Gypsum wall board on 2”x4” wood studs at 16” on center and direct mounted Tectum. The absorption coefficients compared came from Architectural Acoustics: Illustrated and the manufacture’s website respectively. (9; 10)

Clay

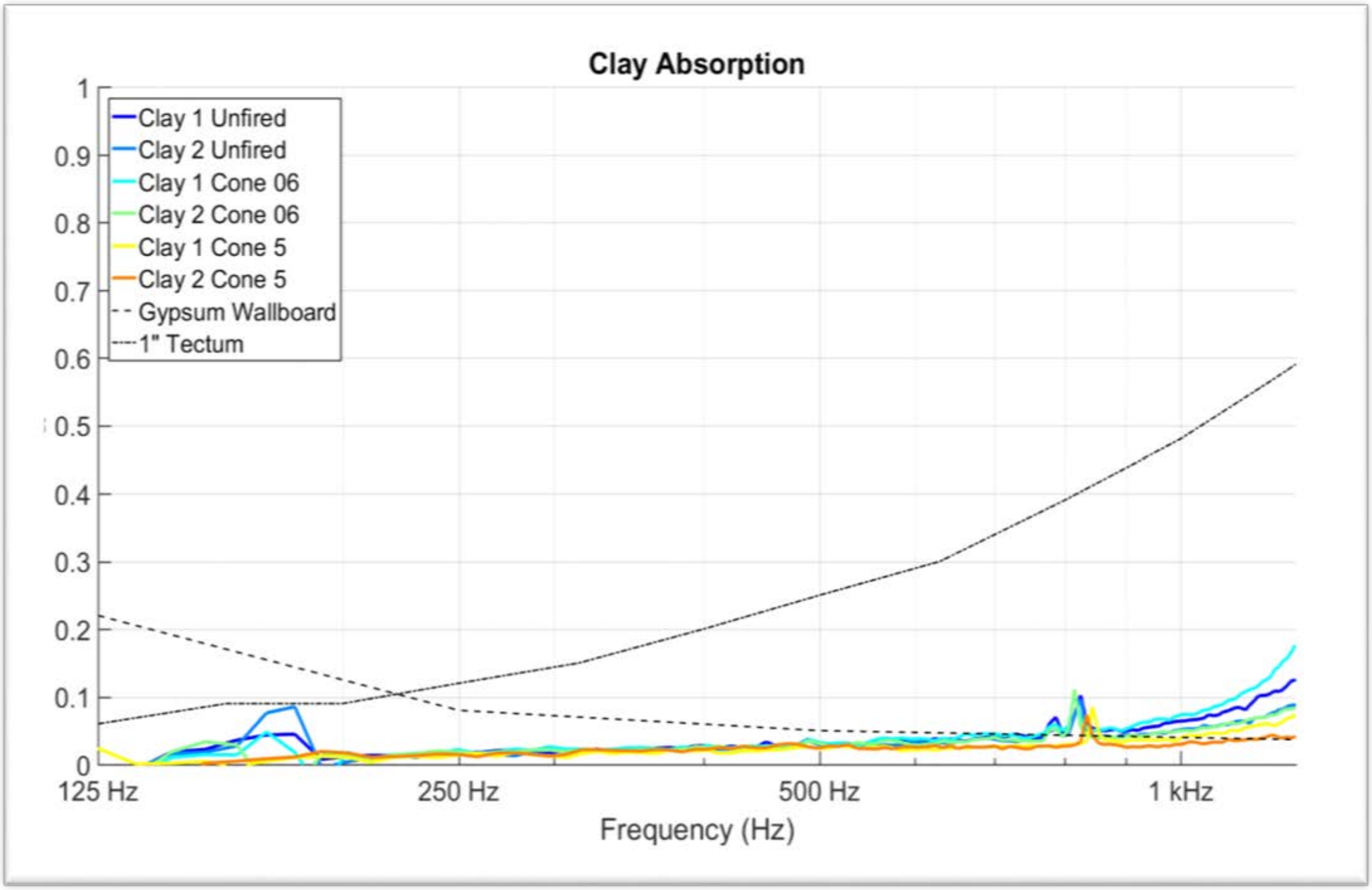

Figure 2: Absorption of Clay Bodies at Three Firing Temperatures

As none of the samples shown here contain any aggregate, the results shown in Figure 4 were expected by the author. As stated in the Introduction of this research the standard Guastavino tiles had approximate 3% absorption which is consistent with the findings here. It does appear that there is greater difference in absorption above 1kHz. Additional studies are needed to determine the effects above 1kHz as the small section captured appears to provide more absorption with higher firing temperatures.

Portland Cement

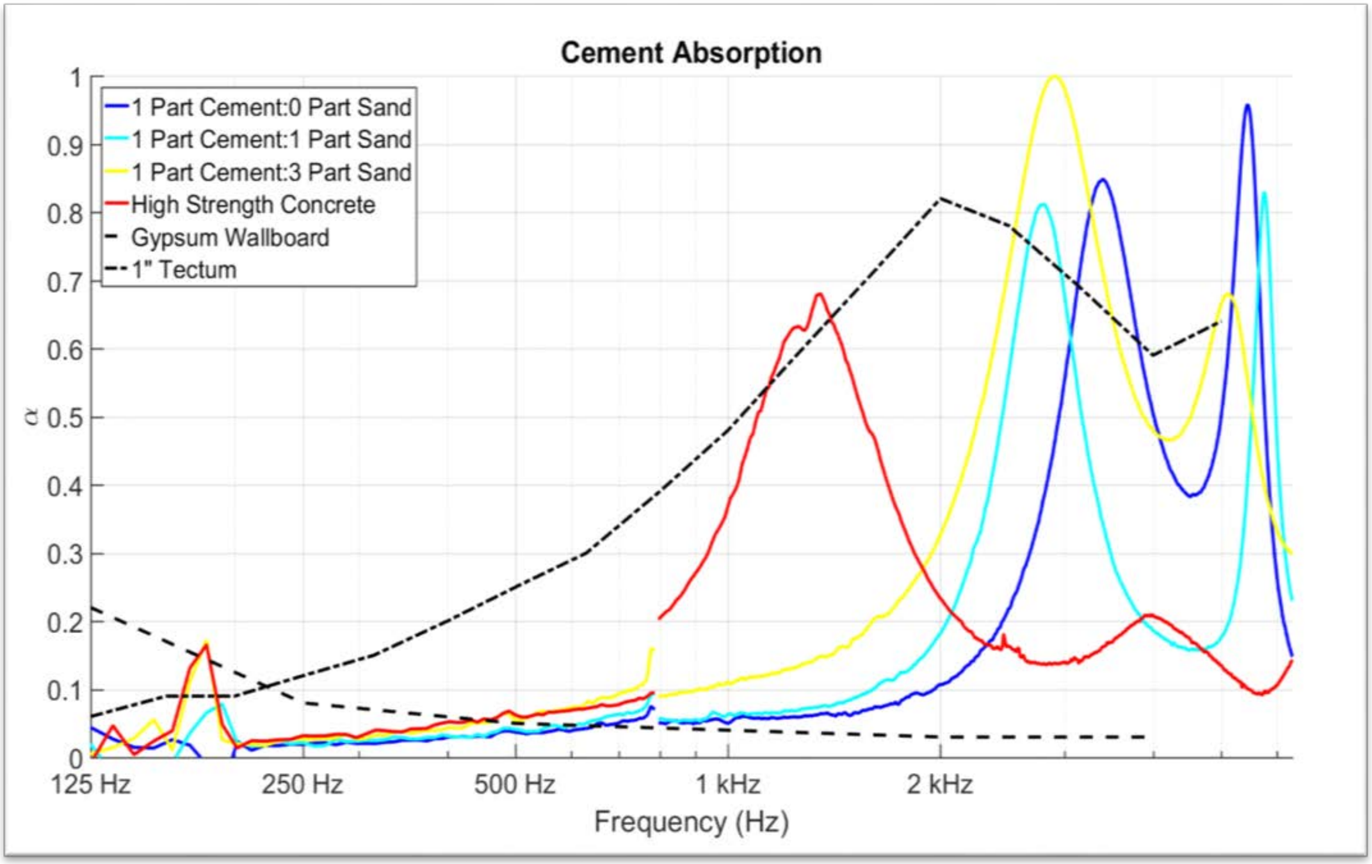

Figure 3: Acoustic Absorption Graph of High Strength Concrete and Portland Cement at Varying Ratios of Dry Components

The amount of absorption recorded here was significantly higher than expected. The four cement samples had low visible porosity, particularly as less aggregate was included. Additionally, in attempting to blow air through the sample to inquire for interconnected pores, no air would pass through the samples suggesting that if pores are present they are not interconnected. For these reasons additional samples need to be created and tested to verify the results achieved.

Packaged Ramen Noodles

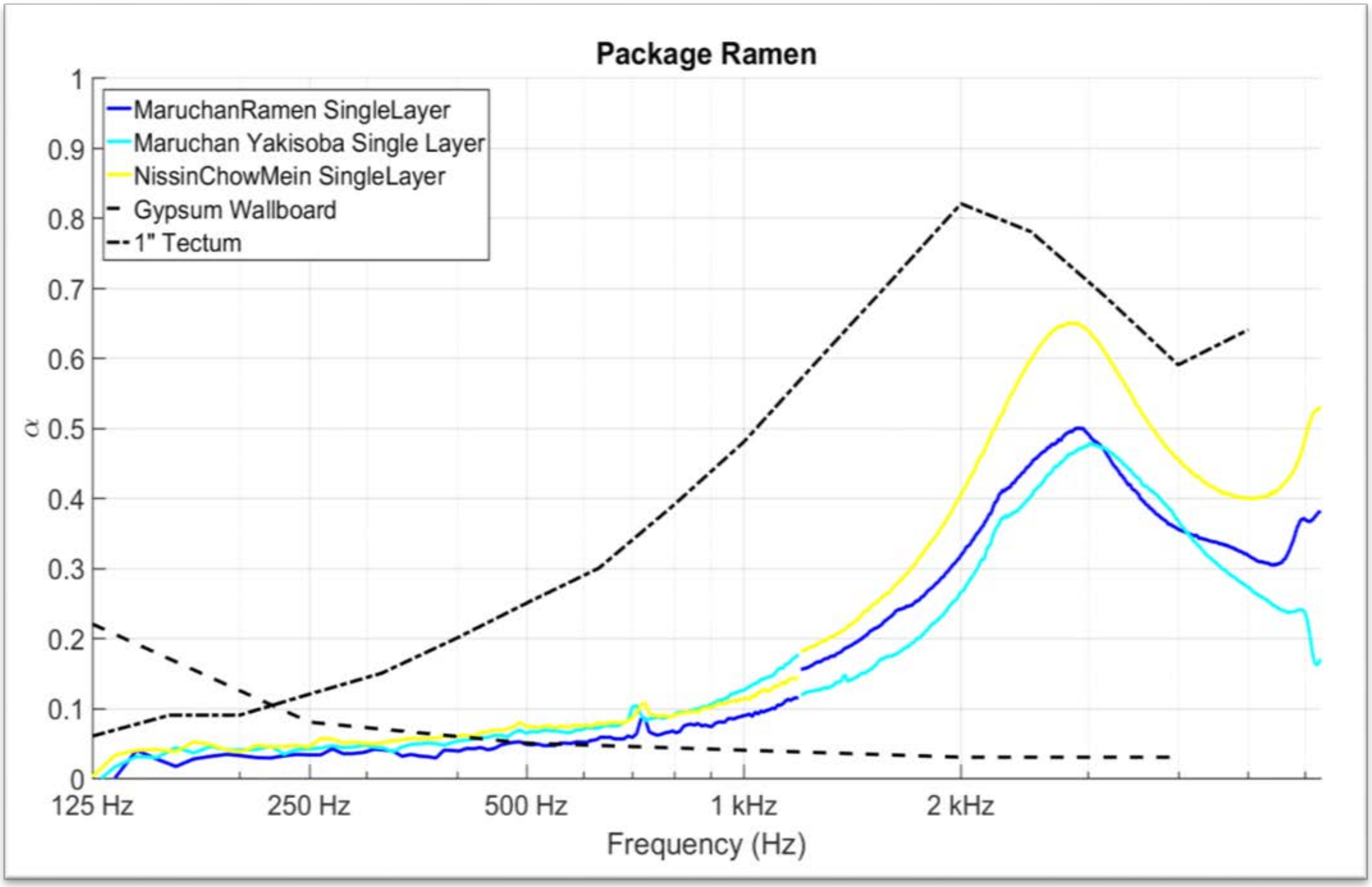

Figure 4: Absorption Coefficients of Three Types of Packaged Ramen Noodles

Since testing these three samples came from a discussion of the aesthetic similarities to Tectum, it was expected that they would perform similar as well. Although a single layer of packaged ramen does not outperform Tectum acoustically, there is some acoustic benefit around the consonant sounds of speech frequencies.

Kiln Brick

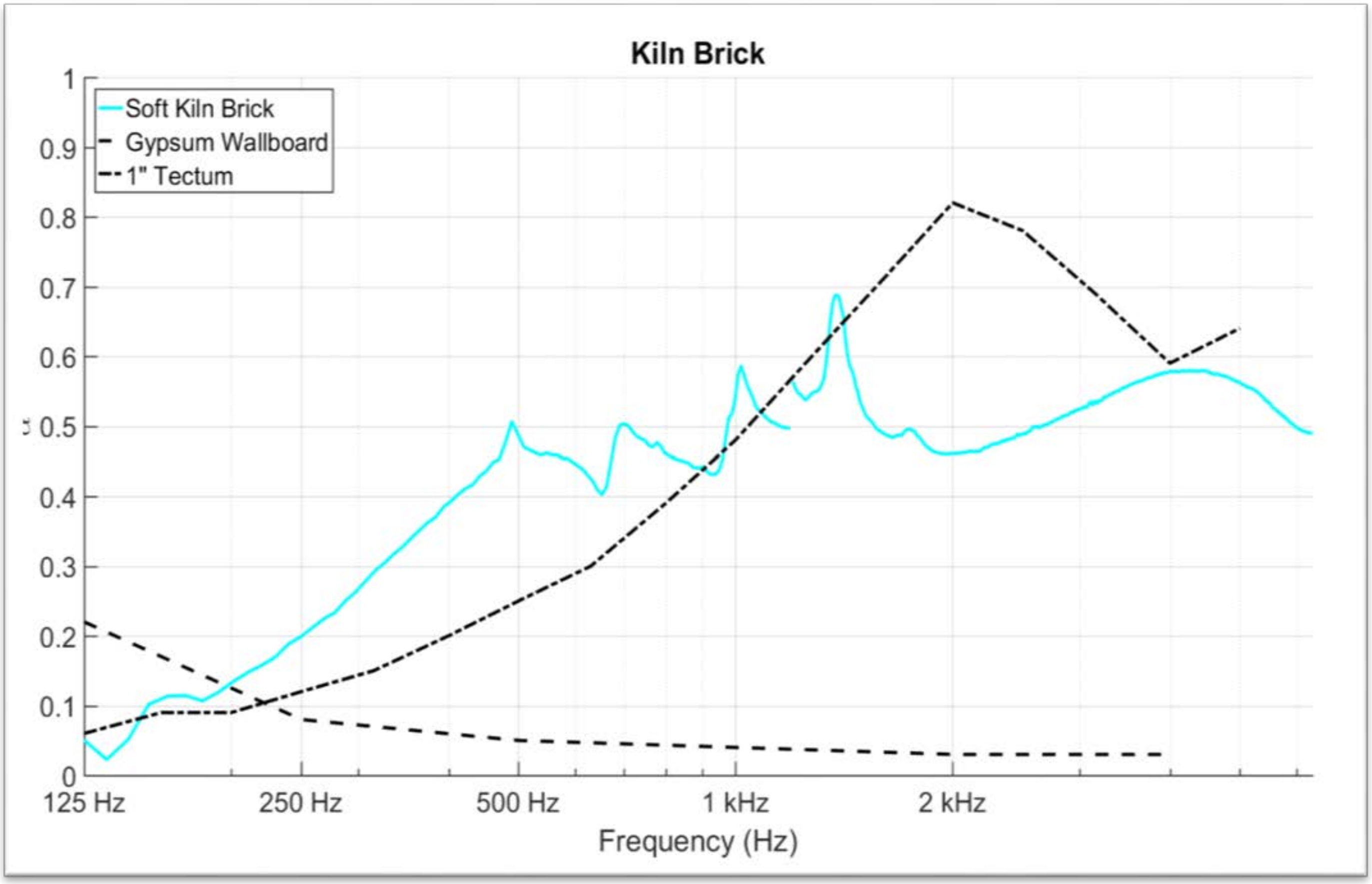

Figure 5: Acoustic Absorption Coeffiecients of a Soft Kiln Brick

Based on the visible porosity of the kiln brick some acoustic absorption was to be expected. This material has the best broadband absorption across the speech frequencies of the materials tested. This is likely from the random volumes of the interconnected pores.

3D Fusion Print

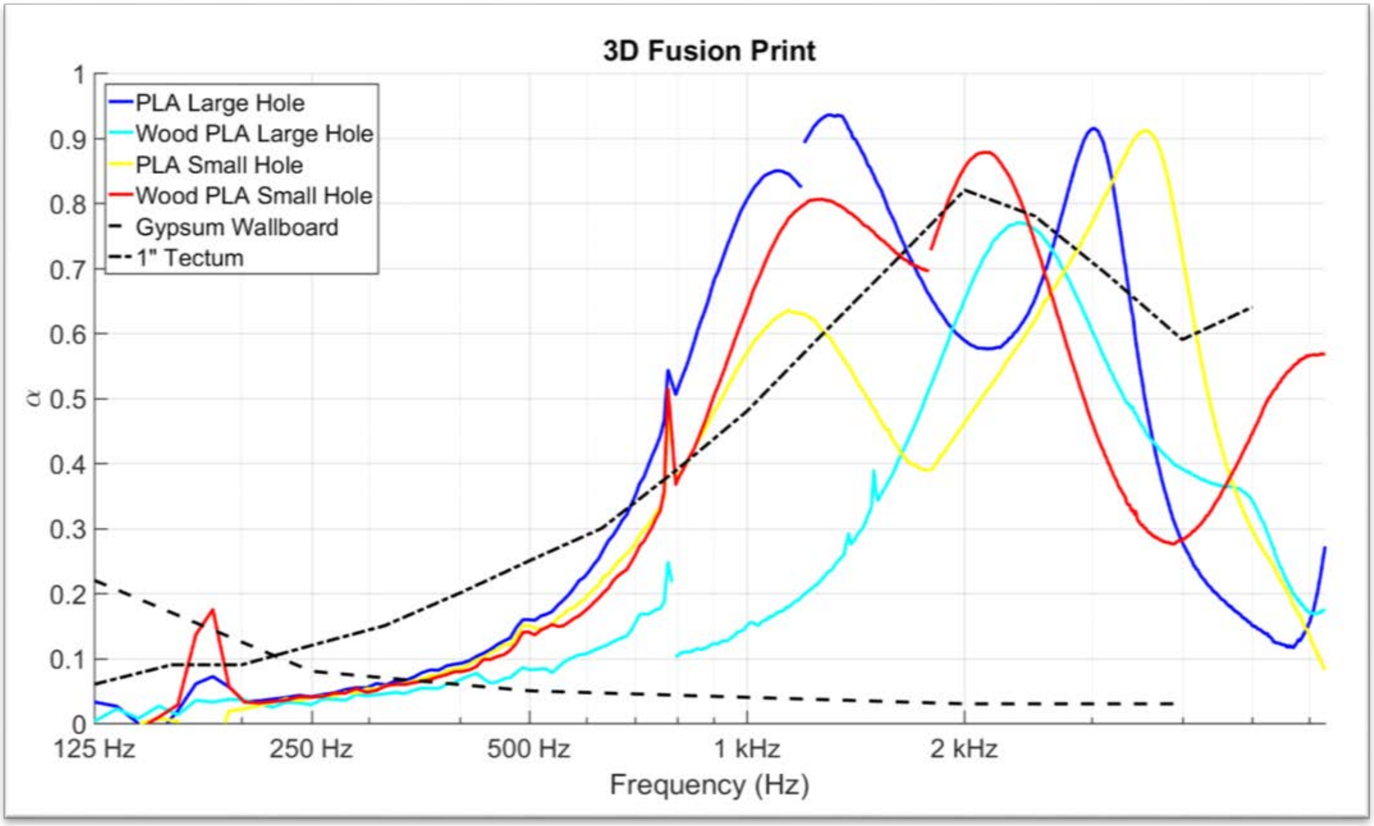

Figure 6: Acoustic Absorption Coeeficients for Four Fusion 3D Printed Tiles of Random Geometry

These fusion printed tiles showed the highest levels of absorption. The design of the pores were not mathematically determined as the Helmholtz resonators in an attempt to approximate the random volumes of interconnected pores. Unlike the Helmholtz resonators these would be challenging to make customizable for targeting specific frequencies.

CONCLUSION

This thesis started by attempting to re-create the tiles patented by Rafael Guastavino and Wallace Sabine in the early 1900s. Their revolutionary product allowed for acoustic absorption in a ceramic product known for its fire proof properties, smooth finish, and modular building system. In the search for a 21st century solution to the same problem, several contemporary materials were tested for their acoustic absorption properties. Additionally, 3D printing was investigated as a means to achieve a modular unit that would be acoustically absorbent through porosity. These early parts of the study gave way to the exploration on the effects of the resonant frequency when altering the cavity's geometry of a Helmholtz resonator while maintaining a single volume.

Although many of the tests conducted led to the discovery of properties desirable in unconventional acoustic products, this research did not produce a singular product that provides a durable, smooth-surfaced, acoustically absorptive, modular building unit. It is the author's hope that this thesis will provide a basis for continued exploration in 3D technology as a means to create new building products for architects to specify in their buildings. By incorporating a variety of sizes of Helmholtz resonators into a quickly modified and printed modular building product rooms can be tuned based on their frequency absorption needs. Perhaps also, future research might explore 3D printed porous surfaces with geometries that are intentionally mathematically derived to maximize broadband absorption.

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