

**THE EFFECT OF INFILL PARAMETERS ON THE SOUND
ABSORPTION CHARACTERISTICS OF 3D PRINTED STRUCTURES**

BY

Moaath Abdulrahman Ali Al Unaizan

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

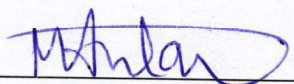
May, 2023

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Moaath Abdulrahman Ali Al Unaizan** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING.**



Dr. Antar, Mohammed A.
Department Chairman



Dr. Al-Homidan, Suliman Saleh
Dean of Graduate Studies

21-May-2023

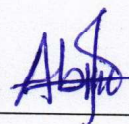
Date



Dr. Hawwa, Muhammad
(Advisor)



Dr. Abdou, Adel A.
(Member)



Dr. Abubakar, Abba Abdulhamid
(Member)



© Moaath Abdulrahman Ali Al Unaizan

2023

Dedication

To my parents, Meznah and Abdulrahman.

I couldn't do it without your support and prayers.

ACKNOWLEDGMENTS

I hereby extend my sincere appreciation to my advisor, Dr. Muhammad Hawwa, for his invaluable guidance and unwavering support throughout the course of this research. Without his expertise and dedication, the completion of this work would not have been possible.

I would also like to express my gratitude to Dr. Adel Abdou for providing me with access to the acoustics lab in the ARE department, which was instrumental in the successful completion of the experimental component of this thesis. His instruction on the utilization of the impedance tube testing set-up was invaluable, and I am grateful for the knowledge and skills that I acquired under his tutelage. Additionally, I extend my gratitude to Mr. Sardar Sharieff, ARE Lab Engineer, whose guidance and assistance were critical to the execution of the experiments.

I would also like to acknowledge the contributions of Dr. Abba Abdulhamid Abubakar, whose insights and inspiration were instrumental in the development of the theoretical framework of this research. I am thankful for his availability and willingness to provide guidance whenever required.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VI
LIST OF TABLES	X
LIST OF FIGURES	XIII
LIST OF ABBREVIATIONS	XIX
ABSTRACT	XXII
ملخص الرسالة	XXIV
CHAPTER 1 INTRODUCTION	1
1.1 Aim of the Study	2
1.2 Scope of Research	3
1.2.1 Study requirements	3
1.2.2 The study methodology	4
1.3 Background	6
CHAPTER 2 LITERATURE REVIEW	10
2.1 Brief Overview	10

2.2	Background on Sound Absorbers.....	12
2.2.1	The use of porous absorbers.....	16
2.3	Previous Studies on the Use of 3D Printing in Sound Absorbers	19
2.4	Concluding Remarks	26
CHAPTER 3 METHODOLOGY		28
3.1	Introduction	28
3.2	Fabrication of Samples	29
3.2.1	Summary of design choices.....	29
3.2.2	Infill parameters choices.....	32
3.2.3	Material Selection.....	45
3.2.4	3D printing details	52
3.2.5	Final list of fabricated samples.....	53
3.3	Experimental Measurements	66
3.3.1	Theoretical background.....	66
3.3.2	Experiment set-up	73
3.3.3	Error analysis and minimization	76
CHAPTER 4 RESULTS AND DISCUSSION.....		78
4.1	Effect of Enclosure Type (Enclosed vs. Open-Faced).....	78

4.1.1	Theory to be tested.....	78
4.1.2	Obtained results	78
4.1.3	Discussion of findings	84
4.2	Effect of Volume Ratio (Infill Density)	85
4.2.1	Theory to be tested.....	85
4.2.2	Obtained results	86
4.2.3	Discussion of findings	90
4.3	Effect of Infill Pattern (Internal Geometry).....	90
4.3.1	Theory to be tested.....	90
4.3.2	Obtained results	91
4.3.3	Discussion of findings	93
4.4	Effect of Material of Construction	94
4.4.1	Theory to be tested.....	94
4.4.2	Obtained results	95
4.4.3	Discussion of findings	97
4.5	Noise Reduction Coefficient.....	98
CHAPTER 5 CONCLUSION		99
5.1	Summary of Results for All Tested Samples.....	99

5.2	Overall Evaluation of the Results	102
5.2.1	Evaluation of maximum absorption coefficient values	102
5.2.2	Evaluation of Noise Reduction Coefficient (NRC) ratings	108
5.3	Effect of Different Infill Parameters	109
5.3.1	End Walls	109
5.3.2	Volume ratio	110
5.3.3	Infill pattern.....	111
5.3.4	Material of construction	112
5.4	Drawbacks and Limitations	113
5.5	Areas of Future Research.....	115
	REFERENCES.....	117
	VITAE.....	124

LIST OF TABLES

Table 1 - Average values of the sound reflection coefficient for the various 3D-printed PLA structures [33].	26
Table 2 - Summary of design choices	31
Table 3 - Showcasing the different geometric configurations	43
Table 4 - Properties of PLA [46]	46
Table 5 - Properties of ABS [48]	48
Table 6 - Properties of ASA [50]	50
Table 7 - Printing specifications for each material	53
Table 8 - List of fabricated samples along with assigned label and number for each	54
Table 9 - Specification of each frequency range	74
Table 10 - Summary of Gyroid infill pattern max results discussed in section 5.1.2	80
Table 11 - Summary of Honeycomb, Pyramidic, and Grid infill patterns max results discussed in section 4.1.2	84
Table 12 - Summary of different volume ratios of Gyroid infill pattern max results discussed in section 5.2.2	87

Table 13 - Summary of different volume ratios of Honeycomb and Grid infill pattern max results discussed in section 5.2.2	89
Table 14 - Summary of different volume ratios of Pyramidic infill pattern max results discussed in section 5.2.2	89
Table 15 - Max α and corresponding frequencies for different infill patterns printed with 75% volume ratio.	92
Table 16 - Max α and corresponding frequencies for different infill patterns printed with 50% volume ratio.	92
Table 17 - Max α and corresponding frequencies for different infill patterns printed with 25% volume ratio.	93
Table 18 - Max α and corresponding frequencies for different materials printed with 75% volume ratio and Gyroid infill pattern.....	96
Table 19 - Max α and corresponding frequencies for different materials printed with 75% volume ratio and Honeycomb infill pattern.....	96
Table 20 - Top 20 NRC rated samples.....	98
Table 21 - Max Sound Absorption Coefficient and corresponding frequency for each of the 37 samples.	100
Table 22 - the four infill pattern designs studied in Monkova et al.'s research.....	102

Table 23 - Comparing the best obtained results from this study to Vasina et al.'s research	103
Table 24 - Comparing the best obtained results from this study to Monkova et al.'s research	104
Table 25 - akustik.ua published data compared to some of the best performing samples from this research.....	105
Table 26 - Comparing the best obtained NRCs from this study to Vasina et al.'s and Monkovas et al.'s studies	109
Table 27 - Best results of enclosed samples	110
Table 28 - Gyroid Vs. Honeycomb infill pattern comparison at 50% and 75% volume ratios.....	112
Table 29 - Time duration for printing each sample	114

LIST OF FIGURES

Figure 1 - A flowchart representing the methodology followed in this thesis research	5
Figure 2 - Typical behavior for alpha Vs. frequency for Porous, membrane and resonating absorbers [9]	7
Figure 3 - SPL measurements for a screw compressor in an EBS plant [10]	7
Figure 4 - Example of most commonly used internal infill patterns [11]	8
Figure 5 - Membrane absorbers being hanged on a concrete wall in a theatre [9]	14
Figure 6 - Boards made of wood with regulated gaps in between them [9]	15
Figure 7 - Perforated bricks [9]	15
Figure 8 - A standing wave pattern is created when an incident sound wave and a reflected sound wave interact in front of a porous material that is mounted on a solid and heavy surface, with a specific thickness [9]	17
Figure 9 - Standing wave formation (p: pressure, v: velocity) [9]	18
Figure 10 - The three different types of porous absorbers, their internal structure, and some of the physical models used to explain their mechanism for absorbing sound are being classified [30]	18
Figure 11 - Resonant absorbers produced by additive manufacturing [31]	20

Figure 12 - One of the samples showing excellent normal sound absorption coefficient measured results [31]	20
Figure 13 - The 3D printed prototypes studied in the experiment [18]	21
Figure 14 - A diagram showing the setup of Sekar et al. design [32].....	23
Figure 15 - Different volume ratios used in the design for the study (from 20% -right- to 100% -left-) [32].	23
Figure 16 - Three different infill patterns (from left to right: Cartesian, Starlit, and Octagonal) [17].	24
Figure 17 - A few of the printed samples showcasing the different infill patterns [33].	25
Figure 18 - Dimensions of the 3D models designed in SolidWorks (not-to-scale)	29
Figure 19 - Sets of printed identical samples, however, one is enclosed (right), and the other is open-faced (left)	30
Figure 20 - The process of 3D printing [37]	32
Figure 21 - A good illustration of the effect of how different infill parameters look [38].....	33
Figure 22 - A 3D representation of the gyroid infill pattern (10% volume ratio) captured through PrusaSlicer	36

Figure 23 - A 3D representation of the Grid infill pattern (10% volume ratio) captured through PrusaSlicer	38
Figure 24 - The normal honeycomb infill pattern [43].	39
Figure 25 - a 3D representation of the 3D honeycomb infill pattern (10% VR) captured through PrusaSlicer	40
Figure 26 - A 3D representation of the 3D honeycomb infill pattern (10% VR) captured through PrusaSlicer	41
Figure 27 - Three sets of samples with different volume ratios being prepared in the slicing software.	42
Figure 28 - Backbone formula of PLA ($C_3H_4O_2$) _n [45]	46
Figure 29 - $(C_8H_8)_x \cdot (C_4H_6)_y \cdot (C_3H_3N)_z$, the chemical formula of ABS [47].	47
Figure 30 - $C_{18}H_{23}NO_2$, Chemical Formula of ASA [49]	49
Figure 31 - A typical FDM printer setup [52].....	52
Figure 32 - Prusa i3 MK3S+ 3D printer	52
Figure 33 - Prusa i3 MK3S+ 3D during the printing process	53
Figure 34 - Setup for an ISO 10534-2 impedance tube	66
Figure 35 - NRC values for common construction materials [61].....	72
Figure 36 - Schematic of lab setup	74

Figure 37 - Experiment set-up in KFUPM-ARE Department Building Materials Lab	75
Figure 38 - Other equipment used in the experiments (Left: Kestrel 5500 Weather Meter. Right: Mettler Toledo precision balance).....	75
Figure 39 - Loading some of the tested samples.....	75
Figure 40 - VA-Lab IMP software.....	76
Figure 41 - Top: A multi-channel Data acquisition and single output hardware, Down: 50W power amplifier	76
Figure 42 - The effect of enclosure type of the sound absorption of Gyroid structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.	79
Figure 43 - The effect of enclosure type of the sound absorption of Honeycomb structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.....	81
Figure 44 - The effect of enclosure type of the sound absorption of Pyramidal structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.....	82
Figure 45 - The effect of enclosure type of the sound absorption of Grid structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.....	83
Figure 46 - Showcasing the closed nature of the Pyramidal pattern (no straight pores from end to end).....	85

Figure 47 - The effect of varying the volume ratio on the sound absorption of Gyroid structures	86
Figure 48 - The effect of varying the volume ratio on the sound absorption of a) Honeycomb Structures, b) Grid Structures.....	88
Figure 49 - The effect of varying the volume ratio on the sound absorption of Pyramidic structures.....	89
Figure 50 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 75% volume ratio.	91
Figure 51 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 50% volume ratio.	92
Figure 52 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 25% volume ratio.	93
Figure 53 - The effect of changing the material of construction on the sound absorption of the structures printed with Gyroid structures.....	95
Figure 54 - The effect of changing the material of construction on the sound absorption of the structures printed with Honeycomb structures	96
Figure 55 – Sound Absorption Curves for the best 12 configurations of printed samples.....	101
Figure 56 - akustik.ua published data compared to some of the best performing samples from this research.....	105

Figure 57 - SPL measurements for a screw compressor in an EBS (Ethylbenzene- Styrene) plant [10]	106
Figure 58 - Noise spectra of food mixer with different speed levels [65]	107
Figure 59 - SPLs from a 1 meter distance of high-pressure thermally insulated steam valves & piping [66]	107

LIST OF ABBREVIATIONS

3D	:	Three-dimensional
ABS	:	Acrylonitrile Butadiene Styrene
ASA	:	Acrylic Styrene Acrylonitrile
c	:	Speed of sound
CAD	:	Computer Aided Design
dB	:	Decibel
e	:	Euler's number
E_a	:	Absorbed Energy
EBS	:	Ethyl Benzene & Styrene
E_i	:	Incident Energy
E_t	:	Transmitted Energy
FDM	:	Fused filament fabrication
FFF	:	Fused Filament Fabrication
H₁₂	:	Ratio of incident wave to the reflected wave
H_I	:	Transfer functions for incident wave
H_R	:	Transfer functions for reflected wave
Hz	:	Hertz
ISO	:	International Organization for Standardization
k	:	Complex wave number
KFUPM	:	King Fahd University of Petroleum and Minerals

ME	:	Mechanical Engineering
mm	:	Millimeter
NRC	:	Noise Reduction Coefficient
P_{1I}	:	Incident wave of microphone 1
P_{1R}	:	Reflected wave of microphone 1
P_{2I}	:	Incident wave of microphone 2
P_{2R}	:	Reflected wave of microphone 2
PET	:	Polyethylene terephthalate
PETG	:	Polyethylene terephthalate glycol
PLA	:	Polylactic Acid
R	:	Reflection coefficient
s	:	Distance between the two microphones
SA	:	Sound Absorption
SAA	:	Sound Absorption Average
SAC	:	Sound Absorption Coefficient, assumed to be for normal incidence unless otherwise specified
SPL	:	Sound Pressure Level
VR	:	Volume Ratio
W	:	Watt
x₁	:	Distance between microphone 1 and the sample
x₂	:	Distance between microphone 2 and the sample
Z₂	:	Surface impedance

α	:	Sound absorption coefficient, assumed to be for normal incidence, unless otherwise specified
α_n	:	Normal Incidence Sound absorption coefficient
α_r	:	Random Incidence Sound Absorption Coefficient
λ	:	Wavelength
ρ	:	Density

ABSTRACT

Full Name : Moaath Abdurlahman Ali Al Unaizan
Thesis Title : The Effect of Infill Parameters on The Sound Absorption Characteristics of 3D Printed Structures
Major Field : Mechanical Engineering
Date of Degree : May, 2023

Noise pollution is a pervasive and consequential issue that affects multiple aspects of society, including the environment, economy, and human health. As such, the development of effective sound absorbers is of great interest to researchers and investors alike. Recently, 3D printing has emerged as a promising approach for producing complex porous absorbers that are difficult to fabricate using traditional manufacturing methods.

In this study, novel sound absorbing structures were designed and fabricated using 3D printing via Fused Deposition Modeling (FDM). Open-faced (open-porous) and enclosed structures were produced using four different materials of construction: Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS), Acrylonitrile-styrene-acrylate (ASA), and Woodfilled-PLA (PLA mixed with 20% wood flour). The study aimed to investigate the effect of varying infill parameters on the sound absorption characteristics of the printed samples. Specifically, four different infill patterns (Gyroid, Honeycomb, Grid, and Pyramidic) with varying levels of complexity were tested, and each sample was printed with three different volume ratios (25%, 50%, and 75%).

The sound absorption properties of the specimens were analyzed using the normal incidence sound absorption coefficient, which was experimentally determined using the

transfer function method with a two-microphone acoustic impedance tube. The results indicated that more complex structures produced better sound absorption properties, with Gyroid infill pattern structures exhibiting superior performance over the other patterns, followed closely by the Honeycomb pattern. Additionally, the infill pattern affected the frequency at which the maximum absorption occurred, with the Honeycomb pattern structures being the most suitable for everyday applications. Higher volume ratios were found to improve sound absorption properties up to a certain limit, beyond which further reduction in porosity resulted in reduced sound absorption effects. Finally, PLA was identified as the most suitable material for this application based on its performance compared to other materials, mechanical properties, and ease of manufacturing.

ملخص الرسالة

الاسم الكامل:

معاذ عبدالرحمن علي العنيزان

عنوان الرسالة:

تأثير معلمات الحشو على خصائص امتصاص الصوت للهياكل المطبوعة بتقنية ثلاثية الأبعاد

التخصص:

الهندسة الميكانيكية

تاريخ الدرجة العلمية:

مايو، 2023

يعتبر التلوث الصوتي مشكلة جوهرية ومنتشرة تؤثر في عدة جوانب من المجتمع بما في ذلك البيئة والاقتصاد وصحة الإنسان، ولذلك فإن تطوير ماصات الصوت ذات فعالية أمر يثير اهتمام الباحثين والمستثمرين على حد سواء. ولقد ظهر التصنيع ثلاثي الأبعاد مؤخرًا كنهج واعد لإنتاج ماصات مسامية معقدة صعبة التصنيع باستخدام الأساليب التقليدية. في بداية هذه الدراسة تم تصميم وتصنيع هياكل جديدة لامتصاص الصوت باستخدام تقنية التصنيع ثلاثي الأبعاد عن طريق نموذج الطباعة المتداخلة (FDM). ثم إنتاج هياكل ذات وجوه مفتوحة (مكشوفة المسامية) وأخرى مغلقة تمامًا باستخدام أربعة مواد مختلفة للبناء وهي عديد حمض اللبنيك (PLA) و أكريلونيتريل بوتادين ستايرين (ABS) وأكريلونيتريل-ستايرين-أكريلات (ASA) وكذلك حمض اللبنيك الممزوج بالخشب (ممزوج ب 20٪ مسحوق الخشب). سعت الدراسة إلى التحقق من تأثير تغيير معلمات الحشو على خصائص امتصاص الصوت للعينات المطبوعة. وعلى وجه التحديد ، تم اختبار أربعة أنماط ملء مختلفة (الشكل الهرمي، الشكل الشبكي، شكل خلية النحل، وشكل الجايرويد -Gyroid-) ذات مستويات مختلفة من التعقيد وتم طباعة كل عينة بثلاث كثافات حشو مختلفة (25٪ و 50٪ و 75٪).

وبعد تحليل خصائص امتصاص الصوت للعينات باستخدام معامل امتصاص للانعكاس الطبيعي، الذي تم تحديده تجريبيًا باستعمال طريقة دالة الانتقال مع أنبوب مقاومة الصوت ذو مكبرين، أشارت النتائج إلى أن الهياكل الأكثر تعقيدًا تؤدي إلى خصائص أفضل لامتصاص الصوت، بحيث تظهر هياكل نمط الحشو الجايرويدي (Gyroid infill) أداءً أحسن مقارنة مع الأنماط الأخرى، يليها نمط خلية النحل (Honeycomb infill). بالإضافة إلى ذلك، فإن نمط الحشو يؤثر

على التردد الذي تحدث فيه أعلى قدرة امتصاص، حيث تعد هياكل نمط خلية النحل الأكثر ملاءمة للتطبيقات اليومية. وتبين أن الكثافات العالية للحشو تحسن خصائص امتصاص الصوت إلى حد معين فقط، ومن ثم تؤدي أي زيادة إضافية في التقليل من المسامية إلى ضعف في خصائص امتصاص الصوت. وأخيرًا، تم استنتاج أن حمض اللبنيك هي المادة الأكثر ملاءمة لهذا الاستخدام بناءً على أدائها مقارنةً بالمواد الأخرى وبناءً على خواصها الميكانيكية وسهولتها في التصنيع.

CHAPTER 1

INTRODUCTION

Researchers in the field of acoustics have always long been interested in developing efficient and cost-effective sound absorbers to improve the acoustic environment of various spaces. The advent of three-dimensional (3D) printing technology has opened up new avenues in this area, allowing for the fabrication of complex structures with unique geometries and high accuracy. 3D printing has been used to produce various types of sound absorbers, such as panels, columns, and porous structures with different perforations [1]. Given that the sound absorption performance of a 3D printed sound absorber is influenced by several complex parameters, including the material properties, the geometry of the absorber, and the infill parameters [2] [3], and since this field is still new, perfecting the development of these absorbers is still a hot area of research.

The infill parameters, such as volume ratio and infill pattern, are critical for determining the mechanical and acoustical properties of 3D printed structures. Volume ratio refers to the amount of material present in the structure, and it affects both the mechanical stability and the sound absorption coefficient of the absorber. Infill pattern, on the other hand, refers to the geometrical configuration of the material within the structure, and it affects the porosity of the absorber and the air flow through it.

In this study, the effect of varying the volume ratio and infill pattern on the sound absorption coefficient of 3D printed sound absorbers is investigated. The study was

conducted by 3D printing multiple structures with different volume ratios, infill patterns, and material, then testing them in an impedance tube, as per ISO 10534-2, to determine their sound absorption coefficient curves. The effect of using different filament materials, such as PLA, ASA, ABS, and Woodfilled PLA, was also investigated. Thus, the objective is to identify the optimal infill parameters and printing material that result in structures with the best sound absorption characteristics and to develop guidelines for the design and production of 3D printed structures for sound absorption applications. The findings of this study will be of great value to researchers and engineers working in the field of acoustics and will provide valuable insights into the design and production of 3D printed structures for sound absorption applications.

1.1 Aim of the Study

This study aims to provide valuable insights into the optimal design of 3D printed sound absorbers and contribute to the advancement of acoustics research. The results of this study will be of interest to engineers, architects, and acousticians who are interested in developing efficient and cost-effective sound absorbers for various applications. Additionally, this study will provide practical guidelines for the design and optimization of 3D-printed sound absorbers based on the infill parameters.

At the end, the work aimed to produce a novel sound absorbing structure having the following characteristic:

- a. An excellent sound absorption coefficient for high frequency noise.
- b. An acceptable sound absorption coefficient for medium to low frequency noise.

- c. Having an overall excellent NRC (Noise Reduction Coefficient) [4]. And an excellent SAA (Sound Absorption Average). Thus, being easily marketable if required.
- d. Having reasonable mechanical properties and being able to be mounted directly to the required surfaces without the need of additional supports and holders.
- e. Being easily reproducible with exact dimensions, thus reducing the expected variations faced when dealing with traditional porous absorbers [5] and having the ability to be fine-tuned to specific applications.
- f. Being aesthetically pleasing.

1.2 Scope of Research

The proposed work aims to take advantage of the complexity in manufacturing allowed only by new additive manufacturing technologies to fabricate a material with excellent sound absorption characteristics, with the aim of producing a porous sound absorber having a great effect over a wider range of frequencies. The use of a 3D printer and Computer Aided Design (CAD) software is needed to design and fabricate a porous structure with internal cavities that are hard to replicate with traditional manufacturing methods.

1.2.1 Study requirements

The work required the use of:

- 1- 3D printer: an FFF (Fused Filament Fabrication) or an FDM (Fused deposition modeling) printer utilizing a 1.75 mm diameter filament to allow for both ease of use and precise samples [6].

- 2- Polymer filament: Polylactic acid (PLA) was used as a starting point, given that it is one of the easiest plastics to print and due to its relatively affordable price[7]. Then other polymers such as ASA, ABS, and Woodfilled PLA were also tested and compared with the baseline PLA structures.
- 3- Computer Aided Design Software: modeling was done through SOLIDWORKS®. Producing a digital file in a “.stl” format.
- 4- Slicing software: “PrusaSlicer” software was utilized. A slicing software is used to convert the “.stl” file produced by the CAD software into a “G-code” that is understood by the printer. In the slicing software, printing temperature parameters need to be chosen to suit the material being printed.
- 5- Sound absorption measurement setup, including:
 - a. Two-microphone impedance tube for low to medium frequencies
 - b. Two-microphone impedance tube for high frequency
 - c. Signal generator
 - d. Signal analyzer
 - e. Power amplifier

1.2.2 The study methodology

The flowchart shown in Figure 1 below showcases the systematic approach followed in this thesis research.

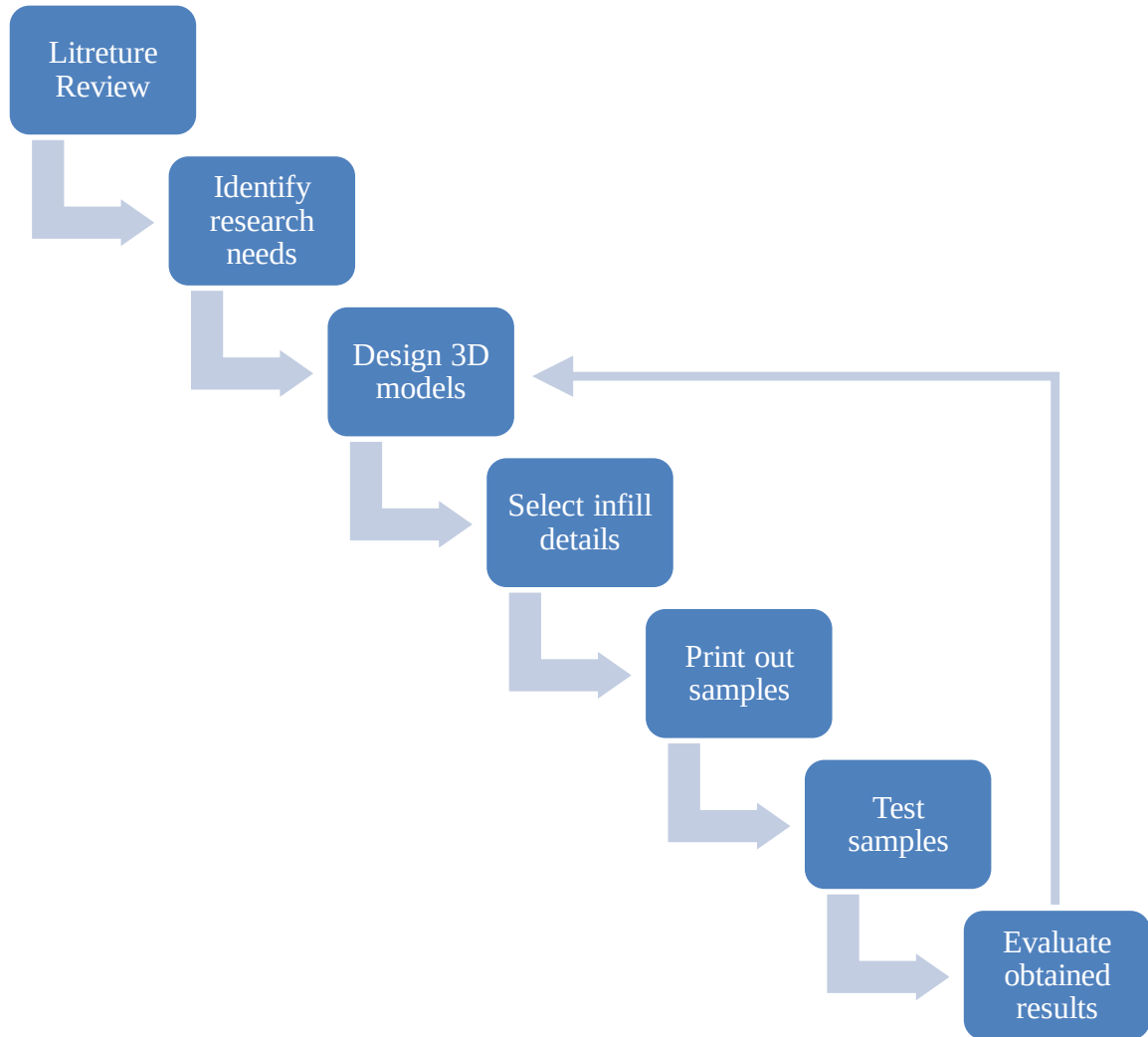


Figure 1 - A flowchart representing the methodology followed in this thesis research

- 1- Utilize literature review to check for the latest research related to the sound absorption characteristic of 3D printed material.
- 2- Identify the requirements for the study, ranging from testing equipment, software, printing filaments, and other requirements as mentioned in section 1.2.1..
- 3- Design 3D models with base values for volume ratio and infill pattern using a CAD software.

- 4- Use appropriate 3D slicing software to select the appropriate material and develop a G-code that can be sent to the 3D printing machine.
- 5- 3D prints the base models.
- 6- Utilize an impedance tube setup to measure the sound absorption coefficient at a wide range of frequency of the test sample and develop a sound absorption coefficient graph for the sample.
- 7- Going back to steps 2-5 and varying the volume ratio until the suitable ratio is determined.
- 8- Going back to steps 2-5 and varying the infill pattern until the suitable geometry is determined.
- 9- Going back to steps 3-5 and varying the printing material until a suitable material is determined.

1.3 Background

As it is well known, the effect of noise pollution cannot be overstated; it could be felt in the environment, economy, and health. Sustained noise pollution at the workplace is documented to lead to a range of adverse effects, such as hearing loss, stress, sleep disturbance, and reduced productivity [8]. To combat this, the research into noise control and sound absorption has always been active and competitive. The research into sound-absorbing materials is still in an emergence phase, and novel methods of manufacturing and refining sound absorbing material are always evolving.

As seen in Figure 2, at octave bands corresponding to frequencies higher than 800 Hz, typical Porous absorbers have higher absorption coefficients than other types, such as Resonator or Membrane absorbers.

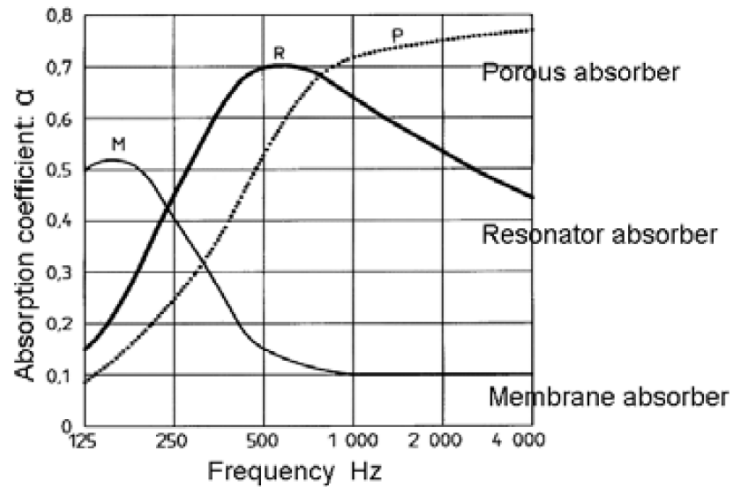


Figure 2 - Typical behavior for alpha Vs. frequency for Porous, membrane and resonating absorbers [9]

It is also observed that most noise-emitting machines and equipment have their highest Sound Pressure Levels at frequencies higher than 800 Hz, as can be seen in Figure 3.

OCTAVE BAND CENTER FREQUENCY (HERTZ)	SOUND PRESSURE LEVEL (SPL) DECIBELS (DB) AT 1 METRE	
	STANDARD EQUIPMENT	EQUIPMENT WITH NOISE TREATMENT
31.5		70
63		72
125		74
250		76
500		79
1000		82
2000		81
4000		77
8000		72
A-WEIGHTED	95	87

Figure 3 - SPL measurements for a screw compressor in an EBS plant [10]

This generates an interest in investment and research in the field of porous absorbers, as evident by the many research papers that have been published recently discussing the sound absorption characteristics of new types of porous absorbers, utilizing new technologies such as 3D printing.

In contrast to most other manufacturing techniques, 3D printing allows for control over interior infill of seemingly rigid structures as most 3D printers allow the user to control both the volume ratio and the infill pattern of the printed structure. Figure 4 below showcases some the most commonly utilized infill pattern.

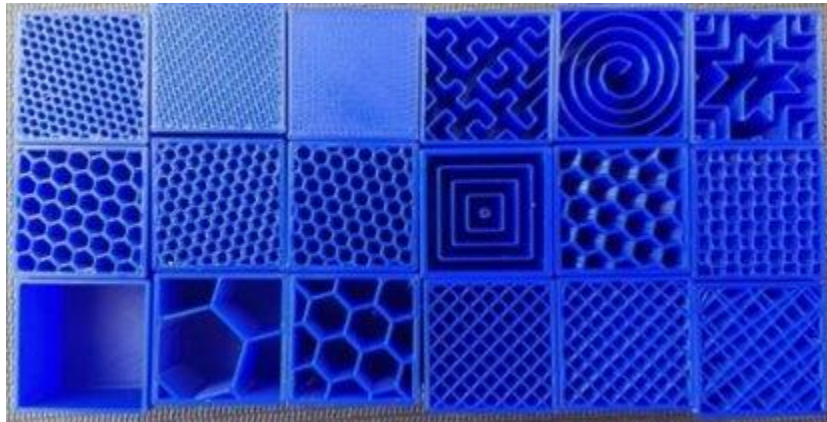


Figure 4 - Example of most commonly used internal infill patterns [11]

Thus, it was decided that the focus of this thesis would be to study the effect of infill parameters on the sound absorption coefficients of 3D printed structures. This is due to the following reasons:

1. Utilizing 3D printing technologies to optimize the design of sound absorbing structures is a novel topic of study and analysis in the acoustic field.

2. Although the analysis has been done on the effect of varying different parameters in the 3D-printing process has been done, the effect of varying infill parameters specifically has not been widely discussed.
3. There are published papers that discuss the effect of infill on other physical properties of printed structures, which can be used to optimize a sound absorbing structure that still has high durability.

Given the nature of the subject, it is expected that the method of study would be mostly experimental, however, the analysis could lead to building a theoretical model for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Brief Overview

Sound absorption has been defined as the loss of sound energy when sound waves contact an incident surface; for instance, contact with ceilings, floors, walls, and other structures [12]. There is plethora of uses of sound absorbing structures, such as controlling of noise in residential areas, theatres, concert venues, cinemas, and many others. As well as having various industrial applications, such as railroad cars, automotive industry, cooling fans in computer servers, rotating machinery in power plants, and so on [13].

Many factors may contribute to a material's sound absorbing capabilities, such as the material density, and structure thickness and porosity [14]. As in example, fibers and foams are typically ideal sound absorbers, which is due to them not having homogenous fully infilled structures, which result in having high porosity[15]. If a sound wave is propagated inside a porous material, it will go through many thin walls (individual fibers) that connect the pores, leading to viscous losses where the acoustic energy will eventually be converted to heat.

In attempts to replicate the natural porosity and complexity found in fibers and foams, researchers have tried to utilize the new 3D printing technology. Monkova et al. [16], utilized a Fused filament fabrication 3D printer to fabricate structures made from Acrylonitrile Butadiene Styrene, which has a complex internal fill that is not fully

homogeneous. The acoustical properties for the tested samples were studied using the normal incident noise reduction and sound absorption coefficients, which were found by the experiment utilizing TFM (transfer function method) as per ISO 10534-2. They produced 4 different structures with varying levels of complexity, and their study showed that the sound absorption characteristics are directly related with the complexity of the pore shape. Although they were not able to widen the range of frequencies for which their samples show good absorption without utilizing an air gap, they concluded that it is possible that producing more complex pore shapes only possible through 3D printing could result in structures having excellent acoustic properties over a wider frequency range.

Vasina et al. [17] similarly examined the absorption properties of an open-porous ABS 3D-printed samples manufactured utilizing Starlit, Cartesian, and Octagonal internal geometries with the same volume ratios. The samples produced with the Starlit structure (the most complex pattern) showed a greater ability to absorb noise compared to the other printed structures that were examined.

Taking a different approach but still utilizing 3D printing technologies, Sailesh et al. [18] examined the effect of designing arbitrarily varying cross-sections of small pores (or perforations) on the acoustical behavior of PLA panels made by 3D printing. Transmission loss and sound absorption values for the printed perforated panels were evaluated through the impedance tube setup. Tests showed that the sound absorption coefficient of perforated panels with complex infill geometries are much better than a normal uniform cross-sectional perforation for any given frequency range.

Khosravani et al. [19] used a 3D printing technology different than FDM or FFF to produce their structure. The team used a 3D printer with photopolymerization technology to produce MPSAs (Multilayer Perforated Sound Absorber). Their study concluded that the acoustic performance observed by the 3D printed perforated panels showcase the capability of additive manufacturing to produce high performance sound absorbing MPSAs.

Amaya-Amaya et al. [20] used unique composites of PLA, which was reinforced with rachis and barbs, that were used to fabricate 3D printed structures in an attempt to enhance a diverse set of acoustic properties. To this end, an electro-acoustic experiment had been used. Their study showed that the acoustic properties of 3D printed structures could be even further improved through utilizing slight reinforcement.

Although most current 3D printers are used for printing polymers or polymer composites, some advanced 3D printers are capable of printing metals. Arjunan et al. [21] 3D printed MPPs (micro-perforated panels) for Titanium and investigated their acoustic properties. Their study showed that complex perforations, which are not perfectly circular, and featuring a porous layer, will show improved sound absorption coefficient.

2.2 Background on Sound Absorbers

Sound absorbers are frequently used in various applications to reduce unwanted sound levels, improve sound quality, and curb the harmful impacts of noise pollution.

One indicator of the performance of a sound absorber is measuring its sound absorption coefficient. The Sound Absorption Coefficient (α) is a way of evaluating a material's effectiveness at absorbing the energy from sound. It is calculated as the proportion of acoustic energy that is absorbed by a material, relative to the total energy that is incident

upon it. When a material absorbs all of the incident energy, the Sound Absorption Coefficient is equal to 1 [22]. This can be mathematically expressed as the following:

$$\alpha = \frac{E_a}{E_i} = 1 - \frac{E_r}{E_i} \quad (2.1)$$

Where formula (2.1) is applicable if zero transmission is assumed. Most sound absorbers work by essentially converting the acoustic energy into heat or thermal energy [23]. Normally, sound absorbers are divided into three main categories: porous absorbers, membrane absorbers and resonance absorbers, where the type of sound absorber used will depend on the frequency range and sound absorption requirements of the space.

More discussion of porous absorbers will follow in a separate section, but in general, porous absorbers are made of materials with a large number of tiny pores, such as fiberglass or rockwool. They work by converting sound energy into thermal energy as the waves of sound move through the numerous pores and passages.

A membrane absorber is described as a device made up of a sheet or panel that is non-porous and positioned a specific distance from a solid backing, creating an air-filled space. The ability of this system to vibrate at a specific frequency is governed through the mass per unit area of the plate (m) and the elasticity of the air within the cavity, which is influenced by the depth (L) of the cavity [24].

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{\rho c^2}{m L}} \quad (2.2)$$

Membrane absorbers, as seen in Figure 5, are frequently used in rooms as wooden floors supported by joists or as walls made of gypsum board or wood paneling. This results in a

regulated low frequency value, unlike rooms constructed completely of solid brick or concrete, which cause the sound to be muffled and indistinct at specifically low frequencies. In addition to regulating low-frequency echoes, the panels also offer some sound diffusion, usually creating a pleasant acoustic experience in large theaters.

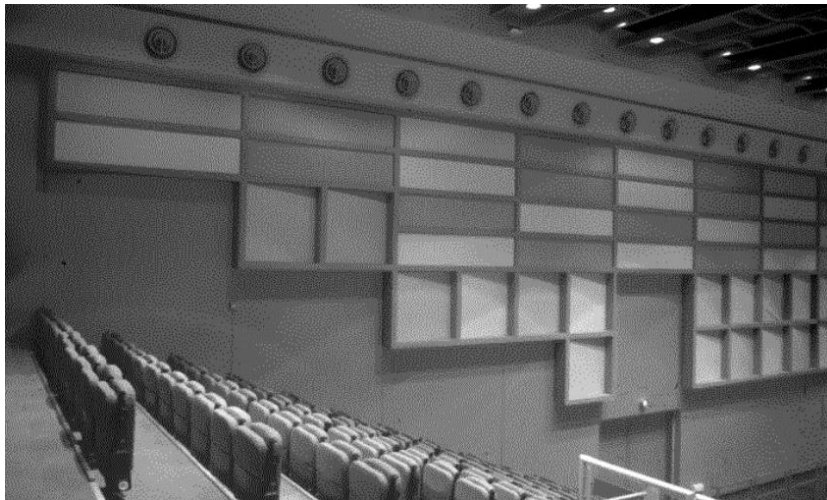


Figure 5 - Membrane absorbers being hunged on a concrete wall in a theatre [9]

A resonant absorber, as seen in Figures 6 and 7, is a device that operates based on sound pressure. It consists of a mass that vibrates opposites a spring, with the mass representing the cabinet and the front wall, and the spring being the air within the resonant absorber's space. By adjusting the stiffness and/or the mass of the spring, the frequency at which resonance occurs for the absorber can be controlled and tuned. The design frequency is determined by the internal mass (or cabinet depth), while the rate of absorption above the resonant frequency is achieved through the spring (or internal air) and cavity [25].

A type of resonant absorber is a perforated panel that can be in the shape of a perforated board of gypsum or a plate of steel (such as those used for common suspended ceilings) or as wooden panels with gaps between each board. Another option is walls made from perforated tiles that utilize the space between the two layers of masonry [26].



Figure 6 - Boards made of wood with regulated gaps in between them [9]



Figure 7 - Perforated bricks [9]

In everyday life, sound absorbers are used in a wide range of areas to reduce unwanted sound levels, improve sound quality, and increase speech intelligibility. Sound absorbers are commonly used in areas such as offices, schools, auditoriums, and homes. In offices, sound absorbers can be used to reduce the amount of noise transmitted between desks and to improve speech intelligibility in open-plan layouts. In schools, sound absorbers can be used to reduce unwanted sound levels in classrooms and to improve speech intelligibility in lecture halls. Sound absorbers are also used in auditoriums and concert halls to control

and reduce unwanted sound levels and to improve the overall acoustics of the space. The type of sound absorber used will depend on the frequency range and sound absorption requirements of the space. [27]. In industrial settings, sound absorbers are widely used as well, since they are usually considered as a safety requirement. In industries where heavy machinery is utilized, sound absorbers, usually in the form of acoustic housings, are used for each machine to reduce noise levels generated by it and to improve speech intelligibility in nearby control rooms.

2.2.1 The use of porous absorbers

As this study aims to create a new design for porous absorbers, this separate review section will be dedicated to give an overview about porous absorbers specifically.

Porous absorbers are a common solution for reducing unwanted noise levels and are used in a variety of settings. They can be found in various forms such as carpets, furniture upholstery, curtains, porous mortar in walls, and dedicated sound-absorbing products for suspended ceilings.

Porous absorbers have an open structure, such as fibers that are woven or glued together, which allows air to flow through. The degree of air flow resistance is dependent on factors such as the density of the weave. The absorption properties come from the viscous friction between the air molecules and the large inside surface area of the structure, which converts the kinetic energy of the sound waves into heat.

When a porous sheet is placed on a hard surface and struck by a normal incidence wave, a standing wave pattern is created with a high particle velocity and kinetic energy where the

pressure amplitude is low. Looking at Figures 8 and 9, it can be seen that for the absorber to be effective, the porous material must have a thickness of at least $\lambda/4$. If the material is too thin, there will be a low limiting frequency under which the absorption decreases. However, a thin sheet can be used if it is placed a specific distance from the rigid wall and has a suitable flow resistance. With diffuse field incidence, the absorbers are effective if the thickness or distance is greater than $\lambda/8$ [9].

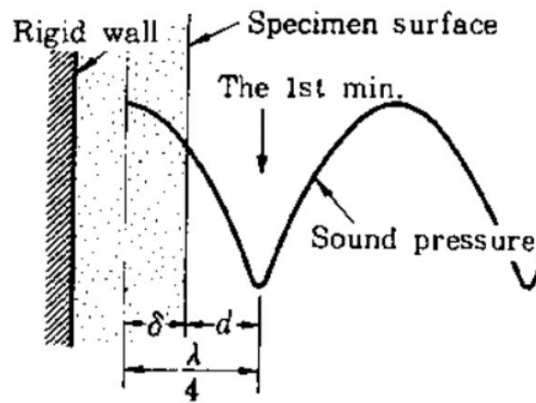


Figure 8 - A standing wave pattern is created when an incident sound wave and a reflected sound wave interact in front of a porous material that is mounted on a solid and heavy surface, with a specific thickness [9]

In other words, for porous absorbers to effectively slow down air particles with high sound velocity, they must be of a specific thickness when mounted directly onto a wall. This allows for absorption of sound waves down to a specific lower limiting frequency. When mounted at a distance from the wall, the thickness of the absorber can be reduced. This effect is utilized by manufacturers of acoustic ceilings. In addition to the distance from the wall, the flow resistance of the material is also a crucial factor [28].

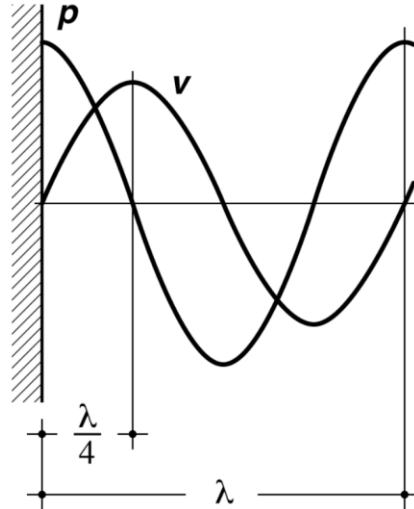


Figure 9 - Standing wave formation (p: pressure, v: velocity) [9]

Categorizing based on the macroscopic structure of the material, one can divide porous absorbers material into three main categories: 1) Cellular, which features cubic cells with connecting pores, 2) Fibrous, consisting of parallel fiber bundles, and 3) Granular, made up of stacked identical spheres [29], as can be seen in Figure 10.

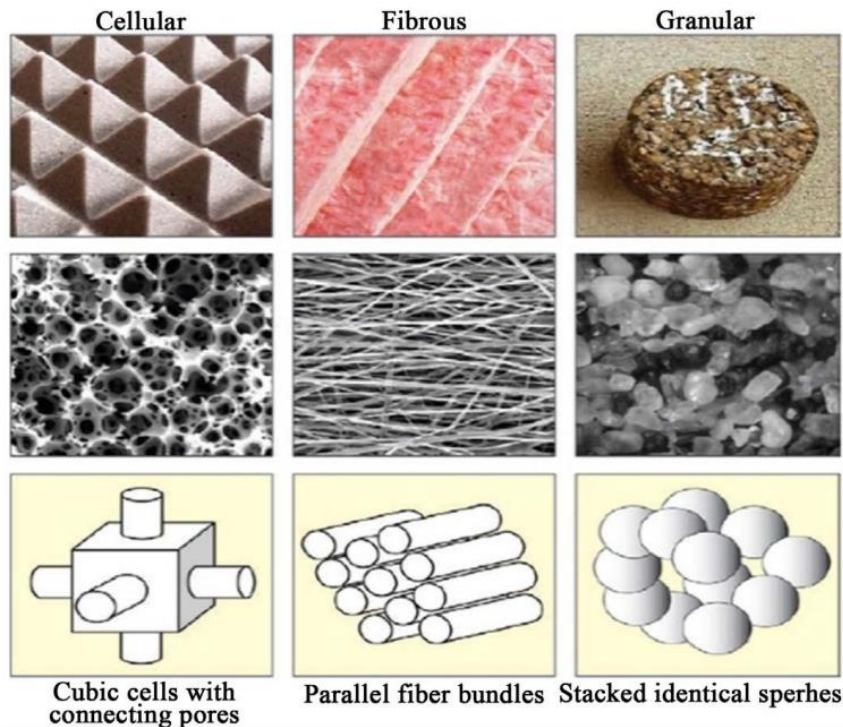


Figure 10 - The three different types of porous absorbers, their internal structure, and some of the physical models used to explain their mechanism for absorbing sound are being classified [30].

2.3 Previous Studies on the Use of 3D Printing in Sound Absorbers

A study by Setaki et al. [31] aimed to examine the relationship between sound absorption and the use of additive manufacturing techniques. The authors were interested in analyzing the impact of the structure and material properties of additively manufactured objects on their sound absorption behavior and investigating the potential for designing sound-absorbing structures using additive manufacturing methods. The authors began by discussing the importance of sound absorption in various fields, including acoustics, architecture, and transportation. The authors performed experiments to measure the sound absorption properties of various 3D printed objects, where they designed a series of “Helmholtz resonators”, as can be seen in Figure 11. It is notable that the authors also investigated what impact the “micro-porosity”, which these polymers filaments naturally have, could have on their acoustic properties.

The authors found that the complex structures allowed by additively manufacturing can lead to a significant impact on their sound absorption behavior. They discovered that the material properties of 3D printed objects, such as porosity and surface roughness, also play a role in determining their sound absorption behavior. Furthermore, the authors showed that the sound absorption behavior of 3D printed objects can be improved through careful design and material selection, which is a luxury that can be afforded by using the 3D printing technique. The authors also noted that additive manufacturing offers numerous benefits over conventional manufacturing methods, such as the ability to manufacture very complex and customized shapes, the potential for mass production, and the ability to reduce waste and cost. The examination of the results compares the actual performance to predictions based on acoustic principles. It appears that the absorbers in question align

better with the Helmholtz resonator theory. It is clear that the basic acoustic theory is insufficient in analyzing the outcomes of these intricate shapes. Therefore, the next steps will involve using 3D BEM or FEM analysis. Additionally, the effects of the manufacturing method may also play a crucial role in improving our understanding and assessment of the acoustic performance. A promising avenue for future investigation would be to examine the sample system and the impedance tube as one entity. An example of one of the samples showing excellent normal sound absorption coefficient measured results is shown in Figure 12.



Figure 11 - Resonant absorbers produced by additive manufacturing [31]

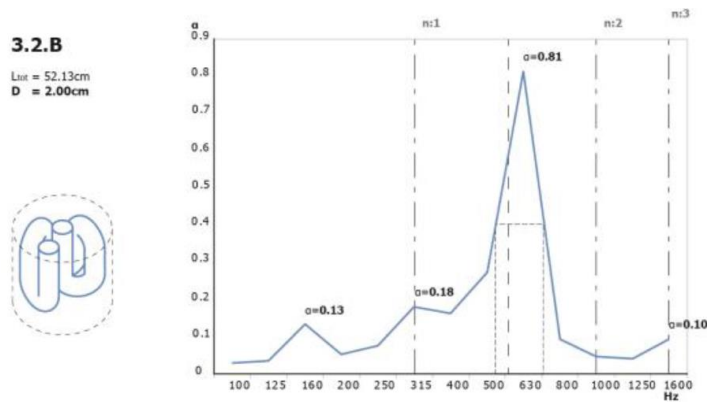


Figure 12 - One of the samples showing excellent normal sound absorption coefficient measured results [31]

In Sailesh et al.'s [18] study, the effect of spherical bubble perforations and their distribution on the acoustic properties of a 3D-printed biodegradable material is studied.

This study analyzes specimens with perforations in the form of spherical bubbles, which vary in size and are either evenly or differently spaced across the thickness of the sample. Additionally, a sample with perforations in the form of typical cylinders is also evaluated for comparison purposes. Figure 13 showcases The 3D printed prototypes studied in the experiment.

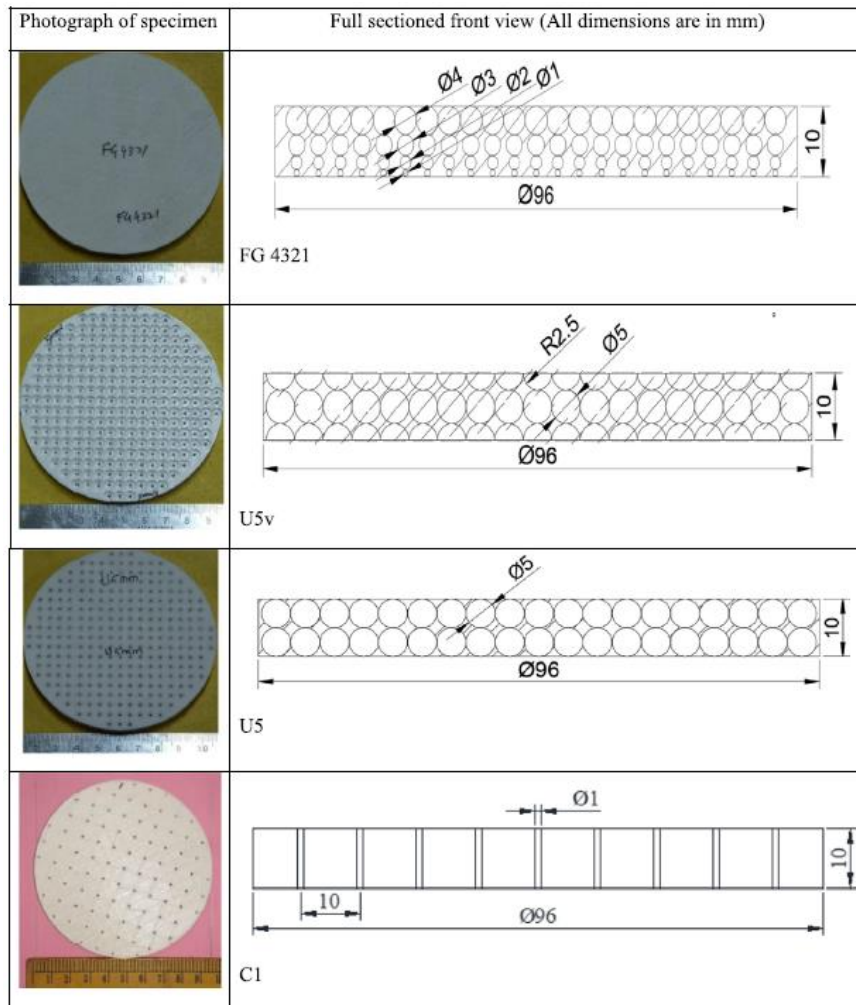


Figure 13 - The 3D printed prototypes studied in the experiment [18]

STL (sound transmission loss) and SA (sound absorption) properties are measured using an impedance tube testing device. The findings indicate that the SA of specimens with graded spherical perforations is better at lower frequencies. For samples with uniform,

smaller spherical perforations, the SA and frequency range are superior at higher frequencies. The sound transmission loss of samples with functionally graded perforations outperforms other specimens and this superiority increases significantly as the frequency increases. These perforations showed exceptional results for both sound absorption and sound transmission loss. What was notable is that the correlation between the theoretical and experimental results is high. According to these findings, it was concluded that the idea of using 3D printing technology in producing complex graded spherical pores can be successfully applied in sound insulation for both the building and transportation industries.

Sekar et al. [32] state that recently, there has been growing interest in using Additive Manufacturing (AM) techniques, specifically Fused Deposition Modeling, to produce Natural Fiber-Reinforced Composites. The appeal of AM lies in its ability to create complex structures which may be difficult to manufacture through traditional methods. In their study, 3D printing was used to manufacture acoustic panels, as seen in Figure 14, made of polylactic acid re-enforced with wooden fiber composites. The thickness and volume ratio of the panels were varied as shown in Figure 15, and the coefficient of sound absorption was evaluated. It was found that thin panels with a back air gap had mid-frequency sound absorption similar to that of a Helmholtz resonator. The sound absorption of thicker panels could be adjusted by controlling their volume ratios (infill densities). This has the potential to allow for the customization of the acoustic absorption of final products.

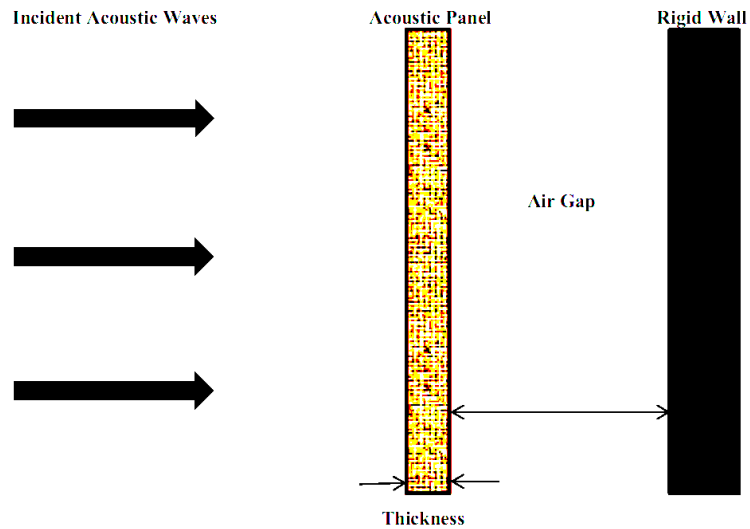


Figure 14 - A diagram showing the setup of Sekar et al. design [32]

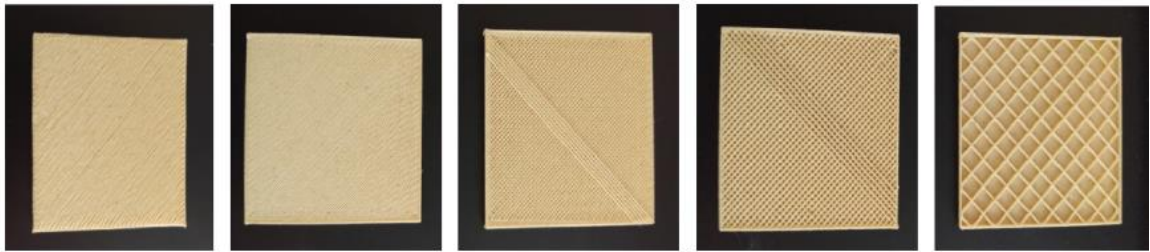


Figure 15 - Different volume ratios used in the design for the study (from 20% -right- to 100% -left-) [32].

The study showed that as the thickness of the sample grows, the sound absorption capacity decreases because lower to midrange frequency waves struggle to pass through panels which are thicker. If the thickness becomes too substantial, the air in the gaps becomes immobile, resulting in a lack of friction and reduced sound absorption. The results also indicate that reducing the volume ratio shifts the peak of sound absorption across the frequency spectrum. Lowering the volume ratio enhances the ability of acoustic waves to penetrate the structure and allows air in the voids to move more freely, increasing viscous friction and absorbing more sound. However, if the volume ratio is reduced too much, the performance decreases at low frequencies as the material becomes too loose for the wave to propagate effectively. The sound absorption is more effective for shorter wavelengths at

higher frequencies. To enhance low-frequency absorption with the same low volume ratio, a thicker panel is needed.

In a study conducted by Vasina et al. [16], [17], the sound absorbing abilities of 3D printed open-pore ABS structures were investigated. To evaluate the material's sound dampening capabilities, the researchers employed the transfer function method with an acoustic impedance tube to determine the normal incidence sound absorption coefficient and the noise reduction coefficient through experimental measurement. Different infill patterns were produced as can be seen in Figure 16. The results indicated that various elements have a considerable effect on the sound absorption behavior of ABS samples, including the type of infill pattern, the frequency of excitation, the sample's thickness, and the air gap located behind the sample.



Figure 16 - Three different infill patterns (from left to right: Cartesian, Starlit, and Octagonal) [17].

The study found that the noise reduction coefficient was higher for ABS samples with Starlit structures compared to those with Cartesian and Octagonal structures, for any given thickness of the sample and size of air gap. This was attributed to the impact of the pore spaces and sizes on airflow resistance and, as a result, the sound absorbing capacity of the open-pore structures were fully utilized compared to the other patterns. Additionally, it was observed that low sound damping occurs at low frequencies of acoustic waves. Thus, it

was necessary to increase the material thickness, which led to enhanced sound absorption in the low frequency range.

In a similar study to the one conducted by Monkova et al. [16], [17], the researchers evaluated four structure types as seen in Figure 17 (Starlit, Rhomboid, Octagonal, and Cartesian), each made in three different volume ratios and three different thicknesses. The sound absorption of the ABS specimens were analyzed, and the noise reduction coefficient as well as the sound absorption coefficient were experimentally determined using the transfer function method with a two-microphone acoustic impedance tube. The results of this study were comparable to those of the previous study. The authors believe that it is possible to improve the efficiency of sound absorption across a wide frequency range in the future by developing and refining new open-pore 3D printing materials with more complex pore shapes and advanced multi-layer 3D printed structures.

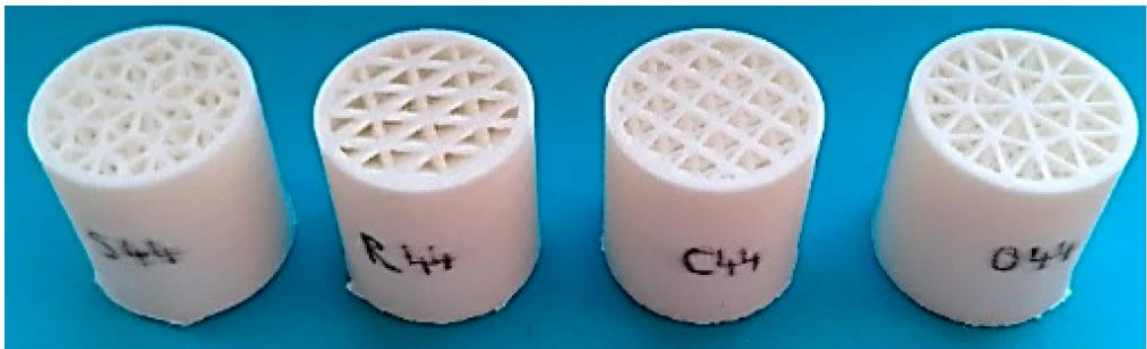


Figure 17 - A few of the printed samples showcasing the different infill patterns [33].

Monka et al. [34] used PLA rather than ABS as the material used to print the open-porous structure. Their study analyzed sound reflection behavior of structures printed with different thicknesses, infill patterns and volume ratios. Table 1 summarizes the main results found from their investigation.

Table 1 - Average values of the sound reflection coefficient for the various 3D-printed PLA structures [33].

Structure Type	t (mm)	P (%)	a (mm)	β_m (-)
Cartesian	10	56	0	0.857
	20	43	50	0.702
	30	30	100	0.598
Octagonal	10	56	0	0.844
	20	43	50	0.699
	30	30	100	0.601
Rhomboid	10	56	0	0.842
	20	43	50	0.692
	30	30	100	0.610
Starlit	10	56	0	0.820
	20	43	50	0.679
	30	30	100	0.589

2.4 Concluding Remarks

The studies reviewed in this literature review demonstrate the potential for using 3D printing technology to create sound absorbers with enhanced performance. The ability to design customized, complex shapes offers numerous benefits over traditional manufacturing methods. It has been shown that the use of 3D printing technology can lead to improved sound absorption properties by only controlling the infill parameters of the 3D printed objects, such as the infill pattern and volume ratio. The studies also demonstrate that 3D printing can be used to produce all three main types of sound absorbers, Porous, Membrane and Resonance absorbers. It is worth noting that a significant proportion of the studies examined in this chapter were published exclusively within the last five years. This observation underscores the fact that the field of research in question is relatively new, and has been gaining increasing attention in recent times. Overall, the reviewed studies provide promising results for the use of 3D printing technology in sound-absorbing applications and suggest the potential for further research in this area.

The investigations carried out by Monkova et al. and Vasina et al. [16], [17] are the most pertinent to the subject of this thesis. Nevertheless, there are certain restrictions that this thesis aims to address. Firstly, the two studies in question were restricted to samples containing basic two-dimensional infill patterns. Secondly, the selected volume ratios examined were less comprehensive than those that will be scrutinized in this thesis. Furthermore, both studies solely examined ABS as the material of choice, without an exploration of other potential materials.

CHAPTER 3

METHODOLOGY

3.1 Introduction

As outlined in Chapter 1 of this report, the methodology employed in this research entails a systematic approach utilizing a range of tools and techniques to examine the sound absorption characteristics of 3D printed materials. Following a comprehensive review of relevant literature, the first step involved identifying the essential requirements for the study, including a 3D printer, polymer filament, computer-aided design software, slicing software, and a sound absorption measurement setup. Subsequently, 3D models were designed with base values for volume ratio and pattern using CAD software, and slicing software was utilized to select appropriate print details and develop G-codes for the 3D printer. Once the base models were 3D printed, an impedance tube setup in accordance with ISO 10534-2 was employed to measure the normal incidence sound absorption coefficient at a wide range of frequencies. The process was repeated with varying values of volume ratios, patterns, and printing materials until suitable configurations were determined through evaluating their maximum sound absorption coefficient values and corresponding frequencies. Importantly, literature review was an indispensable tool employed throughout the research to identify study requirements, establish base values for the design and testing phases, and evaluate the obtained results.

The flowchart shown in Chapter 1 (Figure 1) showcases the process followed in this thesis research.

3.2 Fabrication of Samples

3.2.1 Summary of design choices

The samples were designed using SOLIDWORKS®, the famous CAD software. The outer diameter of the sample was governed by the size of the impedance tubes, thus, for each infill parameters selection, two separate parts need to be fabricated. Outer diameters were 100 mm and 30 mm as seen in Figure 18. This is because the larger sample can only be tested up to 1600 Hz as per the specification of the available impedance tube, whereas the small sample can only be tested for higher frequencies up to 6300 Hz.

The thickness for all the printed samples was chosen to be 1". This decision was made in order to standardize the test and focus only on the impact of varying the infill parameters [35], as well as in order to have a similar thickness to other structures discussed in the literature review, thus making the benchmarking easier [16], [17].

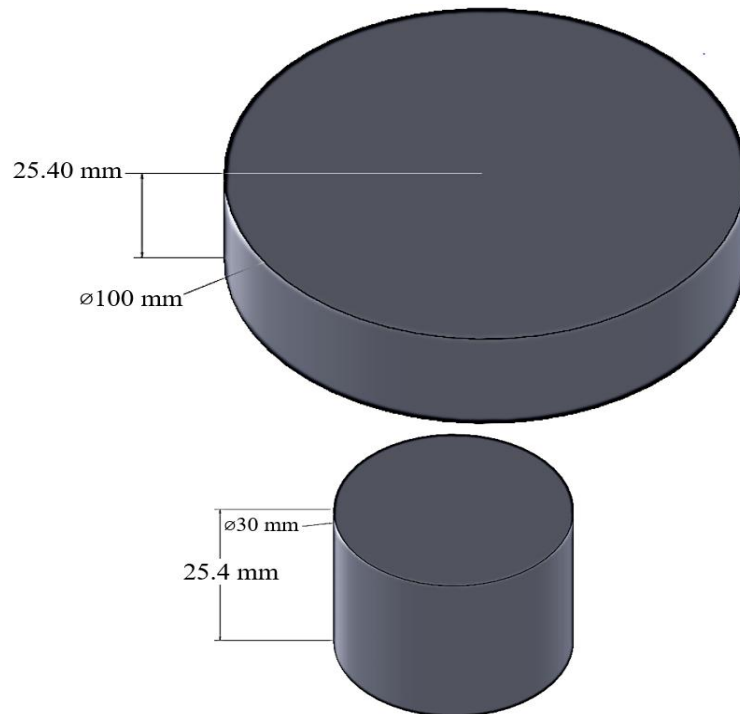


Figure 18 - Dimensions of the 3D models designed in SolidWorks (not-to-scale)

Four different infill geometries (also called infill patterns [36]) were selected to be tested. Each for a unique quality that it has. Grid, Three-dimensional honeycomb, Gyroid, and Pyramidic. A table in a following section will detail the specification of each pattern and show a sample of what that pattern looks like.

For each pattern, three different volume ratios were selected. The volume ratio refers to how much of the internal volume of the printed sample would actually be filled with the material. The volume ratio (also known as the infill density) can be calculated by dividing the volume of the actual material used to build the structure versus the volume of an assumed completely solid structure with the same design but printed with no internal pores. 25%, 50%, and 75% volume ratios were selected to give a broad range of characteristics that can be tested. In addition, a sample with no internal pores and empty spaces (i.e. 100% volume ratio) was printed to be tested out and compared with the other porous material.

For each variation of the above, two sets of samples were printed. One completely enclosed (2 end walls) and the other has only a back wall, allowing the internal porosity to be exposed (1 end wall). This is illustrated in Figure 19 below.

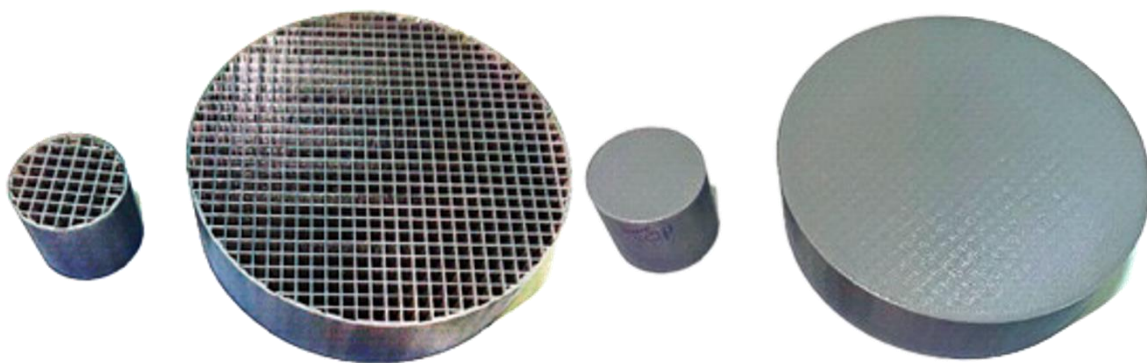


Figure 19 - Sets of printed identical samples, however, one is enclosed (right), and the other is open-faced (left)

Also, noting that more details are coming in the next sections, it is important to note that four different materials were printed and tested as well. The materials are PLA, ABS, ASA, and Woodfilled PLA. However, not every variation of design was printed with all four materials. Only PLA was chosen for all variations. Table 2 summarizes all the design choices discussed and justifications for the selections in order to provide a general overview, however, more details and justification for each design choice will be detailed in separate subsections in this chapter.

Table 2 - Summary of design choices

	Outer Diameters	Thicknesses	Volume Ratios	Infill Pattern	End Walls	Material
Choice	30 and 100 mm.	1" for all samples	- 25%, 50%, and 75% for all different infill patterns - A single 100% volume ratio sample	- Grid, - Honeycomb - Gyroid - Pyramidic	For each variation of infill parameters and materials, two versions are printed: - Enclosed (2-end walls) - Open-faced (1 end wall)	- PLA (for all variation) - ASA, ABS, and Woodfilled PLA (for 75% Honeycomb and Gyroid pattern only)
Justification	Governed by the size of the used impedance tubes as will be highlighted in 3.3.2	To standardize the test as mentioned in section 3.2.1	Will be discussed in sections 3.2.2.1 and 4.2.1	Will be discussed in sections 3.2.2.2 and 4.3.1	Will be discussed in section 4.1.1	Will be discussed in sections 3.2.3 and 4.4.1

As for the process of 3D printing, Figure 20 below shows a diagram of the typical process of 3D printing an object, from the design phase to the application. It is as follows:

1. Design the model using CAD software.
2. Slice the model into layers using slicing software.

3. Set the print parameters.
4. Prepare the printer and load the required filament.
5. Start the print.
6. Allow the print to cool and do any necessary post-processing.

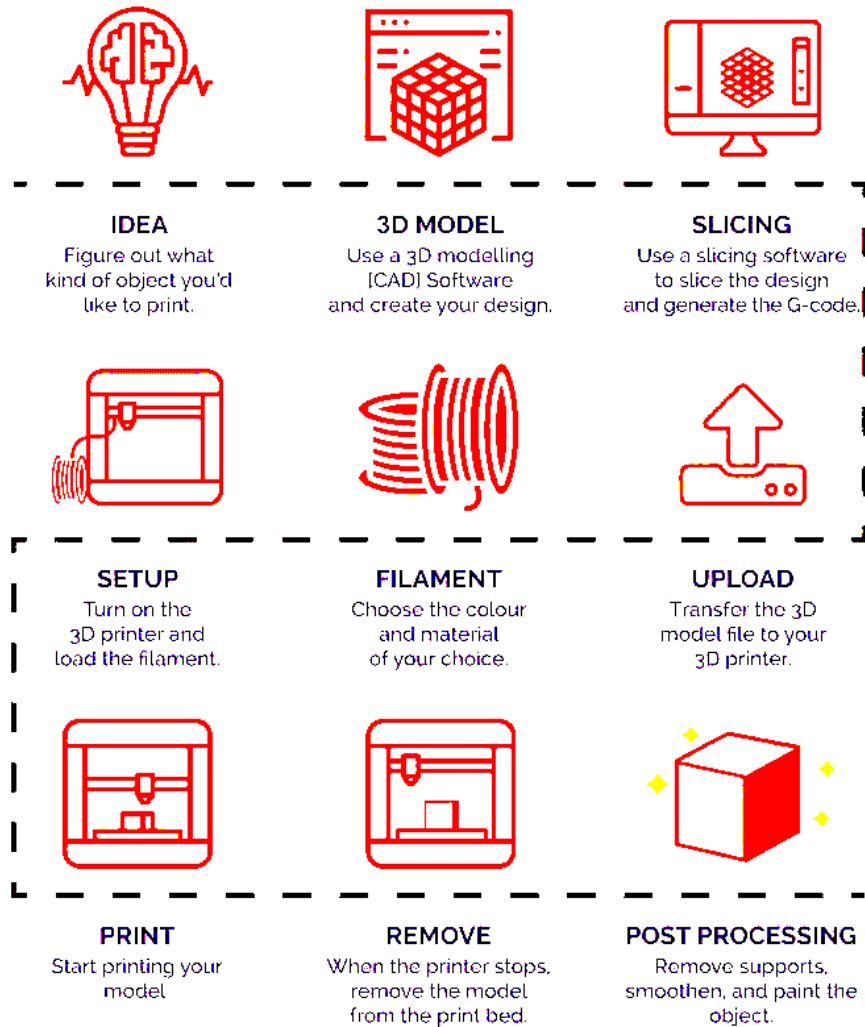


Figure 20 - The process of 3D printing [37]

3.2.2 Infill parameters choices

"Infill parameters" refer to the way the interior of a 3D printed object is filled in. In other words, it refers to the volume ratio, pattern, and orientation of the material that is used to

fill the interior of a 3D object, which provides structure and stability. The infill can be adjusted to meet specific requirements for strength, weight, cost, printing time, or in our case, acoustic properties. For example, a high infill percentage would result in a solid, heavy object that is strong and durable, but takes longer to print. On the other hand, a low infill percentage would result in a lighter object that is more cost-effective and quicker to print, but may not be as strong as a high infill object [36].

In short, the infill parameters are a set of variables that control the interior structure of a 3D printed object and can be adjusted to meet specific requirements for the finished product. For the purposes of our study, we will be focusing on two infill parameters: the volume ratio and the pattern, as well as testing the impact of having either an exposed or a closed off sample. We will be using PrusaSlicer software, which is a 3D slicing software created by Prusa Research. It takes a 3D model and converts it into instructions for a 3D printer, while allowing for inputs regarding infill parameters and other customizations. Figure 21 below shows a good illustration of the effect of how different infill parameters look.

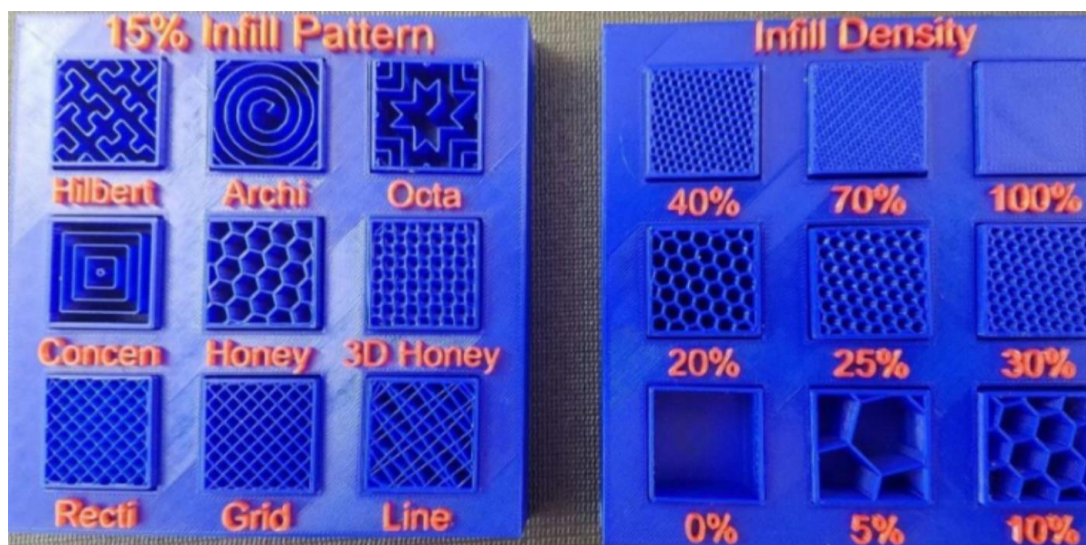


Figure 21 - A good illustration of the effect of how different infill parameters look [38]

3.2.2.1 Volume Ratio (Infill Density)

In 3D printing, "infill density" or "volume ratio" refers to the amount of material that is used to fill the interior of a printed object. When an object is printed, it is usually not printed as a solid block of material, as this would be time-consuming and require a large amount of material. Instead, the interior of the object is usually filled with a pattern of material that is less dense than the outer shell of the object.

The infill density or volume ratio is usually expressed as a percentage or a decimal fraction. For example, a volume ratio of 20% means that 20% of the interior volume of the object is filled with material, while 80% is empty space. A higher volume ratio means that more material is used to fill the object, which can make it stronger and more rigid, but also increases print time and material cost. A lower volume ratio saves on material and print time, but can make the object weaker and more flexible.

Mathematically, the volume ratio can be expressed as [17]:

$$VR\% = \frac{\text{Volume of Material Used in Printing}}{\text{Total Solid Body Volume}} \times 100 \quad (3.1)$$

Since the goal of this study was to understand the effect of the volume ratio on the sound absorption properties of the printed material, it was decided to select 4 different volume ratios covering a wide range. Samples were printed with 25%, 50%, 75% and 100% volume ratios.

3.2.2.2 Infill pattern (infill geometry)

In 3D printing, infill pattern refers to the internal structure of a printed object. When you print a 3D object, it is not solid throughout its entire volume; instead, the object is typically

hollow with a lattice-like internal structure. The infill pattern determines the arrangement of this internal structure. The infill pattern is important because it affects the strength, weight, print time, and, as we will be investigating in this study, the acoustic properties of the printed object. Different infill patterns can be chosen based on the intended use of the printed object [38], [39].

Four different infill patterns were selected, either based on theories that this study wanted to check (as will be clarified in the next chapters), or based on the properties of each pattern. The selected infills are Gyroid, Grid, Three-dimensional Honeycomb, and Pyramidic.

1- Gyroid Infill:

Gyroid infill, as shown in Figure 22, in contrast to more common infill patterns such as rectilinear or honeycomb, is a more complex and organic pattern that can offer several unique benefits.

The gyroid infill pattern is named after the mathematical term "gyroid", which refers to a non-trivial periodic minimal surface. This surface has a complex network of interconnected channels that can be difficult to describe, but when printed in a solid object, it can provide benefits such as improved strength, flexibility, and reduced material usage.

Gyroid infill patterns are created using mathematical algorithms that generate a repeating pattern of interconnected curved channels. The pattern can be adjusted to change the volume ratio and strength of the infill, and can be used in conjunction with other infill patterns to achieve specific properties in the printed object [40].

A trigonometric equation defines the gyroid as follows [41]:

$$\sin\left(\frac{2\pi x}{\lambda}\right) \cdot \cos\left(\frac{2\pi y}{\lambda}\right) + \sin\left(\frac{2\pi y}{\lambda}\right) \cdot \cos\left(\frac{2\pi z}{\lambda}\right) + \sin\left(\frac{2\pi z}{\lambda}\right) \cdot \cos\left(\frac{2\pi x}{\lambda}\right) = 0 \quad (3.2)$$

One of the advantages of gyroid infill is that it can help to reduce the weight of a printed object, making it more efficient and economical to produce. Additionally, because the pattern is complex and interconnected, it can help to distribute stress and strain throughout the printed object, improving its overall strength and resilience.

Overall, gyroid infill is a popular option in 3D printing for its ability to improve the performance and quality of printed objects, especially in applications where strength and weight are important considerations.

Due to the complex repeating pattern of interconnected curved channels, this pattern was selected for this experiment to test whether these complex and interconnected paths will offer a resistance to the sound wave, which may result in a high absorption coefficient.

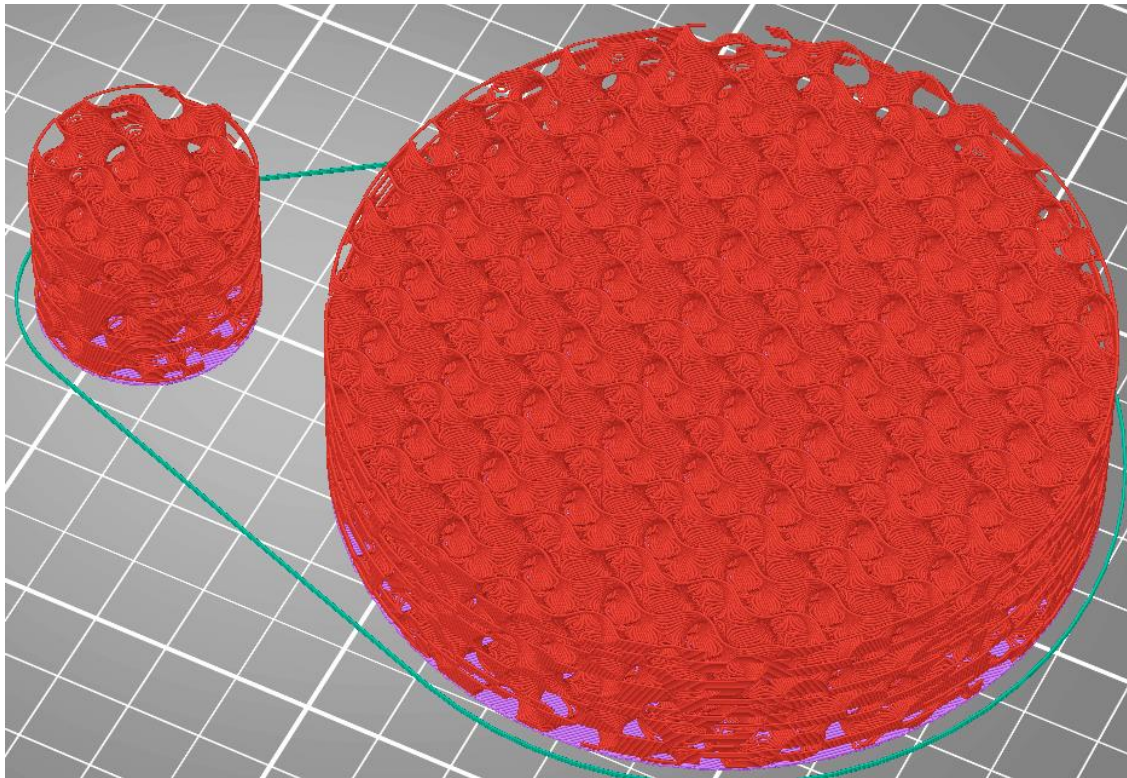


Figure 22 - A 3D representation of the gyroid infill pattern (10% volume ratio) captured through PrusaSlicer

Thus, the benefits of the gyroid pattern can be summarized as follows [42]:

- Because it is three dimensional, it possesses uniform strength in all directions.

- The printing process is relatively fast.
- It does not overlap with itself in the same layer.
- The ratio of its strength to weight is favorable.
- It permits the filling of resin or other liquids.

However, this infill pattern also has some limitations that should be considered when choosing an infill pattern for a specific print. Firstly, the intricate nature of the "Gyroid" pattern can increase the printing time compared to simpler structures. Secondly, although not related to the structures used in this thesis, the complexity of the "Gyroid" infill pattern may require more support material, especially for overhanging structures. Finally, some 3D printing slicing softwares may have limited options for adjusting the volume ratio of the "Gyroid" pattern, which can impact the strength and weight of the final print. It is important to take these limitations into account when deciding on the appropriate infill pattern for a 3D printing project.

2- Grid Infill:

Grid infill, as shown in Figure 23, is a simple pattern that consists of a grid of parallel lines that are oriented perpendicular to each other in alternating layers. The grid infill pattern is easy to print and can provide a good balance of strength and weight to the printed object. It is also an efficient pattern that can help to reduce the material usage and printing time compared to solid infill. The pattern is often used for parts that require moderate strength, such as prototypes or functional parts.

In a grid infill, the spacing and thickness of the lines can be adjusted to achieve different volume ratios and strength properties. The pattern can also be rotated or angled to achieve

specific strength or stiffness properties in a particular direction. However, in our case, we will use a rectilinear monotonic pattern for the grid in order to keep it simple.

While grid infill is a simple and efficient pattern, it may not be the best choice for all applications. For example, parts that require high strength or durability may benefit from more complex and stronger infill patterns such as gyroid or octet infill. In our case, Grid infill pattern was chosen because it is one of the most commonly used patterns, and thus, can be used as a benchmark for comparison. Also, similar studies have included results for this pattern, so the verification of the results is possible.

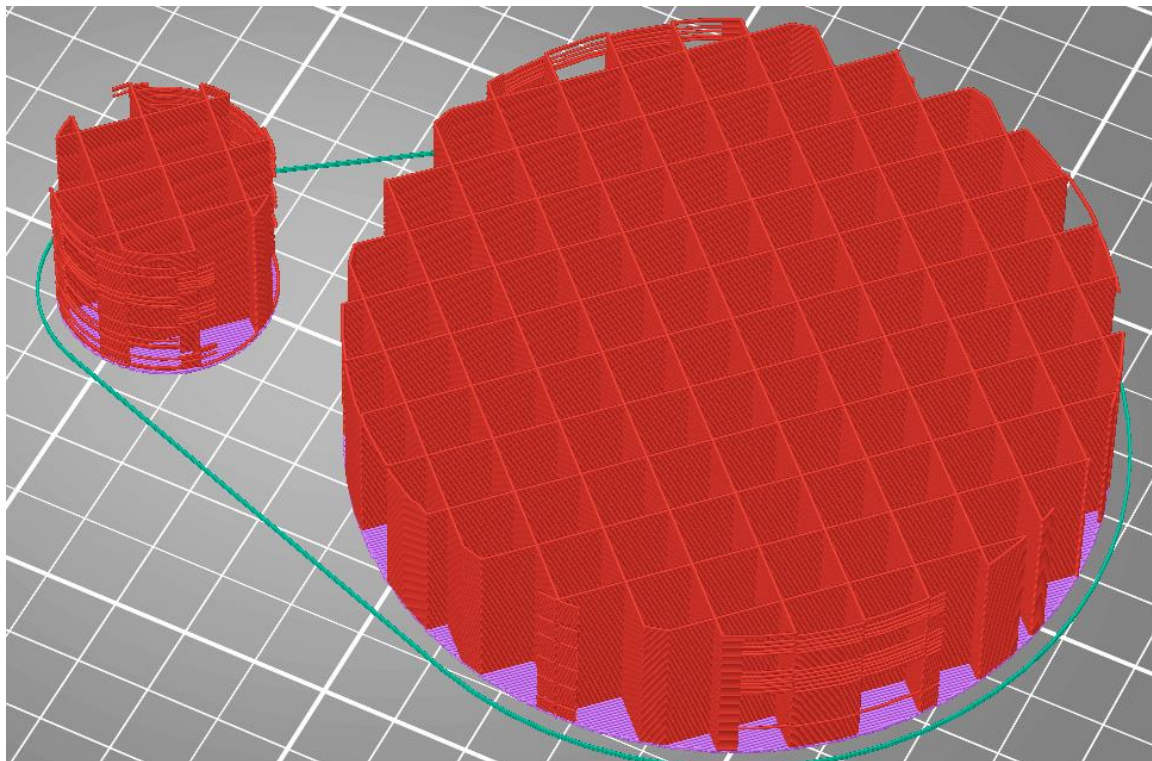


Figure 23 - A 3D representation of the Grid infill pattern (10% volume ratio) captured through PrusaSlicer

3- Three-dimensional Honeycomb Infill:

The normal honeycomb infill pattern, as shown in Figure 23, creates a grid composed of hexagons, which offers advantages such as mechanical strength and efficient paths that do not intersect. However, the infill pattern also has some drawbacks. It consumes more

material than other infills, roughly 25% more, and the printing time is longer, sometimes taking up to twice as long as other options.

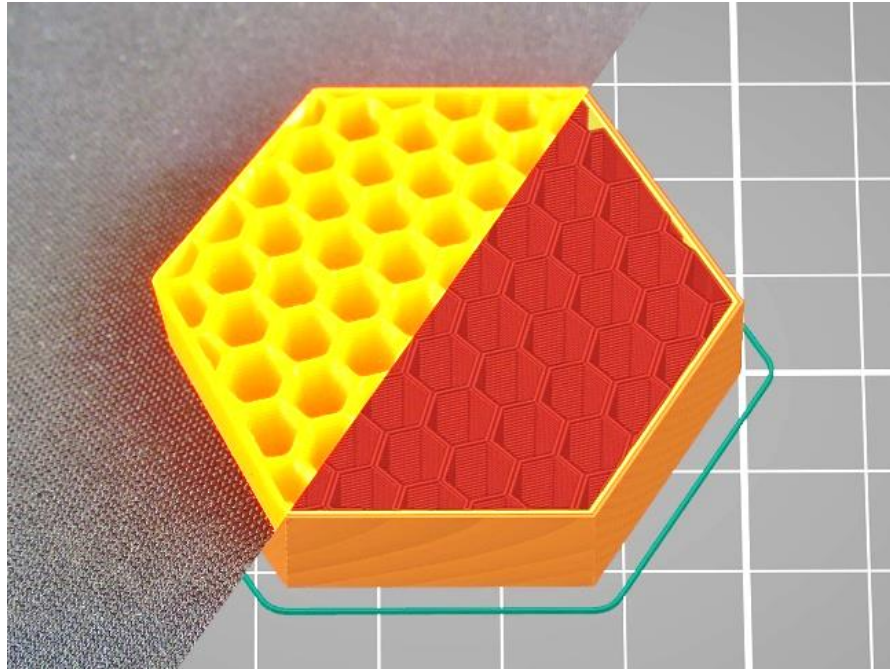


Figure 24 - The normal honeycomb infill pattern [43].

However, the 3D honeycomb infill pattern, as shown in Figure 25, consists of columns made of larger and smaller squares and octagons that create a pattern of alternating thickness. It does not have any overlapping lines within a single layer. However, due to the path of the infill, small gaps may appear between the layers. While this infill pattern provides some advantages, such as the periodic changes in thickness, it also has some drawbacks. The material consumption and print time are slightly higher than those of the regular honeycomb pattern.

The reason this pattern was selected for this research, rather than the regular honeycomb, was to explore the benefits of having these small gaps between the layers, as well as the added benefit of possibly creating many “Helmholtz resonators” due to the repeated increases and decreases in the openings.

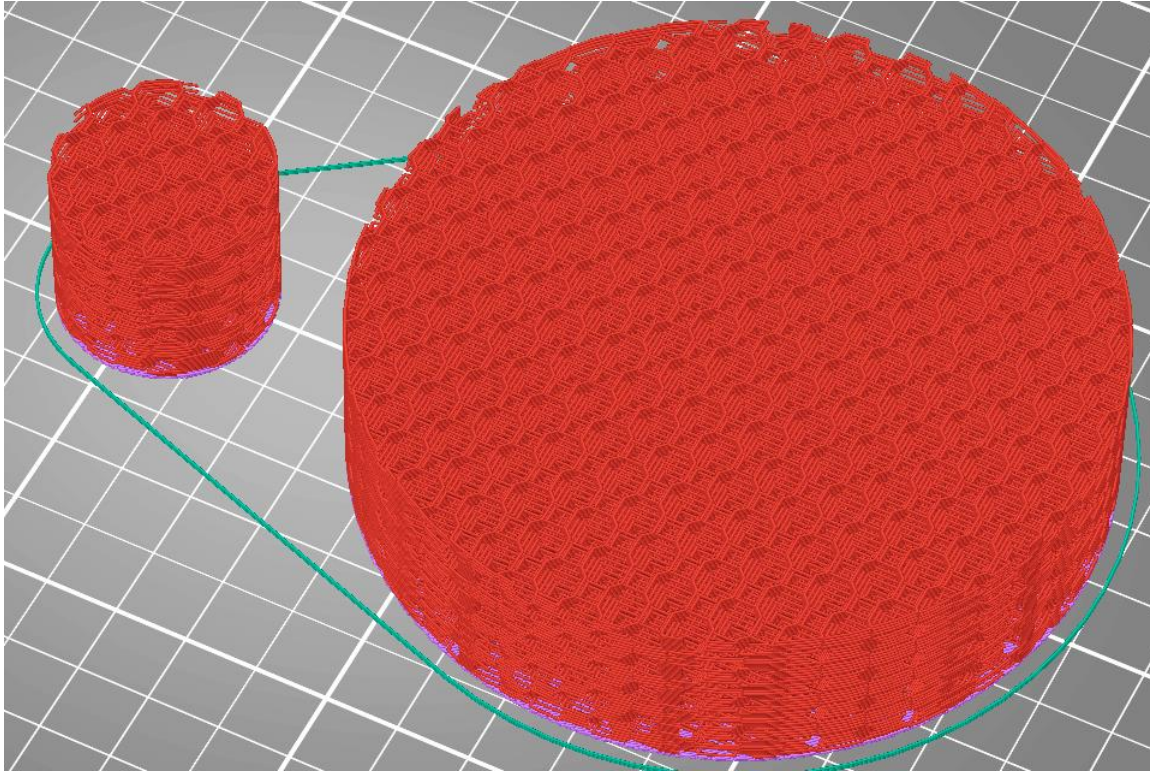


Figure 25 - a 3D representation of the 3D honeycomb infill pattern (10% VR) captured through PrusaSlicer

4- Pyramidic Infill (also known as cubic infill):

In this pattern, as shown in Figure 26, the interior is filled with a repeating pattern of cubes, and each cube is connected to its neighboring cubes along all three axes, creating a solid and interconnected structure. The cubes can be adjusted in size and volume ratio to vary the strength and weight of the printed object. One of the primary benefits of using a cubic infill pattern is that it can provide excellent structural support for the printed object. The interlocking nature of the cubes helps to distribute the load across the entire structure, which can prevent cracking or breaking under stress. The cubic infill pattern is also relatively easy to print and efficient in terms of material usage, which makes it a popular choice for a wide range of applications [42]. It is also considered one of the fastest patterns in terms of printing time. This infill pattern features intersecting paths within a single layer and produces cubes with one corner pointing downwards. The orientation of the cubes

creates multiple air pockets that can act as insulation against heat [42]. In addition, it has been shown that these air pockets cause the printed object to float in water (in case it was printed with a non-porous material such as PETG). This infill was selected precisely for this reason (the presence of the multiple air pockets), as their effect on the sound absorption characteristics will be subject to study.

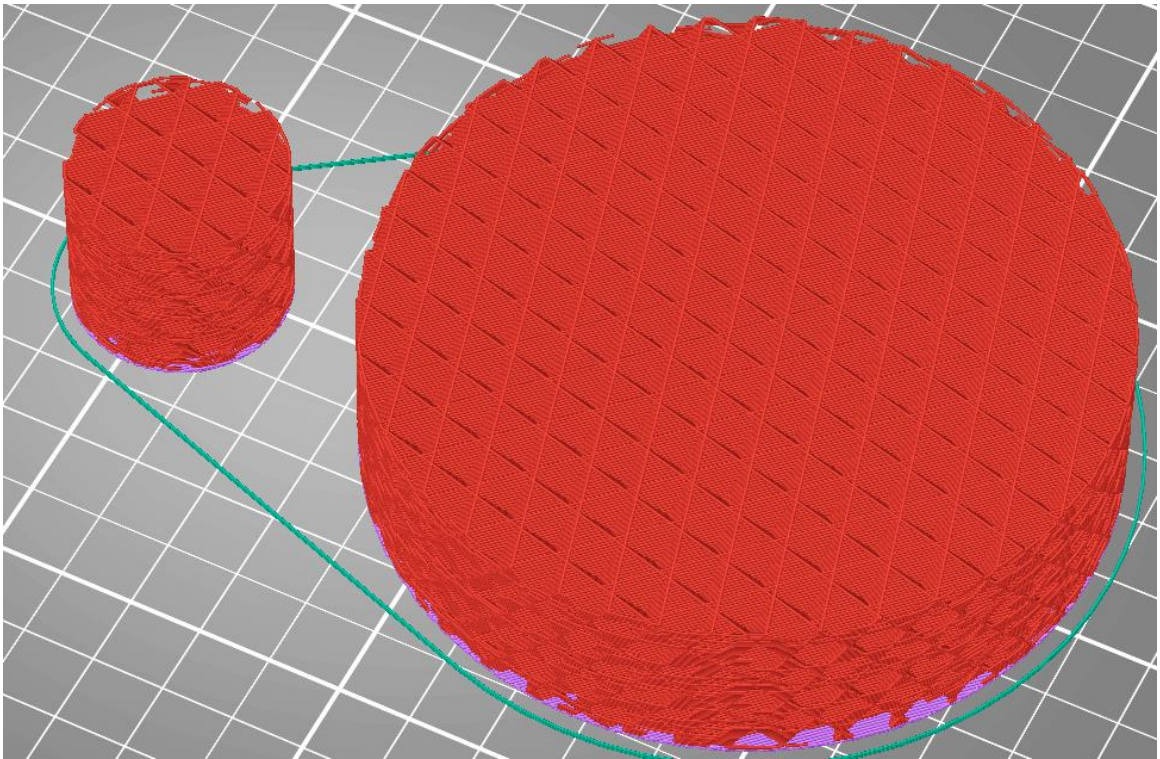


Figure 26 - A 3D representation of the 3D honeycomb infill pattern (10% VR) captured through PrusaSlicer

3.2.2.3 Other design choices

During the slicing process, the user can have the choice wall designs. To keep the focus only on the infill parameters, the below choices were made:

- Number of vertical walls (outer shell layers) = 1
- Thickness of vertical wall = 1 mm
- Number of bottom walls = 1
- Thickness of bottom layers = 1 mm
- Number of top walls = two versions of each set were printed, one with no top layers and one with a single top wall
- Layers height = 0.15 mm

PrusaSlicer give the flexibility to print objects with different infill parameters and design in the same cycle as can be seen in Figure 27.

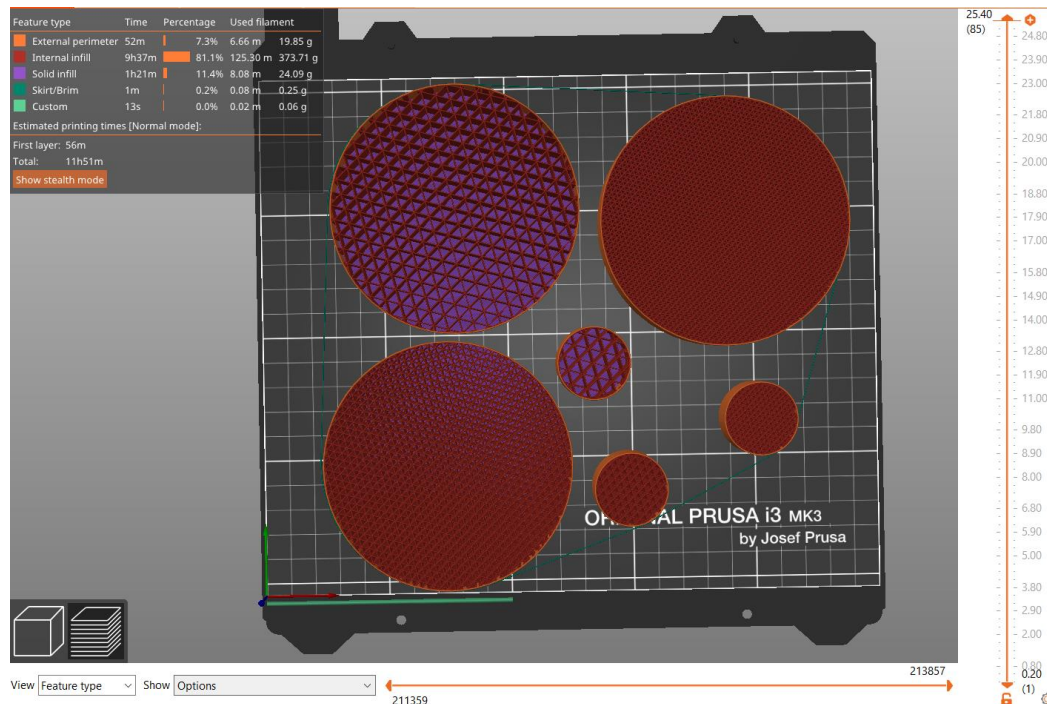


Figure 27 - Three sets of samples with different volume ratios being prepared in the slicing software.

3.2.2.4 Showcasing printed infills

Table 3 - Showcasing the different geometric configurations

Note: The photos are of actual samples that have been printed for this thesis research

#	Volume Ratio	Infill Pattern	Infill Showcase
1	100%	Not applicable for 100% volume ratio	
2	25%	Honeycomb	
3	50%	Honeycomb	
4	75%	Honeycomb	
5	25%	Pyramidic	

Table 3 - Showcasing the different geometric configurations (continued)

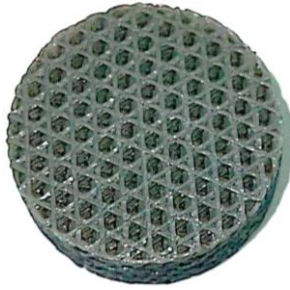
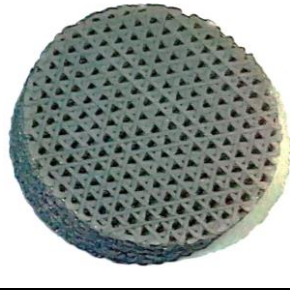
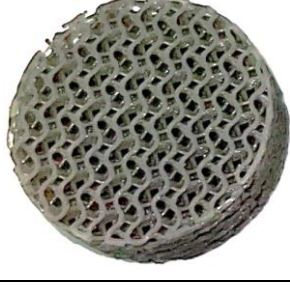
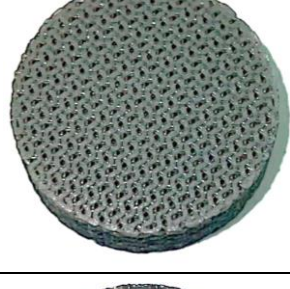
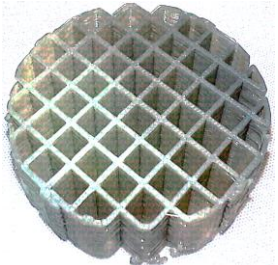
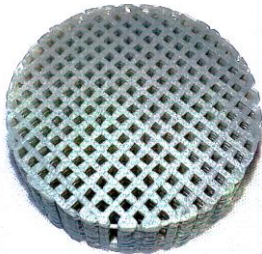
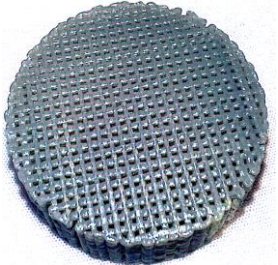
#	Volume Ratio	Infill Pattern	Infill showcase
6	50%	Pyramidic	
7	75%	Pyramidal	
8	25%	Gyroid	
9	50%	Gyroid	
10	75%	Gyroid	

Table 3 - Showcasing the different geometric configurations (continued)

#	Volume Ratio	Infill Pattern	Infill showcase
11	25%	Grid	
12	50%	Grid	
13	75%	Grid	

3.2.3 Material Selection

3.2.3.1 PLA

PLA (Polylactic acid) was chosen as the main material for fabrication as all infill configurations were printed with this material. PLA is gaining ground as the preferred material used in 3D printing, due it having a better stiffness and hardness than ABS or nylon, having a low required printing temperature, and having a better resistance to warping, which is a common issue in 3D printing [44]. Polylactic acid is also biodegradable and bioactive, and is usually derived from renewable resources, such as corn starch, tapioca roots, sugarcane, or potato starch. Thus, PLA is usually considered

an environmentally friendly alternative to traditional plastics, as it is biodegradable and compostable under the right conditions. However, it's important to note that not all PLA is compostable and biodegradable, as some formulations contain additives that may affect its biodegradability. Figure 28 below showcases the backbone formula of PLA, whereas Table 4 lists some of its physical properties.

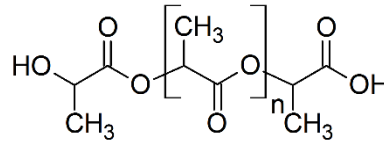


Figure 28 - Backbone formula of PLA ($C_3H_4O_2$)_n [45]

Table 4 - Properties of PLA [46]

Mechanical Properties

Quantity	Value	Unit
Young's modulus	350 - 2800	MPa
Tensile strength	10 - 60	MPa
Elongation	1.5 - 380	%
Bending strength	0.89 - 1.03	MPa
Impact strength	0.16 - 1.35	J/cm

Physical Properties

Quantity	Value	Unit
Melting temperature	150 - 160	°C
Glass temperature	45 - 65	°C
Density	1210 - 1430	kg/m ³
Water absorption	0.5 - 50	%

3.2.3.2 ABS

ABS (Acrylonitrile Butadiene Styrene) is a common thermoplastic material used in 3D printing. It is a popular material because of its toughness, durability, and resistance to impact, heat, and chemicals. ABS has a relatively high melting point, which makes it suitable for use in Fused Deposition Modeling (FDM) 3D printers. The material is typically printed at temperatures between 220 and 250 degrees Celsius. ABS is commonly used in the production of automotive parts, toys, and household items, among other applications. It can be easily machined, sanded, and painted, making it a versatile material for a range of applications.

One important thing to note about ABS is that it emits fumes during the 3D printing process, which can be harmful if inhaled. Therefore, it is important to use ABS in a well-ventilated area or with a specialized 3D printer that is equipped with a ventilation system to minimize exposure to these fumes. For this reason, and for the fact that it requires higher printing nozzle and bed temperatures as well as its tendency to warp, it is currently losing ground to PLA as the more popular filament in FDM 3D printing.

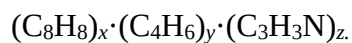


Figure 29 below showcases the chemical formula of ABS, whereas Table 5 lists some of its physical properties.

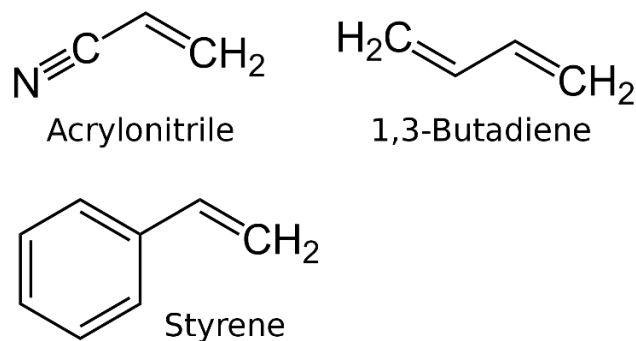


Figure 29 - $(C_8H_8)_x \cdot (C_4H_6)_y \cdot (C_3H_3N)_z$, the chemical formula of ABS [47].

Table 5 - Properties of ABS [48]

Mechanical Properties

Quantity	Value	Unit
Young's modulus	2275 - 2900	MPa
Tensile strength	41 - 60	MPa
Elongation	5 - 25	%
Compressive strength	60 - 86	MPa
Impact strength	0.56 - 2.2	J/cm

Physical Properties

Quantity	Value	Unit
Melting Temperature	220 - 230	°C
Glass temperature	105 - 105	°C
Density	1060 - 1080	kg/m ³
Water absorption	0.2 - 0.45	%

ABS was used in these experiments only to produce the following samples:

- 75% volume ratio, Gyroid Pattern (both open and closed)
- 75% volume ratio, Honeycomb Pattern (both open and closed)

3.2.3.3 ASA

ASA (Acrylonitrile Styrene Acrylate) is another thermoplastic material used in 3D printing. It is similar to ABS in many ways, but with improved weather resistance and UV stability.

ASA has excellent thermal stability, meaning that it can withstand higher temperatures without deforming. This makes it suitable for use in outdoor applications where it may be exposed to sunlight and other weather conditions. ASA is also resistant to chemicals, making it suitable for use in harsh environments.

ASA is commonly used in the production of automotive parts, outdoor equipment, and electrical enclosures, among other applications. It is often used as a replacement for ABS when increased UV stability is required.

ASA is typically printed at temperatures similar to ABS, between 220 and 250 degrees Celsius. However, it may require a slightly higher printing temperature to achieve good layer adhesion and part strength. Like ABS, ASA also emits fumes during the 3D printing process, so it is important to use it in a well-ventilated area or with a specialized 3D printer that is equipped with a ventilation system. In general, ASA is easier to handle during printing than ABS as it tends to warp less.

Figure 30 below showcases the backbone formula of ASA, whereas Table 6 lists some of its physical properties.

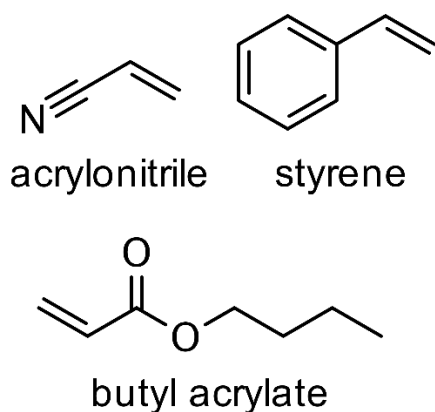


Figure 30 - C₁₈H₂₃NO₂, Chemical Formula of ASA [49]

Table 6 - Properties of ASA [50]

Mechanical Properties

Quantity	Value	Unit
Young's modulus	1800 - 2600	MPa
Tensile strength	32 - 55	MPa
Elongation	20 - 40	%
Bending strength	65 - 80	MPa
Impact strength	0.8 - 3.3	J/cm

Physical Properties

Quantity	Value	Unit
Melting temperature	230 - 250	°C
Glass temperature	112	°C
Density	1040 - 1060	kg/m ³
Water absorption	0.2 - 0.45	%

ASA was used in these experiments only to produce the following samples:

- 75% volume ratio, Gyroid Pattern (both open and closed)
- 75% volume ratio, Honeycomb Pattern (both open and closed)

3.2.3.4 Woodfilled PLA

Woodfilled PLA filament is a composite material used in 3D printing that combines PLA (polylactic acid) plastic with wood fibers. This results in a material that has a wood-like appearance and texture, and can be used to create objects with a natural,

organic look and feel. The particular filament used in these sets of experiments (iSANMATE Wood Filament) is made up of 20% wood flour and 80% PLA

Woodfilled PLA filament is commonly used in artistic and decorative applications, such as sculptures, vases, and other objects that benefit from a wood-like appearance. It is also used in architectural and engineering applications where a natural look is desirable.

The wood fibers in the filament provide the material with a natural color and texture, and also improve the stiffness and strength of the final printed object. This makes it more durable and resistant to deformation than pure PLA. However, it is worth noting that Woodfilled PLA may require some special handling compared to pure PLA filaments. The wood fibers can be abrasive, so it is recommended to use a hardened steel nozzle made specifically for abrasive materials to prevent wear and tear. Additionally, because the wood fibers can absorb moisture, it is important to store the filament in a dry place to avoid warping or degradation. It is one of the most difficult materials to print, thus, it is still not yet widely used, despite its advantages.

Woodfilled PLA was used in these experiments only to produce the following samples:

- 75% volume ratio, Gyroid Pattern (both open and closed)
- 75% volume ratio, Honeycomb Pattern (both open and closed)

3.2.4 3D printing details

3.2.4.1 Choice of technology

Due to the complexity of the proposed structures, and to allow for better iterations in design, it was decided to utilize additive technology through an FDM (fused deposition modeling) 3D printer. An FDM printer, as shown in Figure 31, melts then extrude a filament of polymer and build the structure layer by layer. Although they are typically slower than other 3D printer types, they are the most widely used due to their cheaper cost and ease of handling [51]. A Prusa i3 MK3S+ 3D printer, as shown in Figures 32 and 33, was chosen due to its ability to print different material (PLA, ABS, ASA, PETG, etc.), which is not a characteristic available in all printers.

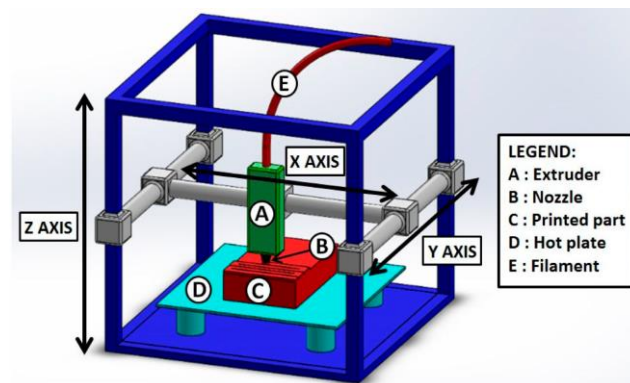


Figure 31 - A typical FDM printer setup [52].



Figure 32 - Prusa i3 MK3S+ 3D printer



Figure 33 - Prusa i3 MK3S+ 3D during the printing process

3.2.4.2 Printing specifications for each material

Table 7 - Printing specifications for each material

Material	Nozzle Temperature (°C)		Heating Bed Temperature (°C)	Layer Height (mm)	Print Speed (mm/s)	
	First Layer	Other Layers			First Layer	Infill
PLA	215	210	60	0.15	20	80
ABS	255	255	105	0.15	20	80
ASA	260	260	110	0.15	20	80
Woodfilled PLA	207	207	55	0.15	20	80

3.2.5 Final list of fabricated samples

After explaining the different types of internal infill patterns and volume ratios as well as showcasing the final printed versions of the internal infill, Table 8 below will contain the final list of all samples developed and tested. It will also indicate how each sample is named to ease tracking in the list of the report.

The naming style follows the below format:

Material – volume ratio – infill Pattern – Closed/Open-faced

Table 8 - List of fabricated samples along with assigned label and number for each

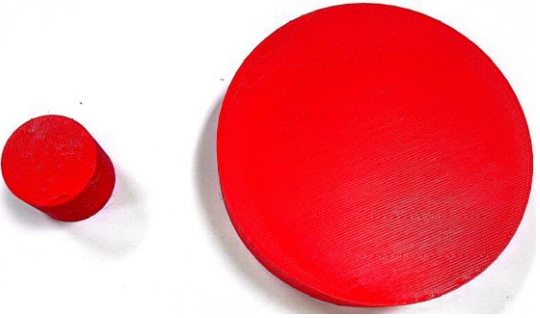
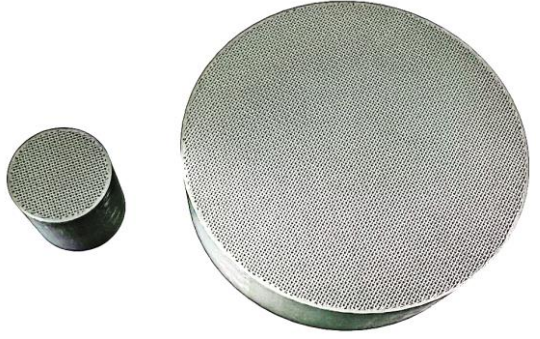
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-100	Polylactic acid	100%	Not applicable	
PLA-25-H-O	Polylactic acid	25%	3D Honeycomb, Open-Faced	
PLA-25-H-C	Polylactic acid	25%	3D Honeycomb, Closed	
PLA-50-H-O	Polylactic acid	50%	3D Honeycomb, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

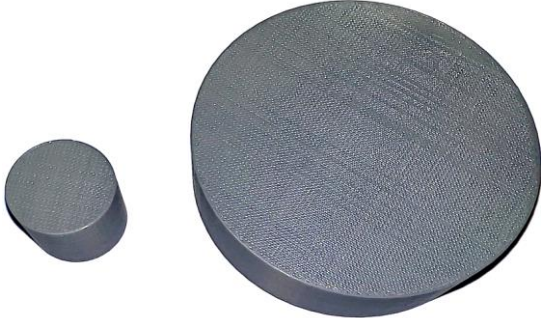
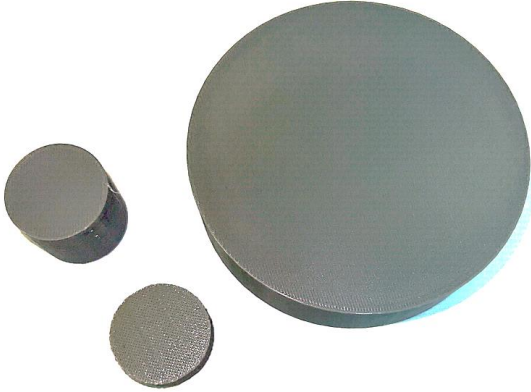
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-50-H-C	Polylactic acid	50%	3D Honeycomb, Closed	
PLA-75-H-O	Polylactic acid	75%	3D Honeycomb, Open-Faced	
PLA-75-H-C	Polylactic acid	75%	3D Honeycomb, Closed	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

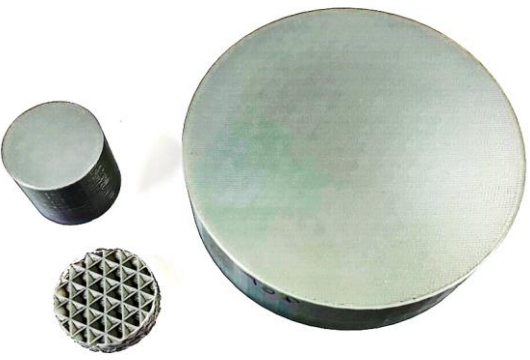
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-25-P-O	Polylactic acid	25%	Pyramidic, Open-Faced	
PLA-25-P-C	Polylactic acid	25%	Pyramidic, Closed	
PLA-50-P-O	Polylactic acid	50%	Pyramidic, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

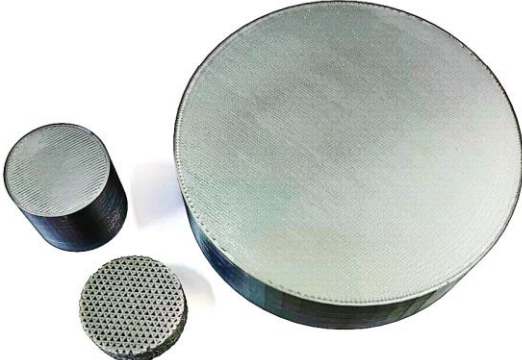
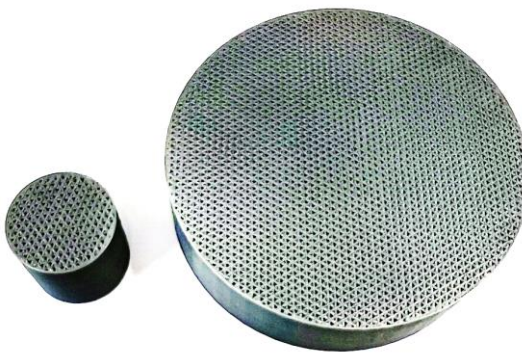
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-50-P-C	Polylactic acid	50%	Pyramidic, Closed	
PLA-75-P-O	Polylactic acid	75%	Pyramidic, Open-Faced	
PLA-75-P-C	Polylactic acid	75%	Pyramidic, Closed	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

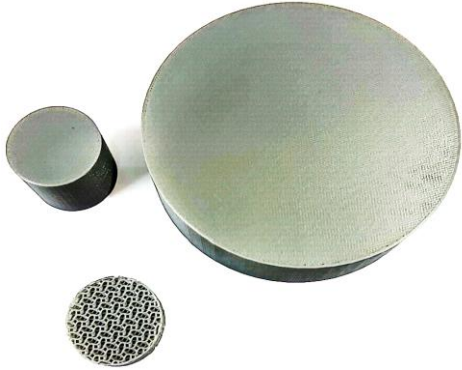
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-25-Gy-O	Polylactic acid	25%	Gyroid, Open-Faced	
PLA-25-Gy-C	Polylactic acid	25%	Gyroid, Closed	
PLA-50-Gy-O	Polylactic acid	50%	Gyroid, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

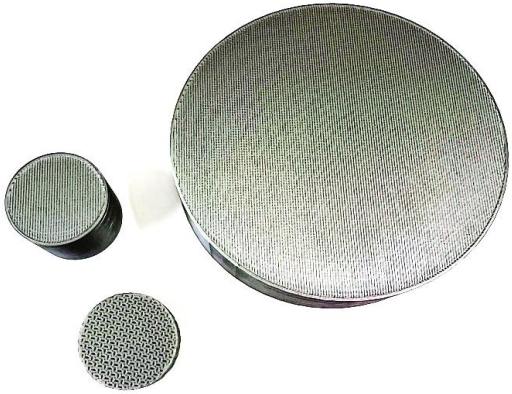
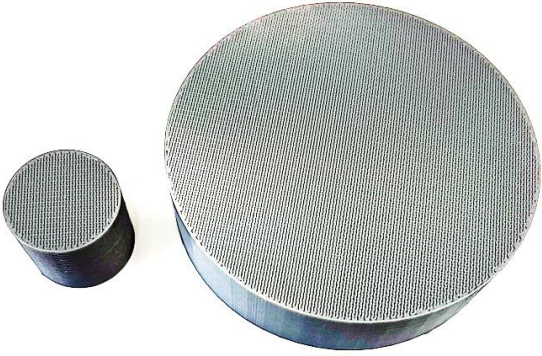
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-50-Gy-C	Polylactic acid	50%	Gyroid, Closed	
PLA-75-Gy-O	Polylactic acid	75%	Gyroid, Open-Faced	
PLA-75-Gy-C	Polylactic acid	75%	Gyroid, Closed	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

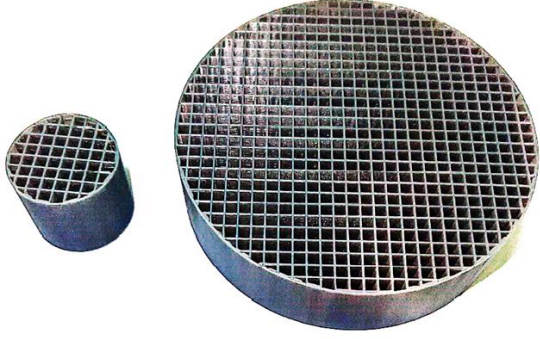
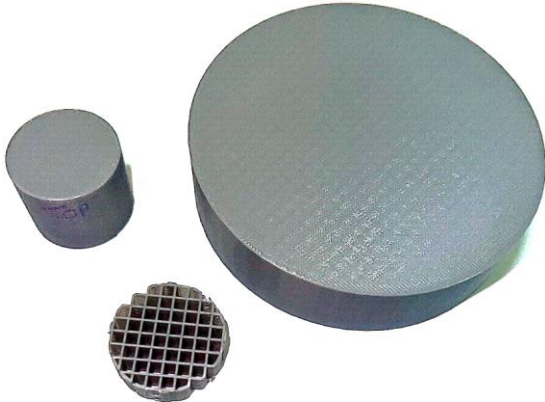
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-25-Gr-O	Polylactic acid	25%	Grid, Open-Faced	
PLA-25-Gr-C	Polylactic acid	25%	Grid, Closed	
PLA-50-Gr-O	Polylactic acid	50%	Grid, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

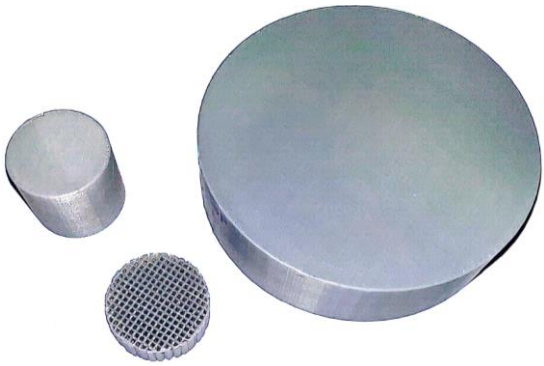
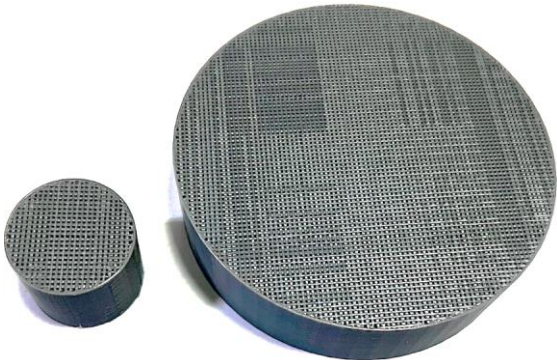
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
PLA-50-Gr-C	Polylactic acid	50%	Grid, Closed	
PLA-75-Gr-O	Polylactic acid	75%	Grid, Open-Faced	
PLA-75-Gr-C	Polylactic acid	75%	Grid, Closed	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

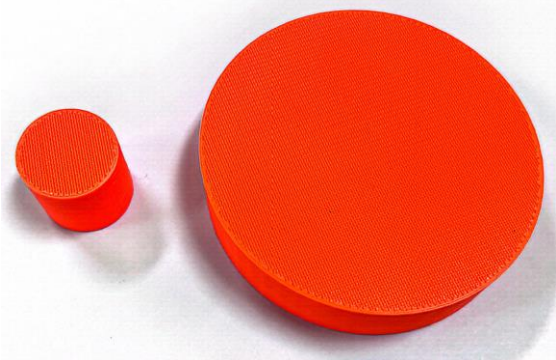
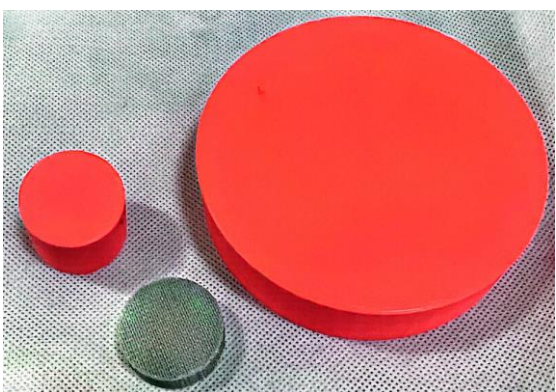
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
ASA-75-Gy-O	Acrylonitrile styrene acrylate	75%	Gyroid, Open-Faced	
ASA-75-Gy-C	Acrylonitrile styrene acrylate	75%	Gyroid, Closed	
ASA-75-H-O	Acrylonitrile styrene acrylate	75%	3D Honeycomb, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

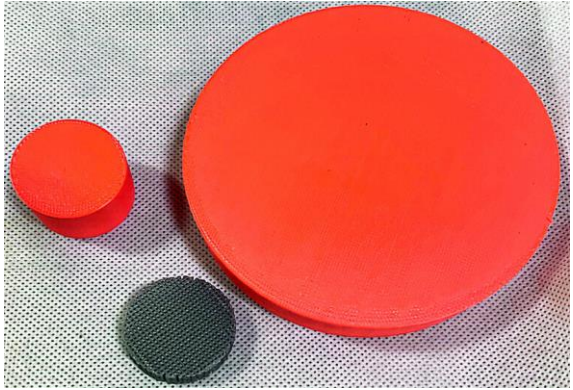
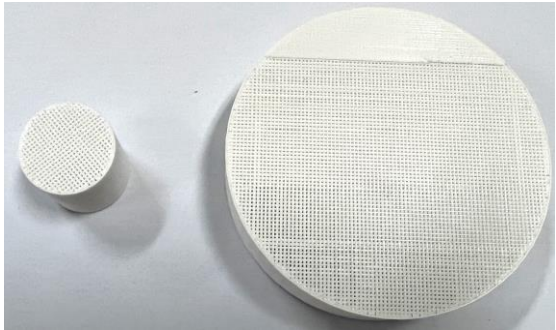
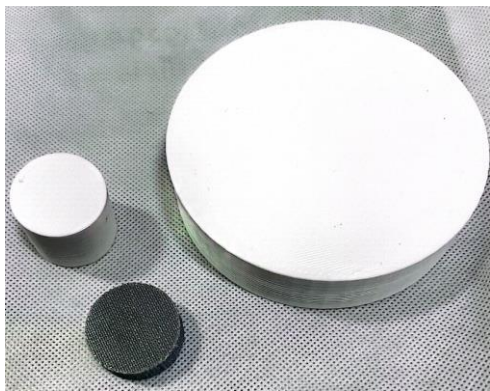
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
ASA-75-H-C	Acrylonitrile styrene acrylate	75%	3D Honeycomb, Closed	
ABS-75-Gy-O	Acrylonitrile butadiene styrene	75%	Gyroid, Open- Faced	
ABS-75-Gy-C	Acrylonitrile butadiene styrene	75%	Gyroid, Closed	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

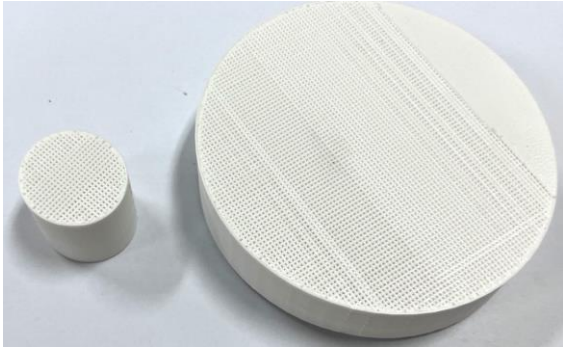
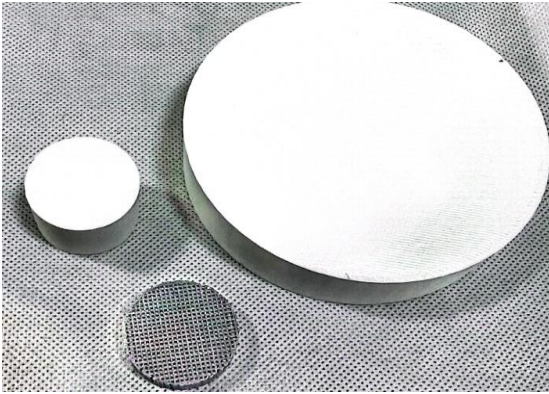
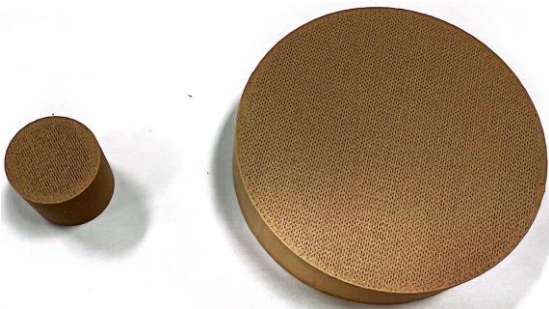
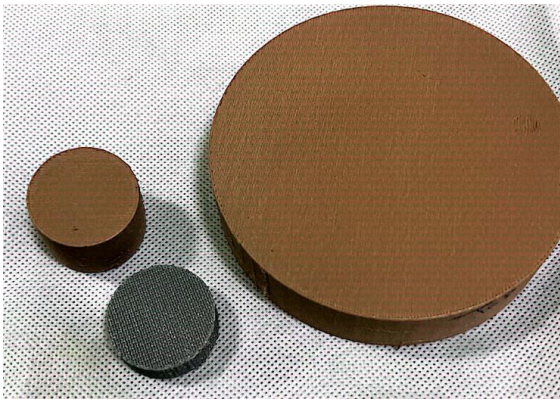
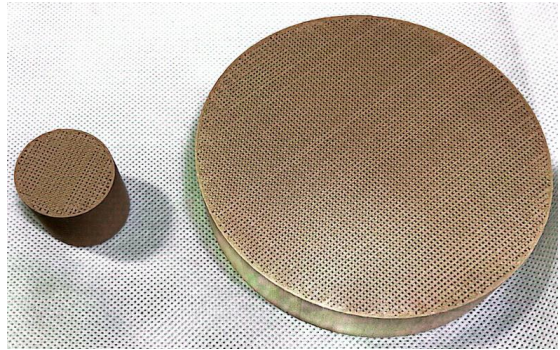
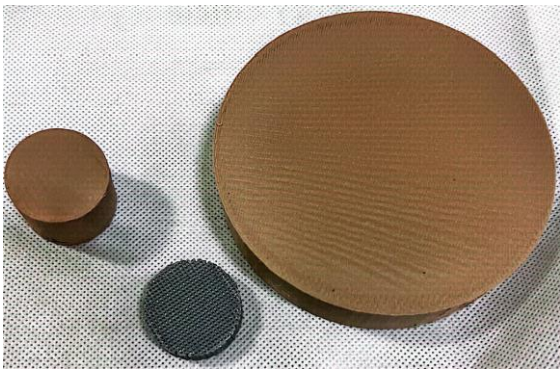
Sample Label	Material	Volume Ratio	Infill Pattern	Photo
ABS-75-H-O	Acrylonitrile butadiene styrene	75%	3D Honeycomb, Open-Faced	
ABS-75-H-C	Acrylonitrile butadiene styrene	75%	3D Honeycomb, Closed	
WP-75-Gy-O	Woodfilled PLA: 20% wood flour-80% PLA	75%	Gyroid, Open-Faced	

Table 8 - List of fabricated samples along with assigned label and number for each (continued)

Sample Label	Material	Volume Ratio	Infill Pattern	Photo
WP-75-Gy-C	Woodfilled PLA: 20% wood flour-80% PLA	75%	Gyroid, Closed	
WP-75-H-O	Woodfilled PLA: 20% wood flour-80% PLA	75%	3D Honeycomb, Open-Faced	
WP-75-H-C	Woodfilled PLA: 20% wood flour-80% PLA	75%	3D Honeycomb, Closed	

3.3 Experimental Measurements

3.3.1 Theoretical background

In order to measure the sound absorption coefficients for the tested samples, the procedure listed in ISO 10534-2 was followed [53]. Sound absorption coefficients measurements through impedance tube was done following the Transfer Function Method, in which the incident and the reflected sound pressures functions are separated from the measured transfer function and then used to estimate the sound absorption coefficient of the test sample. Figure 34 showcases the overall setup for the impedance tube as per the ISO.

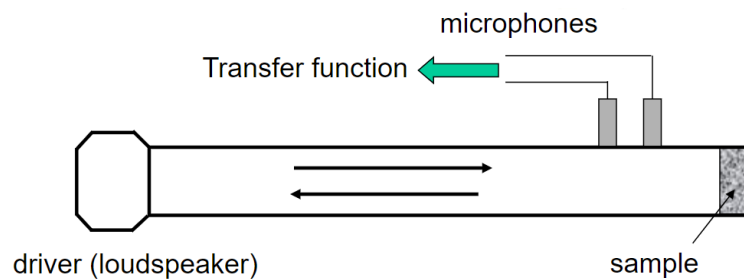


Figure 34 - Setup for an ISO 10534-2 impedance tube

3.3.1.1 ISO 10534

ISO 10534 is a set of standards with the general title "Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes". It includes two parts:

Part 1: employs the standing wave ratio method.

Part 2: uses the transfer function method.

Setaki et al. [54] did a study in which they investigated the acoustic properties of two 3D-printed sound absorbers. Each object is tested using both methods mentioned above. The measured results are compared to one another and to theoretical calculations. The article

discussed the advantages and disadvantages of each testing method and determines which method is better suited for this type of testing. They concluded that although the standing wave method is dependable, it can only measure one frequency at a time, which may result in missing peak frequencies and their corresponding α -values. This can give an inaccurate representation of the sample's performance. On the other hand, the transfer function method is capable of measuring the absorption coefficient across a wide range of frequencies (within certain limits) with just a few speedy measurements.

In addition to the above, it can be seen in almost all the literature review done in section 2.3 of this report that ISO 10534-2 (the transfer function method) is exclusively used rather than ISO 10534-1 (the standing wave ratio method). Thus, to better benchmark the findings of this study to that of other published results, utilizing the same method will be an advantage.

In conclusion, the transfer function method offers several advantages over the standing wave ratio method for measuring sound absorption coefficient, which include:

1. The ability to measure the absorption coefficient across a wider frequency range.
2. Faster calculations, which enable more test samples to be examined.
3. Improved accuracy by not missing peak frequencies and corresponding alpha values, thereby providing a more comprehensive representation of the sample's performance.
4. Widespread utilization of the transfer function method in existing literature reviews, facilitating better benchmarking and comparison of findings with published results.

3.3.1.2 Sound Absorption Coefficient (SAC) – The transfer function method

Let us first recall the below abbreviation:

α :	Sound absorption coefficient	R :	Reflection coefficient
H_I :	Transfer functions for incident wave	s :	Distance between the two microphones
H_R :	Transfer functions for reflected wave	k :	Complex wave number
p_{2I} :	Incident wave of microphone 2	x_1 :	Distance between microphone 1 and the sample
p_{1I} :	Incident wave of microphone 1	x_2 :	Distance between microphone 2 and the sample
c :	Speed of sound	f_e :	Excitation frequency
p_{2R} :	Reflected wave of microphone 2	p_{1R} :	Reflected wave of microphone 1
e :	Euler's number	H_{12} :	Ratio of incident wave to the reflected wave

The experiment involved conducting tests through the impedance tube, where a signal generator and speaker were used to produce sound pressure waves that were sent through the impedance tube. The waves traveled through the tube and hit the sample located at the other end. As a result, the energy of the waves was reduced, causing them to return with a lower amplitude. By measuring the sound pressure levels with two microphones, the transfer function was calculated as well as the sound absorption coefficient (α) [55], [56], [16].

The transfer functions for both the incident wave H_I and reflected wave H_R are expressed mathematically as:

$$H_I = \frac{p_{2I}}{p_{1I}} = e^{-jk(x_1 - x_2)} = e^{-jks} \quad (3.3)$$

$$H_R = \frac{p_{2R}}{p_{1R}} = e^{jk(x_1 - x_2)} = e^{jks} \quad (3.4)$$

Thereafter, the transfer function formula connecting two microphones, which is essentially the proportion of the incident wave to the reflected wave, can be expressed in the following way:

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{jkx_2} + R(e^{-jkx_2})}{e^{jkx_1} + R(e^{-jkx_1})} \quad (3.5)$$

Where k , the wave number, is defined by its real and imaginary parts as:

$$k = k' - jk'' \quad (3.6)$$

$$k' = \frac{2\pi \cdot f_e}{c} \quad (3.7)$$

$$k'' = \frac{4f_e}{c} \cdot \ln \left(\frac{\Delta_n}{2} + \sqrt{\frac{\Delta_n^2}{2} + 1} \right) \quad (3.8)$$

Where Δ_n is experimentally determined through measuring the amplitude of the acoustic pressure and applying:

$$\Delta_n = \frac{|p(x_{min,n+1})| - |p(x_{max,n})|}{|p(x_{max,n})|}, \quad n = 0, 1, 2, \dots \quad (3.9)$$

Thus, R can be expressed as:

$$R = e^{jkx_1} \cdot \frac{H_{12} - H_I}{H_R - H_{12}} \quad (3.10)$$

And finally:

$$\alpha = 1 - |R|^2 \quad (3.11)$$

3.3.1.3 Clarifications regarding the sound absorption coefficient

Using the term “Sound absorption Coefficient” without clarification could lead to miscommunications as there are different types that are studied and discussed in literature. Each of which provides different information. For instance:

- 1- Normal Incidence Sound Absorption Coefficient (α_n): This coefficient represents the fraction of incident sound that is absorbed by a material when sound waves hit it directly and perpendicularly. It is usually measured by the “Two Microphone Impedance Tube method” as will discussed.
- 2- Random Incidence Sound Absorption Coefficient (α_r): This coefficient represents the average absorption of sound waves that arrive at a material from all directions, taking into account both normal and angled sound waves. It can be experimentally determined through the reverberation room method.

The apparatus used in calculating the sound absorption coefficient, the impedance tube method, is limited in that it will yield only the “normal incidence” value of the sound absorption. However, Sound waves in real-world applications rarely incident on materials at normal incidence. In many practical applications, sound waves arrive at materials from various angles and directions. Thus, the normal incidence sound absorption coefficient may not accurately reflect the actual sound absorption performance of the material in these situations.

However, the impedance tube method is widely used in literature for measuring the acoustic properties of materials. This results in the added benefit of making it easier to compare the properties of different materials across different studies, as the same method

is being used. Moreover, the widespread use of the impedance tube method has led to the development of standardized testing procedures and data analysis techniques [57]. This further facilitates the comparison of results between different studies and ensures that the measurements are accurate and reliable.

As this study has utilized the impedance tube method, it should be assumed that any further references to the sound absorption coefficient (SAC) or its symbol (α) to be refereeing to the normal incidence values (NSAC and α_n).

3.3.1.4 Noise Reduction Coefficient (NRC)

The Noise Reduction Coefficient (NRC), typically denoted as a scalar value within the range of 0 to 1, serves as a descriptor of the average acoustic absorption properties of a given material. An NRC of 0.0 signifies the material's inability to attenuate mid-frequency sounds and, instead, its tendency to reflect sound energy. It is essential to note that achieving an NRC of 0.0 is more theoretical than practical. Conversely, an NRC of 1.0 indicates that the material is perfectly absorptive [58].

The Noise Reduction Coefficient (NRC) is calculated by averaging the sound absorption coefficients of a material across four 1/3 octave bands with centra frequencies: 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. and then rounding to the nearest multiple of 0.05 [59].

It can be mathematically represented as shown in Equation (3.12) keeping in mind that α_{250} , α_{500} , α_{1000} and α_{2000} refer to the average SAC values at across the full 1/3 octave band centered around 250, 500, 1000, and 2000 Hz respectively.

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \quad (3.12)$$

The NRC is mostly used to evaluate different types of building materials, since it focuses on how good the material is at absorbing low-mid frequencies. In other words, NRC is used to evaluate whether this material is suitable for domestic or office applications to eliminate noise generated from typical environmental and human sources [60]. Figure 35 below shows NRC values for common construction materials.

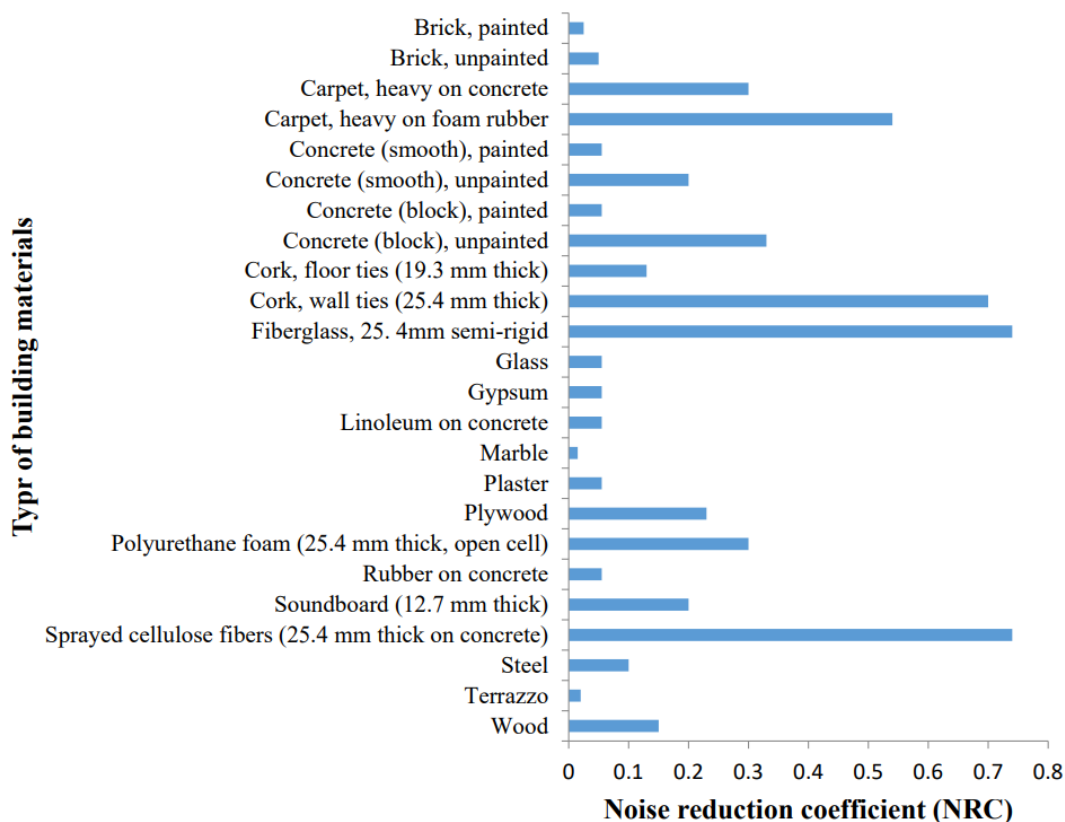


Figure 35 - NRC values for common construction materials [61].

However, it is important to note the following:

- 1- To calculate the Noise Reduction Coefficient, it is usually assumed that sound absorption coefficient discussed is the Random Incidence Sound Absorption Coefficient (α_r) measured through the reverberation room method. This is because it more closely reflects real life situations. However, as have been discussed in the

section 3.3.1.3, what has been measured for this research was the Normal Incidence Sound Absorption Coefficient (α_n), thus, direct comparison with values found in the industry may not be applicable. However, the reason for evaluating the NRC in this study was to compare it with values obtained through similar methods as found in the literature and as will be discussed in chapter 5

- 2- The Sound Absorption Average (SAA) has replaced NRC (Noise Reduction Coefficient) in the 1999 and subsequent versions of the ASTM C423 standard. SAA is a single numerical value rating of a material's sound absorption qualities that is similar to NRC. However, SAA measures twelve one-third octave bands between 200 Hz to 2500 Hz, instead of just four frequencies in a smaller range, and rounds to the nearest 0.01 instead of 0.05. This change has improved the repeatability of the measurement by including more data points. The increased measurement range and number of points make SAA a better indicator of low-frequency sound absorption performance. However, NRC has been chosen as an indicator in this thesis research for the same reason mentioned earlier in, which is to compare it with values obtained through similar methods as found in the literature and as will be discussed in chapter 5.

3.3.2 Experiment set-up

- 1- Impedance tube: Two impedance tubes need to be used in this experiment, as each has a limitation on testing frequencies, based on the diameter of the tube and the spacing between the two microphones. The larger diameter (100 mm) tube will be used for frequencies between 63 to 1600 Hz, although it needs to be done in two steps by changing the microphone spacing. Whereas the small tube (30 mm) will

be used for higher frequencies, up to 6300 Hz. There is overlapping in the covered frequency range, as can be seen in Table 9. Impedance tubes from BSWA TECH are available in the Acoustic and Noise Control unit in the Building Science Lab in building 19 in KFUPM's campus.

Table 9 breaks down the specification required for each frequency range

Table 9 – Specification of each frequency range

Frequency range [Hz]	Tube diameter [cm]	Microphone spacing [cm]	Distance from sample to nearest microphone [cm]	BSWA Impedance tube model
63-500	10	30	5	SW422
250-1600	10	8	5	SW422
1000-6300	3	2.25	1.5	SW477

- 2- Power amplifier: 50W power amplifier, utilized to generate white noise within the above-mentioned frequency range.
- 3- A multi-channel Data accusation and single output hardware
- 4- VA-Lab IMP software

Figure 36 shows the schematic of the lab set up.

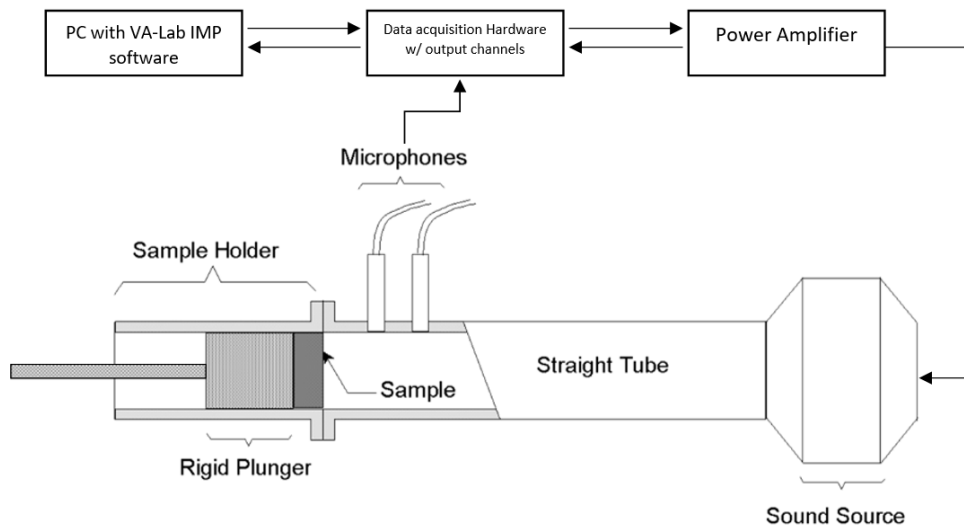


Figure 36 - Schematic of lab setup



Figure 37 - Experiment set-up in KFUPM-ARE Department Building Materials Lab



Figure 38 - Other equipment used in the experiments (Left: Kestrel 5500 Weather Meter. Right: Mettler Toledo precision balance)



Figure 39 - Loading some of the tested samples

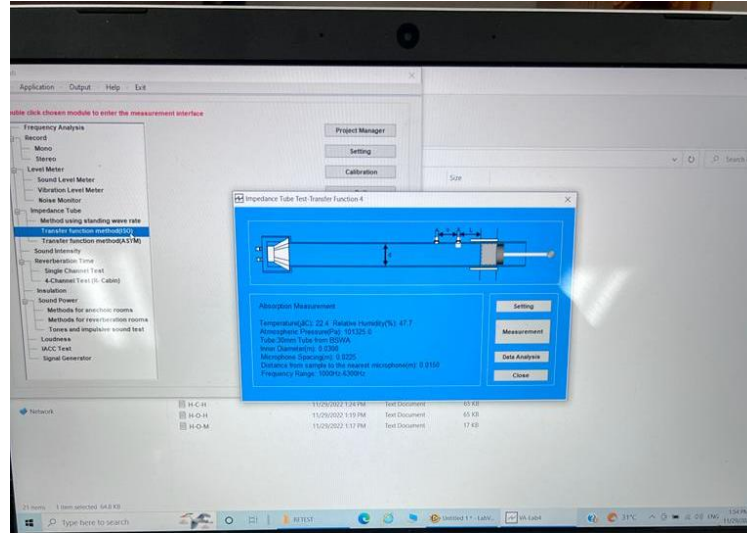


Figure 40 - VA-Lab IMP software



Figure 41 - Top: A multi-channel Data acquisition and single output hardware, Down: 50W power amplifier

3.3.3 Error analysis and minimization

Experiments using an impedance tube to measure the sound absorption coefficient of materials can be affected by several types of errors. One type of error that can occur is the measurement error, which may arise due to inaccurate calibration of the equipment, imprecise measurements of the dimensions of the sample material or misalignment of the microphone within the impedance tube. Another type of error is due to environmental

factors such as temperature, humidity, and air pressure variations that can affect the sound transmission properties.

Thus, to help minimize the potential errors, the below steps were taken:

- 1- Conducted a calibration check for the microphones.
- 2- Processed each measurement three times before recording any results while swapping the microphones prior to each run. This is in order to reduce the effect of phase difference between the two microphones.
- 3- Ran each test for a duration of 120 seconds, exceeding the minimum recommendation set by the manufacturer.
- 4- Repeated each test three times and averaged the results across the attempts.
- 5- Retested the best performing samples separately to confirm the validity of the results.
- 6- Recorded environmental conditions, including temperature and humidity, at the start of each testing session and input them into the software to accurately calculate air impedance.
- 7- Measured background noise levels before each testing session to ensure that the sound pressure level generated for the test was at least 10 dB higher than the background noise level.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of Enclosure Type (Enclosed vs. Open-Faced)

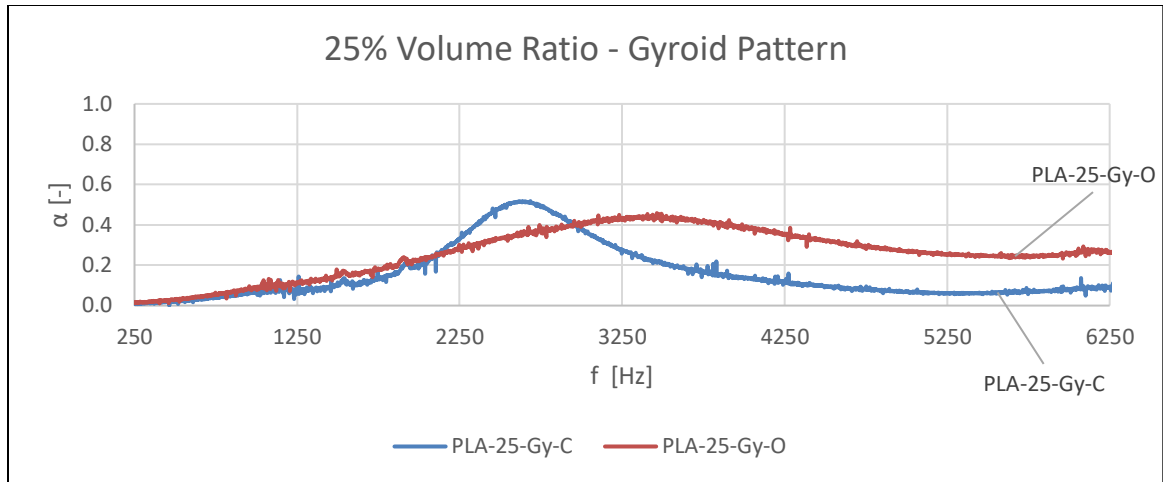
4.1.1 Theory to be tested

According to a study by Alkahari et al. [62], there exists an inherent porosity on all PLA 3D printed structures produced by commercially available printers. This porosity varies depending on the quality of the printer and the print parameters.

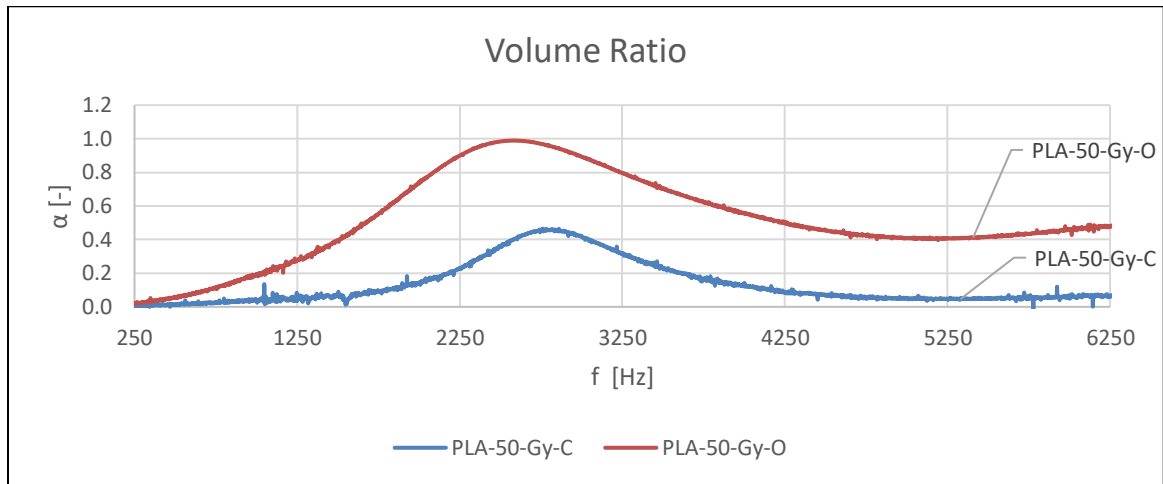
The idea was, if this porosity also exists in the top layer of the structure (although it is in the micro scale), it might still allow sound waves to be absorbed through the structure rather than reflected. If this was successful, it will theoretically allow for building excellent sound absorbing walls, without the needed for added insulation.

4.1.2 Obtained results

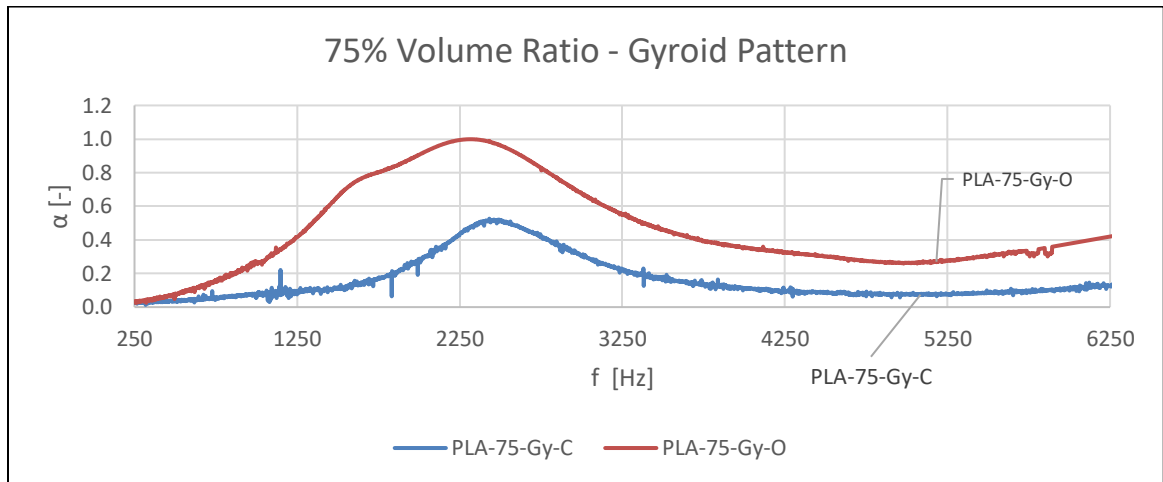
The below figures show the effect of end wall availability on the sound absorption characteristics of the printed samples. Each volume ratio and infill pattern configuration was printed and tested in two ways, one enclosed and one open-faced. The material used for all was PLA as it was the base material for the tests. Figures 42 a, b, and c showcase the difference between the enclosed and open-faced samples for samples printed in the Gyroid pattern, with different volume ratios.



(a)



(b)



(c)

Figure 42 - The effect of enclosure type of the sound absorption of Gyroid structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.

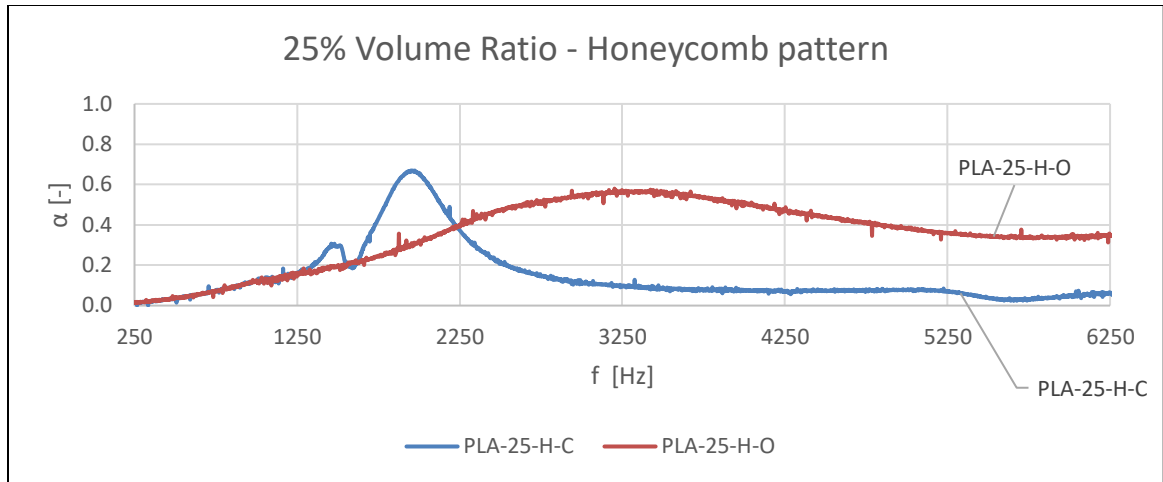
What can be observed from the above graphs is that with low volume ratios, having an enclosed structure will actually increase the value of the maximum sound absorption coefficient and decrease the excitation frequency at which this maximum value occurs. It is also observed that the difference between the maximum value for each configuration becomes even more pronounced the higher the volume ratio becomes.

Table 10 breaks down the values for each of the six samples shown above. Max α and Min corresponding frequencies are highlighted.

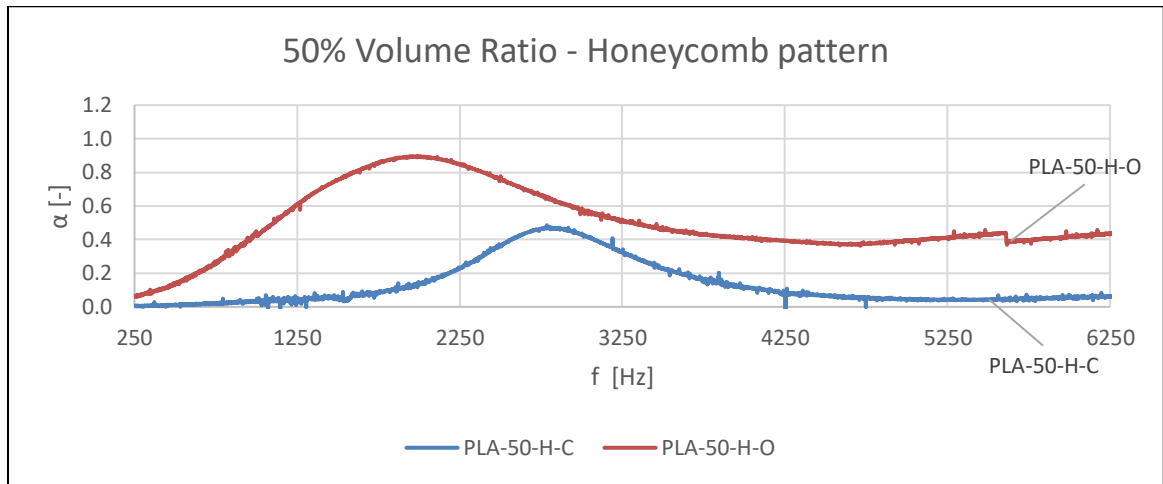
Table 10 - Summary of Gyroid infill pattern max results discussed in section 5.1.2

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-25-Gy-C	0.51801	2686
PLA-25-Gy-O	0.45862	3464
PLA-50-Gy-C	0.46535	2762
PLA-50-Gy-O	0.98958	2582
PLA-75-Gy-C	0.52623	2432
PLA-75-Gy-O	0.99899	2314

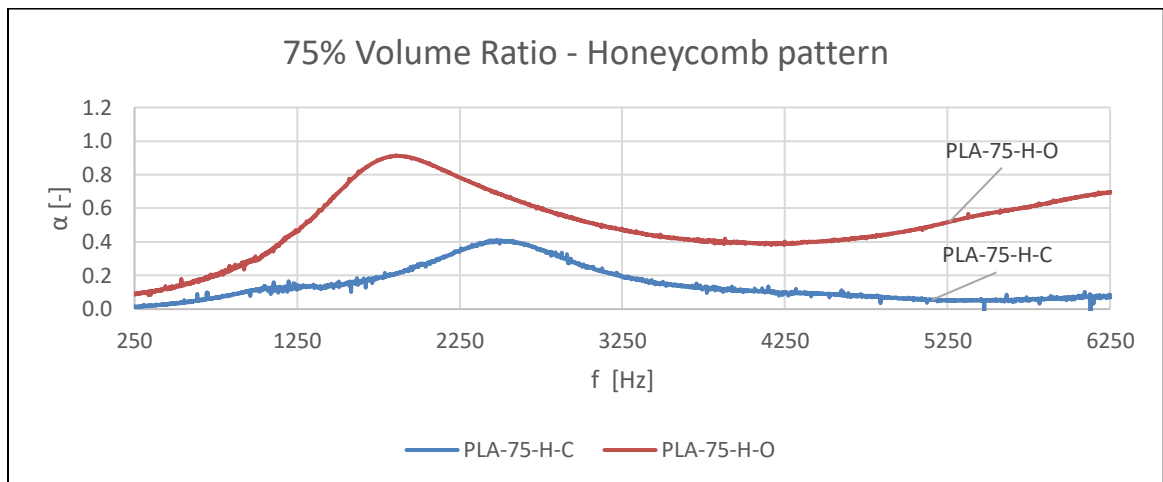
In order to ensure that the above results are not limited to a specific internal geometry or infill pattern, the same comparison was done for the other three infill patterns (as can be seen in the below Figures 43, 44 and 45) with similar results.



(a)

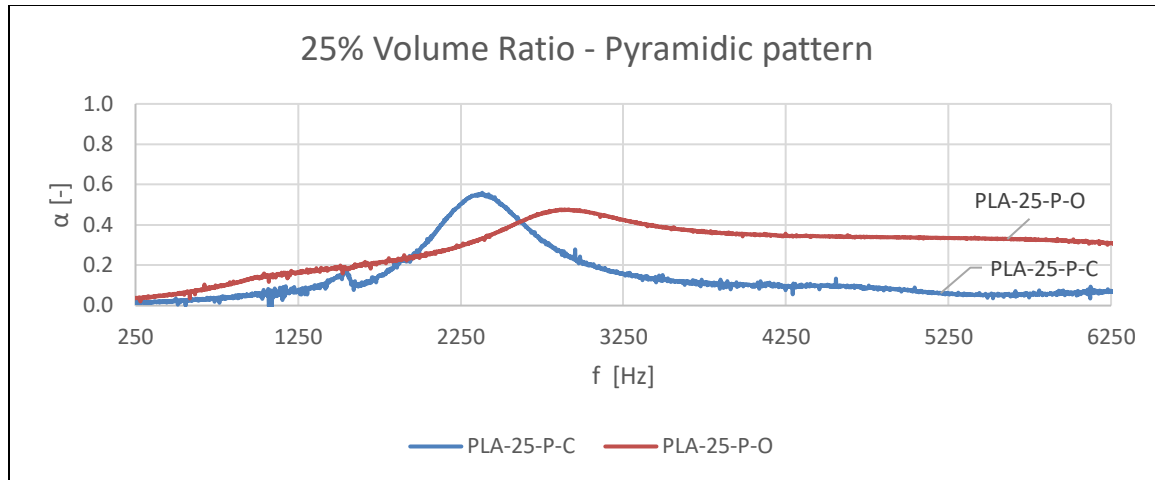


(b)

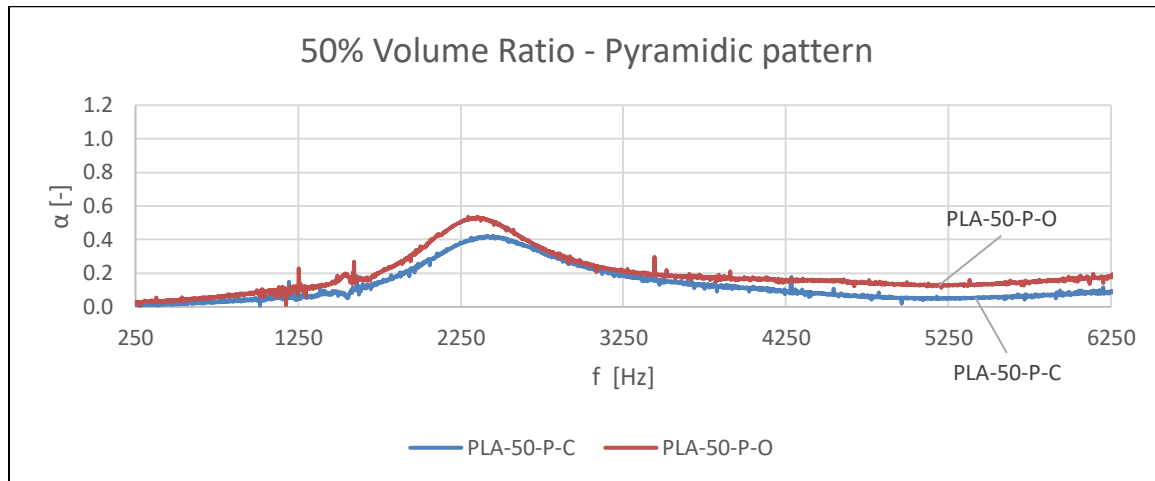


(c)

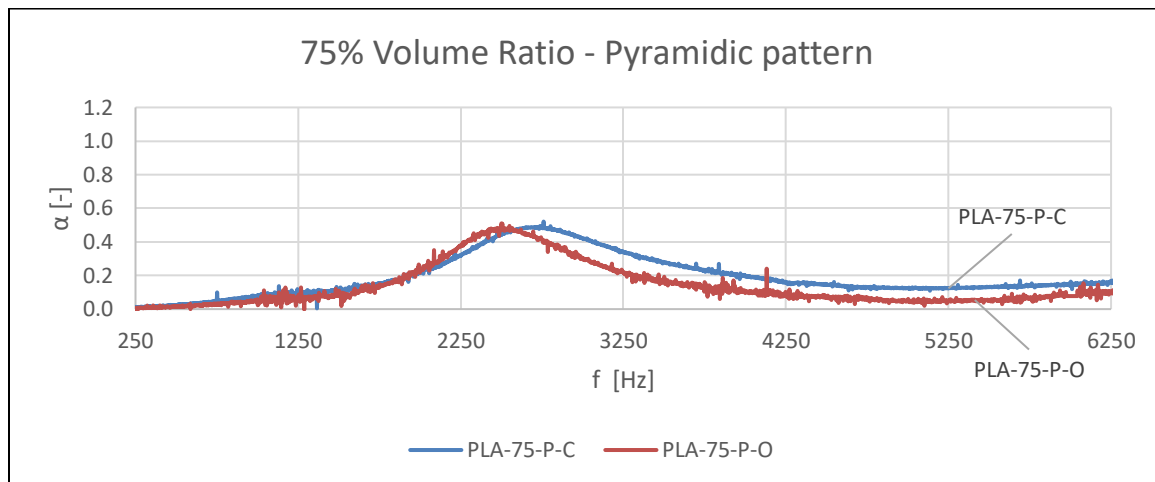
Figure 43 - The effect of enclosure type of the sound absorption of Honeycomb structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.



(a)



(b)



(c)

Figure 44 - The effect of enclosure type of the sound absorption of Pyramidic structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.

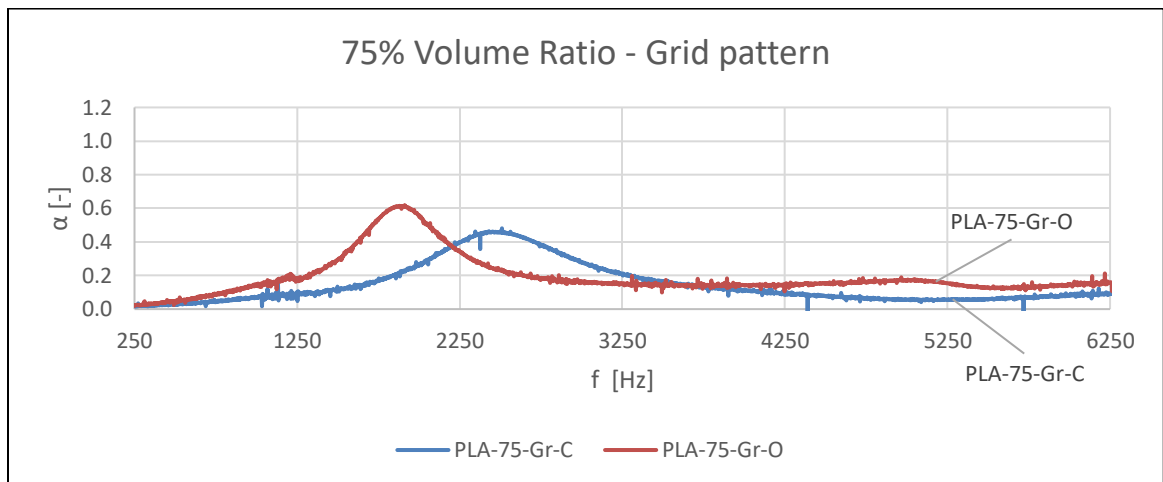
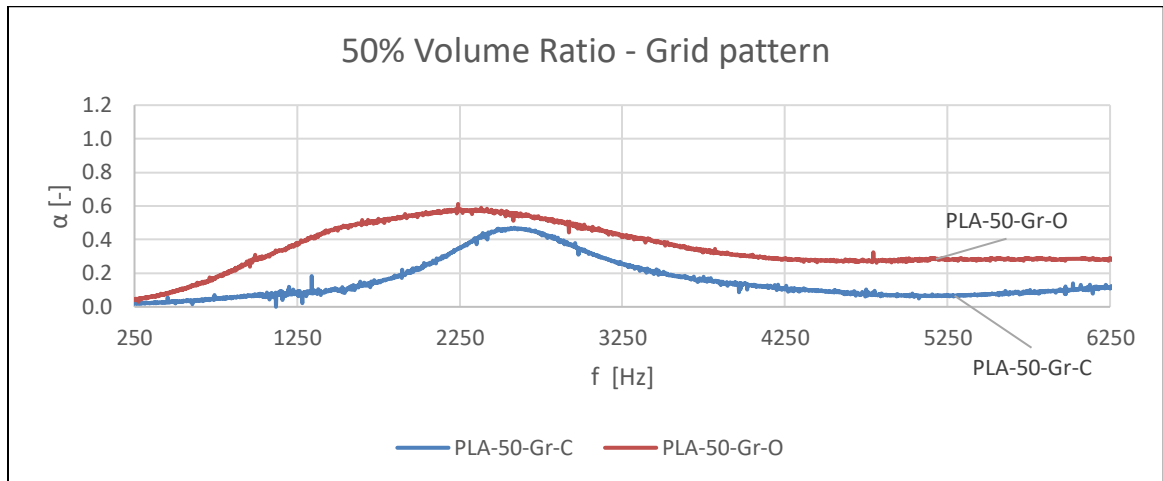
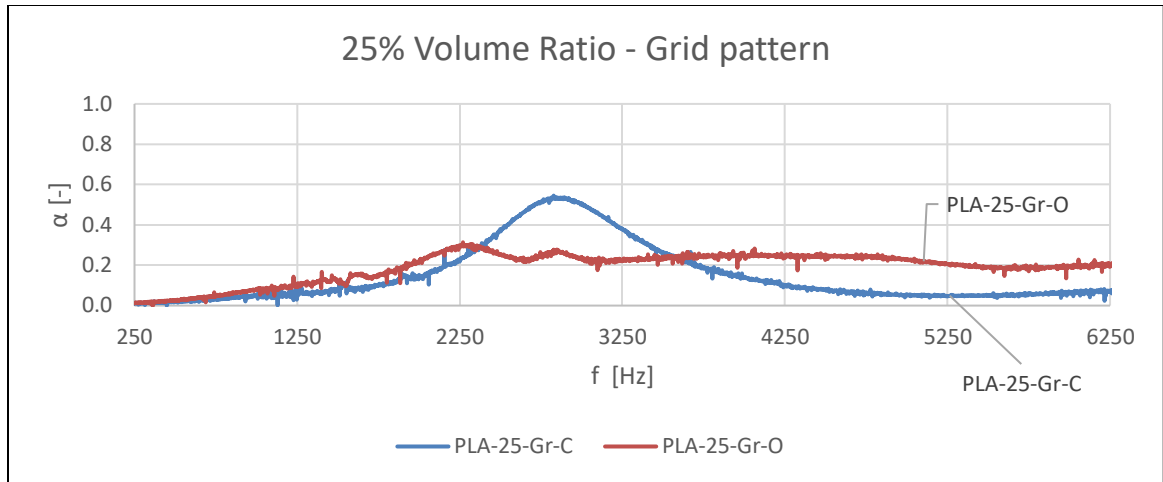


Figure 45 - The effect of enclosure type of the sound absorption of Grid structures with: a) 25% volume ratio, b) 50% volume ratio, c) 75% volume ratio.

It is important to note however that for the Pyramid pattern, this difference between the enclosed and open-faced structures is less pronounced, the justification for this will be discussed in the next section. Table 11 summarizes the maximum values for each of the eighteen samples shown above. Max α and Min corresponding frequencies are highlighted.

Table 11 - Summary of Honeycomb, Pyramidic, and Grid infill patterns max results discussed in section 4.1.2

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-25-Gr-C	0.54533	2828
PLA-25-Gr-O	0.31380	2270
PLA-25-H-C	0.66989	1950
PLA-25-H-O	0.58010	3202
PLA-25-P-C	0.55956	2382
PLA-25-P-O	0.47695	2914
PLA-50-Gr-C	0.47074	2586
PLA-50-Gr-O	0.61235	2240
PLA-50-H-C	0.48554	2786
PLA-50-H-O	0.89811	1990
PLA-50-P-C	0.42243	2412
PLA-50-P-O	0.53594	2296
PLA-75-Gr-C	0.48071	2510
PLA-75-Gr-O	0.61739	1910
PLA-75-H-C	0.41076	2474
PLA-75-H-O	0.91501	1856
PLA-75-P-C	0.52089	2760
PLA-75-P-O	0.50973	2500

4.1.3 Discussion of findings

Alkahari et al.'s [56] study findings appear to be of limited relevance to this thesis research. The reduced significance may stem from the small size of printer defects, particularly relating to the porosity of the top layer, or potentially from the utilization of more advanced printers in this thesis research (compared to the printers analyzed in their 2016 article).

In the context of mid and high volume ratios, the incorporation of an enclosure or end wall served to deflect sound waves that may have otherwise dissipated as heat within the

interconnected inner pores of the structure. Conversely, the low volume ratio structure exhibited characteristics similar to a plate positioned 2.54 cm (equivalent to the structure thickness) in front of a wall when fitted with such an enclosure, thus resulting in greater sound absorption than heat dissipation through the open-faced comparatively larger pores of the 25% infill.

As for the Pyramidic infill pattern, it consists of a completely isolated layers of pyramids that comes one on top of the other, as can be seen in Figure 46. This means that adding or removing the front wall will only cause the additional enclosure of the first few millimeters of the pattern, since the rest of the structure is already enclosed by the nature of the pattern itself.



Figure 46 - Showcasing the closed nature of the Pyramidic pattern (no straight pores from end to end)

4.2 Effect of Volume Ratio (Infill Density)

4.2.1 Theory to be tested

Increasing the volume ratio could allow for more intricate channels in which sound can be dissipated into heat. Also, it was shown through literature review that increasing the volume ratio is in fact a major factor in improving the acoustic properties of the structures. However, given that any increase in volume ratio is a direct increase in both cost and

manufacturing time, it is important to check how can we optimize all these different aspects together.

4.2.2 Obtained results

Figures 47, 48 and 49 show the effect of varying the volume ratio (or volume ratio) on the sound absorption characteristics of the printed samples. Each infill pattern configuration was printed and tested with three different volume ratios: 25%, 50%, and 75%. In addition, a sample with 100% volume ratio (this means that it does not have a unique infill pattern) was also manufactured, tested, and compared with the remaining samples.

The material used for all was PLA as it was the base material for the tests. Figure 47 showcases these differences when all sample were manufactured with the Gyroid pattern.

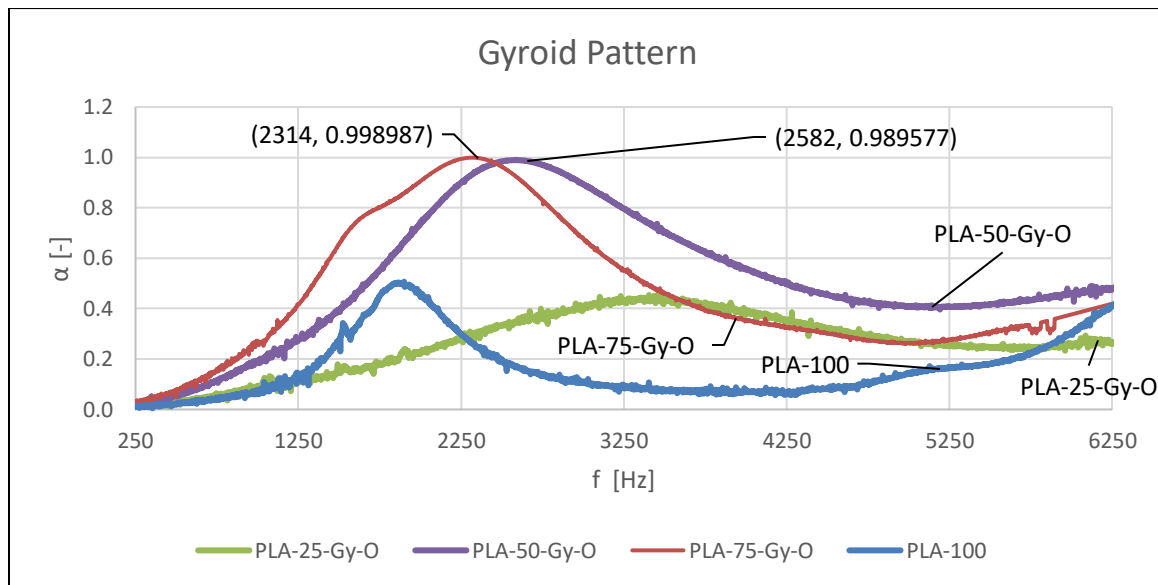


Figure 47 - The effect of varying the volume ratio on the sound absorption of Gyroid structures

As can be seen in the Figure 47 above, increasing the volume ratio resulted in both increasing the maximum sound absorption coefficient value, as well as reducing the frequency at which it occurs. However, this is up to a certain limit only, as the sample

printed with 100% volume ratio actually shows a lower maximum absorption than other printed samples (except for the low infill sample with 25% volume ratio).

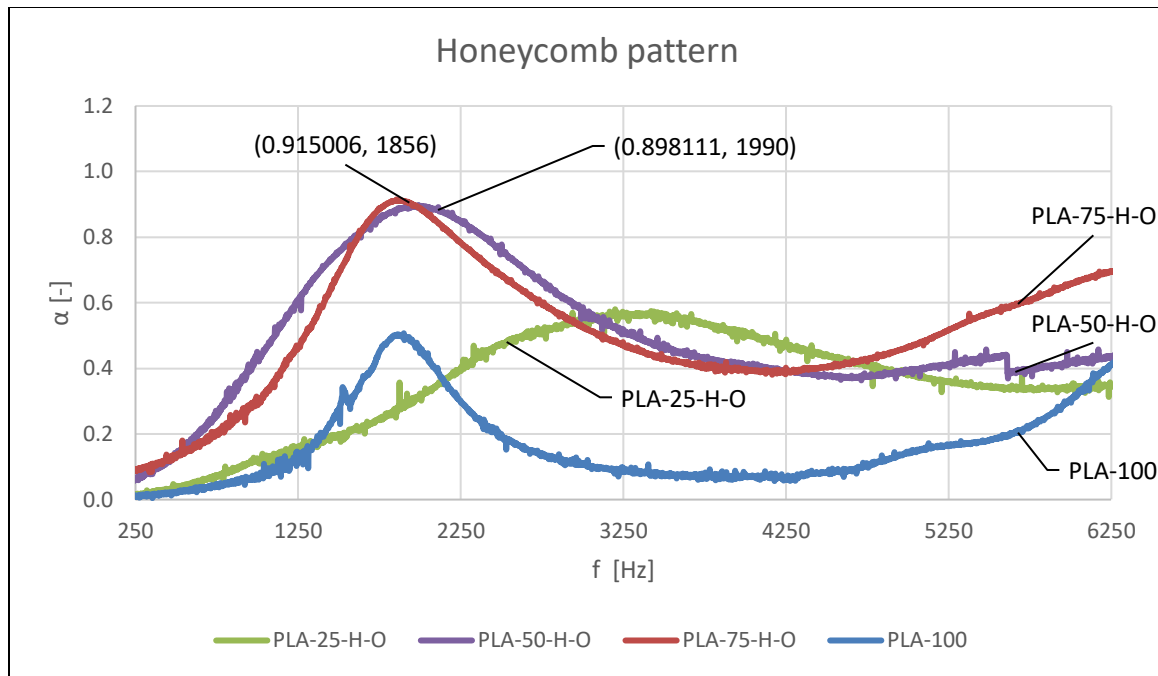
Also, it is good to note that increasing the volume ratio by 25% from 25% to 50% has resulted in increasing the maximum coefficient from 0.458620 to 0.989577 (i.e. a 115% increase) and reduced the corresponding frequency from 3464 Hz to 2582 Hz (i.e. a 25% decrease). However, another 25% increase in the volume ratio (from 50% to 75%) has only resulted in increasing the maximum coefficient by 0.95% and reducing the corresponding frequency by 10%. Above a certain limit, which was not determined by this set of experiments, further increasing the volume ratio will actually reduce the acoustic properties of the printed samples.

Table 12 breaks down the values for each of the four samples shown above. Max α and Min corresponding frequencies are highlighted.

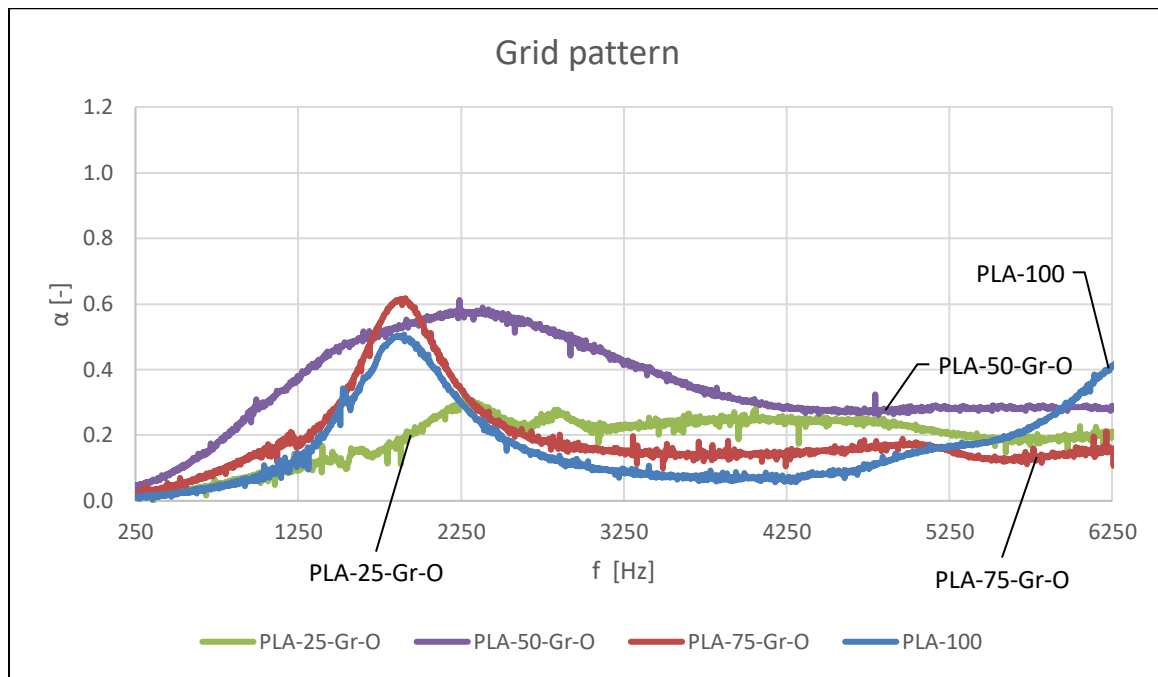
Table 12 - Summary of different volume ratios of Gyroid infill pattern max results discussed in section 5.2.2

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-100	0.50696	1900
PLA-25-Gy-O	0.45862	3464
PLA-50-Gy-O	0.98958	2582
PLA-75-Gy-O	0.99899	2314

This same behavior is repeated across two of the other infill patterns, as can be seen in Figures 48 and 49.



(a)



(b)

Figure 48 - The effect of varying the volume ratio on the sound absorption of a) Honeycomb Structures, b) Grid Structures

Table 13 breaks down the values for each of the seven samples shown above. Max α and Min corresponding frequencies are highlighted.

Table 13 - Summary of different volume ratios of Honeycomb and Grid infill pattern max results discussed in section 5.2.2

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-100	0.50696	1900
PLA-25-Gr-O	0.31380	2270
PLA-25-H-O	0.58010	3202
PLA-50-Gr-O	0.61235	2240
PLA-50-H-O	0.89811	1990
PLA-75-Gr-O	0.61739	1910
PLA-75-H-O	0.91501	1856

However, it is observed that the Pyramidic pattern does not show the same behavior as the others, as shown in Figure 49 and Table 14. This will be discussed in the next section of this thesis.

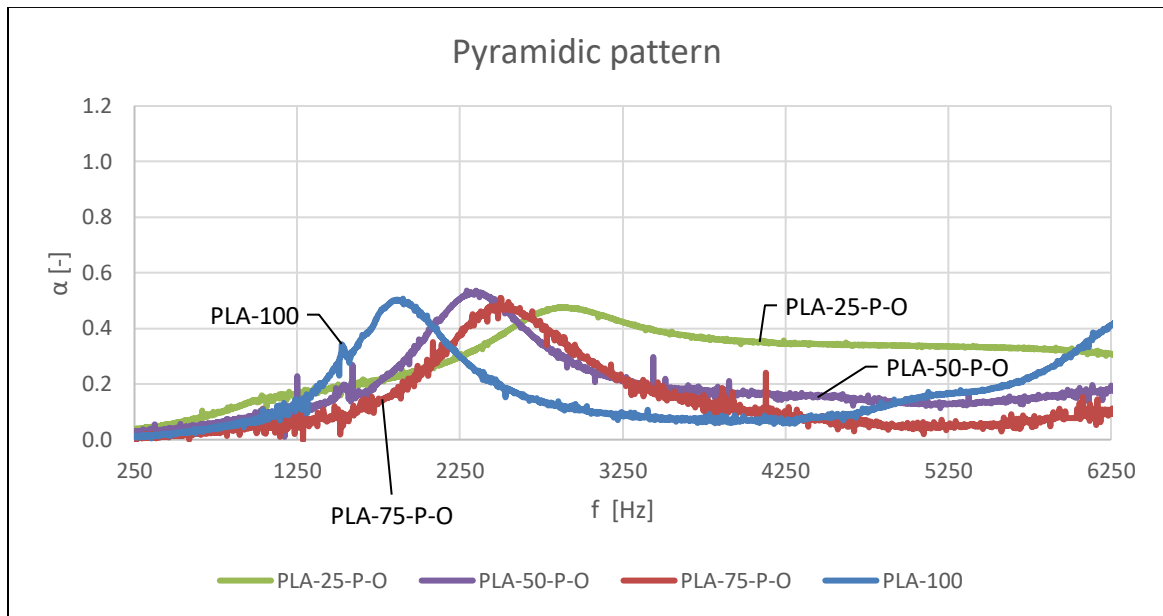


Figure 49 - The effect of varying the volume ratio on the sound absorption of Pyramidic structures

Table 14 - Summary of different volume ratios of Pyramidic infill pattern max results discussed in section 5.2.2

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-100	0.50696	1900
PLA-25-P-O	0.47695	2914
PLA-50-P-O	0.53594	2296
PLA-75-P-O	0.50973	2500

4.2.3 Discussion of findings

Based on the experimental findings presented in this study, a negative correlation was observed between sound absorption behavior and decreasing volume ratio for each printed sample. Despite the intuitive expectation that decreasing volume ratio would lead to improved sound absorption behavior by allowing sound waves to penetrate further into the porous structure, this observation is inconsistent with the remaining results presented in section 5.2.2. The underlying reason for this phenomenon is linked to the reduction in flow resistance of open cell structures, which occurs with decreasing volume ratio. As a result, sound waves are exposed to lower viscous effects, leading to less dissipation of sound energy. This conclusion is supported by a study conducted by Aslan et al. [55], which employed numerical flow analyses to examine various infill pattern open-cell structures across a range of volume ratios using the ANSYS-Fluent package program. However, it should be noted that this phenomenon is only valid up to a certain extent, as for 100% volume ratio, there are no clear paths for flow resistance to be encountered, and the acoustic properties of the material of construction will primarily dictate the outcome.

4.3 Effect of Infill Pattern (Internal Geometry)

4.3.1 Theory to be tested

The theory was to test if the complexities allowed by 3D design can add a significant advantage to sound absorbers made by material traditionally not used in this context. This is true in traditional material through normal manufacturing techniques. For instance, a 1” wide assembly of stainless steel wool could offer more beneficial acoustic properties than

a 1” thick plate of steel. This is due to the intricate web of channels created by the wool, resulting in more sound energy absorption.

4.3.2 Obtained results

Figures 50, 51 and 52 show the effect of varying the infill pattern (or internal geometry) on the sound absorption characteristics of the printed samples. Each volume ratio configuration was printed and tested with four different infill patterns: Gyroid, Honeycomb, Grid, and Pyramidic.

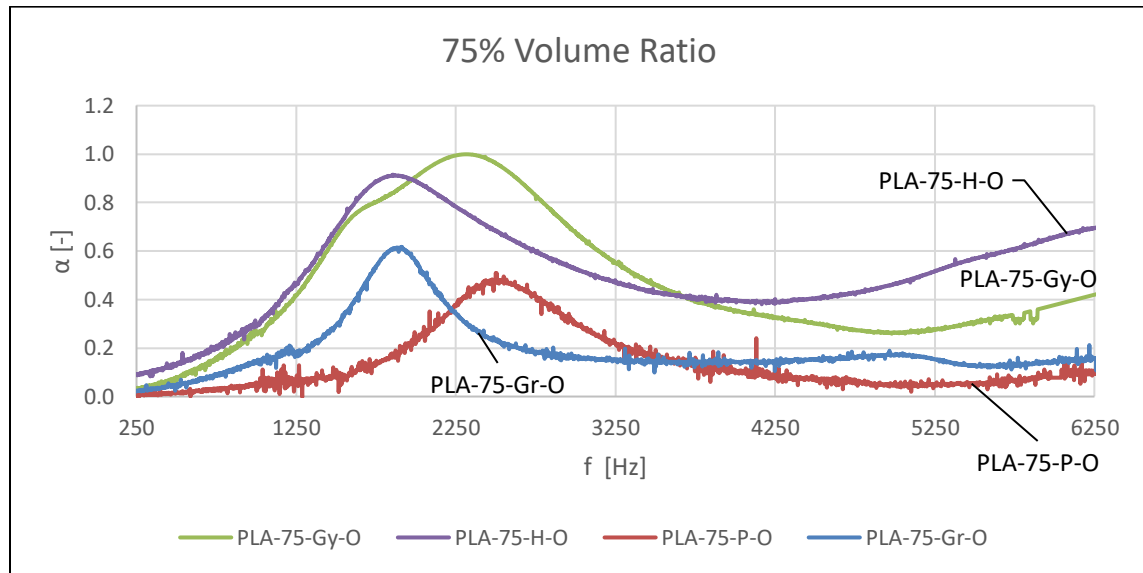


Figure 50 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 75% volume ratio.

Figure 50 above shows that the best candidates for fabricating 3D printed sound absorbers are Gyroid and Honeycomb patterns. Although, the Gyroid patterns offer a better overall maximum SAC (sound absorption coefficient) value, the Honeycomb structure results in a lower corresponding frequency for this maximum, thus, possibly being more desirable for broader real-life applications.

Table 15 - Max α and corresponding frequencies for different infill patterns printed with 75% volume ratio.

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-75-Gr-O	0.61739	1910
PLA-75-Gy-O	0.99899	2314
PLA-75-H-O	0.91509	1856
PLA-75-P-O	0.50973	2500

As can be seen in Table 15, Gyroid infill at 75% volume ratio offers almost a perfect absorption, however, the corresponding frequency is considered high, which limits its application. And although the Honeycomb structure max SAC is 9% is less than the Gyroid one, it is still significant, and it is within a better frequency range.

Figure 51 and Table 16 show the same behavior at structures with 50% volume ratios.

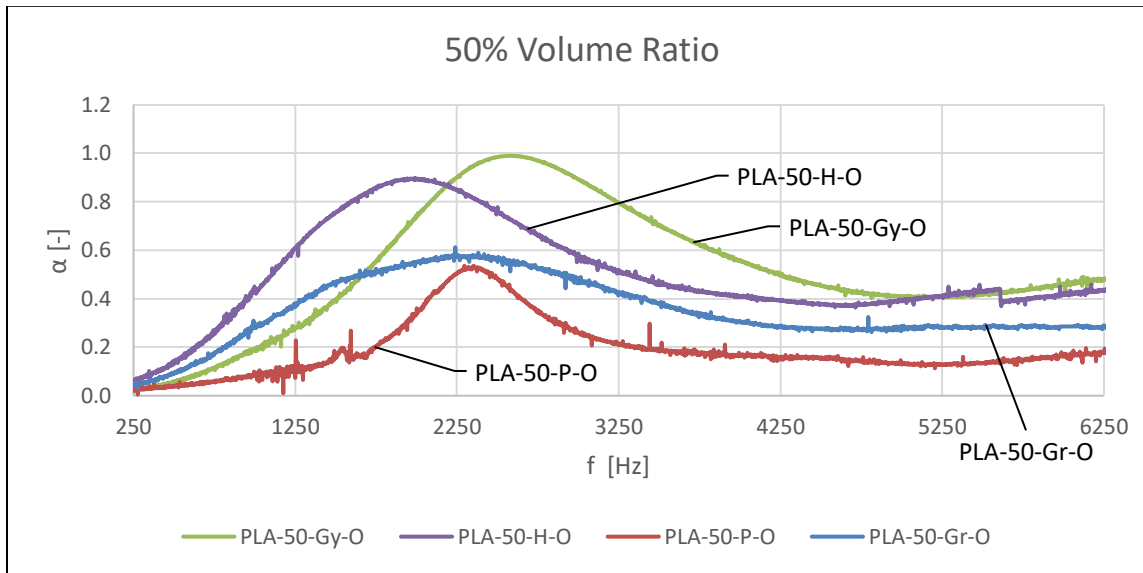


Figure 51 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 50% volume ratio.

Table 16 - Max α and corresponding frequencies for different infill patterns printed with 50% volume ratio.

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-50-Gr-O	0.61235	2240
PLA-50-Gy-O	0.98958	2582
PLA-50-H-O	0.89811	1990
PLA-50-P-O	0.53593	2296

At a 25% volume ratio, however, this effect can't be detected, and the same conclusion can not be reached, as observed in Figure 52 and Table 17.

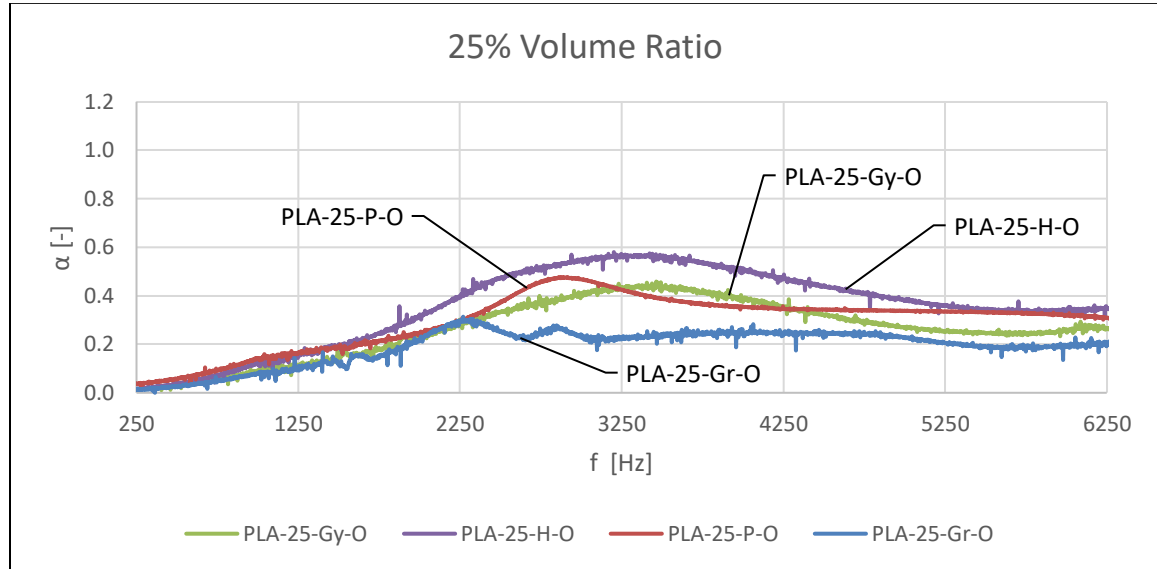


Figure 52 - The effect of using different infill patterns on the sound absorption coefficient of structures printed with 25% volume ratio.

Table 17 - Max α and corresponding frequencies for different infill patterns printed with 25% volume ratio.

Sample	Max α [-]	Corresponding frequency [Hz]
PLA-25-Gr-O	0.31379	2270
PLA-25-Gy-O	0.45862	3464
PLA-25-H-O	0.58010	3202
PLA-25-P-O	0.47694	2914

4.3.3 Discussion of findings

The infill pattern of a 3D printed structure clearly has a significant effect on its sound absorption characteristics. As sound absorption is directly influenced by the flow resistance cause by the viscous effect as the sound wave passes through the structure [55], it makes intuitive sense why more complex three-dimensional structures with interconnected channels in which sound can pass through would result in a better sound absorption.

The gyroid infill pattern is a complex lattice structure that is often used in 3D printing because of its unique geometric properties. When it comes to sound absorption, the gyroid infill pattern is particularly effective because of its high surface area-to-volume ratio, which allows for increased friction and turbulence as sound waves pass through the structure. Specifically, the complex geometry of the gyroid infill pattern creates a large number of interconnected air pockets and channels within the material. These air pockets and channels can effectively trap and dissipate sound energy as it passes through the structure, leading to a high sound absorption coefficient.

The three-dimensional honeycomb pattern offers similar properties to the gyroid pattern, although to a lesser extent. Additionally, the 3D honeycomb pattern consists of small openings of varying sizes and enlarged inner bodies, resembling the design of a Helmholtz Resonator (although a poorly designed one), this could offer an explanation for the reduction in the excitation frequency at which the maximum absorption occurs.

4.4 Effect of Material of Construction

4.4.1 Theory to be tested

The current literature available on the topic, although limited given the novelty of the field, predominantly centers around structures constructed from ABS or ASA. However, PLA has recently gained popularity as a preferred material for 3D printing due to a variety of advantageous features, as will be outlined in section 6.3.4. Consequently, it is of considerable interest for researchers to investigate whether PLA exhibits similar acoustic properties to those observed in ABS and ASA. Similar reasoning is applied for testing out

the Woodfilled-PLA, with the added advantages of being an aesthetically pleasing material and having a natural wood flour engrained into the material.

4.4.2 Obtained results

In addition to PLA, alternative construction materials (ABS, ASA, and Woodfilled PLA) were evaluated for the 75%-Gyroid-Open and 75%-Honeycomb-Open infill configurations, which are the configurations that showed the most promising results.

Starting with the gyroid structures, as expected, ABS and ASA materials performed in a very similar way to each other (given how closely related these two materials are). However, when compared to PLA, it seems that the corresponding frequency for the maximum coefficient is shifted slightly to a larger value. And although the maximum coefficient for both ABS and ASA is higher than that of PLA, it is only higher by 0.09%, whereas it increases the corresponding frequency by up to 20%. Finally, Woodfilled PLA is shown to be a poor material choice for the structures given how it has performed in the test as shown in Figure 53 and Table 18.

Figure 53 - The effect of changing the material of construction on the sound absorption of the structures printed with Gyroid structures

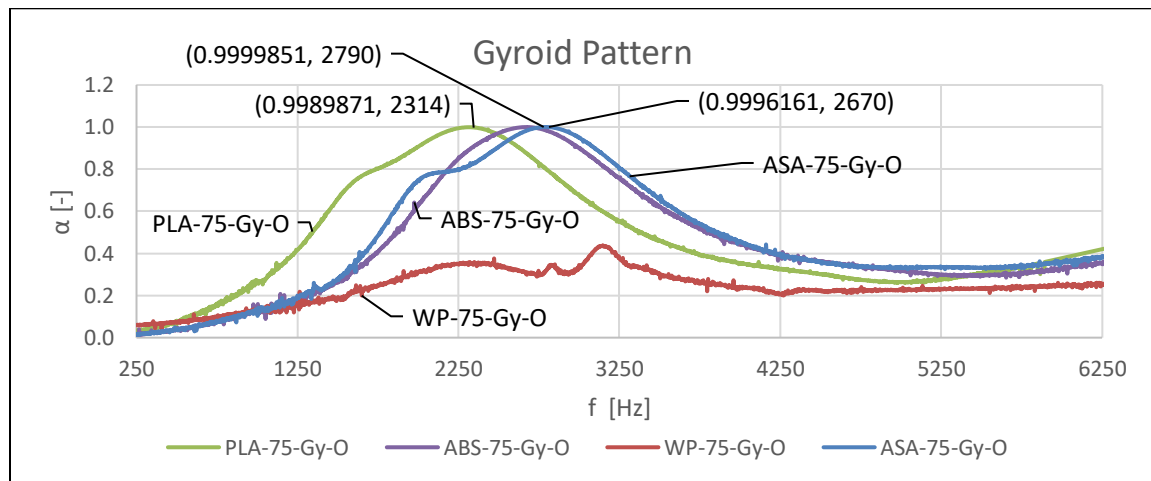


Table 18 - Max α and corresponding frequencies for different materials printed with 75% volume ratio and Gyroid infill pattern

Sample	Max α [-]	Corresponding frequency [Hz]
ABS-75-Gy-O	0.99962	2670
ASA-75-Gy-O	0.99999	2790
PLA-75-Gy-O	0.99899	2314
WP-75-Gy-O	0.43842	3148

As can be seen in Figure 54 and Table 19, this same behavior for Woodfilled PLA is repeated with the Honeycomb pattern as well. In addition, ABS and ASA also show a very similar behavior again. The only difference between the Gyroid and Honeycomb structures was that in the below case, PLA did edge out ABS and ASA by having a slightly higher maximum coefficient, although it was only by 7%.

Figure 54 - The effect of changing the material of construction on the sound absorption of the structures printed with Honeycomb structures

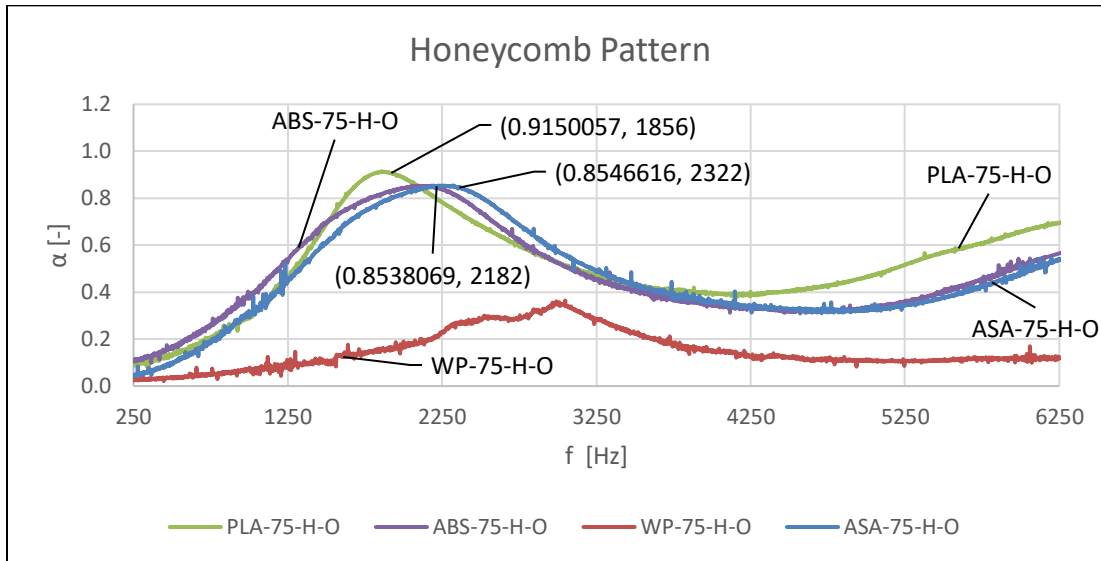


Table 19 - Max α and corresponding frequencies for different materials printed with 75% volume ratio and Honeycomb infill pattern

Sample	Max α [-]	Corresponding frequency [Hz]
ABS-75-H-O	0.85380	2182
ASA-75-H-O	0.85466	2322
PLA-75-H-O	0.91500	1856
WP-75-H-O	0.36436	3048

4.4.3 Discussion of findings

It makes intuitive sense how closely the values of ABS and ASA. ASA (Acrylonitrile Styrene Acrylate) and ABS (Acrylonitrile Butadiene Styrene) are both thermoplastics with similar chemical structures and material properties. In fact, ASA can be considered a modified version of ABS, with the addition of an acrylic ester component that gives it better UV resistance and weatherability. They also have very similar mass densities and other physical properties. PLA on the other hand, which is also a thermoplastic, share many of the characteristics but also a few key differences.

PLA is a biodegradable polyester derived from renewable resources such as cornstarch or sugarcane. Its monomer unit is lactic acid. The polymer chains in PLA are linear and have a regular structure, which contributes to its biodegradability. ABS is a amorphous terpolymer made up of three monomers: acrylonitrile, butadiene, and styrene. The polymer chains in ABS are more complex and branched, with random terpolymer sequences of the three monomers. This structure gives ABS its high impact resistance and toughness. ASA is a terpolymer made up of three monomers: acrylonitrile, styrene, and acrylic ester. The polymer chains in ASA are similar to those in ABS, but with the addition of the acrylic ester monomer, which gives it the better UV resistance and weatherability.

Given that there are no differences in the design or manufacturing process, it can be concluded that the reasoning for the difference in acoustic properties of the printed samples comes down to the differences in the chemical composition of each of these materials.

4.5 Noise Reduction Coefficient

Table 20 showcases the top 20 performing samples relating to their NRC rating.

Table 20 – Top 20 NRC rated samples

Sample Label	Average SAC values at across full 1/3 octave bands				NRC
	α_{250}	α_{500}	α_{1000}	α_{2000}	
PLA-50-H-O	0.06	0.14	0.43	0.88	0.40
ABS-75-H-O	0.11	0.17	0.39	0.84	0.40
PLA-75-H-O	0.09	0.13	0.31	0.87	0.35
PLA-75-Gy-O	0.03	0.08	0.27	0.91	0.30
ASA-75-H-O	0.05	0.10	0.31	0.82	0.30
PLA-50-Gy-O	0.02	0.06	0.19	0.74	0.25
PLA-50-Gr-O	0.04	0.09	0.28	0.55	0.25
ASA-75-Gy-O	0.02	0.04	0.13	0.71	0.20
ASA-75-Gy-C	0.06	0.09	0.17	0.54	0.20
ABS-75-Gy-O	0.02	0.04	0.13	0.63	0.20
PLA-25-H-C	0.01	0.04	0.12	0.56	0.20
PLA-75-Gr-O	0.02	0.05	0.14	0.52	0.20
ABS-75-Gy-C	0.02	0.03	0.08	0.56	0.20
ABS-75-H-C	0.03	0.04	0.09	0.53	0.20
ASA-75-H-C	0.02	0.04	0.10	0.42	0.15
WP-75-Gy-O	0.06	0.07	0.13	0.31	0.15
PLA-100	0.01	0.02	0.07	0.43	0.15
PLA-50-P-O	0.03	0.04	0.08	0.35	0.15
PLA-25-H-O	0.02	0.04	0.12	0.32	0.10
PLA-25-P-O	0.04	0.06	0.14	0.25	0.10

As stated in Section 3.3.1.3, the Noise Reduction Coefficient (NRC), expressed mathematically by Equation (3.12), centers on the capacity of the material to absorb low to mid frequencies. Therefore, as evidenced by the tabulated results, specimens exhibiting a lower excitation frequency associated with the peak maximum absorption coefficient exhibited superior NRC performance relative to counterparts even if they have a higher overall maximum absorption coefficient.

CHAPTER 5

CONCLUSION

5.1 Summary of Results for All Tested Samples

Table 21 shows the Max Sound Absorption Coefficient for each of the 37 samples that were tested. In addition, the corresponding frequency for these values are also listed. And given that the shape of these curves is always very similar to each other (for porous absorbers), this table will give an indication regarding the proper applications for each absorber based on the frequency range. The table is ranked in a descending order related to the max SAC values. Following the table, the top 12 samples are plotted to allow for the reader to compare and contrast the values at different frequency ranges if desired.

It can be seen from the table that the Gyroid infill pattern with 75% volume ratio offers the highest value for SAC for all three different Polymers (ASA, ABS, and PLA). However, this comes at a cost of increasing the corresponding frequency for that maximum, which could limit the applications for these structures in the real world.

On the other hand, the Honeycomb pattern (likely due to the resonance effect), still provides a good SAC value but with a much improved frequency range.

The table also shows that there isn't a noticeable difference in the SAC values between the three main Polymers, however, PLA has the benefit of having its maximum SAC at a lower corresponding frequency. Also, it is clear that Woodfilled-PLA is a terrible choice for a sound absorber given how it performed in the tests.

Table 21 - Max Sound Absorption Coefficient and corresponding frequency for each of the 37 samples.

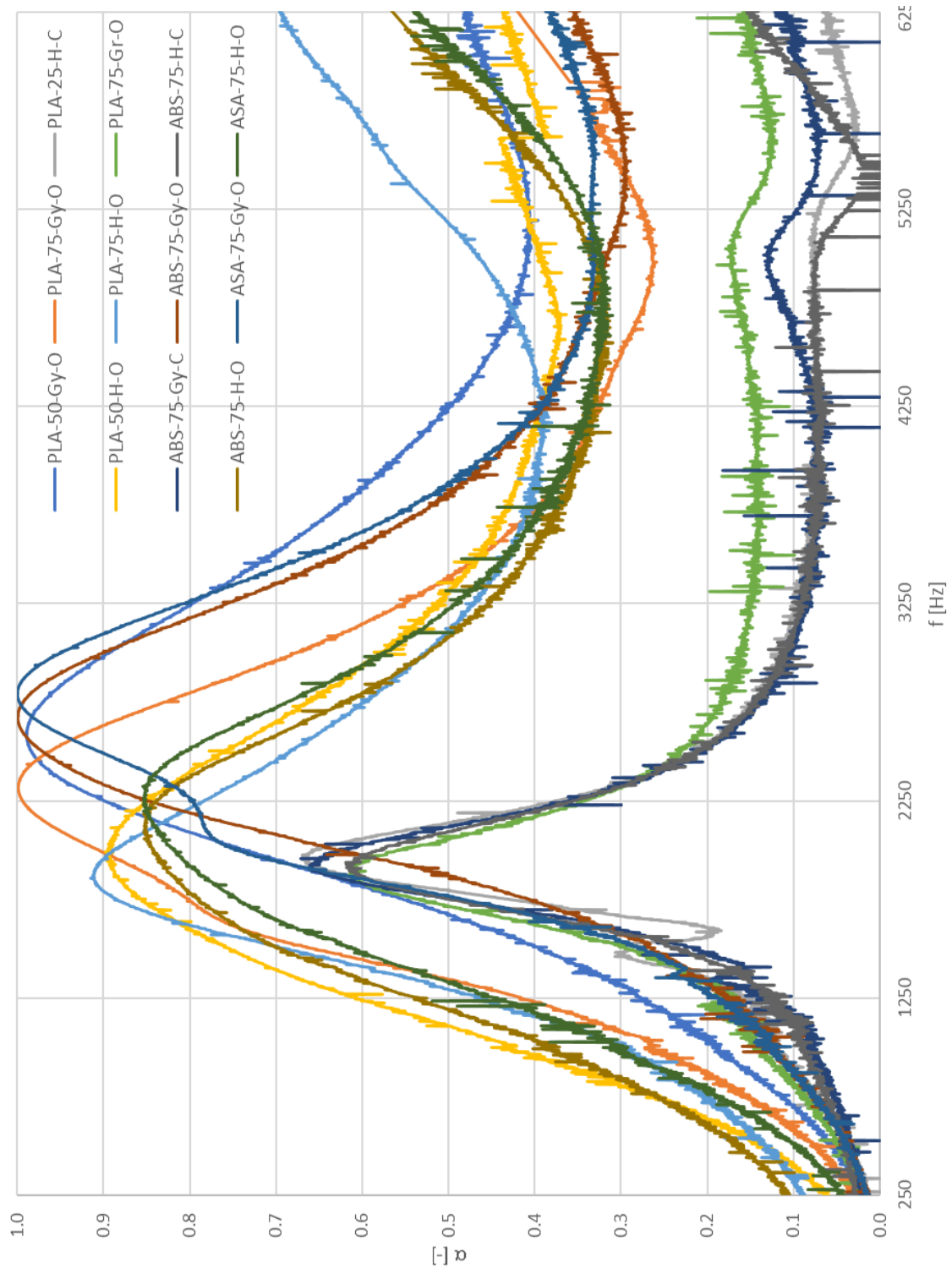
Sample Label	Max α [-]	Corresponding frequency [Hz]
ASA-75-Gy-O	0.99999	2790
ABS-75-Gy-O	0.99962	2670
PLA-75-Gy-O	0.99899	2314
PLA-50-Gy-O	0.98958	2582
PLA-75-H-O	0.91501	1856
PLA-50-H-O	0.89811	1990
ASA-75-H-O	0.85466	2322
ABS-75-H-O	0.85381	2182
ABS-75-Gy-C	0.67141	1956
PLA-25-H-C	0.66989	1950
ABS-75-H-C	0.61914	1936
PLA-75-Gr-O	0.61739	1910
PLA-50-Gr-O	0.61235	2240
ASA-75-Gy-C	0.59976	1992
PLA-25-H-O	0.58010	3202
PLA-25-P-C	0.55956	2382
PLA-25-Gr-C	0.54533	2828
PLA-50-P-O	0.53594	2296
PLA-75-Gy-C	0.52623	2432
PLA-75-P-C	0.52089	2760
PLA-25-Gy-C	0.51801	2686
PLA-75-P-O	0.50973	2500
PLA-100	0.50696	1900
ASA-75-H-C	0.49052	2076
PLA-50-H-C	0.48553	2786
PLA-75-Gr-C	0.48071	2510
PLA-25-P-O	0.47694	2914
PLA-50-Gr-C	0.47074	2586
PLA-50-Gy-C	0.46535	2762
PLA-25-Gy-O	0.45862	3464
WP-75-Gy-O	0.43842	3148
WP-75-Gy-C	0.42405	2426
PLA-50-P-C	0.42243	2412
PLA-75-H-C	0.41076	2474
WP-75-H-O	0.36436	3048
WP-75-H-C	0.31626	1154
PLA-25-Gr-O	0.31379	2270

Less Desirable Values

More Desirable Values

Figure 55 combines the “ α vs. Frequency” plots for the top 12 performing samples as per their maximum SAC values.

Figure 55 – Sound Absorption Curves for the best 12 configurations of printed samples



5.2 Overall Evaluation of the Results

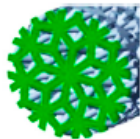
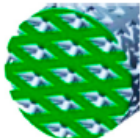
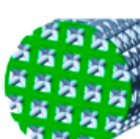
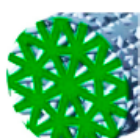
5.2.1 Evaluation of maximum absorption coefficient values

Looking at the summary of the above results, it can be concluded that the efforts done in this thesis research to produce unique sound absorbers through the use of the complexities only allowed by 3D printing technologies were in fact successful. This statement can be justified by the following: comparing the above results with values found in literature and industry, and explaining the possible applications for the produced structures.

5.2.1.1 Comparing results with values found in literature

In Monkova et al.'s study [16], the four designs used as infill patterns were all two dimensional as shown in Table 22:

Table 22 – the four infill pattern designs studied in Monkova et al.'s research

Pattern	Cross Section
Starlit	
Rhomboid	
Cartesian	
Octagonal	

And in their study, they managed to obtain excellent results only by adding an air gap behind the tested samples. Thus, the improvement by using the Gyroid and the three-dimensional honeycomb structure developed and tested in this study is well realized. Eliminating the need to have an air gap allows for direct wall mounting, thus expanding the possible applications for the absorber. Also, this study managed to produce an excellent absorber with a lower volume ratio, thus, saving in both cost and time of manufacturing. Similarly, Vasina et al., [17] did develop similar structures. And in their study, they checked the acoustic properties of the printed samples without employing an air gap as well. However, due to the non-complex infill patterns that were selected, the obtained results were not desirable.

Table 23 compares the best obtained results from Vasina et al.'s study (in which they did not utilize an air gap) to the results obtained from this thesis study.

Table 23 - Comparing the best obtained results from this study to Vasina et al.'s research

Infill pattern (Or sample label)	Volume Ratio [%]	Sample Thickness [cm]	Air Gap [cm]	Max α [-]	Corresponding frequency [Hz]
Cartesian (Vasina's et al.)	57	3	0	0.76	2096
Starlit (Vasina's et al.)	57	2	0	0.88	5328
ASA-75-Gy-O	75	2.54	0	0.999985	2790
ABS-75-Gy-O	75	2.54	0	0.999616	2670
PLA-75-Gy-O	75	2.54	0	0.998987	2314
PLA-50-Gy-O	50	2.54	0	0.989577	2582
PLA-75-H-O	75	2.54	0	0.915006	1856
PLA-50-H-O	50	2.54	0	0.898111	1990

Table 24 shows that the results obtained in this thesis research are also comparable with best results obtained from the Monkova's et al.'s research even while their set-up utilizes an air gap of up to 10 cm behind the tested samples.

Table 24 - Comparing the best obtained results from this study to Monkova et al.'s research

Infill pattern (Or sample label)	Volume Ratio [%]	Sample Thickness [cm]	Air Gap [cm]	Max α [-]	Corresponding frequency [Hz]
Cartesian (Monkova's et al.)	70	3	6	0.999959	3736
Octagonal (Monkova's et al.)	70	3	8	0.999995	3488
Rhomboid (Monkova's et al.)	70	3	10	0.999763	1728
Starlit (Monkova's et al.)	70	3	10	0.999937	3920
ASA-75-Gy-O	75	2.54	0	0.999985	2790
ABS-75-Gy-O	75	2.54	0	0.999616	2670
PLA-75-Gy-O	75	2.54	0	0.998987	2314
PLA-50-Gy-O	50	2.54	0	0.989577	2582
PLA-75-H-O	75	2.54	0	0.915006	1856
PLA-50-H-O	50	2.54	0	0.898111	1990

5.2.1.2 Comparing results with published values by manufacturers.

The “Acoustic Project Design Bureau - akustik.ua” company publishes a list in their website for the sound absorption performance for some of their building material [63], [64]. In this section, multiple 1” traditional sound absorbing material will be compared to the best performing samples from this thesis.

It should be noted that the published values are reported as the average for $1/1$ octave bands with center frequencies varying from 125 to 4000 Hz. Table 25 will list down these values for the 1” samples tested by the company for:

- 1- Melamine-Based Foam.
- 2- Glass wool (16 kg/m³).
- 3- Glass wool (24 kg/m³).

Then Figure 56 will plot these $1/1$ octave sound absorption coefficients for comparison.

Table 25 - akustik.ua published data compared to some of the best performing samples from this research

Sample Label	Average SAC values at across full $1/1$ octave bands				
	α_{250}	α_{500}	α_{1000}	α_{2000}	α_{4000}
PLA-50-H-O	0.07	0.15	0.48	0.80	0.44
ABS-75-H-O	0.11	0.18	0.43	0.76	0.38
PLA-75-H-O	0.09	0.14	0.36	0.76	0.46
PLA-75-Gy-O	0.03	0.09	0.32	0.87	0.38
ASA-75-H-O	0.05	0.11	0.35	0.76	0.39
PLA-50-Gy-O	0.02	0.06	0.22	0.76	0.56
ASA-75-Gy-O	0.02	0.04	0.15	0.71	0.50
ABS-75-Gy-O	0.02	0.04	0.14	0.69	0.48
1" Melamine-Based Foam (akustik.ua)	0.22	0.54	0.76	0.88	0.93
1" Glass Wool - 16 kg/m ³ (akustik.ua)	0.28	0.55	0.71	0.74	0.83
1" Glass Wool - 24 kg/m ³ (akustik.ua)	0.32	0.56	0.77	0.89	0.91

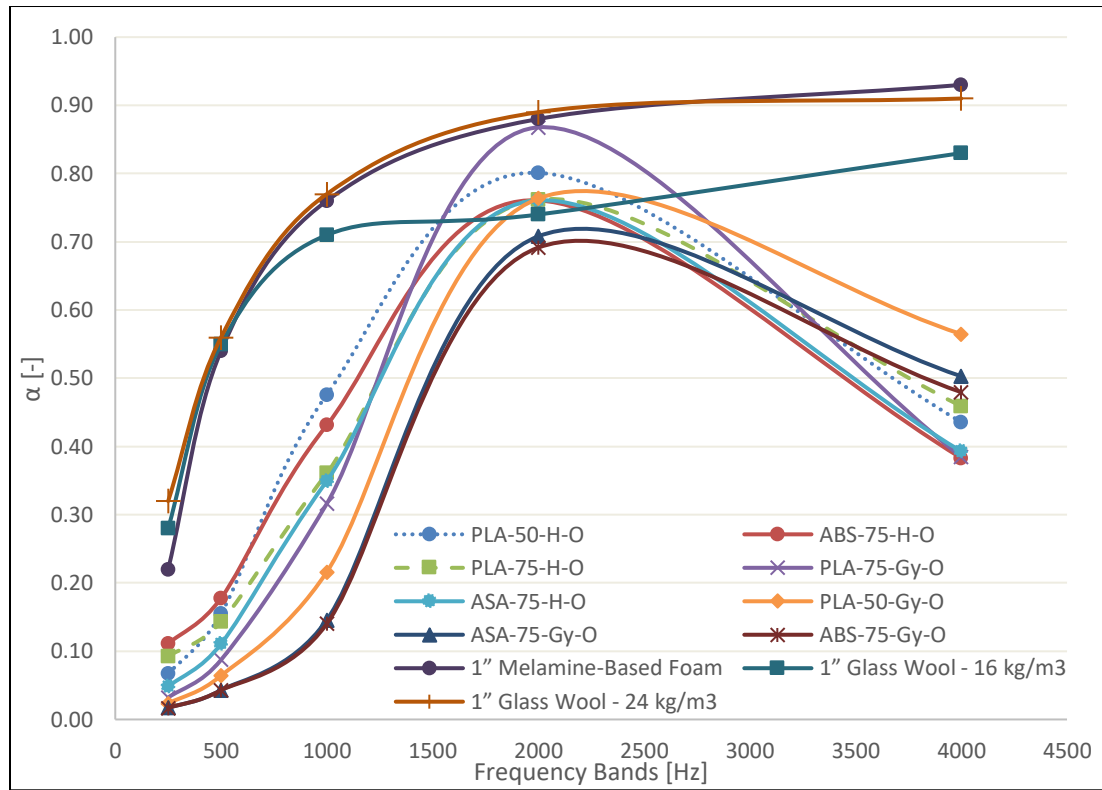


Figure 56 - akustik.ua published data compared to some of the best performing samples from this research

5.2.1.3 Evaluating possible applications for the produced structures

As for the possible applications for the developed structures, since most have shown a max absorption coefficient at the mid frequency range (1000-2000 Hz), it stands to reason that the best application for the developed structure would be in the form of sound insulation for rotating equipment, which include both industrial and household appliances.

Earlier in this thesis report, Figure 57 showcasing sound pressure level vs. frequency distribution table was illustrated, it showed that this particular screw compressor in an EBS plant has its maximum sound pressure within the 1000 and 2000 Hz $1/1$ octave bands. Noting that these sound levels are recorded with noise treatment in the form of a silencer on suction and discharge piping. Thus, safety requirements in the plant requires the use of an acoustic housing around the area of the compressor in order to contain some of the noise pollution caused by the equipment.

OCTAVE BAND CENTER FREQUENCY (HERTZ)	SOUND PRESSURE LEVEL (SPL) DECIBELS (DB) AT 1 METRE	
	STANDARD EQUIPMENT	EQUIPMENT WITH NOISE TREATMENT
31.5		20
63		72
125		74
250		76
500		79
1000		82
2000		81
4000		77
8000		72
A-WEIGHTED	95	87

Figure 57 - SPL measurements for a screw compressor in an EBS (Ethylbenzene-Styrene) plant [10]

Similarly, some house appliances have a similar noise spectra profile to the above, and Figure 58 from a study by G.M. Jackson and Geoff Leventhall [65] showcases this point for common food mixers.

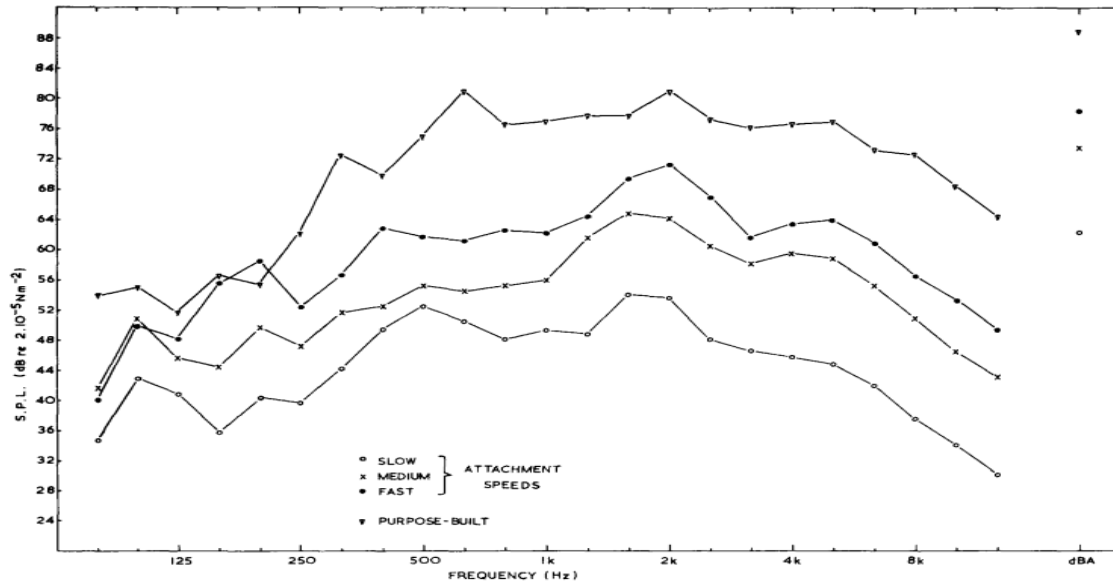


Figure 58 - Noise spectra of food mixer with different speed levels [65]

Although it is important to note that the application is not only limited to rotating equipment, in industry, there are numerous generators of mid-high frequency noise. Figure 59 showcases a sample of the high sound pressure levels for steam piping and valves and their corresponding frequencies.

Octave Frequency (Hz)	Sound Pressure Level (dB)
31	70
63	70
125	70
250	70
500	75
1000	80
2000	85
4000	90
8000	90
A-weighted, dB (A)	94

Figure 59 - SPLs from a 1 meter distance of high-pressure thermally insulated steam valves & piping [66]

5.2.2 Evaluation of Noise Reduction Coefficient (NRC) ratings

Upon comparing the data presented in Section 4.5 (Table 20) with that provided in Section 3.3.1.4 (Figure 35), it is evident that the majority of the printed samples examined do not possess favorable characteristics for use in home insulation applications. Nonetheless, certain printed samples exhibited highly commendable performance, even surpassing that of conventional insulating materials. For instance, a few of the samples demonstrated a noteworthy 0.4 Noise Reduction Coefficient (NRC) rating, which is superior to that of polyurethane foam and comparable to that of a concrete wall covered with carpeting.

Nonetheless, the samples investigated in this thesis demonstrate remarkable performance when juxtaposed with other 3D printed absorbers that were evaluated in the existing literature but with less intricate infill parameters.

To provide a comprehensive comparison, Table 26 compares the most favorable outcomes reported in the studies conducted by Vasina et al. and Monkova et al. [15][16] with those attained in this thesis study, albeit with the caveat that the comparison will solely focus on the outcomes achieved for the samples tested with zero air gap, akin to the samples tested in this thesis.

Table 26 - Comparing the best obtained NRCs from this study to Vasina et al.'s and Monkova's studies

Infill pattern (Or sample label)	Volume Ratio [%]	Sample Thickness [cm]	Air Gap [cm]	NRC [-]
Cartesian (Monkova's et al.)	70	3	0	0.25
Octagonal (Monkova's et al.)	70	3	0	0.25
Rhomboid (Monkova's et al.)	70	3	0	0.20
Starlit (Monkova's et al.)	70	3	0	0.20
Cartesian (Vasina's et al.)	57	2	0	0.25
Octagonal (Vasina's et al.)	57	2	0	0.30
PLA-50-H-O	50	2.54	0	0.40
ABS-75-H-O	75	2.54	0	0.40
PLA-75-H-O	75	2.54	0	0.35
PLA-75-Gy-O	75	2.54	0	0.35
ASA-75-H-O	75	2.54	0	0.30

5.3 Effect of Different Infill Parameters

5.3.1 End Walls

Having the structure being fully enclosed (i.e. not exposing the internal infill), can be beneficial only for low volume ratio structures, increasing both the maximum SAC and decreasing the excitation frequency at which this maximum value occurs. Thus, having the benefit of being aesthetically pleasing while providing the required absorption. However, the higher the volume ratio becomes, enclosed structures become less efficient sound

absorbers. In general, the results obtained for the enclosed samples were not that encouraging, as the best two results were as shown in Table 27 below:

Table 27 - Best results of enclosed samples

Sample Label	Max α [-]	Corresponding frequency [Hz]
ABS-75-Gy-C	0.67141	1956
PLA-25-H-C	0.66980	1950

Thus, as a rule of thumb, it is not recommended to manufacture enclosed samples unless they can be backed up by an air gap, or if they become part of an assembly of insulating materials.

5.3.2 Volume ratio

The experimental findings suggest that augmenting the volume ratio of the printed samples leads to a proportional increase in the maximum sound absorption coefficient value, accompanied by a reduction in the frequency at which it is achieved. Nonetheless, this effect is only evident up to a certain threshold. Indeed, the results demonstrate that the sample printed with 100% volume ratio exhibits a lower maximum absorption than other printed samples, with the exception of the low infill samples having a volume ratio of 25%.

It is noteworthy that elevating the volume ratio from 25% to 50% results in a substantial increase in the maximum coefficient by up to 115%, while simultaneously reducing the corresponding frequency by up to 25%. However, a further augmentation of the volume ratio by 25% (from 50% to 75%) could potentially generate only a minimal increase of less than 1% in the maximum coefficient (depending on the infill pattern), while decreasing the corresponding frequency by 10%. Notably, the experimental findings do not provide

evidence for the determination of a specific volume ratio limit beyond which any further increase would negatively affect the acoustic properties of the printed samples.

With the minimal difference between the 50% and 75% volume ratios, it might be a wiser choice for most applications to opt for the 50% volume ratio despite the slightly lower absorption values. This is because there are several drawbacks to using high volume ratios. One of the main issues is that higher volume ratios increase the overall printing time and material usage, resulting in increased cost and longer production times. Additionally, higher volume ratios can increase the risk of warping and cracking during the printing process, which can result in poor surface finish and reduced overall quality of the printed object.

5.3.3 Infill pattern

As shown in Table 28, the experimental findings demonstrate that the Gyroid and Honeycomb patterns are the most suitable candidates for fabricating 3D printed sound absorbers. While the Gyroid pattern exhibits a superior maximum sound absorption coefficient (SAC), the Honeycomb structure yields a lower frequency at which this maximum value occurs, thereby potentially rendering it more desirable for wider practical applications.

However, the Gyroid pattern confers the added advantage of retaining an excellent maximum SAC, even when utilized at a 50% volume ratio. Consequently, should the objective entail attaining maximum sound absorption at a lower cost, this pattern may prove to be the optimal choice, notwithstanding its heightened excitation frequency for this maximum SAC.

Table 28 - Gyroid Vs. Honeycomb infill pattern comparison at 50% and 75% volume ratios

Sample Label	Max α [-]	Corresponding frequency [Hz]
PLA-75-Gy-O	0.99899	2314
PLA-50-Gy-O	0.98958	2582
PLA-75-H-O	0.91501	1856
PLA-50-H-O	0.89811	1990

5.3.4 Material of construction

ABS and ASA materials exhibits comparable performance, consistent with their close compositional structures. However, in comparison to PLA, the frequency associated with the maximum coefficient, obtained from ASA and ABS structures, appears marginally shifted towards a higher value. Moreover, although the maximum coefficient for both ABS and ASA exceeds that of PLA, the difference is only 0.09%. Conversely, the corresponding frequency can increase up to 20% in these materials. Thus, PLA is more acoustically desirable than ABS or ASA.

Also, PLA has other numerous advantages that makes it the best choice for most 3D printing applications. Firstly, PLA is derived from renewable resources such as corn starch, sugarcane, or potato starch, and is biodegradable, making it an environmentally friendly option compared to petroleum-based plastics. PLA has a lower carbon footprint than other materials used in 3D printing, which is a significant advantage for sustainable manufacturing. Secondly, PLA has a lower printing temperature than other materials, which allows for printing on a wider variety of machines and reduces the likelihood of warping and other issues that can arise during the printing process. Additionally, PLA has a relatively low shrinkage rate, which makes it ideal for printing larger objects with more accuracy. Lastly, PLA has excellent mechanical properties, making it a versatile material

for a wider range of applications. It is strong, stiff, and can withstand impacts, making it suitable for producing functional parts, as well as decorative objects.

Thus, it can be concluded that whether for acoustic or other applications, PLA should always be considered as a first choice.

5.4 Drawbacks and Limitations

While 3D printing has numerous benefits, there are also several drawbacks associated with the technology:

- 1- The 3D printing technology, while offering a wide range of materials for use in manufacturing, still suffers from limitations in material selection compared to traditional manufacturing processes. Materials commonly used in traditional manufacturing, such as metals and ceramics, may not be as easily accessible for 3D printing. This limited material selection is especially evident in acoustic applications, where it would be advantageous to combine the natural sound-absorbing properties of traditional materials with the intricate designs made possible by 3D printing. However, at present, the majority of these materials are not readily available for use in 3D printing.
- 2- Slow Production Time: While 3D printing has come a long way in terms of speed, it is still generally slower than traditional manufacturing methods. Depending on the size and complexity of the part being printed, it can take hours or even days to produce a single part. Table 29 breaks down the time it took to print out each of the 37 samples tested in this thesis (although the printing parameters mentioned in chapter 3 should be noted).

Table 29 – Time duration for printing each sample

Sample Label	Printing Time
ABS-75-Gy-C	32h25m
ABS-75-Gy-O	32h
ABS-75-H-C	45h52m
ABS-75-H-O	45h37m
ASA-75-Gy-C	32h25m
ASA-75-Gy-O	32h
ASA-75-H-C	45h52m
ASA-75-H-O	45h37m
PLA-100	14h2m
PLA-25-Gr-C	5h30m
PLA-25-Gr-O	5h5m
PLA-25-Gy-C	9h32m
PLA-25-Gy-O	9h3m
PLA-25-H-C	13h20m
PLA-25-H-O	12h55m
PLA-25-P-C	5h28m
PLA-25-P-O	5h
PLA-50-Gr-C	8h53m
PLA-50-Gr-O	8h33m
PLA-50-Gy-C	19h48m
PLA-50-Gy-O	19h23m
PLA-50-H-C	29h14m
PLA-50-H-O	28h50m
PLA-50-P-C	8h42m
PLA-50-P-O	8h18m
PLA-75-Gr-C	12h
PLA-75-Gr-O	11h36m
PLA-75-Gy-C	32h25m
PLA-75-Gy-O	32h
PLA-75-H-C	45h52m
PLA-75-H-O	45h37m
PLA-75-P-C	11h54m
PLA-75-P-O	11h29m
WP-75-Gy-C	32h25m
WP-75-Gy-O	32h
WP-75-H-C	45h52m
WP-75-H-O	45h37m
Total	36 Days and 18 Hours

- 3- Limited Size: The size of the part that can be printed is limited by the size of the 3D printer. For larger parts, the printing process may need to be broken down into smaller sections and then assembled later, adding the manufacturing time and adding more weak-points in the design.
- 4- Cost: While the cost of 3D printing has decreased over time, it is still generally more expensive than traditional manufacturing methods. This can be a disadvantage for high-volume production runs. To give an example of this, the total cost of printing only the 37 samples used in this thesis research was approximately \$265 (only factoring in the material cost). Although it is important to keep in mind that for industrial 3D printers, this cost is reduced due to the benefits of mass production.

5.5 Areas of Future Research

The field of 3D printed sound absorbers is an area of active research, and there are several potential avenues for future exploration. Some of the areas of future research in this field include:

- 1- Material development: 3D printing allows for the creation of complex geometries, but the choice of material is critical to the performance of the sound absorber. Research into new materials that are optimized for sound absorption could lead to better performance and more efficient use of materials.
- 2- Geometric optimization: The complex geometries that can be created using 3D printing offer opportunities to optimize sound absorption. Future research could explore the use of artificial intelligence and optimization algorithms to create complex geometries that maximize sound absorption.

- 3- Scale-up: Most current research on 3D printed sound absorbers has focused on small-scale prototypes. Future research could focus on scaling up the technology to produce larger, more practical sound absorbers for use in real-world applications.
- 4- Integration with other technologies: There is potential for 3D printed sound absorbers to be integrated with other technologies, such as sensors or actuators, to create smart materials that can adapt to changing acoustic conditions.
- 5- Application-specific design: Different applications may require different types of sound absorbers. Future research could focus on designing 3D printed sound absorbers that are tailored to specific applications, such as automotive or architectural acoustics.

Overall, the field of 3D printed sound absorbers is still in its early stages, and there is a lot of potential for future research to explore the possibilities of this technology.

REFERENCES

- [1] L. Suárez and M. del Mar Espinosa, “Assessment on the use of additive manufacturing technologies for acoustic applications,” *International Journal of Advanced Manufacturing Technology*, vol. 109, no. 9–12, pp. 2691–2705, Aug. 2020, doi: 10.1007/S00170-020-05853-2/FIGURES/19.
- [2] V. Sekar *et al.*, “Effect of Thickness and Infill Density on Acoustic Performance of 3D Printed Panels made of Natural Fiber Reinforced Composites,” *Journal of Natural Fibers*, 2021, doi: 10.1080/15440478.2021.1944426.
- [3] E. M. Samsudin, L. H. Ismail, and A. A. Kadir, “A REVIEW ON PHYSICAL FACTORS INFLUENCING ABSORPTION PERFORMANCE OFFIBROUS SOUND ABSORPTION MATERIAL FROM NATURAL FIBERS,” vol. 11, no. 6, 2016, Accessed: Feb. 11, 2023. [Online]. Available: www.arpnjournals.com
- [4] V. Tiwari, A. Shukla, and A. Bose, “Acoustic properties of cenosphere reinforced cement and asphalt concrete,” *Applied Acoustics*, vol. 65, no. 3, pp. 263–275, Mar. 2004, doi: 10.1016/J.APACOUST.2003.09.002.
- [5] K. Kobiela-Mendrek, M. Bączek, J. Broda, M. Rom, I. Espelien, and I. Klepp, “Acoustic Performance of Sound Absorbing Materials Produced from Wool of Local Mountain Sheep,” *Materials (Basel)*, vol. 15, no. 9, May 2022, doi: 10.3390/MA15093139.
- [6] R. B. Kristiawan, F. Imaduddin, D. Ariawan, Ubaidillah, and Z. Arifin, “A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters,” *Open Engineering*, vol. 11, no. 1, pp. 639–649, Jan. 2021, doi: 10.1515/ENG-2021-0063/ASSET/GRAPHIC/J_ENG-2021-0063_FIG_003.JPG.
- [7] R. K. Upadhyay, A. K. Mishra, and A. Kumar, “Mechanical Degradation of 3D Printed PLA in Simulated Marine Environment,” *Surfaces and Interfaces*, vol. 21, p. 100778, Dec. 2020, doi: 10.1016/J.SURFIN.2020.100778.
- [8] P. NASSIRI, H. R. HEIDARI, M. KHADEM, H. RAHIMIFARD, and E. ROSTAMI, “Assessment of Noise Annoyance and its Effects on Healthcare Staff Based on Sound Pressure Level and Annoyance Scale,” *International Journal of Occupational Hygiene*, vol. 6, no. 1, pp. 23–30, 2014, Accessed: Feb. 11, 2023. [Online]. Available: <https://ijoh.tums.ac.ir/index.php/ijoh/article/view/93>

- [9] F. Jacobsen, T. Poulsen, J. Rindel, A. Gade, and M. Ohlrich, *Fundamentals of Acoustics and Noise Control*. 2011.
- [10] Ltd. , Kobe Steel, “Operation and Maintenance Manual for Off-Gas Compressor,” *SADAF STYRENE II PROJECT PHASE II, Saudi Petrochemical Company (SADAF)*. Kobe Steel, Ltd., AL JUBAIL, pp. 1–13, 2000.
- [11] “3D Printing Infill: The Basics for Optimal Results | All3DP.” <https://all3dp.com/2/infill-3d-printing-what-it-means-and-how-to-use-it/> (accessed Sep. 15, 2022).
- [12] B. H. Lee, S. W. Cha, and Y. J. Kang, “Study of sound absorption and transmission characteristics for MCPs foaming rate by batch process,” *Proc. KSPE*, pp. 338–342, 2004.
- [13] W. K. Lee, B. H. Park, H. J. Yoon, J. S. Kim, and J. Y. Maeng, “The Optimization of Interior Acoustic Package of Vehicle Using the Sound Absorbing Materials,” *Korean Soc. Automot. Eng*, vol. 2, pp. 1212–1217, 2004.
- [14] S. Amares, E. Sujatmika, T. W. Hong, R. Durairaj, and H. Hamid, “A review: characteristics of noise absorption material,” in *Journal of Physics: Conference Series*, IOP Publishing, 2017, p. 012005.
- [15] G.-S. Liu, Y. Zhou, M.-H. Liu, Y. Yuan, X.-Y. Zou, and J.-C. Cheng, “Acoustic waveguide with virtual soft boundary based on metamaterials,” *Sci Rep*, vol. 10, no. 1, pp. 1–7, 2020.
- [16] K. Monkova, M. Vasina, P. P. Monka, D. Kozak, and J. Vanca, “Effect of the Pore Shape and Size of 3D-Printed Open-Porous ABS Materials on Sound Absorption Performance,” *Materials 2020, Vol. 13, Page 4474*, vol. 13, no. 20, p. 4474, Oct. 2020, doi: 10.3390/MA13204474.
- [17] M. Vasina, K. Monkova, P. P. Monka, D. Kozak, and J. Tkac, “Study of the Sound Absorption Properties of 3D-Printed Open-Porous ABS Material Structures,” *Polymers 2020, Vol. 12, Page 1062*, vol. 12, no. 5, p. 1062, May 2020, doi: 10.3390/POLYM12051062.
- [18] R. Sailesh, L. Yuvaraj, M. Doddamani, L. Babu Mailan Chinnapandi, and J. Pitchaimani, “Sound absorption and transmission loss characteristics of 3D printed bio-degradable material with graded spherical perforations,” *Applied Acoustics*, vol. 186, p. 108457, Jan. 2022, doi: 10.1016/J.APACOUST.2021.108457.

- [19] M. R. Khosravani and T. Reinicke, "Experimental characterization of 3D-printed sound absorber," *European Journal of Mechanics - A/Solids*, vol. 89, p. 104304, Aug. 2021, doi: 10.1016/J.EUROMECHSOL.2021.104304.
- [20] V. Amaya-Amaya, M. de Icaza-Herrera, A. L. Martínez-Hernández, G. Martínez-Barrera, and C. Velasco-Santos, "Experimental approximation of the sound absorption coefficient (α) for 3D printed reentrant auxetic structures of poly lactic acid reinforced with chicken keratin materials," *Mater Lett*, vol. 283, Jan. 2021, doi: 10.1016/J.MATLET.2020.128757.
- [21] A. Arjunan, A. Baroutaji, and A. Latif, "Acoustic behaviour of 3D printed titanium perforated panels," *Results in Engineering*, vol. 11, p. 100252, Sep. 2021, doi: 10.1016/J.RINENG.2021.100252.
- [22] L. Peng, "Sound absorption and insulation functional composites," *Advanced High Strength Natural Fibre Composites in Construction*, pp. 333–373, 2017, doi: 10.1016/B978-0-08-100411-1.00013-3.
- [23] Y. Lee and C. Joo, "SOUND ABSORPTION PROPERTIES OF RECYCLED POLYESTER FIBROUS ASSEMBLY ABSORBERS," *AUTEX Research Journal*, vol. 3, Accessed: Feb. 11, 2023. [Online]. Available: <http://www.autexrj.org/No2-2003/0047.pdf>
- [24] K. Kalinova and K. Kalinova, "Sound Absorbing Resonator Based on the Framed Nanofibrous Membrane," *Acoustics of Materials*, Dec. 2018, doi: 10.5772/INTECHOPEN.82615.
- [25] "Resonant Absorbers & Why You Need Them – Acoustic Fields." <https://www.acousticfields.com/resonant-absorbers/> (accessed Feb. 11, 2023).
- [26] Z. Maekawa, J. Rindel, and P. Lord, "Environmental and Architectural Acoustics," *Environmental and Architectural Acoustics*, Dec. 2010, doi: 10.4324/9780203931356.
- [27] J. S. Bradley, "Optimising sound quality for classrooms," pp. 1–15, Accessed: Feb. 11, 2023. [Online]. Available: <http://irc.nrc-cnrc.gc.ca/ircpubs>
- [28] "hunecke.de | Porous absorbers." <https://www.hunecke.de/en/knowledge/absorbers/porous-absorbers.html> (accessed Feb. 11, 2023).
- [29] M. R. G. Ravandi, H. Mardi, A. A. A. Langari, M. Mohammadian, and N. Khanjani, "A Review on the Acoustical Properties of Natural and Synthetic Noise

- Absorbents,” *OALib*, vol. 02, no. 08, pp. 1–11, 2015, doi: 10.4236/OALIB.1101598.
- [30] J. P. Arenas and M. Crocker, “Recent Trends in Porous Sound-Absorbing Materials,” *Sound and Vibration*, 2010.
- [31] F. Setaki, M. Tenpierik, A. Timmeren, and M. Turrin, *Sound absorption and additive manufacturing*. 2015.
- [32] V. Sekar, S. Y. Eh Noum, S. Sivanesan, A. Putra, D. D. Chin Vui Sheng, and D. H. Kassim, “Effect of Thickness and Infill Density on Acoustic Performance of 3D Printed Panels made of Natural Fiber Reinforced Composites,” <https://doi.org/10.1080/15440478.2021.1944426>, vol. 19, no. 13, pp. 7132–7140, 2021, doi: 10.1080/15440478.2021.1944426.
- [33] K. Monkova, M. Vasina, P. P. Monka, J. Vanca, and D. Kozak, “Effect of 3D-Printed PLA Structure on Sound Reflection Properties,” *Polymers (Basel)*, vol. 14, no. 3, Feb. 2022, doi: 10.3390/POLYM14030413.
- [34] K. Monkova, M. Vasina, P. P. Monka, J. Vanca, and D. Kozak, “Effect of 3D-Printed PLA Structure on Sound Reflection Properties,” *Polymers 2022, Vol. 14, Page 413*, vol. 14, no. 3, p. 413, Jan. 2022, doi: 10.3390/POLYM14030413.
- [35] “Impedance Tube Measurements,” 2020, Accessed: Sep. 14, 2022. [Online]. Available: <https://www.acs.psu.edu/drussell/Demos/waves-intro/waves-intro.html>
- [36] C. Lubombo and M. A. Huneault, “Effect of infill patterns on the mechanical performance of lightweight 3D-printed cellular PLA parts,” *Mater Today Commun*, vol. 17, pp. 214–228, Dec. 2018, doi: 10.1016/J.MTCOMM.2018.09.017.
- [37] “Getting Started with 3D Printing - STEMpedia.” <https://thestempedia.com/tutorials/getting-started-with-3d-printing/> (accessed Feb. 14, 2023).
- [38] M. Qamar Tanveer, G. Mishra, S. Mishra, and R. Sharma, “Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts- a current review,” *Mater Today Proc*, vol. 62, pp. 100–108, Jan. 2022, doi: 10.1016/J.MATPR.2022.02.310.
- [39] J. Suteja, “Effect of Infill Pattern, Infill Density, and Infill Angle on the Printing Time and Filament Length of 3D Printing,” *Jurnal Rekayasa Mesin*, vol. 12, no. 1, pp. 145–152, May 2021, doi: 10.21776/UB.JRM.2021.012.01.16.

- [40] C. Silva, A. I. Pais, G. Caldas, B. P. P. A. Gouveia, J. L. Alves, and J. Belinha, "Study on 3D printing of gyroid-based structures for superior structural behaviour," *Progress in Additive Manufacturing*, vol. 6, no. 4, pp. 689–703, Dec. 2021, doi: 10.1007/S40964-021-00191-5.
- [41] P. Bean, R. A. Lopez-Anido, and S. Vel, "Numerical Modeling and Experimental Investigation of Effective Elastic Properties of the 3D Printed Gyroid Infill," *Applied Sciences 2022, Vol. 12, Page 2180*, vol. 12, no. 4, p. 2180, Feb. 2022, doi: 10.3390/APP12042180.
- [42] B. Pernet, J. K. Nagel, and H. Zhang, "Compressive Strength Assessment of 3D Printing Infill Patterns," *Procedia CIRP*, vol. 105, pp. 682–687, 2022, doi: 10.1016/j.procir.2022.02.114.
- [43] "Infill patterns | Prusa Knowledge Base." https://help.prusa3d.com/article/infill-patterns_177130 (accessed Feb. 15, 2023).
- [44] "PLA 3D Printing: All You Need to Know - AMFG." <https://amfg.ai/2018/07/02/pla-3d-printing-all-you-need-to-know/> (accessed Sep. 14, 2022).
- [45] "PLA Plastic (Polylactic Acid) - Uses, Structure & Material Properties." <https://omnexus.specialchem.com/selection-guide/polylactide-pla-bioplactic> (accessed Feb. 15, 2023).
- [46] "Material Properties of Polylactic Acid (PLA), Agro Based Polymers | Polymers Data Sheets." <https://web.archive.org/web/20120210194852/http://www.matbase.com/material/polymers/agrobased/polylactic-acid-pla/properties> (accessed Feb. 15, 2023).
- [47] J. D. Moore, "Acrylonitrile-butadiene-styrene (ABS) - a review," *Composites*, vol. 4, no. 3, pp. 118–130, 1973, doi: 10.1016/0010-4361(73)90585-5.
- [48] "Material Properties of ABS General Purpose, Commodity Polymers | Polymers Data Sheets." <https://web.archive.org/web/20120221200328/http://www.matbase.com/material/polymers/commodity/abs-general-purpose/properties> (accessed Feb. 15, 2023).
- [49] "UL Prospector." <https://www.ulprospector.com/plastics/en/generics/8> (accessed Feb. 15, 2023).
- [50] "Mechanical, physical and environmental properties of Acrylonitrile styrene acrylate [ASA], Engineering polymers, Polymers | Matbase - Material Properties Database."

- <https://web.archive.org/web/20120531033957/http://www.matbase.com/material/polymers/engineering/asa/properties> (accessed Feb. 15, 2023).
- [51] “3D Printing Technology Comparison: FDM vs. SLA vs. SLS.” <https://formlabs.com/asia/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-3d-printing-technology/> (accessed Sep. 14, 2022).
 - [52] V. Mazzanti, L. Malagutti, and F. Mollica, “FDM 3D Printing of Polymers Containing Natural Fillers: A Review of their Mechanical Properties,” *Polymers* 2019, Vol. 11, Page 1094, vol. 11, no. 7, p. 1094, Jun. 2019, doi: 10.3390/POLYM11071094.
 - [53] “ISO - ISO 10534-2:1998 - Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes — Part 2: Transfer-function method.” <https://www.iso.org/standard/22851.html> (accessed Sep. 15, 2022).
 - [54] F. Setaki, M. Tenpierik, A. Van Timmeren, and M. Turrin, “Comparison of standing wave ratio method and transfer function method for measuring sound absorbing properties of 3d-printed samples”.
 - [55] R. Aslan and O. Turan, “Gypsum-based sound absorber produced by 3D printing technology,” *Applied Acoustics*, vol. 161, p. 107162, Apr. 2020, doi: 10.1016/J.APACOUST.2019.107162.
 - [56] F. Han, G. Seiffert, Y. Zhao, and B. Gibbs, “Acoustic absorption behaviour of an open-celled aluminium foam,” *J Phys D Appl Phys*, vol. 36, no. 3, p. 294, Jan. 2003, doi: 10.1088/0022-3727/36/3/312.
 - [57] H. Koruk, “An assessment on the performance of impedance tube method,” *Noise Control Eng J*, vol. 62, no. 4, pp. 264–274, 2014, doi: 10.3397/1/376226.
 - [58] W. R. Farrell, “Acoustical Materials for Use in Monumental Spaces,” *Noise Control*, vol. 4, no. 1, p. 32, Nov. 2006, doi: 10.1121/1.2369298.
 - [59] M. Zainulabidin, M. H. Abdul Rani, N. Nezere, and A. L. Mohd Tobi, “Optimum Sound Absorption by Materials Fraction Combination,” *International Journal of Mechanical and Mechatronics Engineering*, vol. 14, pp. 118–121, Apr. 2014.
 - [60] C. M. Harris, “Acoustical Properties of Carpet,” *J Acoust Soc Am*, vol. 27, no. 6, p. 1077, Jun. 2005, doi: 10.1121/1.1908124.
 - [61] R. Fediuk, M. Amran, N. Vatin, Y. Vasilev, V. Lesovik, and T. Ozbakkaloglu, “Acoustic properties of innovative concretes: A review,” *Materials*, vol. 14, no. 2, pp. 1–28, Jan. 2021, doi: 10.3390/MA14020398.

- [62] M. R. Alkahari, H. A. Habeeb, F. Ramli, R. Hasan, and M. S, *Strength and porosity of additively manufactured PLA using a low cost 3D printing*. 2016.
- [63] W. A. Ua, “ABSORPTION COEFFICIENTS”, Accessed: May 10, 2023. [Online]. Available: www.akustik.ua
- [64] “Acoustic Project akustik.ua.” <https://www.akustik.ua/en.html> (accessed May 10, 2023).
- [65] G. M. Jackson and H. G. Leventhall, “Household appliance noise,” *Applied Acoustics*, vol. 8, no. 2, pp. 101–118, 1975, doi: 10.1016/0003-682X(75)90028-6.
- [66] J. P. Guyer, “An Introduction to Sound Level Data for Mechanical and Electrical Equipment”.

VITAE

Name : **Moaath Abdulrahman Ali Al Unaizan**

Nationality : **Saudi**

Date of Birth : **12/13/1994**

Email : **MoaathAlunaizan@gmail.com**

Address : **P.O Box 46297, Riyadh 11532, Saudi Arabia**

Academic Background : **Bachelor of Science in Mechanical Engineering (2017)**
King Fahd University of Petroleum and Minerals

Master of Science in Mechanical Engineering – Design and Vibration (2023)
King Fahd University of Petroleum and Minerals

Professional Background : **Rotating Equipment Engineer (2017-2022)**
SABIC – Petrokemya

Energy Efficiency Specialist (2022 -)
Saudi Energy Efficiency Center

Certified Reliability Engineer (2022 -)
American Society for Quality - ASQ

Certified Machine Lubricant Analyst (2021 -)
International Council for Machinery Lubrication - ICML