LODZ UNIVERSITY OF TECHNOLOGY

DOCTORAL THESIS

ACOUSTIC PROPERTIES OF WEAVE STRUCTURE DEPENDING ON THEIR INTERNAL GEOMETRY

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Interdisciplinary Doctoral School at the Lodz University of Technology

Faculty of Material Technologies and Textile Design
Institute of Architecture of Textiles
Discipline of Materials Engineering

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May 2023, Lodz

ABSTRACT

The rapid growth of civilization, especially in urban areas, has led to increased noise pollution, which can have a negative impact on our acoustic well-being. Excessive noise levels can cause stress, sleep disturbances, hearing damage, and other health problems.

Sound insulation materials are designed to reduce the amount of noise that passes through walls, floors, and ceilings, thereby reducing the level of sound that is transmitted from one space to another. This can include materials such as acoustic panels, acoustic ceiling tiles, and soundproofing curtains. On the other hand, sound-absorbing materials are designed to absorb sound energy and prevent it from reflecting into space, reducing the overall noise level. These materials include acoustic porous or foam materials, acoustic wall panels, sound-absorbing tiles, etc.

The sound absorption effectiveness of the porous acoustic material is limited at higher frequencies. To overcome this limitation and to maximize the absorption performance of porous materials, it was necessary to investigate woven fabrics' different weave structures and yarn properties. Therefore, this thesis aims to investigate the acoustic characteristics of woven fabric related to its weave structure and yarn properties. As a result, using woven fabric increases the level of sound absorption at low frequencies in the porous material is the main hypothesis of the study.

To understand the impact of the yarn characteristics on the fabric structure, the samples were prepared using only polyester fiber as textured (dtex 167 f 32 × 2), twisted (dtex 334 f 32 × 2, (S95), and staple yarns (dtex 200 × 2). In addition, four basic weave structures, such as plain, rib, sateen, and twill, were selected based on the assumption of differences in their porosity. The study started with the preparation of fabric samples using the Sample Dobby Loom SL 8900S. Overall, 12 woven fabrics were prepared. Yarn physical characteristics such as yarn twist/m, yarn hairiness, and yarn evenness were investigated. Furthermore, fabric properties such as warp and weft density, fabric thickness, mass per unit area (g/m^2), crimp %, cover factor, porosity, roughness, and air permeability were studied.

The acoustic properties of woven fabrics were measured using two methods. Firstly, acoustic anechoic chambers were utilized to understand fabrics sound absorption phenomena from different incidence angles. The measurements were performed in the range of low to medium acoustic frequencies. As a result, the materials measured at 0° from the sound source demonstrated higher sound absorption than the fabrics measured

at 45° of incidence angle. This result is beneficial when applying such material to obtain satisfactory absorption results. The fabric's sound absorption results are also different based on the yarn they were formed from and the type of weave structure. As a result, the plain weave structure showed higher sound absorption over the rib, sateen, and twill weave structures. Generally, the fabric formed from textured yarn demonstrates higher sound absorption than the other yarn types.

The second acoustic examination was conducted in an impedance tube with a frequency range of 80–5,000 Hz. Fabrics with similar weave structures were measured as single, double, and triple layers, with a combination of nonwoven and air gaps. Acoustic test for only woven fabric with different layers reveals low absorption. In addition, the sample, which consists of a woven fabric with an air gap, exhibits a higher sound reduction coefficient. As a result, except for the sateen and rib weave structures formed from staple yarn, the fabrics can be categorized as useful acoustic materials. The outcomes of combining woven and nonwoven fabrics can be categorized as high-performance absorber materials. The Noise Reduction Coefficient of the nonwoven fabric cannot be classified as an acoustic material because the result is below 0.2. In contrast, single-layer plain fabric with nonwoven fabric and single-layer plain fabric with an air gap indicates a higher sound absorption coefficient at lower frequencies than other results.

Based on additional testing, the most effective soundproofing package consisted of three layers of sateen fabric, nonwoven fabric, three layers of plain fabric, and an air gap (3TS+N+3TP+A) prepared. As described in the preceding section, plain fabrics have a particularly high absorption at low frequencies. In order to maximize acoustic performance, plain fabrics are employed as a base material. In addition to nonwoven fabric and airgap, combining different weave structures sateen with plain fabric with proper layout design and a number of layers can improve the sound absorption performance of multilayered porous materials below 500 Hz. Furthermore, between 400 - 5000 Hz, with increasing and consistent sound absorption obtained between 0.8 – 1(α). Generally, these combined samples (3TS+N+3TP+A) can be acoustic in environments with low to high frequency bands.

STRESZCZENIE

Szybki rozwój cywilizacyjny, szczególnie w obszarach miejskich, spowodował wzrost zanieczyszczenia hałasem, który może negatywnie wpłynąć na nasze samopoczucie akustyczne. Nadmierny poziom hałasu może powodować stres, zaburzenia snu, uszkodzenie słuchu i inne problemy zdrowotne. Materiały dźwiękochłonne mają na celu zmniejszenie poziomu hałasu przechodzącego przez ściany, podłogi i sufity, obniżając jednocześnie poziom dźwięku przenoszonego z jednego pomieszczenia do drugiego. Należą do nich panele akustyczne, akustyczne płyty sufitowe i dźwiękoszczelne zasłony. Poza tym materiały dźwiękochłonne mają za zadanie pochłaniać energię dźwiękową i zapobiegać jej odbijaniu się w przestrzeń. Należą do nich akustyczne materiały porowate lub piankowe, akustyczne panele ścienne, płytki dźwiękochłonne itp.

Skuteczność pochłaniania dźwięku przez porowaty materiał akustyczny jest większa przy wyższych częstotliwościach. W celu przezwyciężenia tego ograniczenia i zmaksymalizowania wydajności absorpcji materiałów porowatych, konieczne było zbadanie różnych struktur splotu i właściwości przędzy tkanin. Dlatego niniejsza praca ma na celu przeanalizowanie właściwości akustycznych tkanin w powiązaniu z jej strukturą splotu i właściwościami przędzy. W rezultacie zastosowanie struktury tkanej zwiększa poziom pochłaniania dźwięku przy niskich częstotliwościach w materiale porowatym, co jest główną hipotezą badań.

Aby zrozumieć wpływ właściwości przędzy na tkaninę, próbki zostały przygotowane przy użyciu wyłącznie trzech rodzajów przędz z włókien poliestrowych tj. z przędzy teksturowanej (dtex 167 f 32 × 2), skręcanego multifilamentu (dtex 334 f 32 × 2, (S95) i przędzy skręcanej z włókien ciętych (dtex 200 × 2). Dodatkowo wybrano cztery podstawowe struktury splotów, tj. płócienny, rypsowy, atłasowy i skośny, wychodząc z założenia o różnicach w ich porowatości. Badania rozpoczęto od przygotowania 12 próbek tkanin na krośnie laboratoryjnym Sample Dobby Loom SL 8900. Zbadano właściwości fizyczne przędzy, takie jak skręt przędzy/m, włochatość i równomierość przędzy. Ponadto właściwości tkaniny, takie jak liczność osnowy i wątku, grubość tkaniny, masa powierzchniowa (g/m^2), wrobienie nitek %, współczynnik pokrycia, porowatość, chropowatość i przepuszczalność powietrza.

Właściwości akustyczne tkanin mierzono dwiema metodami. Po pierwsze, wykorzystano akustyczną komorę bezechową do zrozumienia zjawisk pochłaniania dźwięku przez tkaniny pod różnymi kątami padania. Pomiary przeprowadzono w

zakresie niskich i średnich częstotliwości akustycznych. W rezultacie materiały mierzone pod kątem 0° od źródła dźwięku wykazywały wyższą absorpcję dźwięku niż tkaniny mierzone pod kątem 45°. Wyniki pochłaniania dźwięku przez tkaniny różnią się również w zależności od przędzy, z której zostały wykonane, oraz rodzaju struktury splotu. W rezultacie struktura o splocie płóciennym wykazywała wyższą absorpcję dźwięku niż struktury o splocie rypsowym, atłasowym i skośnym. Ogólnie rzecz biorąc, tkanina utworzona z przędzy teksturowanej wykazuje wyższą absorpcję dźwięku niż inne rodzaje przędzy.

Drugie badanie akustyczne przeprowadzono w tubie impedancyjnej w zakresie częstotliwości 80–5000 Hz. Tkaniny o podobnej strukturze splotu mierzono jako pojedyncze, podwójne i potrójne warstwy, z kombinacją włóknin i szczelin powietrznych. Test akustyczny dla pakietu wielowarstwowego tkanin wykazał niską chłonność dźwięku. Próbka, która składa się z tkaniny ze szczeliną powietrzną, wykazuje wyższy współczynnik izolacyjności akustycznej. W rezultacie, z wyjątkiem struktur o splocie atłasowym i rypsowym utworzonych z przędzy ciętej, tkaniny można zaliczyć do użytecznych materiałów akustycznych. Wyniki łączenia tkanin i włóknin można sklasyfikować jako wysokowydajne materiały pochłaniające. Współczynnik redukcji hałasu dla włókniny jest mniejszy niż 0,2, dlatego nie można jej zaliczyć do materiałów akustycznych. Natomiast jednowarstwowa tkanina płócienna z włókniną i jednowarstwowa tkanina płócienna ze szczeliną powietrzną wykazuje wyższy współczynnik pochłaniania dźwięku i szczególnie wysoką absorpcję przy niższych częstotliwościach niż inne pakiety.

Na podstawie dodatkowych badań najskuteczniejszy pakiet dźwiękochłonny składał się z trzech warstw tkaniny atłasowej, włókniny, trzech warstw tkaniny płóciennej oraz szczeliny powietrznej (3TS+N+3TP+A). Jak opisano w poprzedniej sekcji, płócienne tkaniny mają szczególnie wysoką absorpcję przy niskich częstotliwościach. Aby zmaksymalizować wydajność akustyczną, jako materiał bazowy zastosowano tkaniny płócienne. Oprócz włókniny i szczeliny powietrznej, połączenie tkaniny atłasowej tkaniną płócienną o odpowiednim układzie z wieloma warstwami może poprawić właściwości pochłaniania dźwięku wielowarstwowych materiałów porowatych poniżej 500 Hz. Ponadto, pomiędzy 400 - 5000 Hz, przy rosnącym i stałym pochłanianiu dźwięku uzyskanym pomiędzy 0,8 - 1(α). Ogólnie rzecz biorąc, te połączone próbki (3TS+N+3TP+A) mogą być akustyczne w środowiskach z pasmami od niskich do wysokich częstotliwości.

ACKNOWLEDGMENTS

I would like to begin by giving glory and thanks to the Almighty God, who showered me with blessings throughout my research and helped me reach my goal of completing it.

I would like to express my enormous and sincere gratitude to my research supervisor, Dr hab.Eng. Marcin Barburski, Professor of TUL, for providing me with the opportunity to conduct research and for providing invaluable guidance throughout the course of this research. His goals, dynamism, sincerity, and motivation have inspired me tremendously. In addition, I am extremely grateful for the guidance, inspiration, and empathy he provided me when I began my parenting life while studying. It was an incredible privilege and honor to work and study under his supervision.

In addition, I would like to thank Dr. Ewa Witczak for her consistent support and professional guidance throughout the entirety of the research implementation process. I would also like to thank the entire Lukasiewicz Research Network-Lodz Institute of Technology staff for their insightful responses and assistance during sample preparation and research implementation.

In addition, I am grateful to Prof. Krzysztof Jozwik for providing me access to the anechoic acoustic chamber laboratory and to Dr. Eng. Jaroslaw R. Blaszczak for his assistance in conducting the test. I extended my gratitude to Prof. Izabella Krucińska for allowing me to use their laboratory and to Dr. hab. Adam K. Puszkarz for his assistance during the implementation of the porosity test. In addition, I am very appreciative to Prof. Malgorzata Matusiak for allowing me to use her roughness tester machine and for providing guidance throughout the testing process. In addition, I would like to thank Dr. hab. Eng. Magdalena Tokarska for assisting me with a statistical analysis-based test.

I am extremely grateful to my parents for their love, care, and prayers. I am extending my heartfelt thanks to my husband, MSc. Taleyihun Tadesse, for his understanding, and the time he sacrifices by supporting me throughout these years. Thanks to my son Hananiah for showering me with unconditional love and giving me the courage to go through this study. My special thanks go to my friend MSc. Eng. Tsegaye Lemmi for his support from the beginning of the study in Poland until the successful completion of this thesis without unwavering brotherly support personally and professionally. I am extending my thanks to my only brother, Dr. Yididiya Samuel, for his caring, love, and prayers during my ups and downs.

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NOMENCLATURE

A - Amplitude of the acoustic sign

P - Acoustic pressure (Pa)

F - Frequency (Hz)

Mp - Mass per unit area al (Pa)

Δp *- Pressure drop*

Q - Raw material

Ra- Roughness index

R_f *- Specific flow resistance*

S - Surface area

TL - Sound transmission loss

α *- Sound absorption coefficient*

L - Sound pressure level (dB)

ΔL *- Sound pressure level drop (dB)*

τ *- Transmission coefficient*

Δx *- Thickness of the layer*

h - Thickness of fabric

V_0 *- Volume flow rate*

Pv -Volume porosity

ACRONYM

A - Air gap

DTY- Drawn Textured Yarn

MPP - Microperforated Panel Resonator

Mic - Microphone

N – Nonwoven

NRC- Noise Reduction Coefficient

OCT - Optical Coherence Tomography

PES – Polyester

SP- Staple yarn, Plain fabric

SR- Staple yarn, Rib fabric

SS- Staple yarn, Sateen fabric

ST- Staple yarn, Twill fabric

TP- Textured yarn, Plain fabric

TR- Textured yarn, Rib fabric

TS- Textured yarn, Sateen fabric

TT- Textured yarn, Twill fabric

TWP- Twisted yarn, Plain fabric

TWR- Twisted yarn, Rib fabric

TWS- Twisted yarn, Sateen fabric

TWT- Twisted yarn, Twill fabric

1. INTRODUCTION

The acoustic environment has a significant impact on the success of daily activities. The problem with the surrounding noise pollution is that it causes health issues such as sleep disturbances, tinnitus, increased stress levels, elevated blood pressure, and loss of concentration. Living in an acoustically protected environment can aid in mitigating the negative effects of excessive noise pollution. The purpose of acoustics is to shape the interior appropriately to achieve the desired acoustic climate. An acoustically protected environment is one in which sound waves are effectively blocked, diffused, or absorbed so that they do not cause excessive noise levels or disturbances [1–3].

In order to develop acoustic barriers, it is essential to identify the frequency ranges that must be reduced in order to improve the acoustic environment in an office or home. A sound is an auditory impression produced by acoustic waves, which are vibrations of particles propagating in the air or another medium and stimulating the hearing organ. In rooms, the acoustic wave cannot propagate freely. After traversing a specific path, it encounters an obstruction and reflects off it. This phenomenon transforms a portion of the energy into heat by absorbing it. In addition to reflecting, the acoustic wave simultaneously experiences absorption and diffraction as it travels through the medium [4].

The behavior of waves is highly dependent on both their specific properties and the characteristics of the medium through which they travel. However, in general, sound waves with lower frequencies. have longer wavelengths and exhibit a more diffusive behavior, which means they are more readily scattered or absorbed by obstacles in their path. This is especially true for extremely low-frequency sound waves, which are frequently absorbed by the air and may not travel far. Conversely, sound waves with higher frequencies have shorter wavelengths and are capable of propagating over more distances without significant energy loss. However, sound waves at high-frequency can be influenced by impediments in their path and, depending on the obstacle or material type, may exhibit some degree of diffusive behavior. When sound energy reflects off a wall, floor, ceiling, or piece of furniture, its energy is reduced by a factor in the range of 0 to 1 (0 to 100%). In other words, the energy of a reflected sound wave is always less than the energy of an incident sound wave, despite being greater than zero. The coefficient of absorption, denoted by the symbol, α is used to quantify sound absorption. The sound absorption coefficient (α) is the fraction of wave energy reflected in a wave energy incident. The coefficient value of reflective materials is zero, while the coefficient value of highly absorbent porous structures is 1.5 [4, 5]. Porous materials are used as sound-absorbent materials, and their performance depends on the sound frequency range. Generally, porous materials' effectiveness in absorbing sound at low frequencies is low. In addition, the absorption of sound by woven materials is not as effective as that of nonwoven materials [6, 7].

The sound absorption efficiency of porous materials, mainly woven fabric, can be optimized by investigating how the yarn's properties and the weave interlacement's internal structures influence the material's acoustic properties. Therefore, this dissertation utilized woven and nonwoven fabric, specifically utilizing the benefit of different structural properties of the woven fabric, which increases the possibility of developing optimized fabrics for the application of low-frequency absorption and persistent sound wave absorption across a broad range of frequencies.

1.1 Objectives

Enhancing the performance of woven fabric in the acoustic sector gives advantages in increasing the application of porous materials. In order to optimize porous material absorption, particularly at lower frequencies, it was necessary to investigate the geometrical and raw material properties of woven fabrics. Due to this assumption, the **project's main objective** was **to develop an optimized fabric-based acoustic material that focuses on enhancing the acoustic performance of woven fabrics via the internal geometry of the weave, yarn properties, and the layout of fabric assemblies.** In order to achieve the main objective of the project, it was necessary to undertake **specific objectives** such as;-

- ✓ To produce four woven fabrics with different weave structures using three different PES yarn properties.
- ✓ To investigate the physical characteristics of woven fabrics regarding yarn characteristics and weave geometrical structure.
- ✓ To investigate the sound absorption of woven fabrics using an anechoic chamber.
- ✓ To investigate woven fabrics' sound absorption phenomena in an impedance tube.
- ✓ To investigate the influence of yarn and weave physical characteristics on the sound absorption performance of woven fabrics and their correlations.
- ✓ To investigate the sound absorption phenomena of multilayer woven fabrics.
- ✓ To investigate the influence of nonwoven fabric and air gaps on the multilayers of woven fabrics' sound absorption efficiency.
- ✓ Utilizing selective weave structures and nonwoven fabrics for designing and optimizing the sound absorption efficiency of porous materials.

1.2 Hypothesis

In connection with the above thesis objectives, the following research hypotheses were assumed to be verified and confirmed:

Primary hypothesis:

- ✓ The woven fabric increases the level of sound absorption at low frequencies in the porous material.

Secondary hypotheses:

- ✓ The sound absorption performance of multilayer fabrics increases with the layer numbers of woven fabrics.
- ✓ The sound absorption efficiency of a fabric depends on the roughness properties of the fabric.

1.3 Significance of the Study

The acoustic quality of an area is crucial for social and economic development. Noise is recognized as a severe health threat and is a relatively recent phenomenon. Noise is described as an "unpleasant or unwanted sound" or disruption. What one person perceives as sound may be perceived as noise by another. While many people enjoy amplified music, which is more commonly called "sound" than "noise." However, only a small number of people or no one is likely to enjoy the high decibel levels (noise) of contemporary industrial noise. To address this issue, more commonly used solutions include using noise-reducing materials, wearing ear protection, using sound absorber materials, and so on. In addition, one of the primary concepts was applying sound-absorbing porous materials for homes, offices, etc. However, porous materials' effectiveness is generally limited at higher frequencies. Absorption of low frequencies is frequently challenging when using porous materials to stabilize acoustic environments. This study utilized fabrics to enhance the sound absorption performance of porous materials, specifically at low frequencies. Different weave structure combinations with nonwoven fabric improved low-frequency absorption while obtaining a high and consistent range of sound absorption from low to high frequencies. Furthermore, the advantage of using porous material, especially with a high proportion of woven fabric, is that it increases the material's mechanical properties and enhances its durability. Moreover, woven fabrics' versatile aesthetic properties and ease of manufacturing compared to nonwoven fabrics make them preferable in the acoustic sector. This research investigation allows one step forward in applying acoustic noise barriers based on the woven structure.

1.4 Structure of the Dissertation

The thesis contains six chapters.

The first chapter presents an introduction that provides an overview of the topic. Also, the objective of the thesis, hypotheses, and significance of the research are included in this chapter. **The second chapter** discusses an extensive literature review related to the topic. **In the third chapter**, the raw materials used for the study are presented, along with in detailed description of how fabric samples were prepared. In addition, the results of fabric sound reduction obtained from an anechoic acoustic chamber and the discussion of the relationship between sound reduction and the physical characteristics of woven fabric and yarn properties are presented. **In the fourth chapter,** a verification of the acoustic absorption performance of woven fabric in an impedance tube is discussed. In addition, this chapter contains the results of the investigation of nonwoven fabric and an air gap combined with woven fabrics of varying layers. **The fifth chapter** focuses on the optimization study of woven fabrics by combining different weave structures and the influence of woven fabric layout in relation to the air gap and the layout of the nonwoven fabric in the sample. The **six chapters** present key findings, conclusions, and recommendations based on those findings.

2. LITERATURE REVIEW

Sound is created when pressure changes, or oscillations, occur in an elastic medium as a result of mechanical vibrations. When a sound wave hits or is introduced into a material, the medium's particles vibrate at the same frequency as the sound wave around a fixed point. As a result, the particles inside the material do not move with the wave; instead, they react back to the wave energy, and the wave energy travels through the material [8].

Sound can be described both objectively and subjectively. Frequency is an objective sound attribute that describes the frequency of waveform repetition per unit of time. Sound, on the other hand, is subjectively defined as pitch. The human ear hears distinct pitches of gentle and loud 100-Hz tones. High frequency can be recognized as a high pitch, and low frequency is distinguished as a low pitch. There are three portions to the sound spectrum: audible, infrasonic, and ultrasonic. The auditory frequency range is 20 to 20,000 Hz. This range is significant because the human ear can perceive its frequencies. Human speech, tone, and music are also included in the audible spectrum. Low-frequency (1–20 Hz) ranges are included in the infrasonic range. In the field of geological phenomena, such a low-frequency range is employed for research. The ultrasonic range includes frequencies of 20,000 Hz and higher. Therefore, since the wavelength in this range is short, the application has more excellent imaging technology resolution for this spectrum [4, 8]. On the other hand, as a consequence of an overlap of stimuli arising from audible high-frequency noise and ultrasonic signals in the inner ear, the risk of hearing impairment may increase when an individual is subjected to audible high-frequency noises as well as ultrasonic transmissions that are beyond the range of human hearing [9, 10].

The sound speed is different in the air, water, and solid materials (Table 1). Temperature, pressure, and humidity are all factors that influence the speed of sound. Sound waves propagate uniformly due to the stable medium of the atmosphere above the earth.

However, the air temperature rises as it gets closer to the earth's surface at times, and the air becomes colder as the distance from the earth's surface increases. Sound travels more quickly in warm air than it does in cool air. Sound wave propagation in seawater is faster and more efficient than in air. The speed of sound propagation increases as the ocean's depth increases as a result of increasing pressure. On the other hand, as the temperature rises on the surface, the propagation speed rises and decreases as the temperature of the waterfalls [10].

Table 1. Sound propagation through different mediums [11].

Speed of sound Medium	Ft/sec	Meters/sec
Air	1130	344
Sea water	4900	1500
Wood, fir	12500	3800
Steel bar	16600	5050
Gypsum board	22300	6800

The interaction of sound propagation, or when a sound source is placed within boundaries or obstacles made of solid materials, can result in three phenomena. Part of the sound energy has been reflected to some extent, while a portion of the sound energy is absorbed, and a portion is transmitted. The nature of the material or boundary type has a significant impact on the refraction of sound energy. Sound is absorbed differently by different materials and transmitted differently by different surfaces, known as acoustic material properties [11, 12]. The sound transmission coefficient (STC) rating for air, water, and gas, for example, is 0. In contrast, the sound insulation properties of solid materials depend on their thickness, density, and other characteristics. As a result, the average sound transmission of solid materials ranges between 20 and 60, with a higher number indicating higher sound insulation [13].

2.1 Acoustic Properties of Materials

2.1.1 Sound Reflection

The amount of acoustic wave energy a surface reflects is directly proportional to the material surface's compactness, hardness, and smoothness. For example, if a room's border surfaces are made of a material that reflects sound, direct sound rebounds from one boundary to another, creating reflected sound. The more incident sound is reflected, the more the reflected sound contributes to the overall sound in a closed environment. This "built-up" noise continues when the source is off. This process is called reverberation; the areas where it occurs are known as reverberant sound fields. The noise level depends on the acoustic power radiated, the room's size, and acoustic absorption properties**.** There is always the possibility of sound absorption at each reflection (Figure 1) [14]. Hence, most conference rooms, office buildings, etc., can be classified as semi-reverberant.

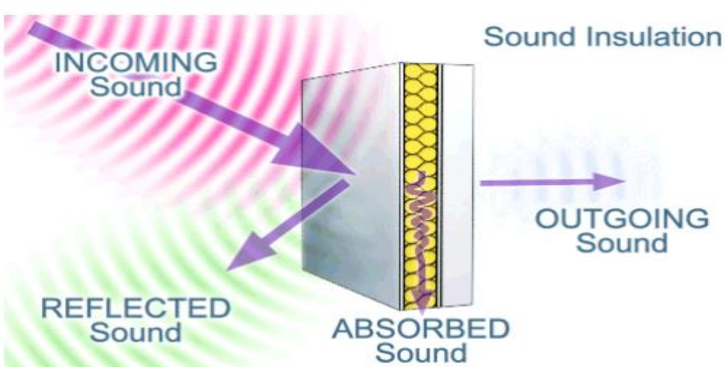


Figure 1. Sound absorption, transmission, and reflection phenomena [9].

2.1.2 Sound Transmission

Sound transmission occurs when sound waves from the source flow through the medium and receiver without being absorbed or reflected and pass through the recipient material without frequency loss. In another way, the transmission coefficient is the proportion of incident energy transferred (τ). Without energy dissipation or reflections, the transmission and attenuation coefficients (α) are related as follows.

$$\tau = 1 - \alpha^2 \qquad (1)$$

Transmission loss is the accumulated decrease in the power of a sound wave as it propagates away from its source. TL (sound transmission loss) describes flat surface acoustic materials properties, such as metal panels, etc. [15].

$$TL = -10 \; Log_{10}{}^{\tau} \qquad (2)$$

2.1.3 Sound Absorption

Sound absorption is the quantity of sound wave energy absorbed without being reflected or transmitted. The sound absorption coefficient varies from 0 to 1. 1.0 shows total absorption. On the other hand, 0.0 indicates total reflection. Sound absorber materials are classified into two types: resonance absorber materials and porous absorber materials. The materials division depended on the performance of the frequency range [4, 16–19].

Resonance Absorber Materials

The resonant absorbers work by dissipating acoustic energy through structural vibration. Resonant absorbers' effectiveness generally depends on the broadband sound frequency difference only in a narrow, tunable low-frequency band [10]. Membrane/panel absorbers and Helmholtz absorbers are the two most common types of resonant absorbers. The mechanism of sound absorption in a membrane or panel absorber is the dissipation of energy through membrane or panel vibration. The flexible membranes or panels must couple with and be driven by the sound field, regardless of whether they are positioned beside an air gap or on a suspended ceiling [19, 20].

The other sound absorber is a microperforated panel resonator (MPP) (Figure 2 (a)), which recently became very acceptable due to being made of recyclable materials and is increasingly used in sound field control, especially in industrial environments where porous materials degrade. MPP is formed from a thin sheet panel perforated with a lattice of sub-millimeter holes that provide the high acoustic resistance and low acoustic mass reactance required for broadband sound absorption without extra porous material. MPP's absorption material working principle is associated with the resonance effect, in which the air inside the openings of the MPP vibrates like a mass, and the air inside the cavity operates like a spring. Hence, the efficient acoustic absorption spectral range is around the resonance peak.

Furthermore, it is possible to utilize additional MPPs in the backing cavity to build multiple-layer absorbers. This will allow the absorption width of the frequency range to be increased. However, MPP absorbers' frequency range is not acceptable in many practical applications, especially low-frequency sound absorption, which requires a bigger cavity. To overcome this limitation, "pressure releasing" on the back of the MPP or "impedance matching" of the surface area of the hybrid noise control system is implemented to obtain the desired acoustic environments [21–31]. The sound absorption mechanism of Helmholtz resonators can be obtained by adding porous material near the neck (Figure 2 b) where the particle velocity is higher or by making the opening very narrow in order to achieve maximum acoustic dissipation [19, 32].

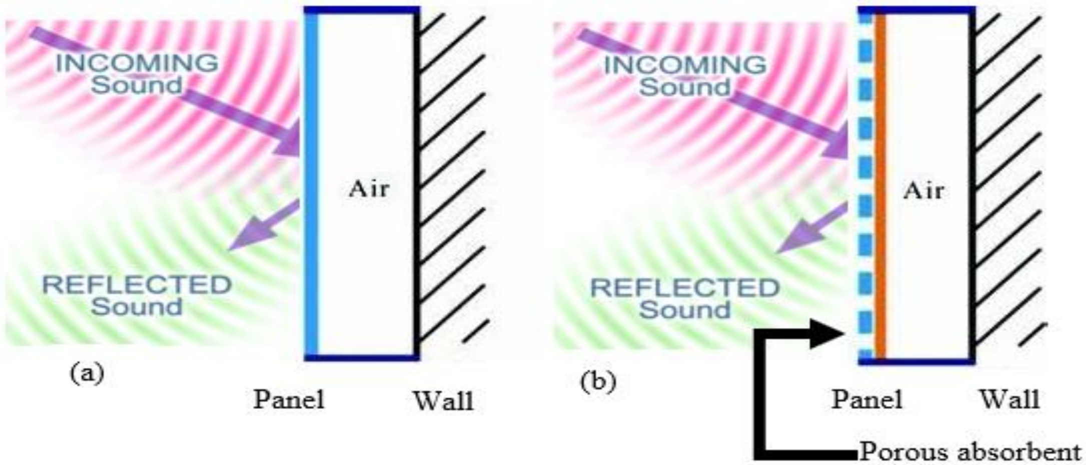


Figure 2. A schematic sound absorber of (a) panel absorber and (b) Helmholtz absorber.

Porous Sound Absorber Materials

Porous sound absorber materials can be created from woven fabric, composites, sponges, or nonwoven fabrics with pores with a small internal diameter, interconnecting channels, and fractures or holes spread evenly or randomly throughout the material. Sound waves may propagate to the material because of the porous structure's characteristics. The process of converting acoustic energy into heat energy occurs when sound waves collide with pore walls or solid threads, decreasing the sound wave's energy of propagation. As a result, porous materials offer strong noise absorption characteristics, especially in the mid- and high-frequency wave bands [1, 33].

The effectiveness of sound-absorbing materials is dependent on their nonwoven or porous structure. Viscous losses, friction losses, internal resonance, and internal damping losses cause sound absorption and related acoustic wave energy losses in a given material.

Viscous losses: - Viscous losses define the porous substances in which air occupies a substantial portion of the volume. When sound waves penetrate into non-woven material, the acoustic wave travels through a small cross-section of the material's pore.

Due to the asymmetrical internal structure, air movement within the pores is slowed, and air oscillations diminish in proportion to the frictional resistance caused by the significant influence of air viscosity in small holes [4].

In the case of the fibers in the fabric, the elasticity of the fiber type makes the weave structure loose, and as a result, during the propagation of sound waves through the fabric, they start to displace and rub against one another. This phenomenon depends on the material's elasticity. On the other hand, if a porous material has zero elasticity, no acoustic energy will be lost [4, 34].

Friction loss: - Defined as being related to the rubbing of elastic fibers against one another. The porosity of the material, in addition to its thickness, plays an important role in friction loss phenomena in woven and nonwoven fabrics. When the wave energy travels through the thickness of the material, it rubs against the porous structures. As a result, the sound wave will be lost while traveling through the thickness of the material [4, 35–37].

Internal damping losses: - The phenomenon of acoustic energy loss resulting from internal damping in the material is residual in non-woven materials; it has a high potential to have a major impact on materials susceptible to the effect of acoustic waves, such as sponges or rubber. The deviation is caused by acoustic energy, the magnitude of which determines how far the position is from where it began. The amount of energy lost is affected by the material's internal damping and is directly proportional to the square of the amount of local deformation in a single element. A porous material's structure is composed of a rigid skeleton and numerous interconnected chambers. The airflow resistance of materials with damping properties is higher [4, 36, 38, 39].

Internal resonance: - The absorption of sound in the pores of the material. Follows physical phenomena. A porous material contains multiple resonators (created during the manufacturing process), such as mini chambers with contractions (necks), whose effect resembles that of Helmholtz resonators and causes acoustic energy damping in frequencies dependent on chamber size as well as neck length and cross-section [4].

2.2 Types of Porous Materials

2.2.1 Composite Sound Absorber Materials

The composites' remarkable qualities, such as low weight, high strength, and stiffness, allow them to be used in a variety of technological fields, including acoustics. The compact surface of the composite material contributes to the sound waves being reflected. In addition, sound transmission loss as well as sound absorption, can be improved by combining the composites with other sound barrier fillers and using them in combination with each other. For instance, improvement in absorption performance was shown at both mid- and high-frequency when porous glass-fiber-reinforced polyurethane was utilized as the matrix. Furthermore, cotton fibers combined with cellulose ultra-fine fibers and ultra-short fibers, particularly using nanofibers as a reinforcement, can be used to enhance sound absorption [36, 40–46]. Other studies [47] indicated the possibility of enhancing the composite's sound absorption by adding a relief with a protrusion diameter higher than 10 mm to the composite surface. In addition, other methods, such as utilizing optical coherence tomography (OCT) image analysis to control the polymer thickness applied on the surface of the composite, enhance the possibility of a sound absorption coefficient at a specific frequency as the application requires [48].

The matrix of a composite can be formed of a porous sound-absorbing material, and different amounts of blowing agents can be employed to achieve pores of varying sizes in order to enhance the composite's ability to absorb sound at medium and high frequencies. In general, voids are considered a disadvantage in the manufacture of composites due to their influence on mechanical performance as a result of the possibility of failure. However, there are advantages when utilization of composite voids, another intriguing way to enhance the acoustic characteristics of 3D composites. Due to the presence of pores in 3D composites, the mechanical properties of the composite are not easily influenced, and as a result, the presence of voids in the composite improves its sound absorption properties in the medium- to high-frequency region. Composites can be used as noise-controlling materials in cars, planes, ships, trains, and other types of transportation applications [44, 45, 49, 50].

2.2.2 Nonwoven Material as Sound Absorber Material

Nonwoven materials are one of the primary acoustic materials classified as porous acoustic materials. Nonwoven fabrics are distinguished by their high specific surface area, high porosity, light weight, and low cost. Apart from that, nonwovens may be found in a variety of fiber assemblies. As a result of these qualities, nonwovens have found widespread use in a variety of applications, including sound absorption and thermal insulation applications [51, 52].

Nonwoven fabrics are widely used as a base material in the sound absorption sector because they can be found in different types of fiber orientation, different structures, different manufacturing techniques, and different types of bonding.

The needle punching method is the most studied method for producing nonwovens for sound insulation. The fibers or fiber mixture are opened, and a web is formed during the carding process, after which the web is fed to the needle-punching operation to entangle the fibers. In this method, the web's fibers are mechanically tangled up by the repeated insertion of needles with barbed tips.

Different parameters, such as web orientation, needle punching density, final weight per unit area, the mass percentage of various fibers, etc., are changed throughout the needle punching process to get the desired end result [36, 53].

According to the findings of a study that was conducted on a nonwoven that is made up of synthetic fibers, natural fibers, and agricultural lignocellulosic fibers, the sound absorption result is high at higher frequencies (2000–6300 Hz), and improved sound absorption is obtained at mid-frequency ranges (500–1600 Hz). However, the sound absorption is low at low frequencies (100–400 Hz). Additionally, the research findings indicate that increasing the thickness of the nonwoven fabric enhances the possibility of sound absorption at frequencies in the midrange [52–56].

In general, the effectiveness of materials as noise barriers is determined by the frequency of the sound waves to which they are subjected. The sound absorption properties of nonwoven fabrics are determined by the fiber arrangement and fiber geometry within the fabric's structure.

2.2.3 Woven Fabric as Sound Absorber Material

Woven fabrics are fibrous materials that are characterized as porous due to their structure. The production of woven fabric consists of warp and weft yarn interlacing. The way the strands are interwoven depends on the weave pattern. The noise attenuation provided by woven material is determined by the fabric’s thickness, yarn type and yarn characteristics, interlacement type (weave structure), weaving process parameters, and porosity. The general fiber type influences the sound absorption of all fiber-based fabrics, with lower yarn linear density and finer yarns enhancing sound absorption [17, 57]. However, sound absorption is influenced more by the gaps between fibers in fabric than by fiber diameter or cross-section shape. Textiles with hollow and round cross-section fibers have similar results; however, fabrics with flat ribbon and triangular cross-section fibers have dramatically different outcomes [7, 58, 59].

Fabrics formed from jute fibers have higher sound-absorbing characteristics than other synthetic materials. Furthermore, sound reduction using jute fibers at lower frequencies is highly effective in comparison to higher frequencies [60]. Regarding the weave properties of woven fabrics, a plain weave structure absorbs sound waves higher than other weave structures due to the fabric’s shorter free-float of yarn, higher density, higher interlacement, and higher crimping yarns. Twill fabric has more thread floats and fewer interlacing points than plain weave. Moreover, the stability of plain-weave fabrics results from the higher interlacing points of the warp and weft yarns [31].

The amount of sound waves that can be absorbed by porous materials depends on their structure and features. There are two types of porosity in woven fabric: macroporosity and microporosity. Microporosity is generated by a space between yarn fibers, while macroporosity is formed by yarn strands. It is mainly characterized by its interlacing degree and weave type. Regarding the porosity of fabrics, the approximate air permeability value can be predicted based on the linear density of the yarns and the diameter of the pores (one inter-yarn). Depending on the degree of interwoven threads, the pores’ size and shape in the woven fabric may be distorted and altered by airflow. Additionally, the air pressure can cause yarns to float, developing new pores on the fabric's surface [61, 62].

The advantages of using woven fabric in acoustic applications are listed as follows.

- The manufacturing method is well-developed and cheap in comparison to others.
- It can be fabricated with different fabric weave structures, different weaving designs, and density, openness, and light properties.

- Fabrics can be treated with special finishes to make them water-repellent, soil-resistant, flame-resistant, etc.
- The durability properties of woven fabrics are higher than those of nonwoven fabrics as a result of the high mechanical properties of woven fabrics.

As wall coverings, combinations of fabrics are used not only for aesthetic purposes, however, but also to increase the acoustic environment or used for soundproofing purposes [63].

2.3 Porous Material Characteristics That Influence Acoustic Properties

The acoustic performance of a material is dependent on the properties of the material it is made up of. Following is a list of some acoustic material characteristics:

2.3.1 Areal Density (Mass)

Areal density is also referred to as the fabric's mass. The weight of a specific area of the fabric could be defined as its area density. In general, textiles such as woven fabric, knitted fabric, and melt-blown nonwoven fabrics are included in two-dimensional materials and, as a result, have a very small thickness. Materials that are not very uniform and the result can be displayed as an average. ASTM D3776/D3776M is the standard test method for determining the areal density of textile materials [32, 64].

2.3.2 Particle Size

During the preparation of composite acoustic materials from natural materials like agricultural waste, hemp straw, rice straw with synthetics, and wood-based material, it is crucial to determine the particle dispersibility. The measurement can be done by scanning electron microscope or optical microscope images and image processing using the appropriate software [64, 65] to understand the size range.

2.3.3 Volumetric Mass Density or Bulk Density

The textiles used in acoustic applications are porous and in volume. The fabric’s bulkiness is assessed by weighing and measuring the fabric's three dimensions. As a result of the fact that textile-based acoustic materials are not homogeneous, 10 measurements are needed to provide accurate results. The unit of bulk density is measured in g/cm^3. This parameter utilized predominantly bulky materials, such as nonwoven fabrics [32].

2.3.4 Porosity

The air gap inside a textile or porous material is called a "void" or "pore." The benefit of porous or open areas in a textile material is that sound energy can be converted into heat and kinetic energy due to internal friction between the porosity wall and the sound's incident wave. As a result, porosity plays a vital role in sound absorbing materials. There are two types of porosity measurements: pore size distribution and total reachable porosity.

Total reachable porosity is calculated as follows:

$$\text{Porosity} = (1 - \text{Density of fabric}) / \text{Density of the fiber}$$

The porosity of the material could be determined using extrusion porosimetry, extrusion flow porosimetry, mercury intrusion porosimetry, gas absorption, non-mercury intrusion porosimetry methods, optical microscopy, micro-computed tomography, and neutron scattering methods. This study examined the fabrics' porosity properties using optical microscopy and micro-computed tomography analysis.

The porosity values of fabrics play a significant role in their air permeability and sound absorption properties. The porosity of different structures can be measured as a volume fraction of the empty space within the structure. It is expressed as a fraction of the volume of empty space relative to the total volume and can range from 0 to 1. This value is crucial for the acoustic qualities of the material since a smaller pore size will result in a high number of fibers in a given area, hence increasing acoustic absorption. Therefore, a material with the same volumetric density, with larger pores, shows less sound absorption [4, 66–69].

In addition, the porous space is created on the fabric surface, and the porous size has an influence on the determination of the absorption capacity of sound waves by the woven fabrics. The movement of sound waves in the porous space of the fabric or in a complex structure leads to the construction of tortuous paths. As the tortuosity of the material increases, it indicates that more complicated paths through the material indicate high resistance to sound waves [70, 71].

2.3.5 Air Permeability

Air permeability measures how effectively a fabric enables air to pass through it when there is a pressure difference between its sides (face and back). Besides, the air permeability of materials can be measured to compare the relative porosity of different materials.

The correlation between air permeability and impedance allows for modifying sound absorption characteristics. The property of sound absorption is enhanced as the resistivity of a fibrous material increases but decreases as the resistivity exceeds a certain threshold. If the air flow resistance is too low, internal friction's attenuation of acoustic energy is minimal, and the absorption outcome is poor. If the air permeability is too low, the majority of acoustic waves will be reflected, and absorption will decrease.

In general, air permeability and sound absorption are inversely proportional, and the result of air permeability can be used as criteria for sound absorption behavior. During air permeability tests, five to ten samples of one type of material can be measured in accordance with the ISO standard for air permeability (ISO 9237:1995), and the result can be determined by averaging the material results [49, 66–68].

2.3.6 Fabric Thickness

Compared to nonwoven materials, textiles such as woven and knitted fabrics are exceptionally thin. The thickness of nonwoven fabrics is dependent on the types of fiber from which they are formed. Thickness and sound absorption have been found to be directly related by researchers since the 1980s.

The lack of structural integrity of these materials is due to their softness. Therefore, textile thickness measurements are not as simple as solid thickness measurements. Thickness is measured using ASTM D5729, and ASTM D5736 is used for nonwoven fabrics, while ASTM D1777 or PN-EN ISO 5084:1999 is used to measure the thickness of textiles. The methods consist primarily of measuring the thickness by weight. Regarding the relationship between fabric thickness and the sound absorption performance of porous materials, only low-frequency sound absorption is influenced by material thickness. An increase in material thickness from 5 cm to 10 cm has no significant effect on sound absorption above 500 Hz; however, it has a significant effect below 500 Hz frequency [4, 72, 73]. In general, the thickness of porous material is a distinctive property in the preparation of sound absorption materials.

2.3.7 Yarn and Fiber Characteristics

The characteristics of yarn, as well as the spaces between the fibers and the cross-section of the fiber, significantly impact sound attenuation. Besides, the nature or type of raw material affects the sound absorption capacity, and lower yarn linear density and finer yarns improve sound absorption, as explained in [7, 58]. However, sound absorption is influenced more by the gaps between fibers in fabric than by fiber diameter or cross-section shape [7, 58–60]. Textiles with hollow and round cross-section fibers have similar results; however, fabrics with flat ribbon and triangular cross-section fibers have dramatically different outcomes.

2.4 Sound Absorption Measurement Methods

Common methods for measuring the sound absorption coefficient include the impedance tube method, the reverberant room approach, and the anechoic chamber method. The impedance tube method measures normal incidence absorption coefficients, whereas the reverberant room method measures random incidence absorption coefficients [19, 76, 77].

2.4.1 Impedance Tube Method

The impedance tube, also known as a Kundt tube, measures the surface impedance and the normal incidence absorption coefficient. This is particularly valuable since it allows measurement in well-defined and controlled settings. As a result, it is extensively employed in verifying prediction models for porous materials. This measurement technique has the benefit of requiring relatively small samples (a few centimeters in diameter), which makes it perfect for material developers. The last significant benefit is that the impedance room requires no specialized testing chamber. As a result, the impedance tube method can be performed using relatively modest equipment in a typical laboratory. The fundamental drawback of impedance tube measurement is that absorption from a small sample does not correctly represent the behavior of a large sample.

Cutting and mounting samples appropriately is the most critical experimental part before measuring. The specimen must fit snugly within the tube. Any holes surrounding the sample's edge must be plugged and sealed; otherwise, the measured absorption will be abnormally high and uncertain. Typically, petroleum jelly (Vaseline), mastic, or plasticine are utilized to cover the borders of the sample. It is also vital not to wedge porous absorbers into the tube since this modifies the mechanics of the absorber frame and can lead to erroneous measurements due to the restricted vibration of the absorber frame. Therefore, the sample should be 0.5–1 mm smaller than the diameter (or width) of the tube, such that the measured impedance and absorption coefficient are equal to those of an indefinitely sized sample.

Generally, the impedance tube measures the fabric's normal incidence, surface impedance, transmission coefficient, and absorption coefficient. It can also be utilized to extract porosity, tortuosity, and characteristic lengths using inverse techniques. The measurement requires a small sample size, and the data are used for absorber and prediction model building and evaluation [78–80].

2.4.2 Transfer Function Method

This method uses easy and quick tests to get the absorption coefficient and impedance for all frequencies (within specified limitations). The transfer function between two microphone positions within a tube is used to measure the pressure ratio. By measuring the resulting pressure, it is possible to calculate the surface impedance and the sample normal incidence absorption coefficient (Figure 3) [78]

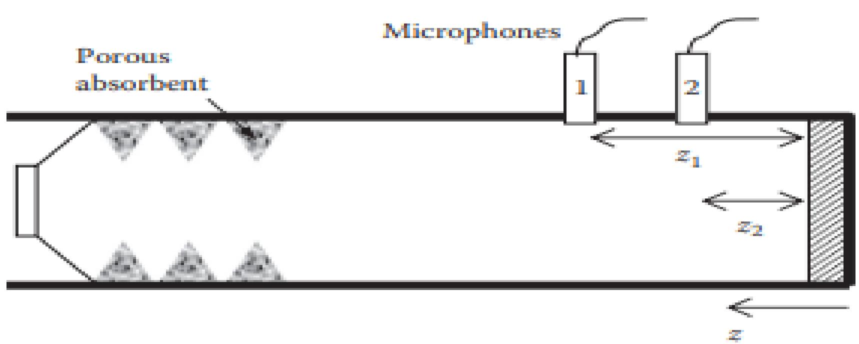


Figure 3. Impedance tube measurement using two microphone techniques [78].

2.4.3 Reverberation Chamber Room Method

The coefficient of random incidence absorption is the design parameter most frequently used to specify the absorption capability of materials. It is well-known and defined; however, it is notoriously difficult to predict. Therefore, while the random incidence absorption coefficient is necessary for room design, it is not particularly useful for verifying prediction models. Consequently, this method was not utilized in the present study. Experiments involving reverberation chambers require a large sample and a specialized room, which is more expensive and challenging. Therefore, absorptive material developers first utilize the impedance tube on small samples rather than conducting in a reverberation room with large samples [81].

The overall absorption in a room determines the reverberation time of the room. Therefore, the random incidence absorption coefficient can be determined by measuring the reverberation duration of a room before and after an absorbent sample is added. Diffusers are used in the room to achieve uniform distribution of auditory circumstances and reflection of sound energy. This can be done by minimizing the room, and the room must have irrational dimensions.

The source is usually situated in the corner of a room, pointed into the corner, to enhance room mode excitation and limit loudspeaker radiation reaching the test sample. Receivers should be located at least 1 m from space boundaries, diffusers, and the sample, which must be selected to sample the room volume diversely. Generally, the results obtained at low frequencies are more inaccurate than those at high frequencies [71, 82].

2.4.4 Anechoic Chamber Method

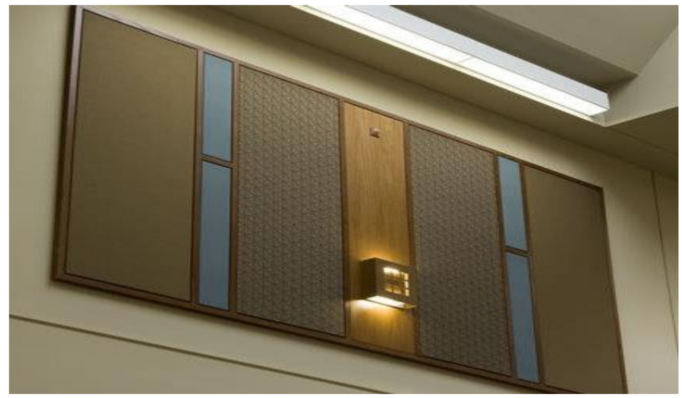
The anechoic chamber is classified as an acoustically dead space. Typically, the energy absorption in this kind of chamber is between 99 and 100%, or the reflected sound pressure is 10 % or less. The frequency at which energy absorption decreases below 99.9 % or pressure reflection exceeds 10 %. Such rooms are designed to eliminate frequency interference (Figure 4) [83]. As a result, the room must be devoid of reflections from the wall, ceiling, and floor; otherwise, they must be attenuated by at least 25 dB. In an anechoic chamber, every surface must be covered in absorbing wedges composed of open-cell foam, fiberglass, and other materials to eliminate boundary reflections. Forming the absorbent into wedges decreases reflections from impedance discontinuities at the boundary. This means that it is suitable for assessing the response of diffusers because the room does not affect the measurements.

Figure 4. Aeroacoustics chamber at Łódz University of Technology Institute of Turbomachinery [83]. Contains 368 m^2 of aeroacoustics room dimensions surface area.

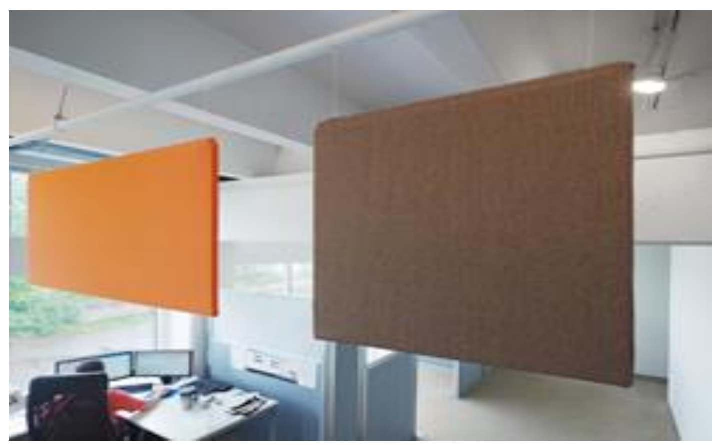
2.5 Application of Acoustic Material

The general advantage of acoustic porous materials is that they absorb and prevent the reflection of acoustic sound energy. Additionally, it reduces reverberation levels in a room and improves the room's aesthetic appearance, etc. The porous acoustic materials that are found in the markets are wall panels, ceiling panels, foams, carpets, fiber boards, insulation blankets, etc. (Figure 5). Application areas include churches, hotels, hallways, auditoriums, offices, music rooms, etc. Below are some examples of porous materials [84–86].

A. Wall sound panels



B. Ceiling sound panels



C. Soundproof foam panels

Figure 5. Application of porous sound absorber materials. A. Wall sound panels, B. Ceiling sound panels and C. Soundproof foam panels [84-86]

2.6 Conclusion of Literature Review

The versatile application of porous materials in the acoustic sector makes them important for controlling noise levels in various environments. However, porous material acoustic performance depends on the physio-mechanical properties of porous materials, such as areal density, particle size, volumetric mass density, porosity, air permeability, fabric thickness, yarn and fiber characteristics, airflow resistance, tortuosity, etc.

Previous studies show that nonwoven fabrics were commonly used as sound absorbers. However, nonwoven fabrics' acoustic performance is limited to higher frequencies. Therefore, it is necessary to investigate their acoustic properties to increase the acoustic efficiency of the nonwoven fabric and the woven fabric. In comparison, utilizing woven fabric provides many advantages beyond its acoustic properties, such as high mechanical properties, aesthetic value, etc. In addition, woven fabrics' ease of production and, most importantly, their ability to be woven into various pattern structures by varying the yarn's characteristics and weave type make them extremely valuable and give a wide range of possibilities and clues for the investigation and development of acoustic materials. As a result, improving the performance of porous materials by increasing their ability to absorb a wide range of frequencies is a key research area to be considered for the development of acoustic materials based on porous materials.

To overcome the research gap, this study began by manufacturing woven fabrics with different weave structures formed from different yarn characteristics of polyester fibers. Subsequently, an anechoic acoustic chamber and impedance tube measurements were used to investigate the sound absorption properties of the woven fabrics.

3. WOVEN FABRIC MANUFACTURING PROCESS AND EVALUATING THEIR ACOUSTIC PERFORMANCE USING AN ANECHOIC CHAMBER.

According to previous research, porous materials' sound absorption at low frequencies is generally low. To overcome this limitation, it is necessary to investigate the sound absorption phenomena of woven fabric related to the physical characteristics of yarn and the geometrical properties of fabrics. In addition, utilizing woven fabric for the application of acoustic material requires understanding the role of yarn types and the weave structure influences.

Therefore, the primary research stage started with selecting the fiber type. Polyester fiber is preferable for such uses due to its durability, environmental tolerance, cost-effectiveness, and nontoxicity. As a result, materials formed from the polyester fiber can be used as acoustic materials in schools and, generally, places where people are present. Furthermore, the performance of polyester fiber in previous studies indicates that the sound absorption performance of polyester materials at medium and higher frequencies obtained outstanding results. [64, 87, 88].

To understand the yarn properties, this study utilized three different yarns with different characteristics: staple textured and twisted yarn. Furthermore, weave structures are selected by assuming the porosity structures that can be formed due to the interlacing of woven fabrics. The process of weaving fabrics and measurements of the physical properties of woven fabrics are described. In addition, acoustic fabric measurements and the advantages of conducting within an anechoic chamber are discussed.

3.1 Materials

Three types of polyester yarn (PES): drawn textured yarn (dtex 167 × 2 (filament number 32 × 2)) (DTY), polyester twisted yarn dtex 334 (filament number 32 × 2), S95 and polyester staple yarn 200 × 2 dtex were used for sample preparation. The yarn's physical differences are shown in (Figure 6).

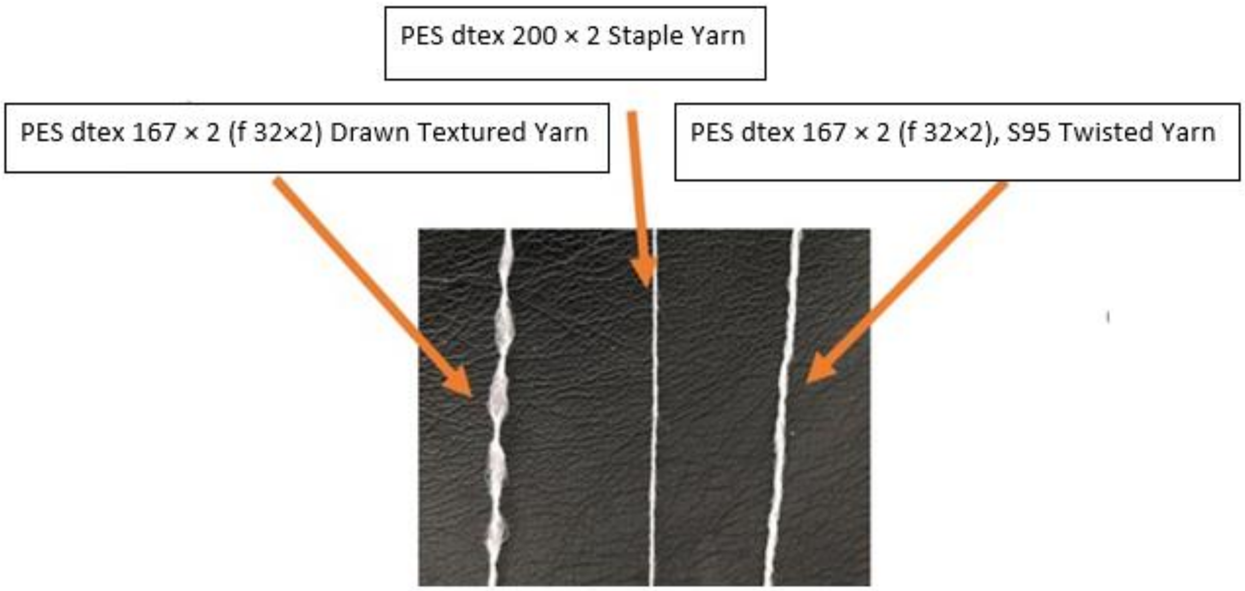


Figure 6. Types of polyester yarn, drawn textured yarn, staple yarn, and twisted yarn.

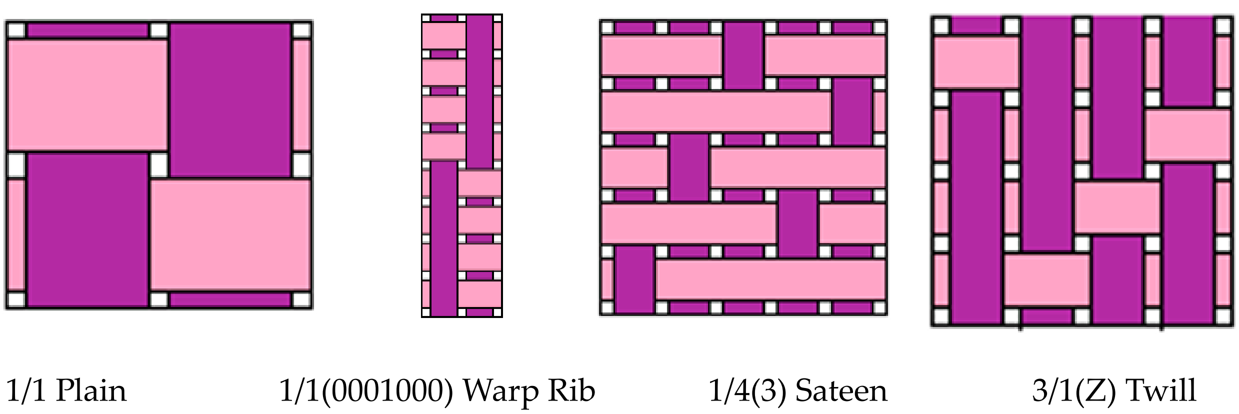


Figure 7. Basic fabric weave structures, plain, rib, sateen, and twill.

Twelve woven fabric samples were prepared for this research. Fabrics were woven on a Sample Dobby loom (SL 8900S) at the Lukasiewcz Research Network-Textile Research Institute (CCI Tech Inc., Lodz, Poland).

The preparation of woven samples started by winding 1500 warp yarns on the weaver beams. Consequently, the drafting process continued by inserting each yarn ends into the heddle eye using 8 harness frames to form the desired fabric pattern and design. An important step continued with the denting process, which involves passing each warp thread through a separate dent in the reed. The denting plan process helps to separate and space the warp threads evenly, and during the weaving, after each beat-up process, it helps to pack the weft threads tightly together and push the weft threads into place. The beater moves back and forth while weaving, pushing each weft thread into place against the previously woven fabric. Figure 8 shows loom preparation in the sequence of the weaving process. This process was repeated to produce 12 woven fabrics, which were performed from three types of yarn (textured, staple, and twisted yarn) indicated in Figure 6 and woven into different basic weave patterns (plain, sateen, rib, and twill) that are presented in Figure 7. The fabric design or pattern was selected by considering the porous space created by the interlacing and the free-floating of threads without interlacement. Polyester yarn with the same yarn characteristics was employed in both directions (warp and weft)

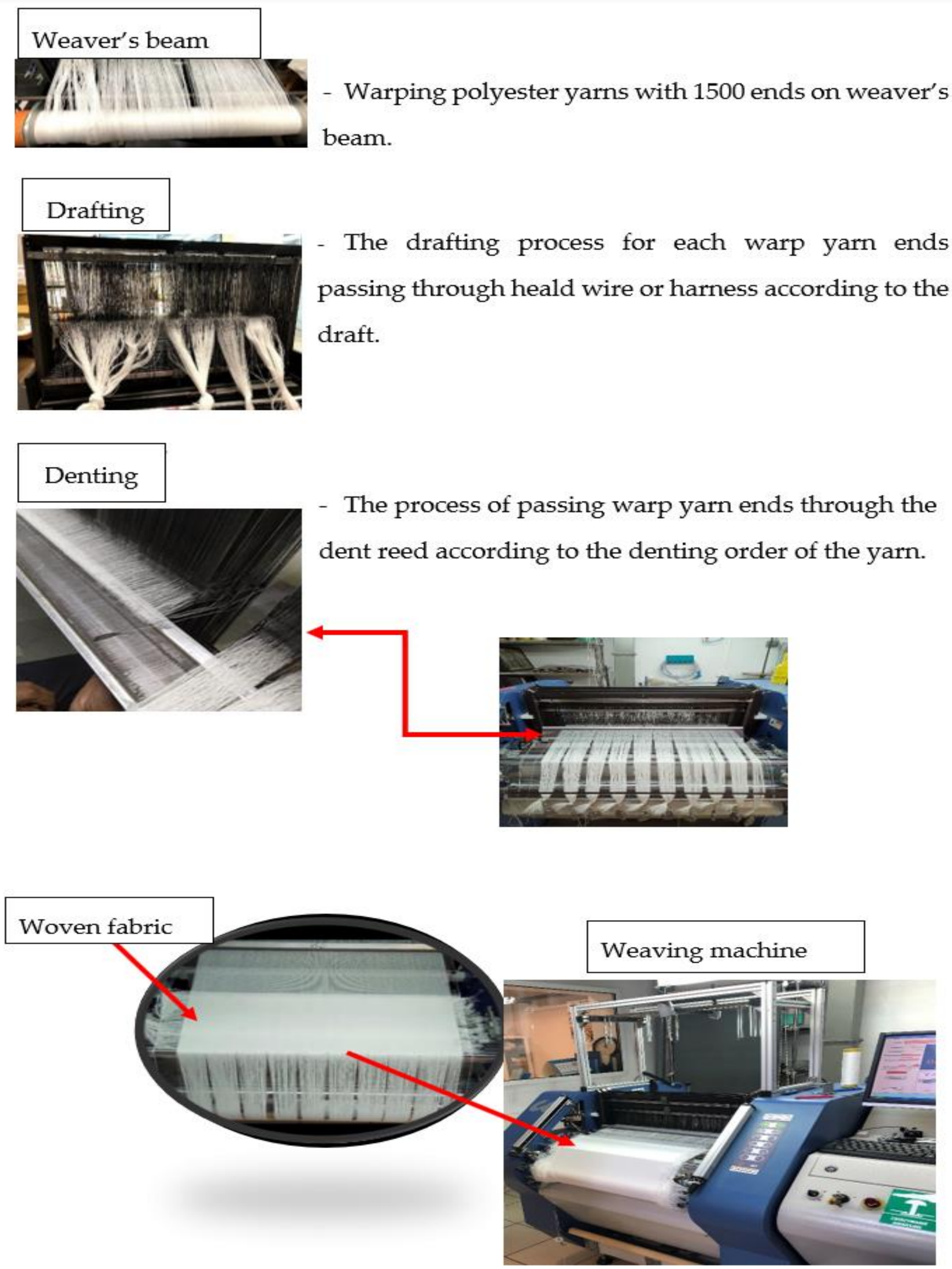


Figure 8. Loom preparation and fabric manufacturing process, yarn winding on weaver's beam, drafting, denting, and weaving process.

During the manufacturing of woven samples, the setting density of warp and weft yarns was comparable for all fabrics. The fabric design or pattern was selected by considering the porous space created by the interlacing and the free-floating threads without interlacement. The samples naming and manufacturing warp/weft yarn density presented in Table 2.

Table 2. Yarn type and fabric manufacturing setting [98,99].

Yarn Type	**Weave Type**	**Samples Name**	**Set Density Warp/Weft (cm)**
Textured	Plain	TP	30/16
	Rib	TR	32/16
	Sateen	TS	30/16
	Twill	TT	30/16
Staple	Plain	SP	32/16
	Rib	SR	31/16
	Sateen	SS	31/16
	Twill	ST	31/16
Twisted	Plain	TWP	32/16
	Rib	TWR	31/16
	Sateen	TWS	32/16
	Twill	TWT	31/16

3.2 Methods

The methodologies used for sound absorption testing and the physical characteristics of the yarn and woven fabrics are presented as follows:

3.2.1 Physical Characteristics of Yarn and Fabrics

Yarn properties were measured for all yarn types. USTER TESTER 3 was used to assess yarn hairiness and evenness per ISO 2649-1974 [89] (temperature: 20 °C, relative humidity: 69%). Yarn twist testing was conducted per ISO 2061–2010 under normal environmental conditions [90]. The results of yarn twist, hairiness, and yarn evenness are presented in Table 3.

Table 3. Yarn types and physical characteristics [91, 92].

Type of Yarn	Yarn twist/m	Yarn Hairiness	Measured Linear Density of Yarns (Tex)	Yarn Evenness	
				Thin/km	Thick/km
Textured yarn **PES DTY dtex 167 f 32 × 2**	—	—	36.62 ± 0.04	—	—
Staple yarn **PES 20 × 2 tex**	511.4	7.24	41.16 ± 0.09	80	34.6
Twisted yarn. **PES dtex 334 f 64, S95**	90.1	—	36.93 ± 0.01	—	—

Table 4 **o**utlines the characteristics of the fabric as determined by post-manufacturing measurements. Fabric thickness tests were conducted using PN-EN ISO 5084:1999 [93], with a measurement area of 20 cm^2 and a pressure of 1 kPa (relative humidity: 65 ± 5% and temperature: 20 ± 0 °C). The fabric's yarn crimp was calculated in accordance with ISO 7211-3:1984 [94]. The fabric's mass per unit area was evaluated per PN-ISO 3801:1993

[95] (relative humidity 66 ± 5% and temperature 21 ± 0 °C). In addition, the density of the warp and weft yarns in the fabric was measured.

Table 4. Measured fabric construction parameters for 12 woven fabrics [91, 92].

Samples name	Measured warp density (Ends/cm)	Measured weft density (Picks/cm)	Fabric thickness (mm)	Crimp%		Mass per unit area, (g/m²)
				Warp	Weft	
TP	31.0 ± 0.5	18 ± 0	0.52 ± 0.01	8.7 ± 0.4	0.9 ± 0.1	195± 2
TR	38 ± 0	17 ± 0	0.80 ± 0.02	1.9 ± 0.1	17.9 ± 0.7	224 ± 3
TS	34 ± 0.4	20 ± 0.6	0.90 ± 0.03	11.1 ± 0.1	2.0 ± 0.1	213 ± 2
TT	32 ± 0	18 ± 0.6	0.79 ± 0.02	10.9 ± 0.2	1.8 ± 0.1	210 ± 4
SP	32 ± 0.2	17 ± 0.6	0.57 ± 0.01	14.7 ± 0.3	2.3 ± 0.1	213 ± 2
SR	35 ± 0	17 ± 0.5	0.74 ± 0.01	1.3 ± 0.1	11.0 ± 0.2	211 ± 2
SS	33 ± 1.1	16 ± 0	0.71 ± 0.03	6.6 ± 0.1	3.2 ± 0.1	202 ± 1
ST	33 ± 0.2	18 ± 0	0.75 ± 0.01	7.5 ± 0.3	2.1 ± 0,1	210 ± 3
TWP	31 ± 0	17 ± 0.8	0.46 ± 0.01	7.4 ± 0.2	0.3 ± 0.1	189 ± 1
TWR	35 ± 0.1	16 ± 0.6	0.73 ± 0.02	3.1 ± 0.2	11.9 ± 0.2	203 ± 2
TWS	35 ± 0	17 ± 1	0.76 ± 0.02	5 ± 0.2	2.5 ± 0.1	195 ± 1
TWT	34 ± 0.2	20 ± 1	0.94 ± 0.01	6.7 ± 0.2	1.9 ± 0.1	197 ± 1
Nonwoven (N)	____	____	30 ± 0.01	____	____	623 ± 0.1

An air permeability test was performed on 12 woven fabrics made up of textured, staple, and twisted yarn, and from each yarn type, four different weave structures, such as plain, rib, sateen, and twill. According to the standard, the fabrics were measured selectively on wrinkle-free surfaces with a 20 cm² surface area. Air pressure drops of 100pa were used in ten different areas from one sample. The measurement procedures and calculations were performed according to ISO 9237:1995 [96]. After a 24-hour acclimatization period in normal climatic conditions for fabrics (temperature 20 °C, relative humidity 65%), and the Fx 3300 air permeability tester (Figure 9) was utilized to conduct the tests. The Fx 3300 air permeability tester is used to determine the airflow of materials such as flat fabrics and foams in a simple, accurate, and straightforward manner [97]. The tests were conducted in the laboratory of the Lodz University of Technology's Department of Materials Science, Commodity Science, and Textile Metrology (Lodz, Poland).

$$Q = (qv/Ap) \times 167$$

The air permeability test is calculated where Q (mm/s) is for the velocity of airflow perpendicular to a sample, qv (dm^3/min or liter/min) is the average mean of the airflow, Ap (cm^2) test area of the specimen, 167 is the conversion factor from (dm^3 or liters/min and cm^2 to mm/s).

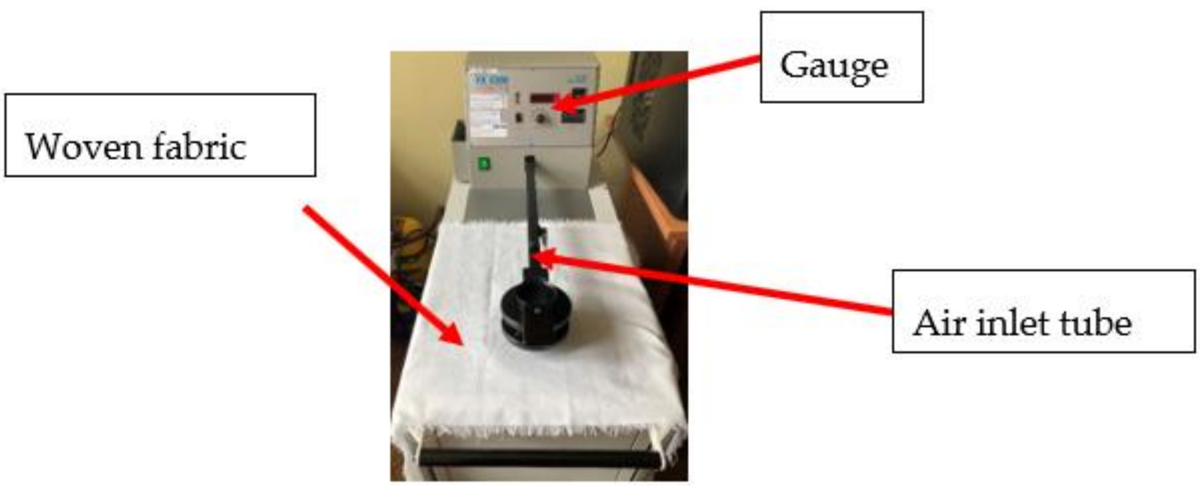


Figure 9. Woven fabric air permeability measurement using Fx 3300 Air permeability tester.

3.2.2 Sound Absorption Test

In the Laboratory of Aeroacoustics Institute of Turbomachinery at the Lodz University of Technology, sound absorption tests were determined in a free-field environment within an aeroacoustics anechoic chamber. The building was built in a different style, with a flat floor, walls, and a ceiling. The interior was finished with contemporary materials that absorb sound. Without conventional acoustic patterns or linings such as wedges, cones, pyramids, or other projecting features, no additional or unnecessary noise generation accompanies inside-out flows [83].

Samples include four fabric structures generated from three yarn types (total 12 fabrics), sound level drops were measured in an aeroacoustics anechoic chamber based on the selected frequency ranges and angle directions. The study based on angle differences is primarily concerned with maximizing acoustic materials' performance by understanding the fabric's effectiveness in relation to the sound source. The first test was conducted at the fabric's center by positioning the sound source directly in front of the first microphone (Mic #1) at an incidence angle of 0°. The sound source was angled at 45° during the second test. A 1 m distance was maintained between the fabric surface and the sound source in each measurement case. Figure 10 illustrates the microphone (Mic) placement and the fabric arrangement on the acoustic test's special frame.

All experiments were conducted with an amplifier-powered directional sound source (Figure 10 c, microphone (Mic) #3) (frequency response from 5 Hz to 60 kHz at 1 dB). The frequencies were established using a sinusoidal signal generator, and the signal profiles were examined with an oscilloscope in every instance (Figure 11). Before the signal was sent to the sound source, its amplitude was set to 300 mV and amplified. After calibration, three half-inch microphones (Mic) with built-in preamplifiers were utilized (Figure 10 c, Mic #2; sensitivity 50 mV, frequency range 3.15 Hz to 40 kHz with 200 V polarization).

Before beginning the main tests, the sound levels were measured without any fabrics for the purpose of validating the measurement system and as a point of reference. The fabrics were then tested in the chosen frequency ranges in accordance with the international standard ISO 26101:2012 [98]. The measurements were conducted within the frequency ranges of 63, 125, 250, 500, 1000, and 2000 hertz (temperature was 22 ° C, and the relative humidity was 65%).

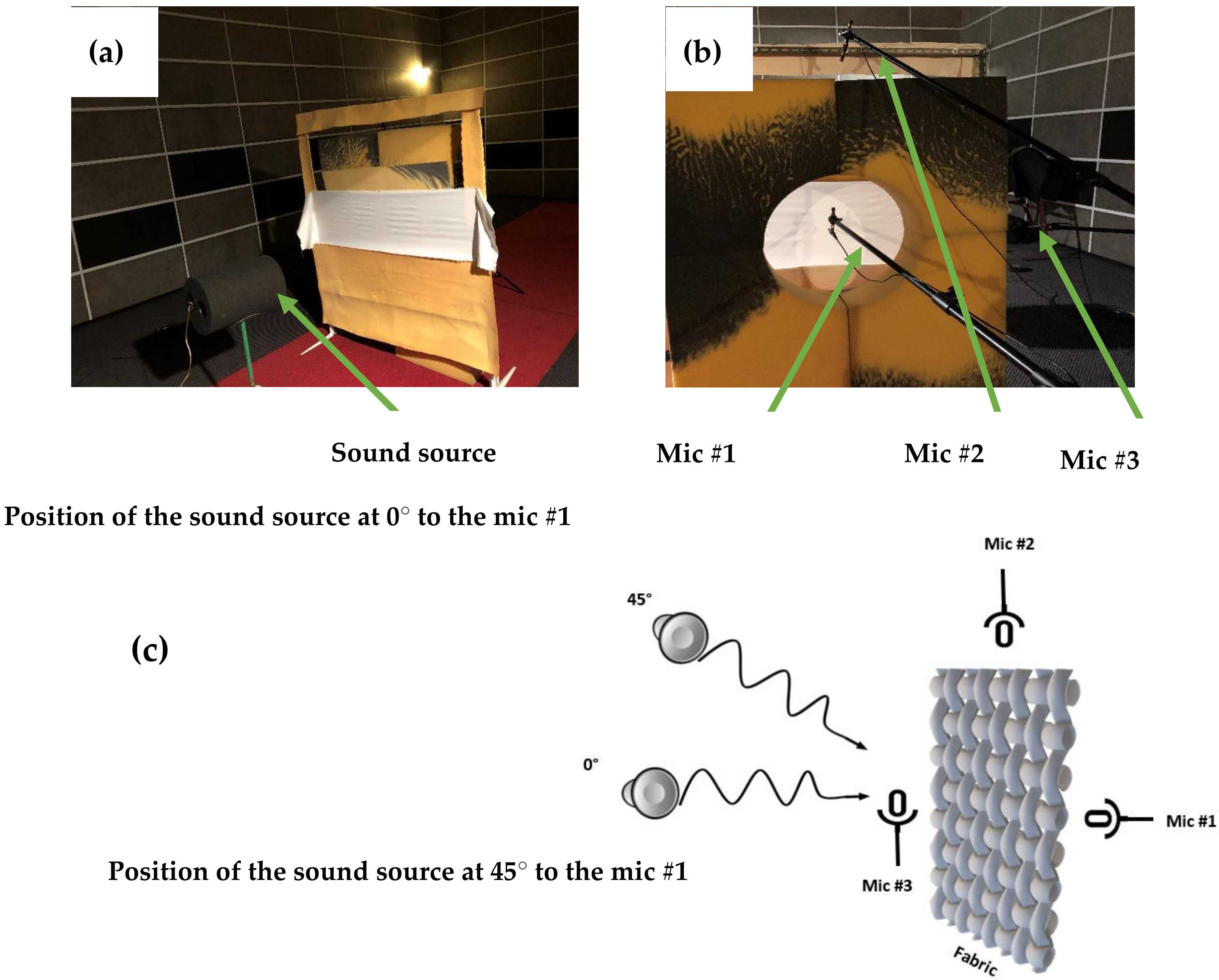


Figure 10. Acoustic materials test stand in anechoic chamber; - (a) front view of measurement area and (b) back view of measurement area and (c) Illustrations of sound absorption measurement area.

The distance between the fabric and the first microphone was 0.1 meters. The second microphone was positioned vertically on the same line as the first microphone, 0.1 m above the fabric-covered frame, and was used to verify the reference conditions. Mic#3 was positioned on a horizontal line with microphone number one and the center of the sound source's output plane, and it was 0.1 m from the fabric. The fabric on the frame was positioned between microphones No. 1 and No. 2. According to the standards, the sound pressure level p_0 of reference was 20 μPa. The results of the sound pressure level were calculated using the following formula [99].

$$L = 20\ log_{10}\ \frac{\tilde{p}}{20\mu Pa}$$

Where:

L – sound pressure level

$\tilde{p}$ – sound pressure

$20\mu Pa$ - reference acoustic pressure

The experimental procedures and explanations for the anechoic chamber were described in detail in publications [7, 83, 100, 101].

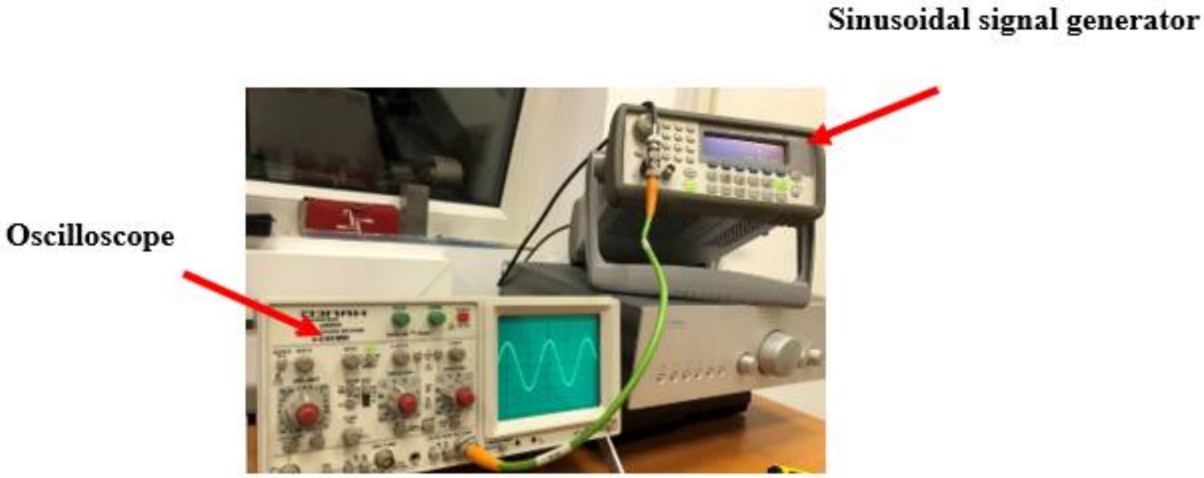


Figure 11. Anechoic chamber sound reduction measurement, Test stand sinusoidal signal generator, and oscilloscope.

3.3 Results and Discussion

3.3.1 Sound Absorption Test Results

One of the advantages of sound absorption measurement using an aeroacoustics anechoic chamber is that the fabrics can be measured for their sound absorption performance from different incoming sound source positions. This result description includes the sound reduction performance of different fabric weave structures at different sound incidence angles. Twelve fabrics sound absorption was measured at 0° and 45° angles for frequency ranges of 63, 125, 250, 500, 1000, and 2000 Hz.

Fabrics sound pressure level reduction result

During this measurement, the position of the sound source was set in relation to the fabric's center. The four fabric structures made from three yarn types, generally 12 fabrics, exhibited different responses of sound reduction at 0 degrees. The sound absorption analysis depends on their yarn and weave structure sound reduction properties. The outcome demonstrates that the type of yarn impacts the performance of each fabric type in terms of sound absorption. The sound reduction result of fabrics formed from textured yarn is presented in Figure 12. TT fabric shows higher sound absorption results at lower frequencies than the rest of the fabrics. Starting from mid to higher (500 - 2000 f(Hz)) frequencies, plain fabric (TP) shows high sound level reduction as a comparison. The rest of the fabrics demonstrated comparable sound reduction properties.

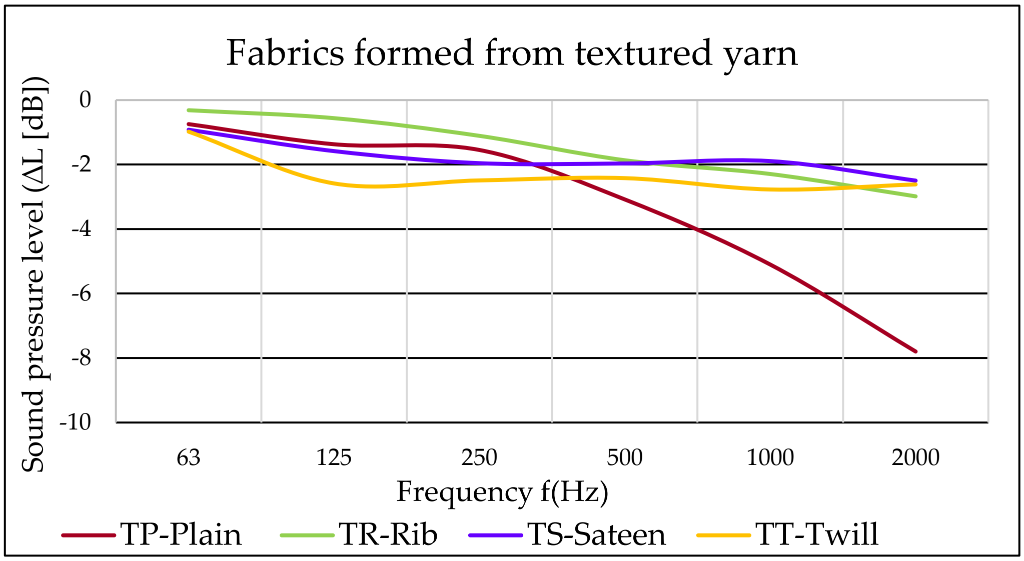


Figure 12. Sound level reduction result for fabrics that are formed from textured yarn and their comparison depend on weave structure type.

The fabrics that are formed from the staple yarn (Figure 13) shows comparable sound reduction result except plain fabric (SP) that demonstrate higher sound pressure reduction result at 500 - 1000 f(Hz).

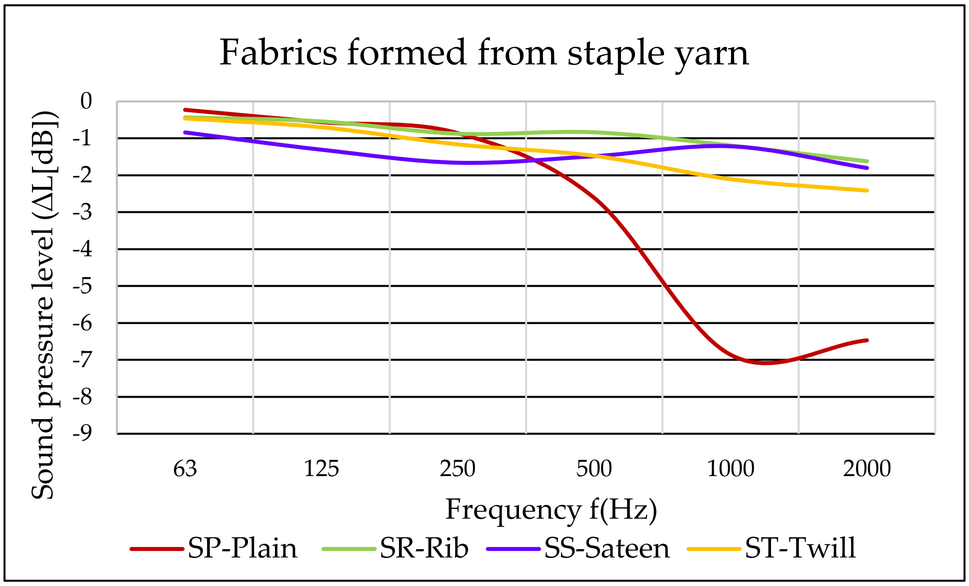


Figure 13. Sound level reduction result for fabrics that are formed from staple yarn and their comparison depend on weave structure type.

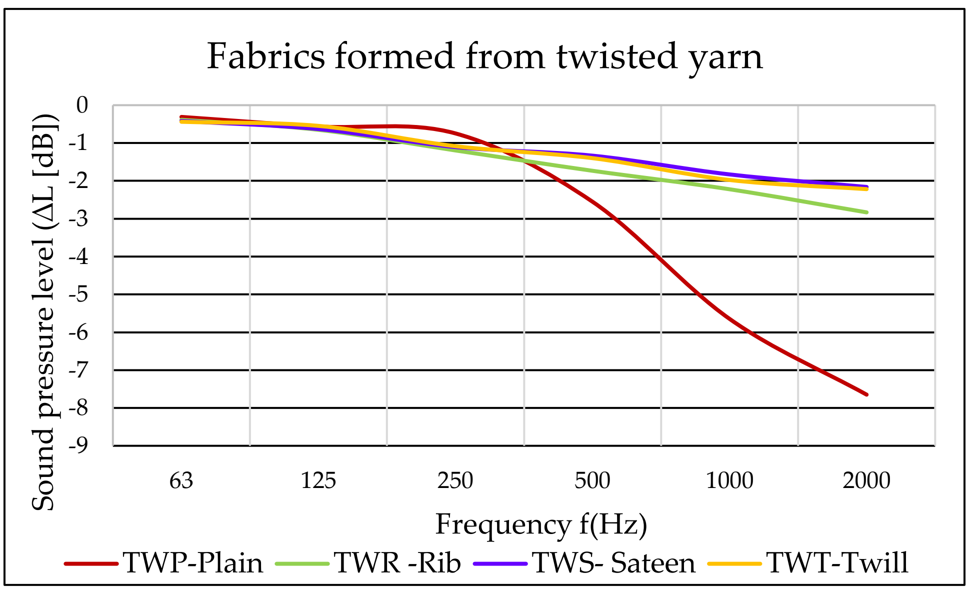


Figure 14. Sound level reduction result for fabrics that are formed from twisted yarn and their comparison depend on weave structure type.

Plain (TWP) fabric was formed from twisted yarn, showing increasing sound reduction results starting from 500 - 2000 f(Hz) (Figure 14). The fabrics TWR (rib), TWS (sateen), and TWT (twill) show low sound reduction results and are comparable to each other.

The results demonstrated in Figure 12, 13, and 14 are included in Figure 15 for comparison reasons depending on the frequency. The results (Figure 15) show that the selected woven fabric structure has a low-frequency sound absorption performance. However, the performance of sound absorption is enhanced at higher frequencies.

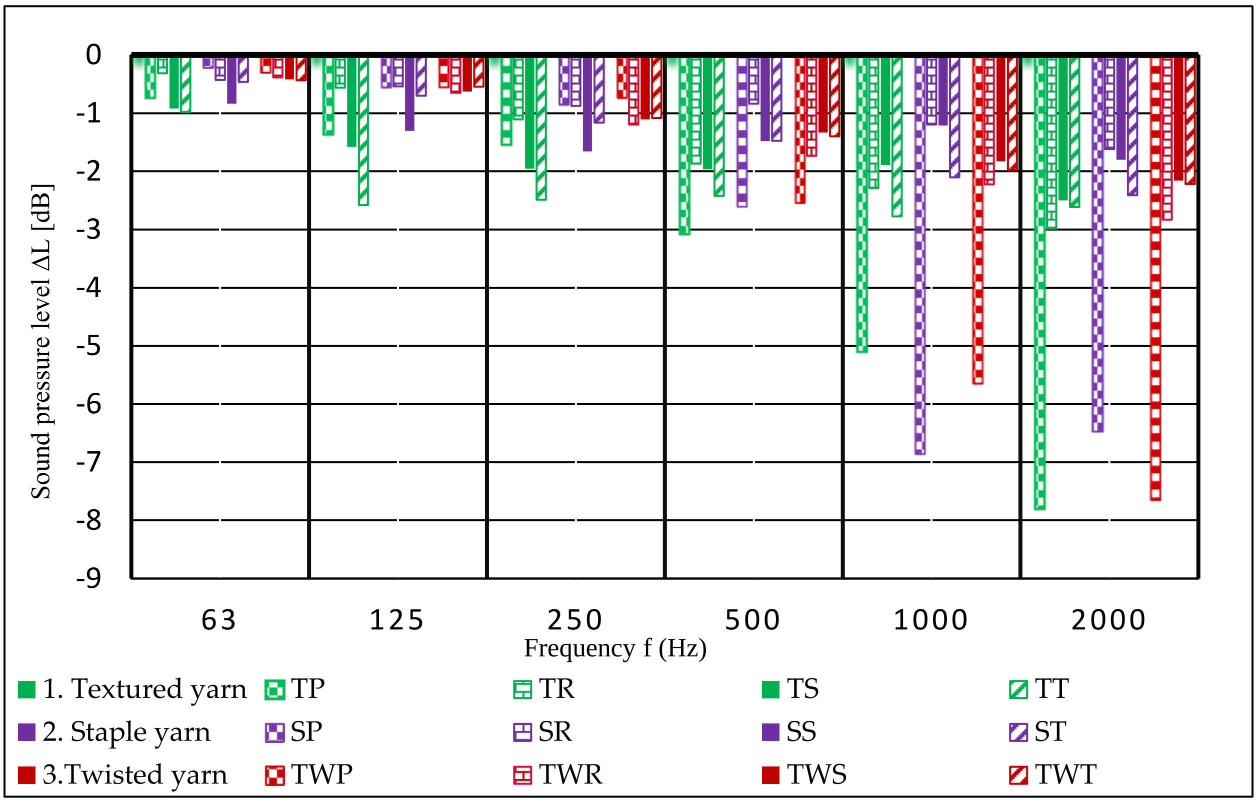


Figure 15. General Sound level reduction comparison results versus frequency range for all fabrics that are formed from all yarn types.

In addition, the yarn type significantly impacts the sound attenuation properties of fabrics. The staple yarn was thin because it had a higher number of twists per meter than other types of yarn mentioned. The cohesiveness between fibers rises as the number of twists imparted increases. As a result, the yarn becomes thinner and the porosity area between the fibers shrinks. As a result of interlacement on the fabric structure, the possibility of porous space on the fabric surface increases proportionally with yarn thickness. This phenomenon can vary according to weave structure type and manufacturing conditions, such as beet-up during the weaving process. According to the results, the hairiness of the fabric's staple yarns has no effect on the sound level drop.

The low number of twists per meter imparted to the twisted PES yarn results in higher surface evenness throughout the yarn. The outcome indicates that the sound absorption of fabrics made with twisted yarn is higher than that of fabrics made with staple yarn. In addition, the bulkiness of the textured yarn allows for the passage of sound waves between the fiber strands. This effect may increase the probability of sound energy absorption through the fibers. As a result, the fabrics that are formed from textured yarn, the sound absorption result is higher than fabrics that are formed from staple and twisted yarns.

Each weave structure performs differently in the measured frequency ranges. First, in the low-frequency region of 63–250 Hz, the twill fabric from textured yarn (TT) absorbs sound higher than other fabric structures. The sateen fabric from textured yarn (TS) in the same range demonstrates an intermediate result. In a comparable range, from staple yarn, sateen fabric (SS) has the highest absorption, followed by the ST twill fabric. Compared to staple yarn and textured yarn, fabrics constructed from twisted yarn exhibit the lowest sound level drop between 63 and 250 Hz. Plain fabrics (TP, TWP, and SP) have higher sound pressure levels that drop as the frequency increases (from 500 Hz to 1000 Hz). Specifically, SP (plain fabric from staple yarn) fabric has a higher ability to absorb sound at a frequency of 1000 Hz (Figure 15). Except for the TWT (twill fabric made of twisted yarn), fabric structures had the second-highest absorption at 1000 Hz after plain fabric.

The overall reduction in sound level implies that fabrics made with textured yarn absorb sound significantly higher than other weave structures. The plain weave structure outperforms all other structures in terms of sound reduction at 2000 Hz (Figure 16).

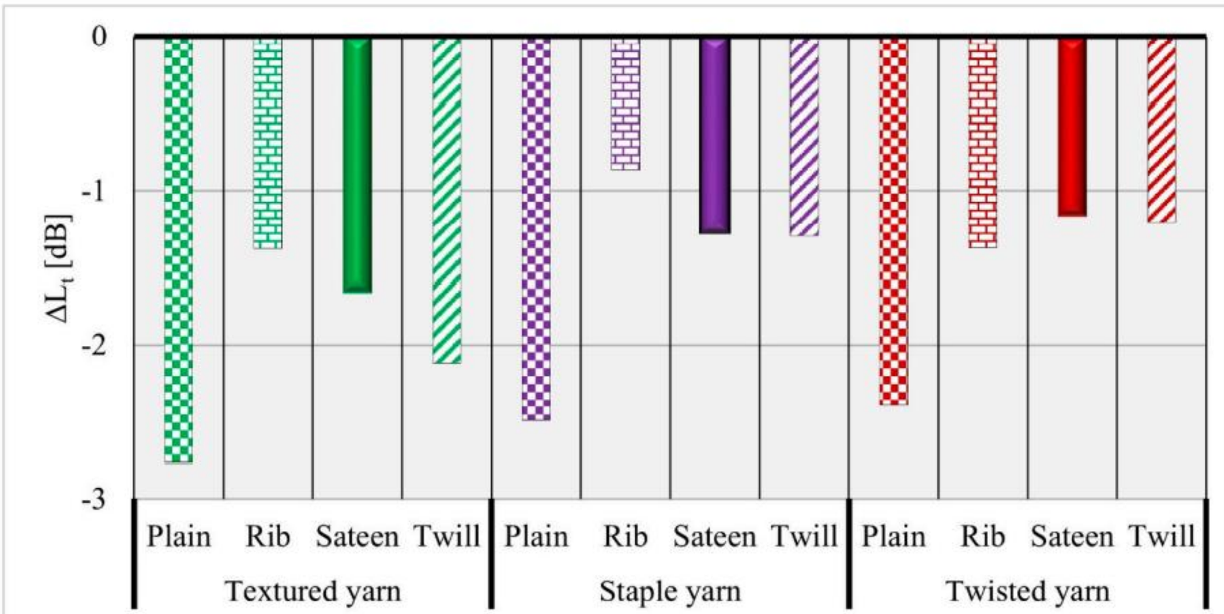


Figure 16. Total sound pressure level drop in connection to the different types of yarn and fabric constructions.

Fabric sound pressure level drop comparison based on different acoustic incidence angles.

Depending on the incidence angle, the sound absorption performance of fabrics exposed to a sound source at different incidence angles. During measurement, the position of the sound source relative to the center of the fabric was adjusted. Four different fabric structures generated from three yarn types (12 fabrics) exhibited distinct responses based on the direction of the sound source wave. In general, the sound absorption properties of 0° were higher than those of 45°. When the angle was altered to 45°, the sound absorption capacity of each material decreased slightly (Figure 17).

This phenomenon can be represented in two ways: first, a sound source setting of 0° increases the probability of the incidence wave propagating directly to the porous portion of the fabric. As a result, the absorption can be increased due to the friction between the porous walls and the sound wave. Second, the sound absorption of fabrics at an angle of 45 ° decreases due to the high probability of sound wave reflection from the fabric surface because of lower contact with the porous surface of the fabric.

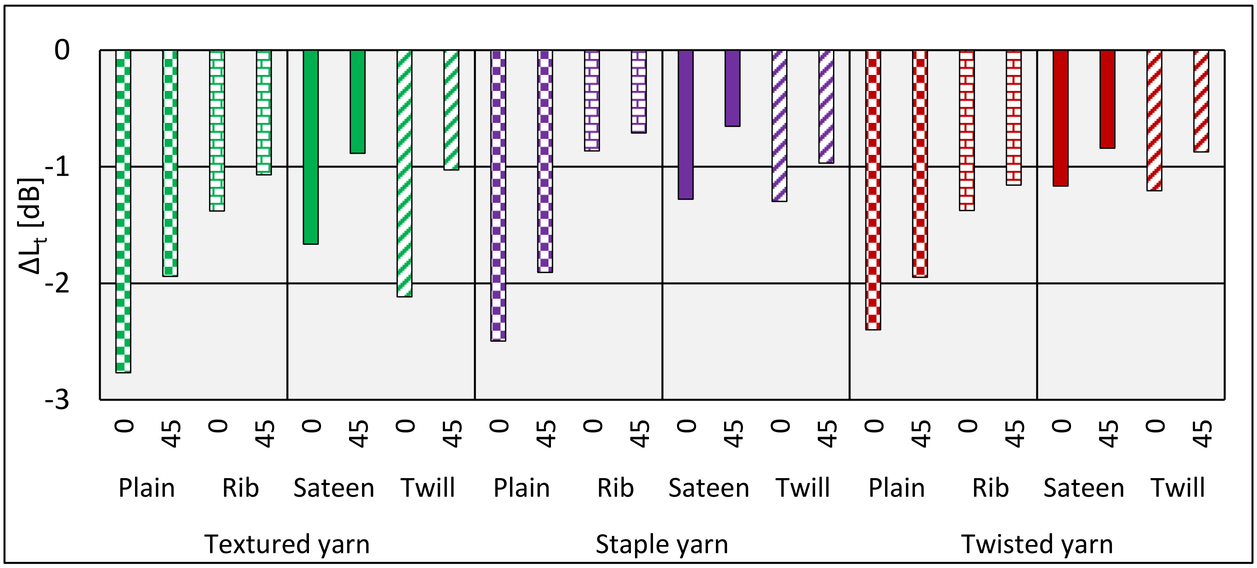


Figure 17. Sound absorption result comparison of at 0° and 45° incoming incidence waves.

Air permeability test results

The air permeability of a fabric refers to its capacity to allow air to pass through a particular region. The relationship between air permeability and the characteristics of the yarn and fabric weave influence is either direct or indirect.

The influence of yarn type and geometric fabric structure on the air permeability of the woven fabric

Woven fabrics that are formed from three different yarn types with similar linear surfaces evaluated their air permeability properties. The first yarn was a drawn textured yarn (DTY), and the fabric from using textured yarn is shown in green in Figure 18. It is a multifilament yarn noted for its high bulkiness, softness, and crimping. The second staple polyester yarn had a thin, hairy, high twist imparted to the yarn, and the fabric formed from this yarn is indicated in Figure 18 in purple color. Finally, the third fabric is formed from twisted polyester yarn (dark red color) with a twist count that falls between textured and staple yarns. As a result, the thin and thick areas generated across the strand results in a higher yarn evenness outcome (Table 3).

The air permeability test results indicate that staple yarn fabrics have a high air permeability. Except for the twill fabric, the twisted yarn fabrics (dark red bar) demonstrated low air permeability. The fabrics that are formed from textured yarn (green bar) contain the second-lowest air permeability among all weave structures (Figure 18).

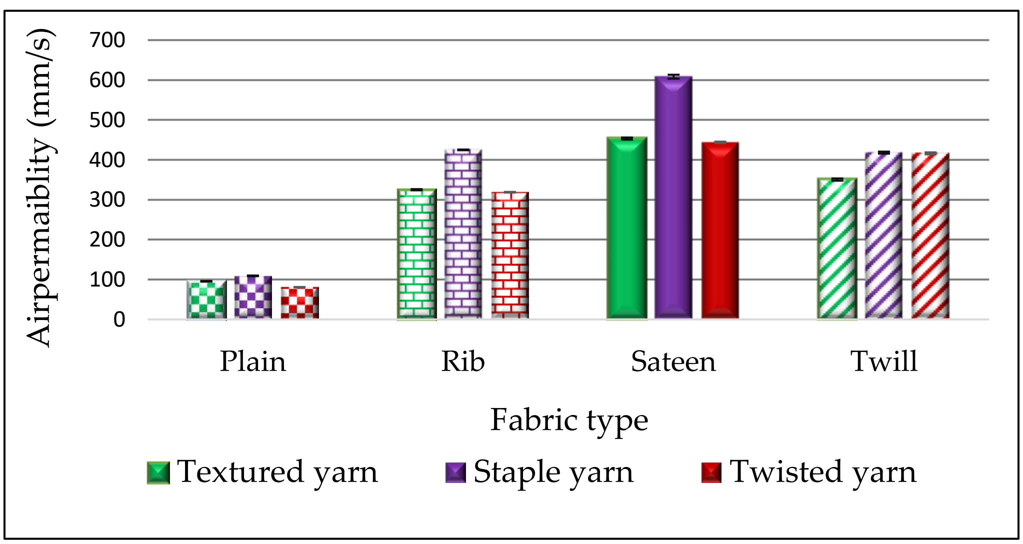


Figure 18. Air permeability of woven fabrics formed from different characteristics of varn and weave structures.

The patterns indicated in Figure 18 were used to express the interlacement characteristics of weave structures. As a result, Plain fabric structure (rectangular 1/1 pattern) and the distinguishing characteristics of twill fabric (diagonal pattern). On one side, the sateen weave is smooth and shiny, while on the other side, it has a dull appearance, and the rib weave structures show it is a derivative of plain fabrics with a yarn floating structure.

The fabrics' air permeability result shows that plain fabric demonstrates the lower air permeability result for all fabrics, which are formed from different characteristics of PES yarns (Figure 18). The second lower air permeability result is obtained by rib weave structure except for the fabric formed from staple yarn. The third low air permeability result was obtained with twill fabrics. Sateen fabrics show higher air permeability characteristics in comparison to the rest of the fabric.

Directly or indirectly, the air permeability is determined by the inter-geometrical structure of the fabric. As the number of interlacement points increases, the stiffness of the fabric also increases, which prevents the yarn from floating. Yarn floating occurs when a warp or weft yarn floats over two or more opposing yarns without becoming entangled. Plain fabrics initially feature a dense interlacement pattern. Consequently, the interlacement points are high than the other structures, and this creates the stiffness behavior of the fabric. This contributes to the air's resistance to air pressure. Rib and twill fabric constructions provide comparable outcomes. Specifically, rib 1/1 fabrics created from textured yarn (TR) and twisted yarn (TWR) have a lower permeability than rib (SR), which is formed from staple yarn.

Fabric weave and yarn properties correlation to sound absorption properties and air permeability of fabrics

The fabrication of woven fabric samples was weaved using 1500 warp ends for each fabric structure. Depending on the weave structure, the warp density per meter was different

Table 4. The correlation of warp yarn density with the total sound pressure drops, as shown in Figure 19 that plain fabrics (TP, SP, and TWP) have a low warp number per/cm, and the result of the total pressure drop of those fabrics shows higher than other fabrics result.

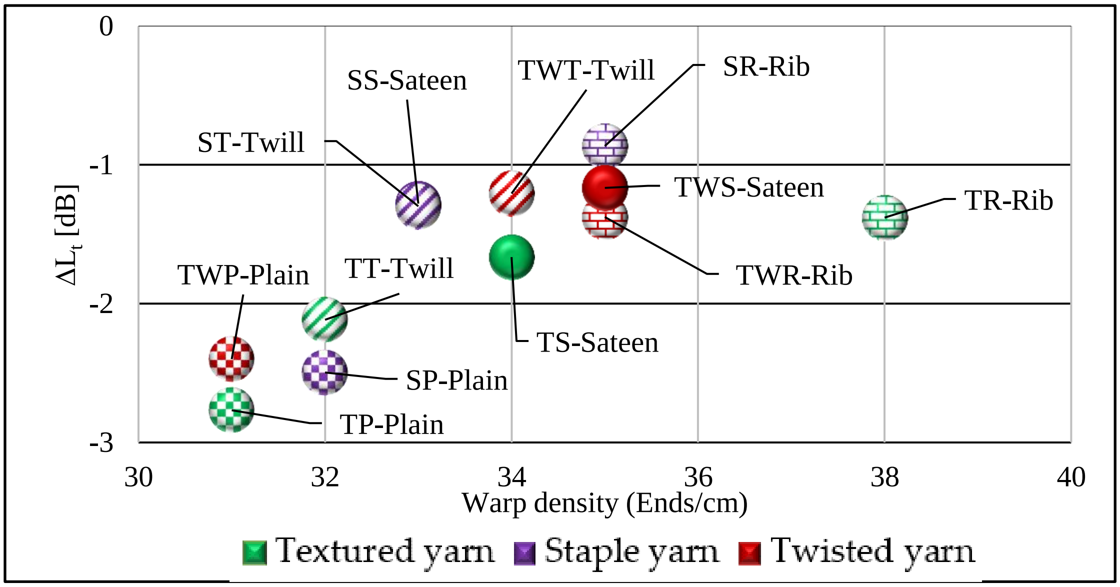


Figure 19. The relationship of fabrics warp density with total sound pressure reduction characteristics of fabrics.

The weft yarns per cm variation for the high sound pressure reduction fabrics is between 16 and 18. In comparison, fabrics that have low weft density, such as SS and TWR (Figure 20), and that have a high number of weft yarns per cm, such as TS and TT, don't show any significant relation between the sound reduction results.

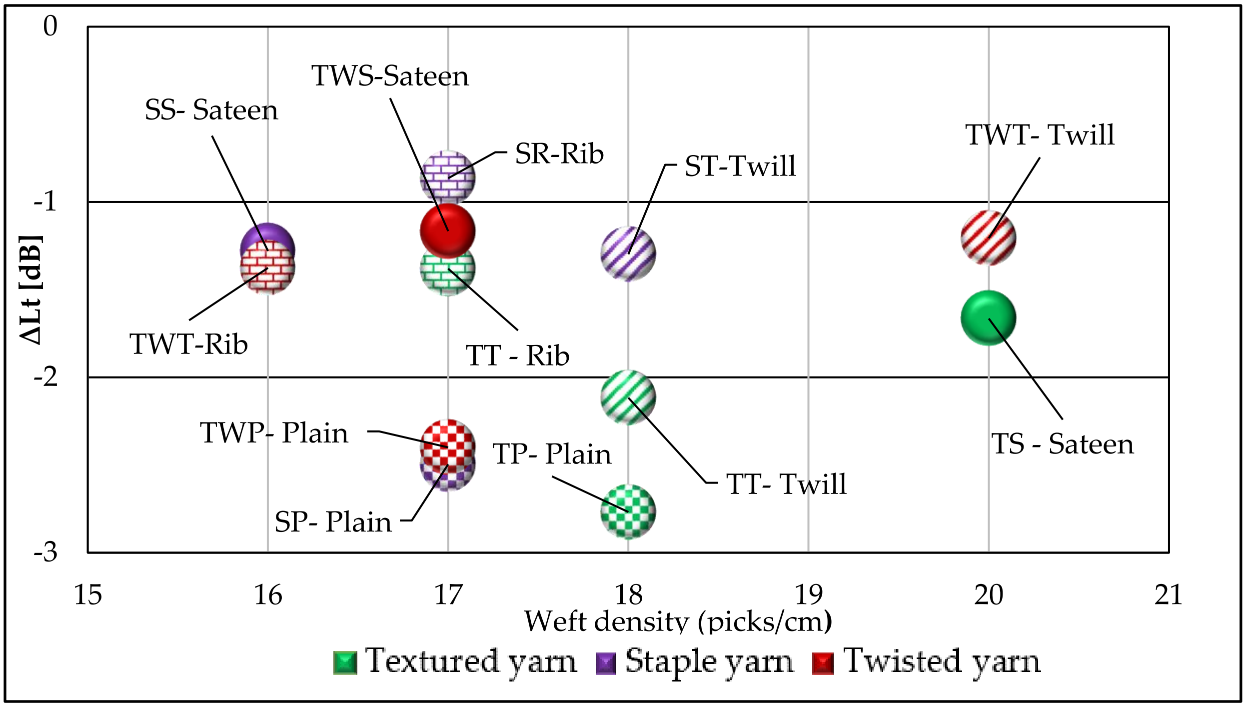


Figure 20. The relationship of weft density of fabrics with total sound pressure

Plain fabric interlacement is one-to-one, which increases interlacement points and, at the same time, increases the porous area due to the warp and weft interlacement points. This phenomenon increases the roughness of the surface of the fabric. This may increase the possibility of sound level reduction by changing the direction of the sound incidence angle on the fabric surface, and at the same time, there is a possibility of being absorbed by the fabric's porous area.

According to this investigation, there are no significant differences in the thickness properties. The TWT-0.94 mm twill structure has the highest thickness and the lowest sound absorption performance. As a comparison, the fabrics that demonstrate high sound reduction results have low fabric thickness (TWP, TP, and SP) (Figure 21). This outcome shows that rather than fabric thickness, the fabric weave structure determines the sound pressure reduction of the woven fabrics.

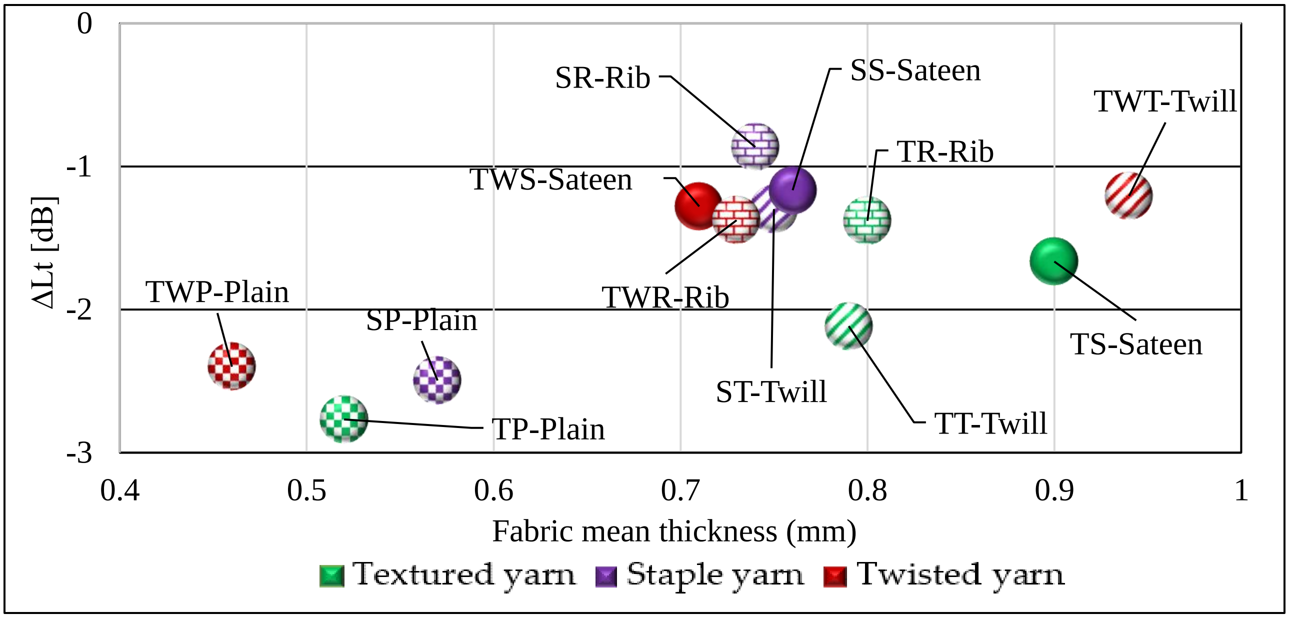


Figure 21. The relationship of fabric thickness with total sound pressure reduction of fabrics.

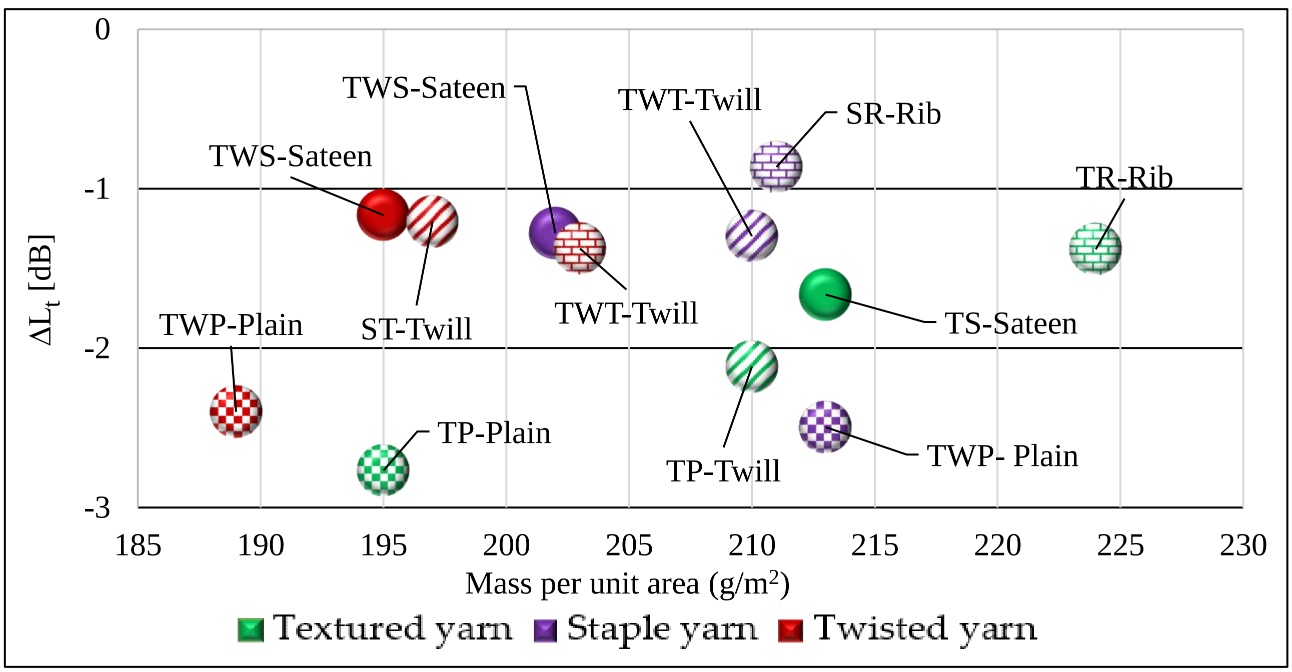


Figure 22. The correlation of mass per unit area and total sound pressure reduction of fabrics.

TR has a higher mass per unit area (Figure 22) than the other fabric structures. However, TR fabric's absorption performance is low. On the other hand, fabrics such as plain, with a low mass per unit area demonstrate high sound reduction efficiency (TP, TWP). In contrast, the fabric with a medium mass per unit area of 213 g/m² (SP) demonstrates high sound absorption.

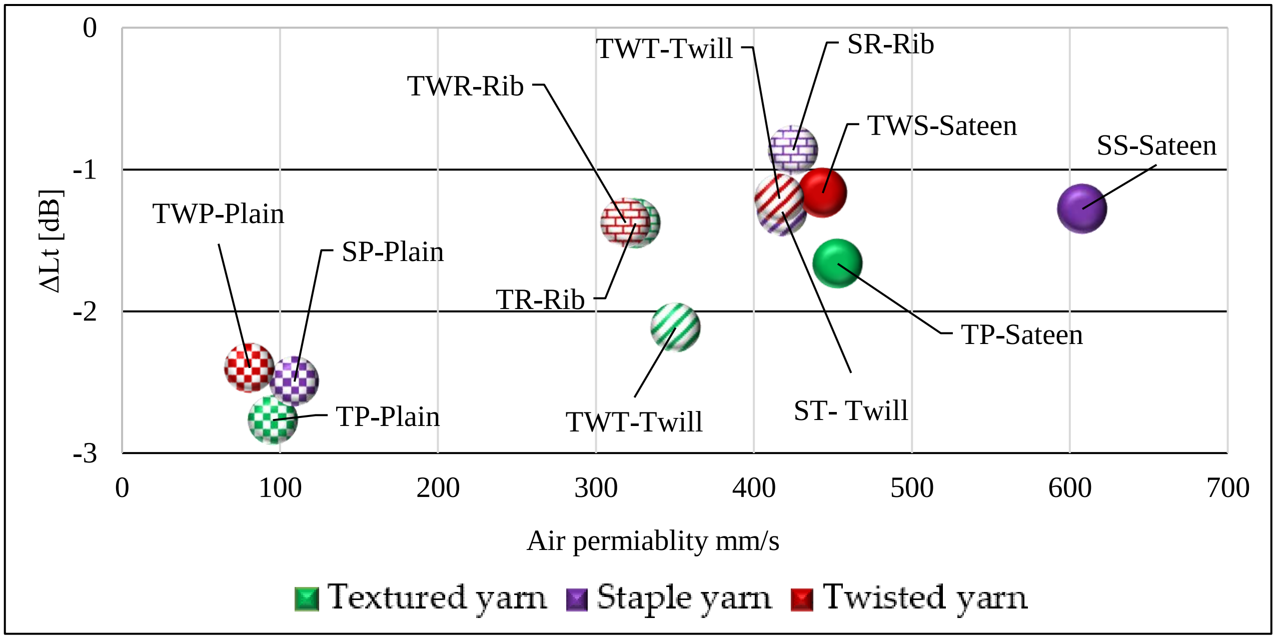


Figure 23. The correlation of air permeability and total sound pressure reduction characteristics of fabrics.

The outcome suggests that air permeability and sound absorption properties are inversely related. Similarly, the fabrics with the lowest air permeability offer higher sound absorption properties. This phenomenon, depicted in Figure 23, that when fabrics with a high total sound pressure level drop, the air permeability is low. The comparison based on yarns reveals that the fabrics formed from the textured yarn have low air permeability, and the sound reduction is higher with the textured yarn fabric. The comparisons relying on the weave structure, in general, revealed that plain weave structures have low air permeability and a high sound pressure level drop. Following plain fabrics, TT fabric is the second fabric that indicates higher sound reduction and low air permeability.

3.4 Conclusion of the Chapter

The preliminary study of the sound reduction performance of woven fabric using an anechoic chamber and its correlation with the properties of woven and yarn primary outcomes are concluded as follows.

- ✓ One of the materials used was PES staple yarn which had thin characteristics and a high number of twists per meter in comparison. As a result, fabrics formed from the staple thread exhibited different acoustic characteristics compared to other yarn types. The sound reduction capabilities of fabrics from staple yarn depend on two possibilities: either sound waves can reflect due to the yarn's stiffness, or sound waves can flow directly through the material with no energy loss caused by friction between the strands and the sound wave. In general, in terms of sound attenuation comparisons between yarns, fabrics made from staple yarn demonstrated low results. In contrast, the hairiness of staple yarn has no substantial effect on sound absorption or air permeability. Therefore, materials made from staple yarn have a high air permeability and, on the other hand, low reduction in sound pressure.
- ✓ The twisted yarn came in second after staple yarn in terms of the number of twists packed per meter. Low air permeability values were also recorded for all twisted-yarn textiles, excluding those with a twill structure. Nevertheless, the sound attenuation is less than -2 [dB] for all fabric structures except plain fabric. In contrast, the PES DTY dtex 167 filaments of 32×2 textured yarns have a dense construction throughout. The bulkiness allows sound waves to enter between the filaments, which increases the possibility of sound energy's friction. This occurrence has the potential

to cause sound waves to be absorbed between the fibers. All textured-yarn fabrics responded significantly well in terms of their efficiency for sound level reduction.

- ✓ The measurement of anechoic sound has the advantage over other methods because it gives the possibility of measurement from several different angles. As a result of, measurements taken in various directions within the anechoic chamber at an incidence angle of 0° demonstrated higher levels of sound pressure reduction properties at all measured frequency ranges than those obtained at an incidence angle of 45°.

To achieve the highest sound absorption potential by woven fabrics, choosing the yarn type in terms of the twist imparted or degree of bulkiness is vital. In addition, the yarn type's characteristics can affect the weave structure's acoustic properties. Furthermore, the position of the sound source and the incidence angle determines the maximum sound pressure reduction achieved by the fabric.

4. VERIFICATION OF THE ACOUSTIC PERFORMANCE OF FABRICS USING AN IMPEDANCE TUBE

The primary study shows that the sound reduction of various fabric structures depends on yarn characteristics, weave structure, and sound source incidence angle. Furthermore, the air permeability of fabric shows an inversely proportional relationship with the sound reduction performance of fabrics, specifically plain fabrics.

As a continuation of studies using impedance tubes to determine the sound absorption coefficient, this part of the study examined to understand the influence of increasing layers of woven fabrics within the same weave structure. As well as integrating woven fabric with nonwoven fabric and adding air gaps on different layers of woven fabric were determined.

The purpose of integrating woven and nonwoven fabrics is to maximize the sound absorption performance of both materials. In addition, introducing an air gap during measurement can aid in comprehending the effect of air gaps during the application of woven fabric or porous materials.

4.1 Materials

Twelve woven fabrics used in this section are similar to those described in the primary study section titled Materials 3.1. In addition, a fluffy nonwoven fabric with 30 mm thickness and a mass per unit area of 623 g/m^2 (Figure 24) was used, which was formed by the mechanical technique at a technological laboratory line at Befamatex in Poland. Two types of fibers were used in the production process: polyester (PET) fibers with a linear mass of 3.3 dtex and a length of 66 mm and bicomponent fibers of the skin-core type (PET/PET) with a linear mass of 4.4 dtex and a length of 51 mm. The two types of fibers were blended in a ratio of 90:10, and the resulting nonwoven web was formed on carded systems and fed to a horizontal stacker.

The nonwoven fleece layer was then subjected to a needling process to thicken the structure. The needling density used was 50 needle-needlings/cm^2, with a needle-needling depth of 11 cm. To combine the fibers in the fleece, the nonwoven fabric was annealed in a 12-meter-long belt infrared dryer at a nominal temperature of 140°C. The transfer speed of the nonwoven fabric was 2 m/min during the annealing process.

Figure 24. Top view of nonwoven fabric

4.2 Methods

Acoustic measurement and non-acoustical fabric properties such as volume porosity, surface roughness, and fabric porosity measurement details are described.

4.2.1 Volume Porosity or Percentage of Yarn in the Fabric

The volume porosity of the fabric is used to know the percentage of the fibers that are present in the fabric. These properties help to identify and give clarity to the porosity of the fabric. The following formula is used to calculate the percentage of polyester fiber present in the total volume of the fabric (Pv - volume porosity).

$$Pv = {}^{Mp}/_{(\mathrm{h} \times \mathrm{q})} \times 100\%$$

Where:

h - Thickness of fabric [m],

Mp - Mass per unit area [kg/m^2],

Q - Raw material (polymer) density [kg/m^3] for polyester, 1.38 g/cm^3 = 1380 kg/m^3

4.2.2 Fabric Surface Roughness Measurement

The measurements were performed using a MicroSpy® profile profilometer equipped with a FRT CWL sensor. The roughness index (Ra) of a total of twelve woven fabrics was measured and analyzed. The first thing that needed to be done was to get the square samples that were exactly 5 cm × 5 cm and would fit in the MicroSpy® measuring area (Figure 25). After that, the measurements were carried out in accordance with the guidelines provided by DIN EN ISO 4287 [102]. Three separate and repeated measurements were carried out on the fabric surface in both warp and weft directions.

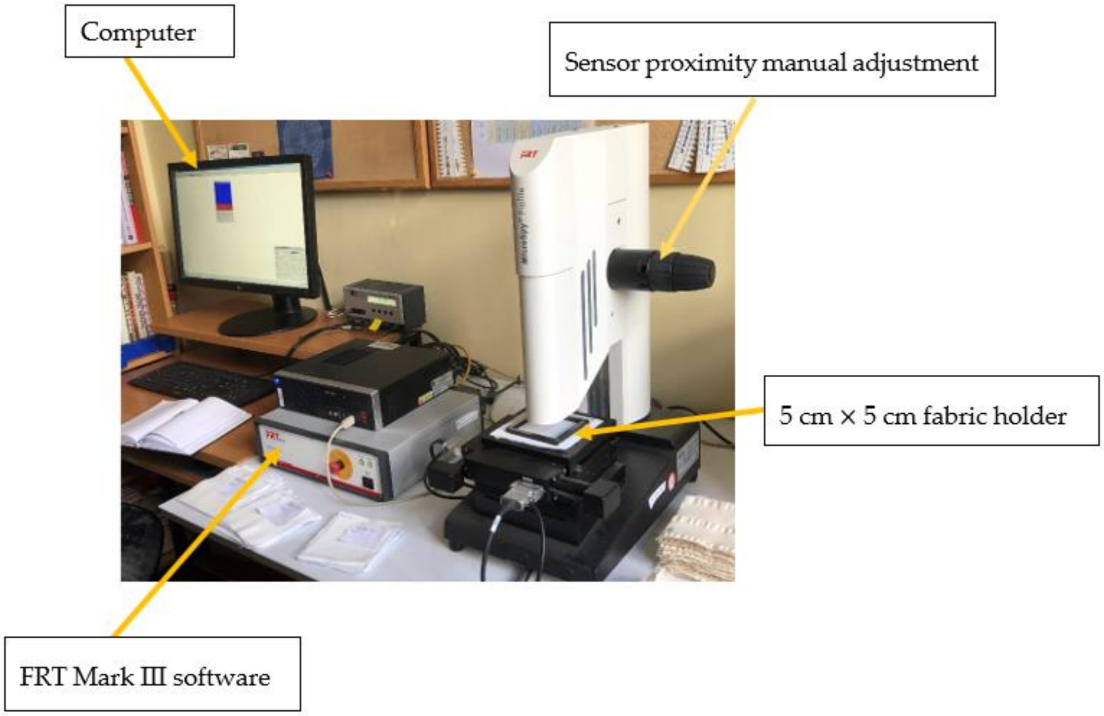


Figure 25. Optical profiler Microspy Roughness tester

4.2.3 Fabric Porosity

The optical porosity test was analyzed by using a 10x magnification Olympus stereoscopic microscope integrated with an internal table-mounted transmitted light source. Test Procedure No. 60, developed in the Textile Research Institute, was utilized to determine the sample's porosity. The quantity of light that flows through the textile sample when laid flat on the microscope table is used to determine the value for this measurement. The sample was illuminated with natural light at a consistent intensity of one thousand lux throughout the experiment. Porosity is measured as the ratio of the threshold area to the entire sample image area. The sample region through which light traveled typically consists of pores in fabric constructions. The picture of samples captured under such conditions is thresholded to identify woven fabric pores and solid material regions. Calculating the total area of pores yields the proportion of sample regions covered by light-transmitting pores. In accordance with PN-EN-ISO

139:2006/A1:2012, the test was conducted at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 4% [103].

4.2.4 Fabrics Sound Absorption Measurement

To determine the acoustic behavior of fabrics, their sound absorption properties were measured with an impedance acoustic measuring instrument. The sound absorption coefficient (α) of samples was measured as a function of the octave band frequencies of the impinging wave, which fell between 80 and 5000 Hz. The coefficient of sound absorption was determined using PN-EN ISO 10534-2:2003. The absorption coefficient test was performed using the transfer function method [78] in accordance with PN-EN ISO 10534-2:2003. Using an impedance tube (Figure 26), each sample was measured three times depending on the standard's parameters, and the mean value was calculated.

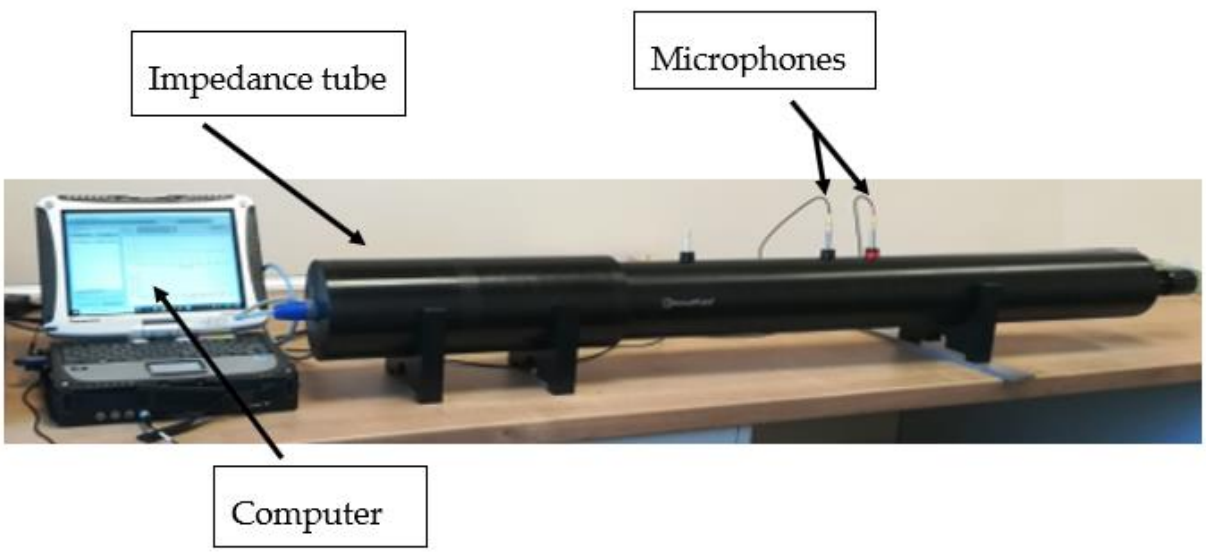


Figure 26. Impedance tube – fabric sound absorption coefficient measurement.

This section of the study examined woven fabrics with varying numbers of layers in order to comprehend the influence of layer differences on sound absorption. As a result, woven fabrics are grouped for measurement as single, double, and triple layers, as presented in

Table 5. Furthermore, woven fabric layer differences listed above are arranged in the impedance tube with different variants. The first variant measurement consists of only a single woven fabric, whereas the second variant consists of woven fabric with a nonwoven fabric (PES) as a base material was evaluated. The third variant is the fabric with a 30 mm air gap between it and the solid plate (Table 6). The acrylic woven fabric holder was used as a seal, and it helps secure fabrics as firmly as possible to prevent their displacement during measurement.

Table 5 Fabric arrangement setting inside impedance tube.

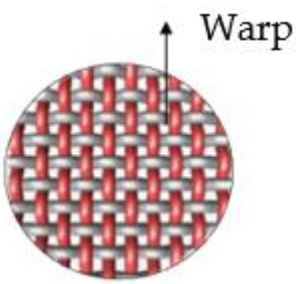
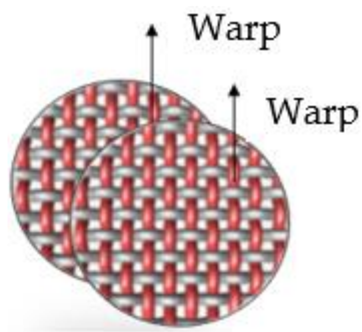
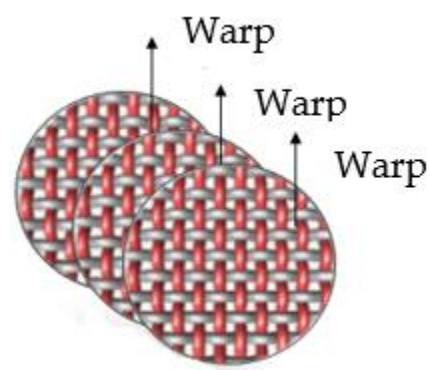
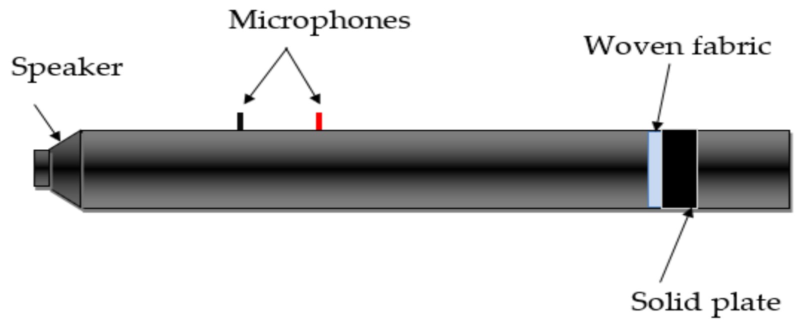
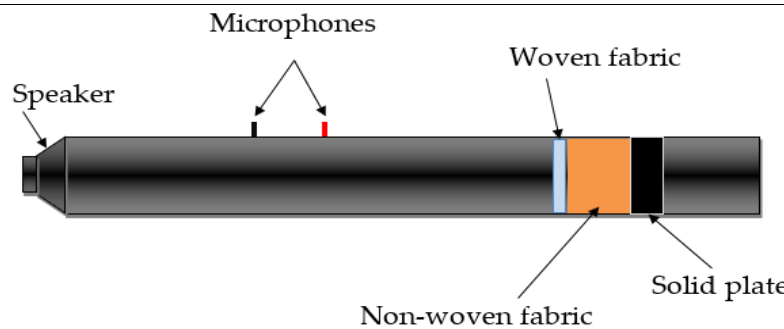
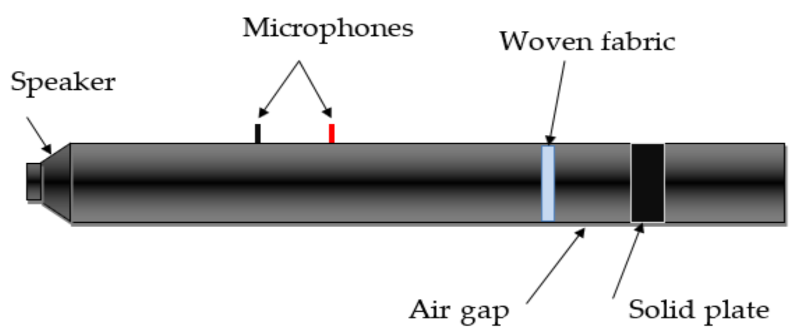
Group 1	Group 2	Group 3
Single layer woven fabric 	Double layer woven fabric 	Triple layer woven fabric 

Table 6 Sample placement within the impedance tube.

The setting of tested samples inside the impedance tube	
Variant I Woven fabric	
Variant II Woven fabric + nonwoven	
Variant III Woven fabric + air gap	

4.3 Results and Discussion

4.3.1 Sound Reduction Coefficient of Fabrics

The sound absorption coefficient of woven fabrics is categorized and outlined based on variant differences, as presented in Table 6. In each variant layer difference measurement, 12 woven fabrics were utilized. In this study, woven fabrics made from textured yarn, such as plain (TP), rib (TR), sateen (TS), and twill (TT), as well as fabrics made from staple yarn, such as plain (SP), rib (SR), sateen (SS), and twill (ST), and fabrics made from textured yarn weave structures, such as plain (TWP), rib (TWR), sateen (TWS), and twill (TWT), were used.

In the variant I, included only the woven fabric absorption coefficient. Variant II consists of woven fabric with combination of nonwoven fabric. Variant III presents the result for woven fabric in addition to nonwoven fabric. As per the sequence of the variant, the result and discussion are presented as follows.

The description included a statistics analysis that were measured using the Friedman ANOVA test [104]. When the Friedman test yields statistically significant results, at least one group differs from the other groups. Nevertheless, the test does not indicate where and how many differences occur. As a result, a Post-Hoc test was utilized to determine the specific differences between groups.

The p-value is calculated through statistical analysis. A comparison is made between the p-value (probability value) and the critical value for rejecting the null hypothesis. If $\alpha < p$, the null hypothesis cannot be rejected. The significance level assumed is alpha ($\alpha = 0.05$). When $p > \alpha$, there are no significant differences between the fabrics. On the other hand, if $p < \alpha$, a significant difference in Friedman statics shows between the samples.

Variant I

Variant I (Table **6**) indicate that only woven fabrics (plain, rib, sateen, and twill) that are formed from textured, staple, and twisted yarn are measured for sound absorption in the impendence tube. The setting of woven fabric in Group 1 consists only of single-layer woven fabric, and the results are presented in Figure *27* A, B, and C, and Group 2 consists of two layers of woven fabric in Figure 28. The 3rd group contains three layers of woven fabrics, and the results are presented in Figure 29. Furthermore, the setting description of the fabrics is presented in Table 5 and Table 6.

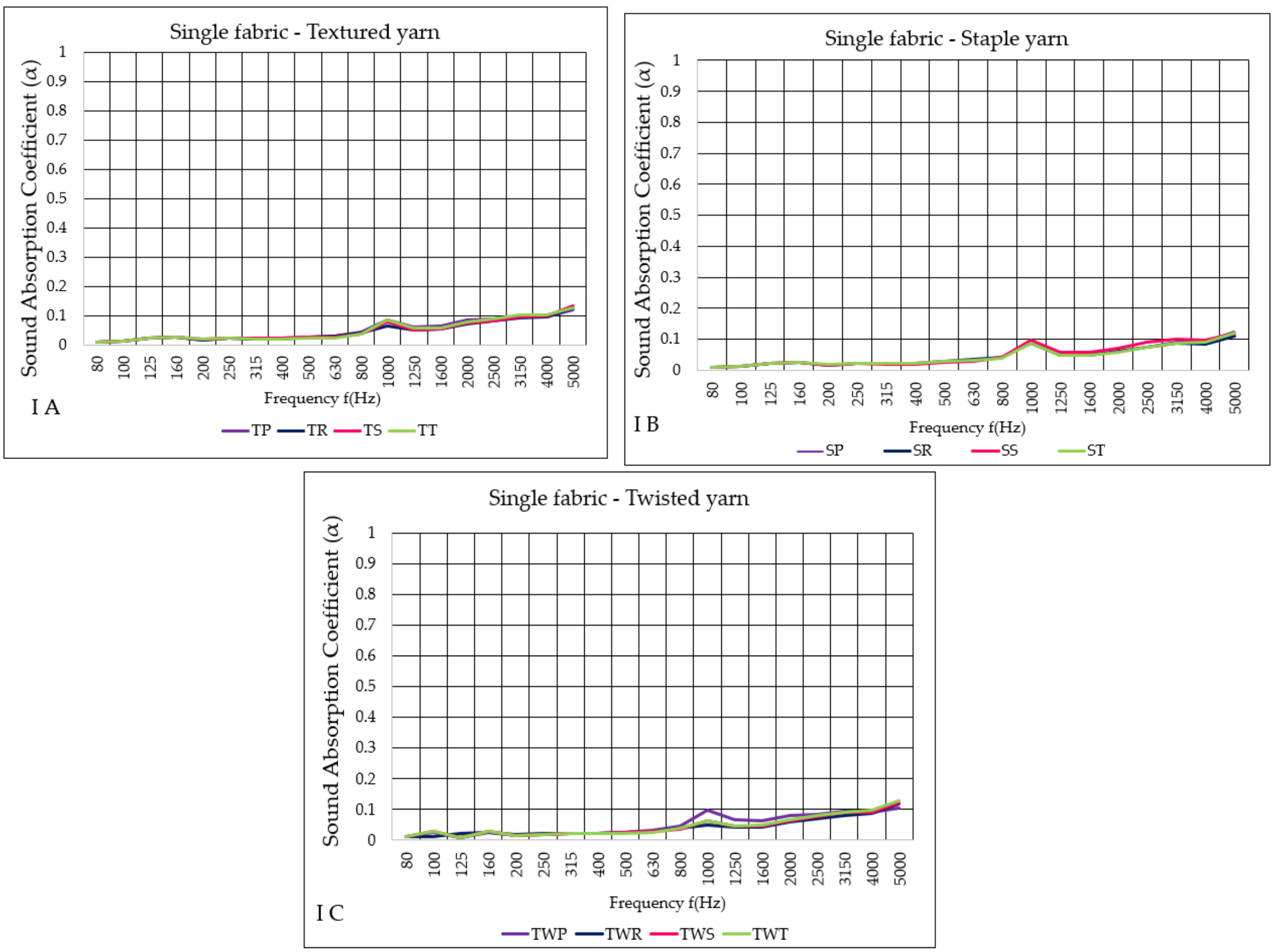


Figure 27. The relationship between the sound absorption coefficient (α) and frequency f (Hz) for single-woven fabrics (A, B, and C) using the measurement variant (I).

The following results are presented according to the type of yarn that fabrics are formed from. The abbreviation TP stands for plain fabric formed from textured yarn; similarly, the fabrics formed from textured yarn are TR for rib fabric structure, TS for sateen fabric structure, and TT for twill fabric structure. Fabrics made from staple yarn include plain (SP) rib (SR), sateen (SS), and twill fabric (ST). Twisted yarn fabrics are denoted by letters such as plain (TWP), rib (TWR), sateen (TWS), and twill (TWT).

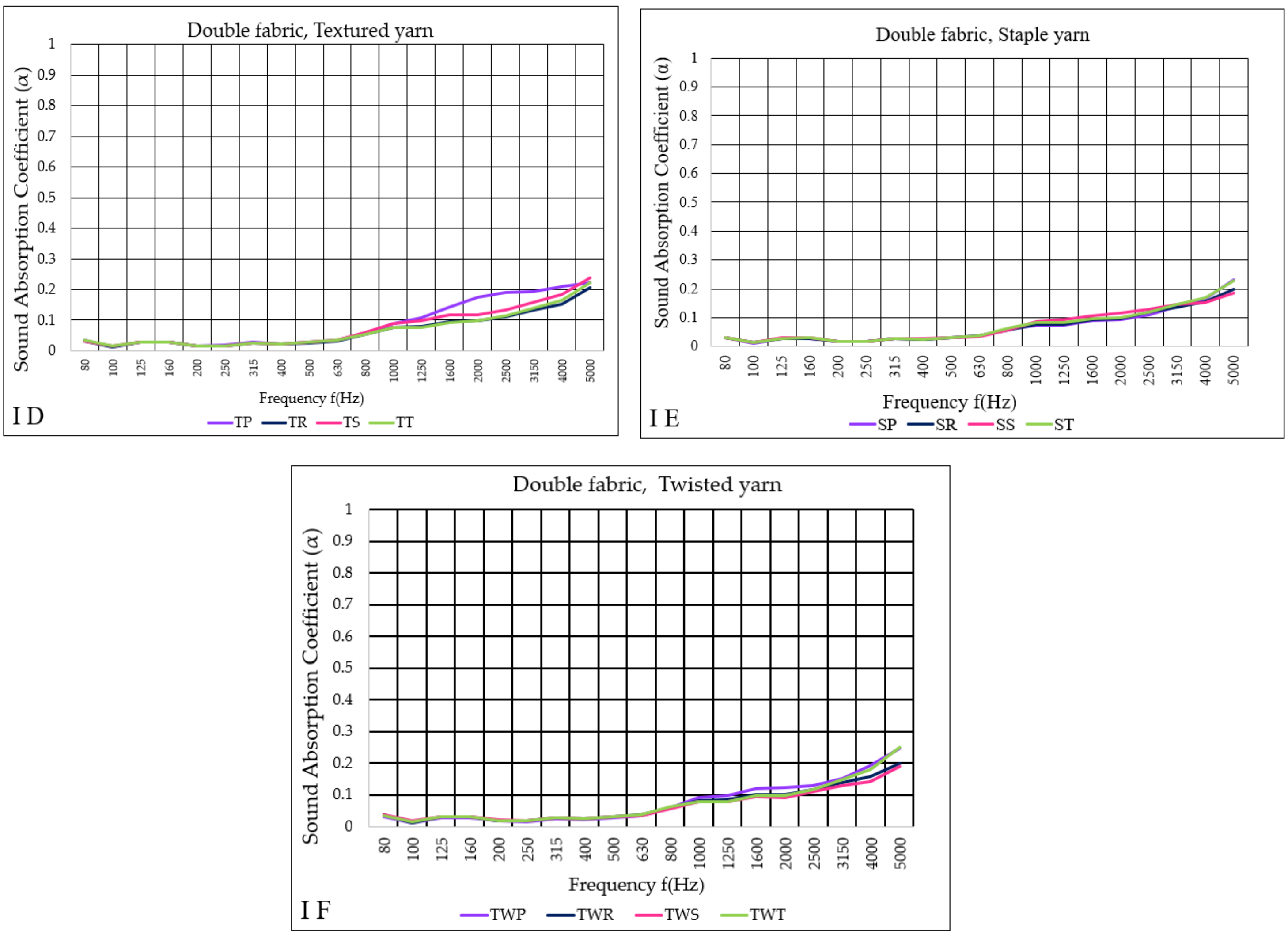


Figure 28. The relationship between the sound absorption coefficient (α) and frequency f (Hz) for double woven fabrics (D, E, and F) using the measurement variant (I).

The sound absorption coefficient (α) in all fabrics increases slightly with frequency (Figure 28). The single-fabric tests revealed negligible coefficients of sound absorption, indicating that they have almost no effect on blocking or absorbing sound incidence waves in all fabrics. These results were verified in nonparametric statistical measurement that was used for comparing four different weave samples using the Friedman test.

The statistical analysis obtained verifies that there is no significant difference in the level of sound absorption between different weave structures that are formed from the same yarn types. As a result, the fabrics formed from staple yarn show, in general, no significant difference with a p-value of 43%, which is higher than the significance level of 0.05 or 5%. Fabrics formed from textured yarn show a probability value of 7% and no significant differences. Also, the fabrics formed from twisted yarn show no significant difference in absorption, with a p-value of 7%.

The sound absorption of double-woven fabrics results presented in Figure 28 is consistent with the results shown in Figure 27. Nonetheless, as the frequency range increased, the absorption in double fabrics improved starting at 1000 Hz compared to the measurement results for a single fabric. The Friedman statics test probability difference shows < 0.05, which indicates that the sound absorption performance difference is high between the single and double fabrics.

The plain fabric (TP) increased absorption to the same extent as the other fabrics between 1600 and 4000 Hz. The statics analysis shows that the double fabrics formed from staple yarn have no significant difference in absorptions between weave structures. At the same time, for double fabrics formed from textured, the probability value is < 0.05 between weave differences. Also, the fabrics formed from twisted yarns show a significant difference of 2%, which is $< 5\%$ between fabrics.

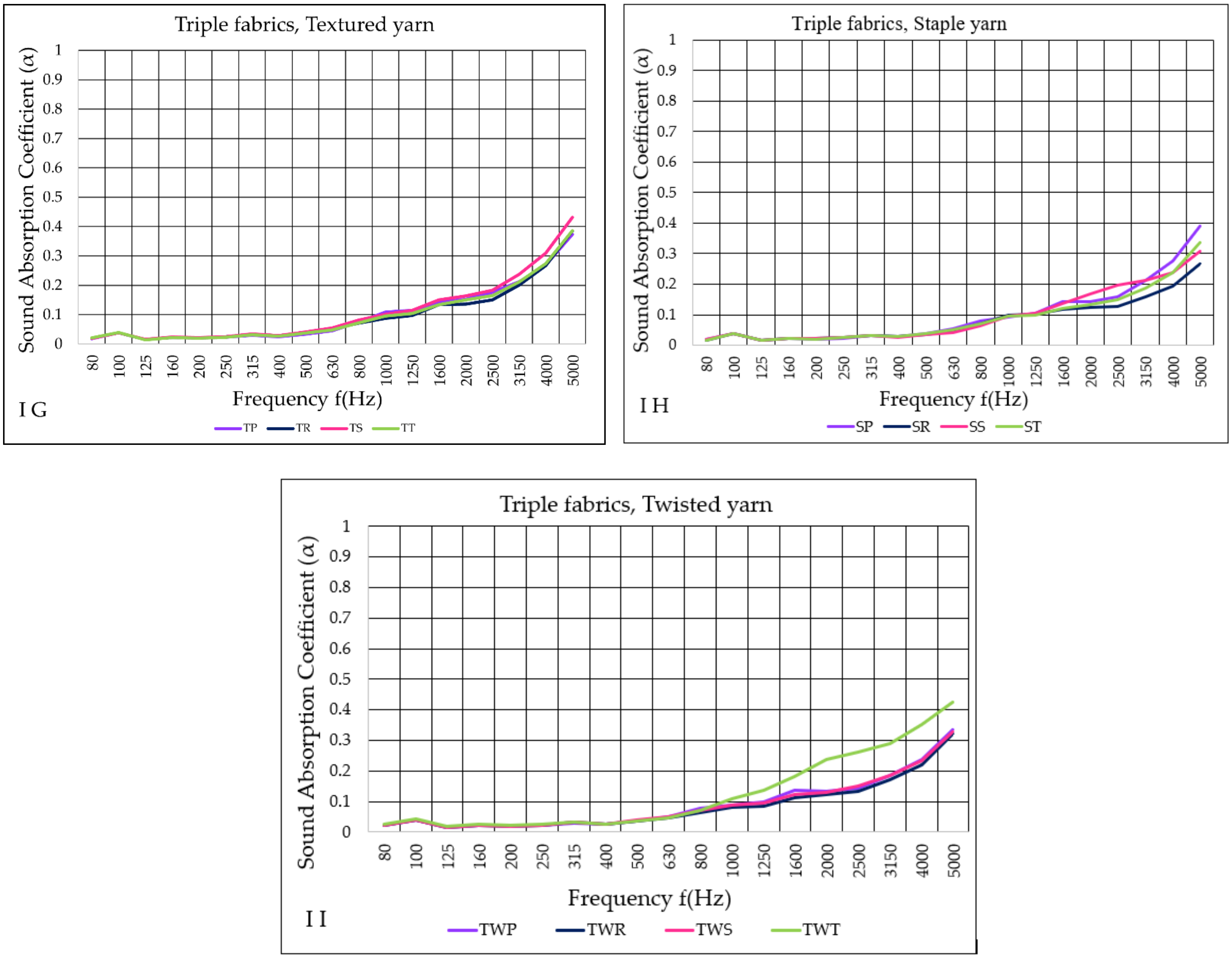


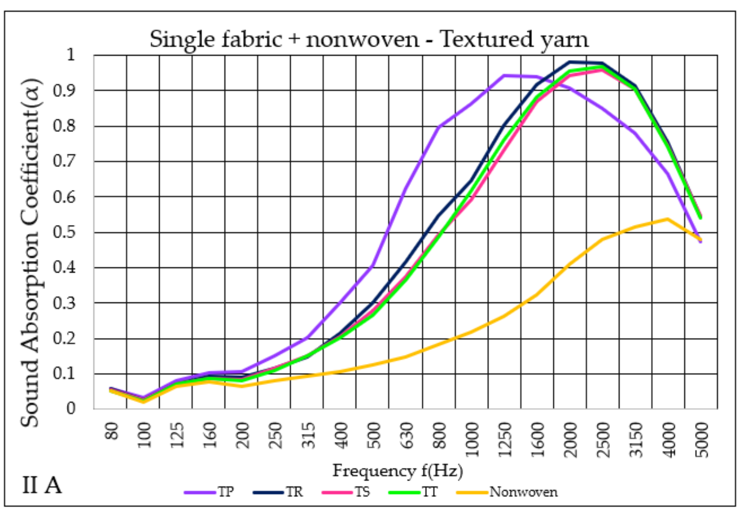
Figure 29. The relationship between the sound absorption coefficient (α) verses frequency f (Hz) for triple-woven fabrics (G, H, and I) using the measurement variant (I).

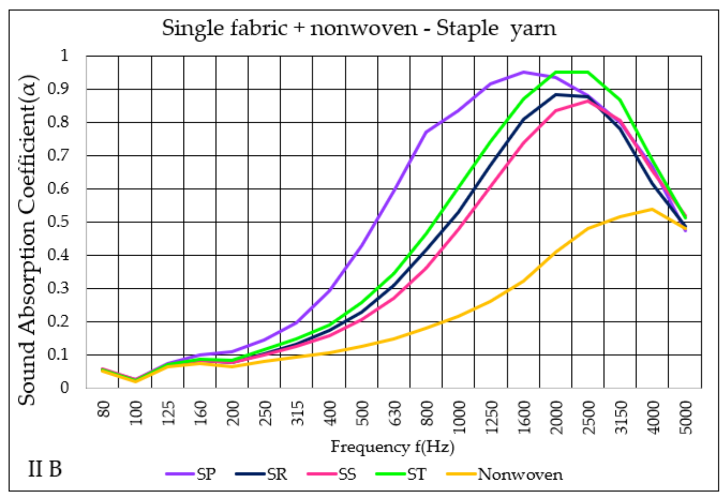
The sound absorption of the three layers of woven fabrics is depicted in Figure 29 G-I. Compared to the double fabric results, the absorption at higher frequencies increases as the number of fabric layers increases. In addition, the static analysis by Friedman shows a significant absorption difference (<0,05) as fabric layers increased.

Different types of fabrics formed from staple and twisted yarns show various degrees of sound absorption, specifically at higher frequencies. For instance, fabrics formed from staple yarn and twisted yarn show a significant difference of < 0.05. In a comparison between the fabrics, twill fabric (TWT) showed the highest results at higher frequencies than other fabrics. On the other hand, fabrics formed from textured yarn show no significant difference in sound absorption between the fabrics, with a probability level of 15%.

Variant II

This section discusses the results obtained from woven and nonwoven fabric, as described in Table 6. The arrangement of the fabrics was woven fabric on the front and nonwoven fabric sandwiched between the woven fabric and solid plate. The measurement outcomes are discussed as follows; -





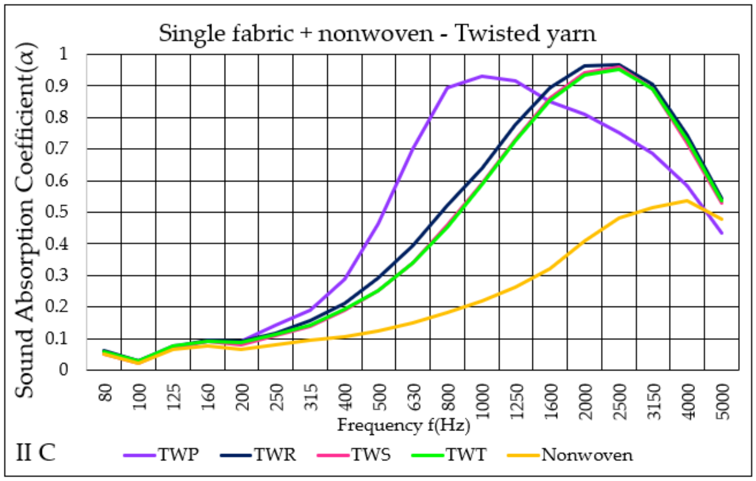


Figure 30. Sound absorption coefficient (α) of single layer fabric with the addition of nonwoven fabric verses frequency f (Hz) for single layer woven fabrics (A, B, and C) using the measurement variant (II).

The II variant of the measurement results comprised both single-woven and nonwoven fabric. The nonwoven fabric's (yellow graph) maximum sound absorption coefficient performance is between 0.5 and 0.6 (α) at higher frequencies (2500 - 4000). The remaining findings revealed the sound absorption capabilities of the combination of woven and nonwoven materials.

The outcome demonstrated very different results from variant (I) absorption results. For instance, the result for single woven fabrics formed from textured yarn shows that the p-value for only woven fabric is 7%, which indicates no significant differences. On the other hand, single fabric with the addition of nonwoven fabric demonstrates a significant difference in absorption probability value of < 0.05. The Variant II sound absorption outcomes are generally higher than that of Variant I.

In addition, plain fabrics demonstrated different sound absorption outcomes compared to other materials in Figure 30. The progressive increase in absorption points of plain fabrics (TP and SP) began between 200 and 250 Hz and peaked at 1600 Hz. The result suggests that plain fabrics can absorb sound at lower frequencies than other materials. The plain fabric (TWP) obtained the highest result at 1000 Hz.

Aside from the coefficient of the plain fabric, the rest of the woven fabric, made up of textured and twisted yarn, has a high absorption capacity and comparable results at higher frequencies, between 1600 and 4000 Hz. In addition, the statistical analysis shows no significant differences, with a p-value of 100% of the comparable results for TP and TWP.

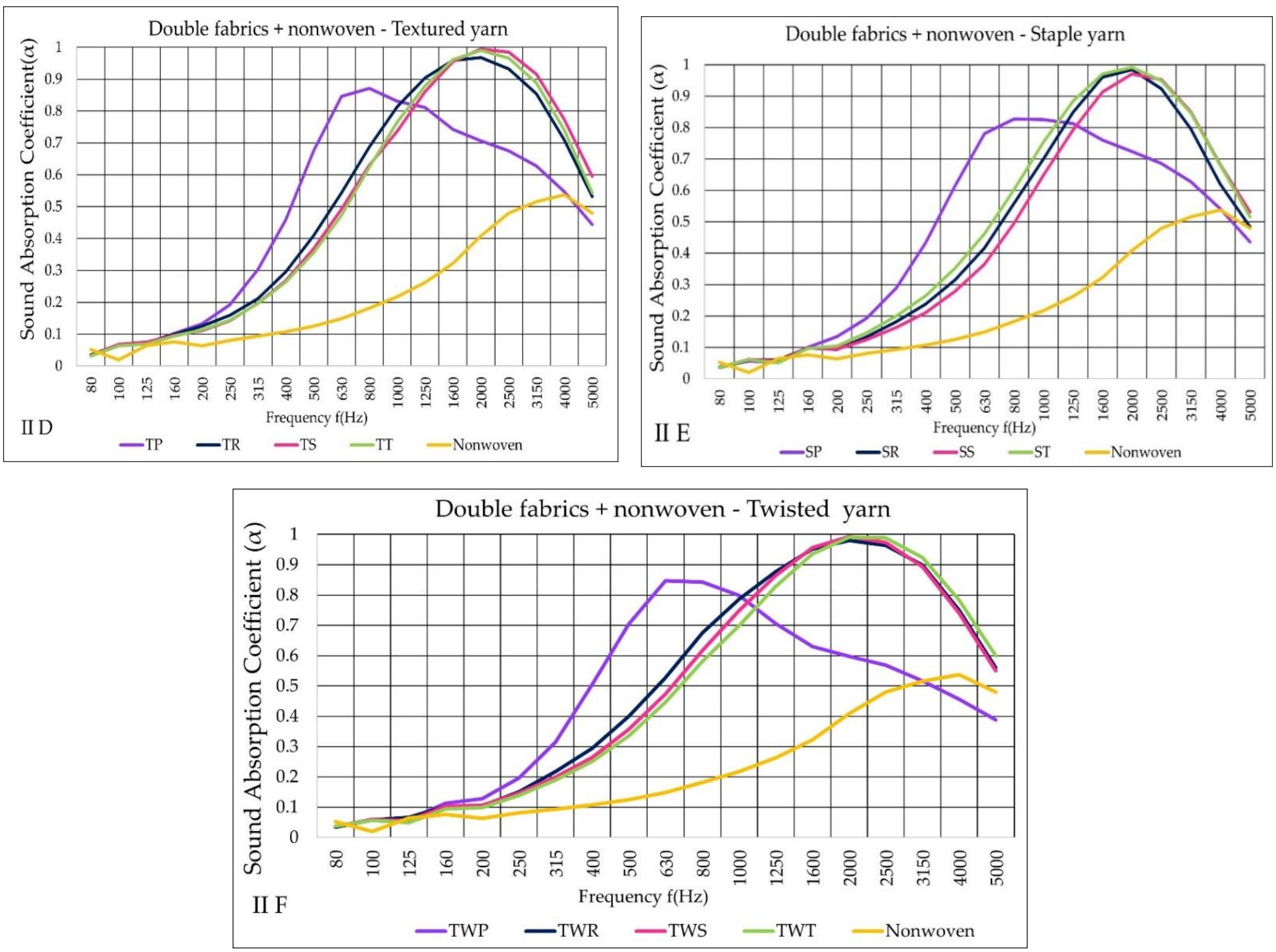
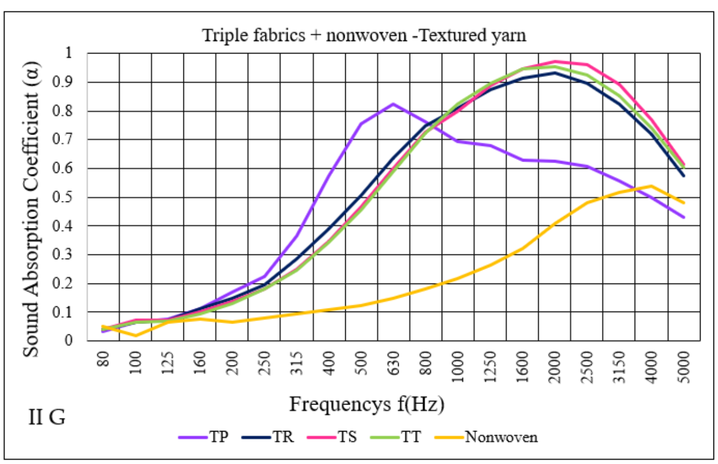
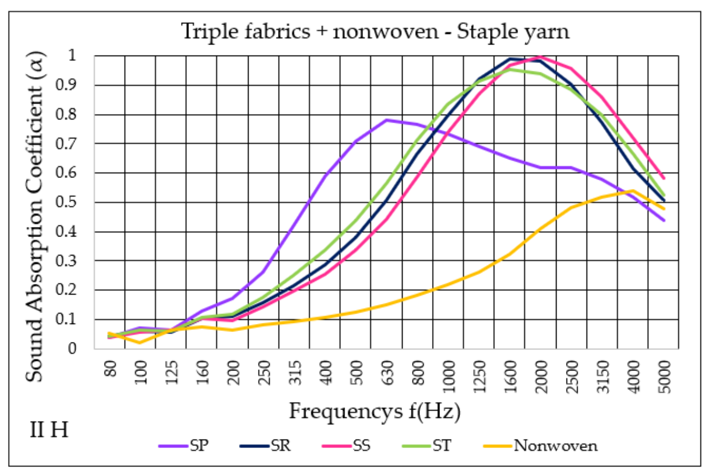


Figure 31. Sound absorption coefficient (α) of double layer fabrics (D, E and F) with the addition of nonwoven fabric verses frequency f(Hz) for the measurement variant (II).

The II variant with double fabric shows that, compared to other woven structures, plain fabrics demonstrated (Figure 31 D, E, and F) higher sound absorption performance at low-frequency, similar to the II variant results previously presented for single-layer woven fabrics (Figure 30). As shown in Figure 30 and Figure 31, as the layers of plain fabrics increase from single to double, the sound absorption performance decreases in comparison. In addition, the effect of reducing sound absorption was observed beginning at 1000 Hz. However, the difference using Post-Hoc analysis p-value is 100%, which indicates no significant difference between the single and double plain fabrics sound reduction results.

Other woven fabrics shown in variant II (Figure 31) demonstrate highly comparable results with a maximum sound absorption coefficient approaching $1(\alpha)$ at higher frequency levels between 1600 and 3150 Hz. Besides, above >3150 Hz, the effect of the absorption coefficient starts to decrease. The Post-Hoc analysis between the samples, except for plain fabric, shows no significant absorption differences with a p-value of 100%.





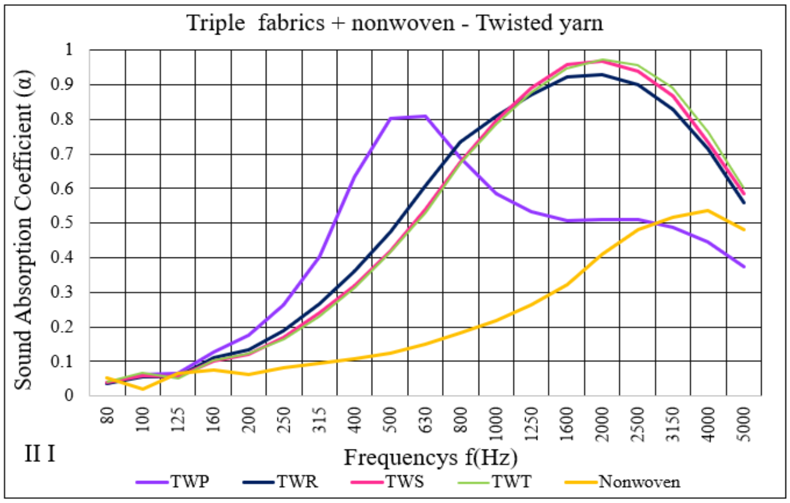


Figure 32. Sound absorption coefficient (α) of double layer fabrics with the addition of nonwoven fabric (G, H, and I) verses frequency f(Hz) for the measurement variant (II).

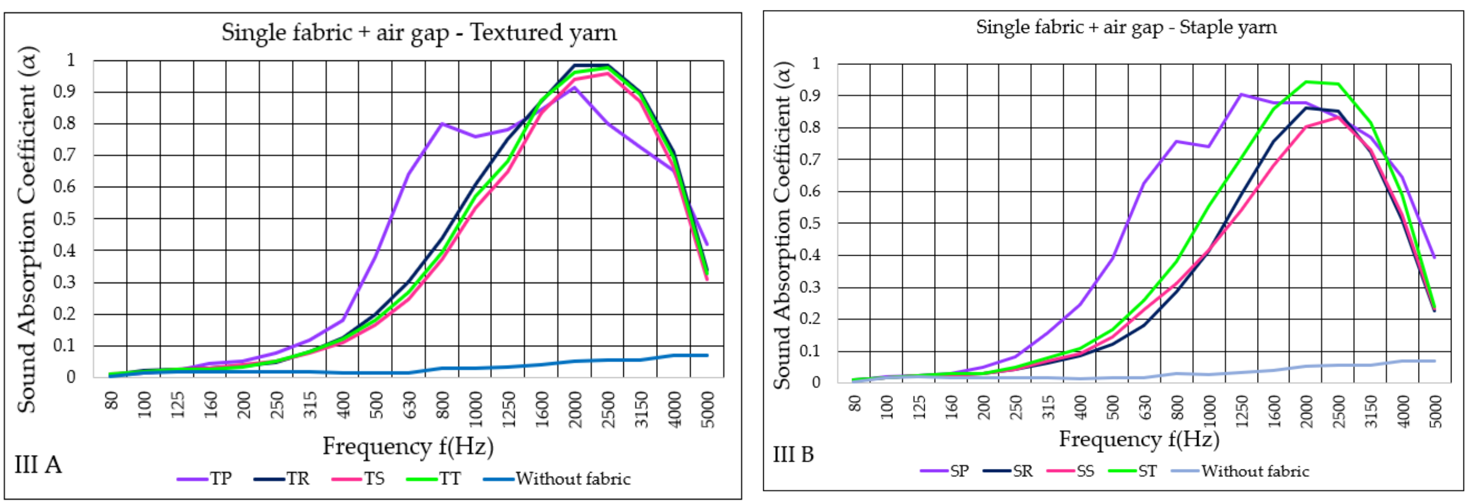
The result of the II variant (Figure 32) indicates that triple fabrics combined with nonwovens provided a sound absorption coefficient between 0.90 and 1 (α) from 1600 to 2500 Hz, except for plain fabrics. These outcomes were comparable to the results for double-woven fabric in the II variant (Figure 31).

In contrast, plain fabrics absorb lower frequencies than other fabrics. On the other hand, plain fabrics demonstrated low sound absorption as the number of woven fabric layers increased compared to the double and single layers in the II variant. This phenomenon may occur as a result of overcovering the porous surfaces as the fabric layer increases. However, the Post-Hoc statics show no significant differences in absorption performance as increasing fabric layers (p = 57%).

Variant III.

In this part of the research (variant III), the woven fabrics are set by adding a 30 mm air gap between the fabric and the solid plate (woven fabric + air gap). The blue line in the graphs represents the test result for sound absorption without fabric, which is less than 0.1(α) absorption coefficient. However, when the air gap was followed by woven fabric, their absorption performance increased dramatically compared to the I variant, which consists of only woven fabric.

The air gap method (Figure 33) revealed that plain fabric absorbs low-frequency sound higher than other fabrics. However, the result began to shift above 800 Hz. At a frequency of 2000 Hz, the fabric has a higher absorption value, indicating (α) 0.90. Finally, at 1250 Hz, the plain fabric formed from staple yarn (SP) proved its enhanced sound absorption characteristics. ST (twill) fabric has recorded the second-highest absorption efficiency among staple yarn fabrics, next to SP fabric. Figure 33 (B) indicates SR (rib) and SS (sateen) fabrics exhibited the third and lowest sound absorption.



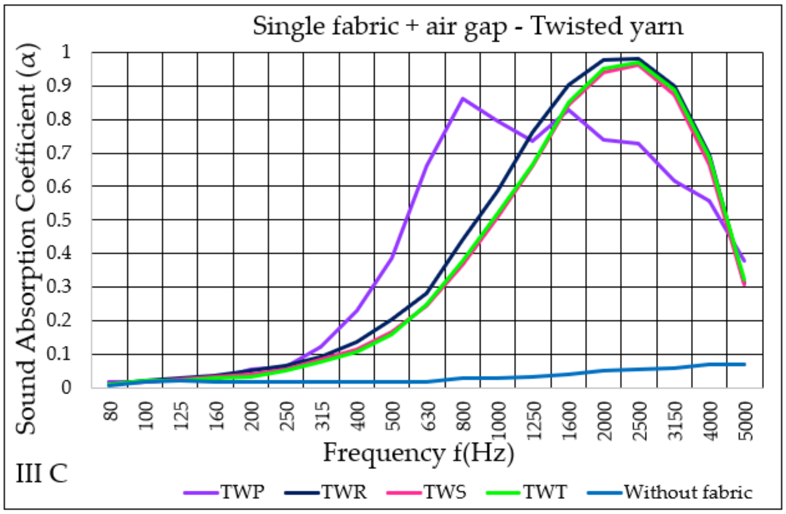


Figure 33. A, B, C, Sound absorption coefficient (α) of single layer fabrics with the addition of air gap verses frequency f(Hz) for the measurement variant (III).

The coefficients of rib (TR, TWR), sateen (TS, TWS), and twill (TT) (TWT) fabrics formed from textured and twisted yarn appear similar, with the highest absorption at frequencies (2000–2500 Hz). Unlike plain textiles, textured and twisted yarn fabrics typically have a maximum sound absorption value of approximately 1 (α).

The Friedman static analysis shows the significant difference between each yarn type of fabric formed. For instance, a significant difference in fabrics from staple yarn is with a p-value of < 0.05. Between textured yarn fabrics, the significant difference in p-value is < 0.05. Finally, the fabrics from the twisted yarn show a significant difference between the weave structure p-value of < 0.05. Generally, the statistical analysis shows that the sound absorption result of all the fabrics from each yarn type significantly differs between weave structures.

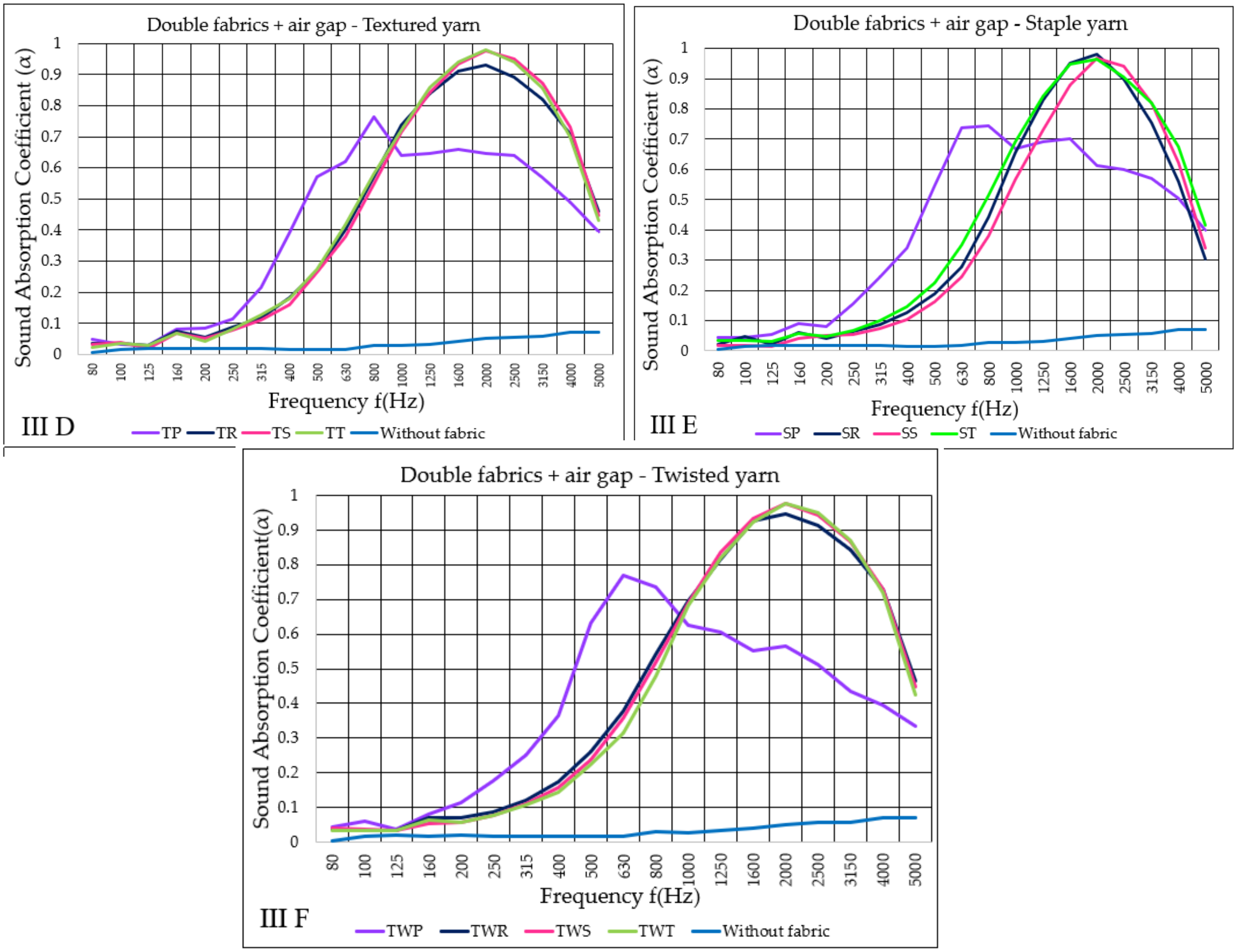


Figure 34. (DEF) Sound absorption coefficient (α) of double layer fabrics with the addition of air gap verses frequency f(Hz) for the measurement variant (III).

According to the results of the III variant (Figure 34), consisting of a double layer of woven fabric and an air gap, the plain fabric exhibited a lower sound absorption coefficient than the variant tested in variant II. In contrast, the air gap variant enhanced the absorption of low frequency.

Therefore, at 800 Hz, the maximum sound absorption of TP fabric is exhibited. Other weave structures show comparable findings, with the maximum sound absorption coefficient (α = 1) being reached at 2000 Hz. The statistics test result shown in Figure 34 results with a probability value of < 0.05, significantly different between fabrics. Using the Post- Hoc, the differences in each sample were identified, and except for plain fabric, all fabrics presented in Figure 34 show no significant difference in sound absorption. The statical analysis obtained proves the actual result.

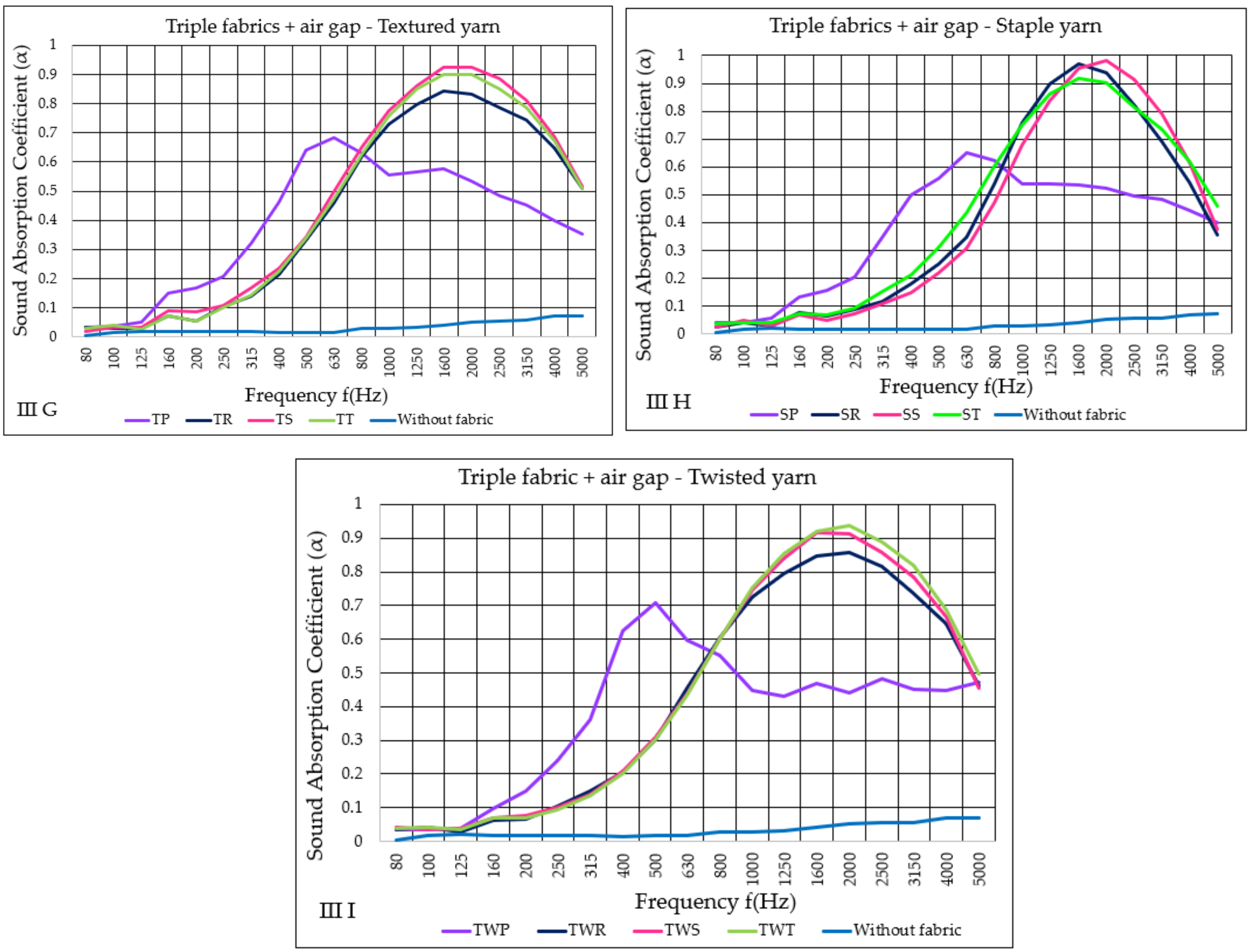


Figure 35. (GHI) Sound absorption coefficient (α) of double layer fabrics with the addition of air gap verses frequency f(Hz) for the measurement variant (III).

The III variant (Figure 35) GHI, consisting of three layers of woven fabric and airgap, demonstrates that the plain fabrics had a lower sound absorption rate than the single and double fabrics; however, the Post-Hoc test shows there are no significant differences. Similarly, to the III variant, sateen and twill fabrics formed from textured and twisted yarn (TS, TT and TWS, TWT) with triple layers achieved the maximum sound absorption coefficient (0.9) (α). The absorption coefficient of rib (SR) and sateen (SS) fabrics from staple yarn is approximately 1 between 1600 and 2000 Hz (Figure 35 H).

4.3.2 General Comparison of Sound Absorption Depends on Yarn Type, Weave Type, and Influence of Variant Difference.

The influence of the woven fabric layer shows three different main outcomes. First, the sound absorption coefficients of woven fabric were lower. As the number of fabric layers increases, sound absorption somewhat improves. Furthermore, the difference between the double layer and triple layer is highly significant, with $p < 0.05$. Similarly, the comparison of the difference between the single to triple layers shows a highly significant difference. Secondly, the sound absorption properties of plain fabrics exhibited a higher sound absorption performance, particularly at lower frequencies. The effectiveness of sound absorption at lower frequencies is exhibited only with plain fabrics, which were formed with three different yarn characteristics. As a result, it's possible to conclude that the weave structure of plain fabric increases the possibility of sound wave propagation through the fabric. For plain fabrics, increasing the number of layers, particularly with the nonwoven and with the addition of air gap, reduces sound absorption at lower frequencies. As a result, the high interlacement pattern in the plain fabric may increase the possibility of reflection of sound waves from the fabric surface due to covering up each layer's porous surface by the other plain fabric layer. Consequently, it increases the prevention of the sound wave from penetrating through the fabric from one layer to another. Thirdly, except for plain fabrics, the increasing number of layers of woven fabric with nonwovens and air gaps has shown approximately similar results as obtained between 0.8 and 1 (α). This result confirmed with Post-Hoc test and shows there are no significant differences.

In general, Except for plain fabric, the effectiveness of various weave structures' absorption at higher frequencies increases sound waves and considerably improves as the frequency increases. Compared to the I and III variants, the II variant (fabric with nonwoven) demonstrated higher sound-absorbing performance.

4.3.3 Noise Reduction Properties of Porous Fabrics

The noise reduction coefficient (NRC) is provided to assess the efficacy of sound absorption between different fabrics. The NRC measurement result is proportional to the sound absorption coefficient and quantifies the sound absorption properties of the fabric. The NRC of the fabrics was calculated at the frequencies where the human ear is most sensitive. The frequency ranges of 250, 500, 1000, and 2000 Hz octaves were chosen to calculate the NRC of 12 woven fabrics, and the arithmetic average of the NRC was used for comparison. The noise reduction coefficient (NRC) is often required to evaluate the effectiveness of sound-absorbing materials. High-efficiency sound-absorbing materials are those with an NRC greater than 0.56. Materials with values greater than or equal to 0.4 are deemed practically useful. For materials to be classified as sound-absorbing, the NRC value must be greater than or equal to 0.2 [94-96]. According to the different sorts of measurement variations, the noise reduction coefficients (NRC) of the textiles and the reflection of sound incidence are provided. The NRC of the nonwoven fabric is 0.21, and sound reflectance is 79%. Moreover, the NRC and reflection of the test conducted without the sample were 0.028 and 97%, respectively.

$$\mathrm{NRC} = (\alpha 250 + \alpha 500 + \alpha 1000 + \alpha 2000)/_{4}$$

The NRC result validates the sound absorption coefficients obtained and summarizes reflection coefficient findings presented in Table 7 according to their variant differences. The NRC results also show that as the layer of woven fabric increases, noise reduction increases, somehow in variant I and significantly in variants II and III, with the exception of plain fabrics. In contrast, equivalent results are shown for twisted and textured yarn fabrics with higher sound absorption than other staple yarn fabrics, particularly variants II and III.

In comparison to the I and II variations, the II variant displays a significant increase in NRC. The second variant is composed of nonwoven fabric as the base material. Therefore, by combining woven and nonwoven materials, the performance of both types of fabrics is improved. In addition, the combination of these fabrics has numerous advantages, including the ability to simultaneously increase the mechanical properties of nonwovens and the artistic value of materials.

In both variant II (TWP) and III (TP, SP, TWP) fabrics, the efficiency of sound attenuation decreases as the number of layers increases when the plain fabric is evaluated. Consequently, the sound absorption capabilities of the TP SP and TWP fabrics in variants II and III were superior to those of the other fabrics studied. In variant II, a triple-woven fabric (TR, TS, TT, ST, TWR) obtained the highest level of noise reduction (0.6) with the lowest percentage of reflection (40%) achievable. In addition, 0.61 % of the NRC results were displayed by textured yarn triple-woven rib fabric combined with nonwoven fabric.

As described in [105, 106], the I variant revealed that the tested materials could not be categorized as sound-absorbing materials because their NRC values were less than 0.2. Compared to the other variants, the second variant's (II) results demonstrated the highest reduction in sound level. Consequently, a single layer of plain fabric with nonwoven fabric (Variant II) which are TP, SP, and TWP, can be categorized as high-performance materials.

Except for the sateen (SS) weave structure, triple fabrics with nonwovens exhibited effective sound attenuation. According to the results, fabrics woven with textured yarn appeared to have a higher absorption rate than fabrics woven with other types of yarn in variant II (woven fabric with nonwoven fabric) and, consequently, a reduced sound reflection. Furthermore, the III variant produced somewhat inferior findings to those of the II variant. With the exception of rib (SR) and sateen (SS) fabrics from staple yarn, all III variant samples (woven fabric with air gap) were classed as useful acoustic materials due to absorption coefficient values between 0.40 and 0.56.

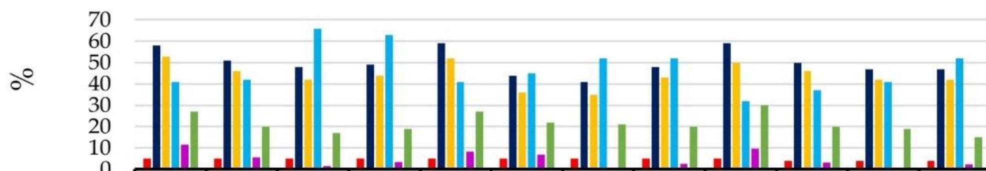
Weave structure differences possess varied degrees of sound absorption capacity. As indicated in Chapter Three, the plain 1/1 fabric weave structure has a higher amount of interlacing than other weave types. In addition, the thickness of plain fabrics varied between 0.4 and 0.6 mm, showing that they are thinner than other structures. The mass per unit area of TWP (plain fabric formed from twisted yarn) (189 g/m^2) and TP (plain fabric formed from textured yarn) (195 g/m^2) is less than that of SP (plain fabric formed from staple yarn) (213 g/m^2). Plain fabrics demonstrated low air permeability compared to other weave structures. Furthermore, findings from the anechoic chamber show that plain fabrics other than rib and sateen demonstrate higher sound absorption properties. The equivalent measurement of a single fabric with an air gap in an impedance tube shows that plain fabric shows high sound absorption (between 0.8 and 0.9) at lower frequencies in comparison to other fabrics (Figure 32), and as the frequency increases, the sound absorption drops. In addition, the impendence tube acoustic data demonstrate that a single fabric of plain weave structures yields superior NRC results when combined with nonwoven. The remaining weave structures show a different range of NRC values.

Table 7. The noise reduction coefficient (NRC) and sound wave reflection [99]

	Variant I			Variant II			Variant III		
Sample code	Single woven fabric NRC/ Reflection %	Double woven fabric NRC/ Reflection %	Triple woven. fabric NRC/ Reflection %	Single woven + nonwoven NRC/ Reflection %	Double woven fabric + nonwoven NRC/ Reflection %	Triple woven fabric + nonwoven NRC/ Reflection %	Single woven fabric + air gap NRC/ Reflection %	Double woven fabric + air gap NRC/ Reflection %	Triple woven fabric + air gap NRC/ Reflection %
TP	0.05/95	0.08/92	0.08/92	0.58/42	0.6/40	0.57/43	0.53/47	0.49/51	0.48/52
TR	0.05/95	0.05/95	0.07/93	0.51/49	0.59/41	0.61/39	0.46/54	0.51/49	0.5/50
TS	0.05/95	0.06/94	0.08/92	0.48/52	0.56/44	0.6/40	0.42/58	0.51/49	0.54/46
TT	0.05/95	0.06/94	0.08/92	0.49/51	0.56/44	0.6/40	0.44/56	0.51/49	0.52/48
SP	0.05/95	0.05/95	0.07/93	0.59/41	0.59/41	0.58/42	0.52/48	0.5/50	0.46/54
SR	0.05/95	0.06/94	0.07/93	0.44/56	0.53/47	0.58/42	0.36/64	0.47/53	0.51/49
SS	0.05/95	0.06/94	0.08/92	0.41/59	0.51/49	0.55/45	0.35/65	0.44/56	0.49/51
ST	0.05/95	0.06/94	0.07/93	0.48/52	0.56/44	0.6/40	0.43/57	0.49/51	0.51/49
TWP	0.05/95	0.06/94	0.07/93	0.59/41	0.57/43	0.56/44	0.49/51	0.5/50	0.46/54
TWR	0.04/96	0.06/94	0.07/93	0.5/50	0.58/42	0.6/40	0.46/54	0.5/50	0.5/50
TWS	0.04/96	0.05/95	0.07/93	0.47/53	0.56/44	0.59/41	0.42/58	0.5/50	0.52/48
TWT	0.04/96	0.06/94	0.1/90	0.47/53	0.54/46	0.58/42	0.42/58	0.49/51	0.52/48

4.3.4 Correlation of Physical Fabric Characteristics and the Noise Reduction Coefficient of Fabrics

In order to comprehend the impact of woven fabric properties on the effectiveness of sound reduction phenomena, this section of the research analyzed the woven fabric characteristics. Consequently, the percentage of PES fiber in the fabric, surface roughness, and porosity are investigated, and an analysis is given regarding yarn characteristics, weave structure, and other physical properties of fabrics. In addition, the correlations with sound absorption efficiency are investigated and discussed as follows: Table 7 is the source of the NRC's findings. For comparison with the physical properties of woven fabrics, the NRC is expressed in percentages in Figure 36.



	TP	TR	TS	TT	SP	SR	SS	ST	TWP	TWR	TWS	TWTT
Single woven fabric (NRC %)	5	5	5	5	5	5	5	5	5	4	4	4
Single woven + nonwoven (NRC %)	58	51	48	49	59	44	41	48	59	50	47	47
Single woven + air gap (NRC %)	53	46	42	44	52	36	35	43	50	46	42	42
Roughness (Ra) %	41	42	66	63	41	45	52	52	32	37	41	52
Porosity %	11.7	5.5	1.5	3.4	8.4	6.9	0.8	2.7	9.7	3.1	0.4	2.3
Pv % (fiber percentage in the fabric)	27	20	17	19	27	22	21	20	30	20	19	15

Fabric type

Figure 36. Noise reduction capability of the woven fabric and its relationship to the fabric's properties.

Volume percentage of PES fibers (Pv%)

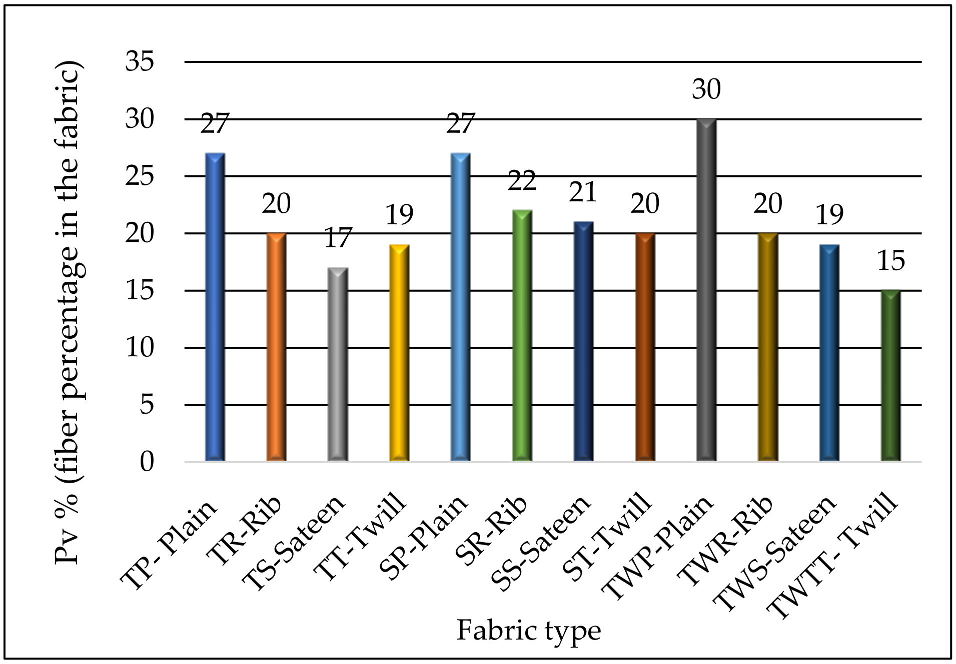


Figure 37. Pv % (fiber percentage in the fabric)

The amount of fiber contained in the fabric was related to the weave structure type, as demonstrated by the green bar in Figure 37. For instance, the structure of the plain fabric had more fiber than others. The rib fabric structure has the second-highest percentage of fibers. Comparable percentages of fibers are present in sateen and twill fabrics. The correlation between noise reduction and the percentage of fibers in the fabric demonstrates that noise absorption improved as the percentage of fibers increased in the fabric Figure 36. Specifically, plain fabrics formed from all types of yarns (TP, SP, and TWP) fabrics confirmed this association.

Fabric porosity and its correlation with NRC of fabric

The results of the porosity Figure 38 indicate that the structure of the plain fabric has a larger pore surface area than other weave types. Plain fabric (TP) has the most porous surface (11.4%) in comparison to other yarn types. In contrast, sateen fabric typically has a minimal porosity surface. Therefore, sateen fabric (TWS) has the least porous area (0.4%). The figure illustrates the threshold porous surfaces of all fabrics. The area of fabric pores is depicted with vivid, light green colors in Figure 39. As demonstrated, the porous surface is formed in two ways: first, the visible porous surface varies based on the characteristics of the yarn. In addition, the surface porosity of the fabric varies according to the weave structure.

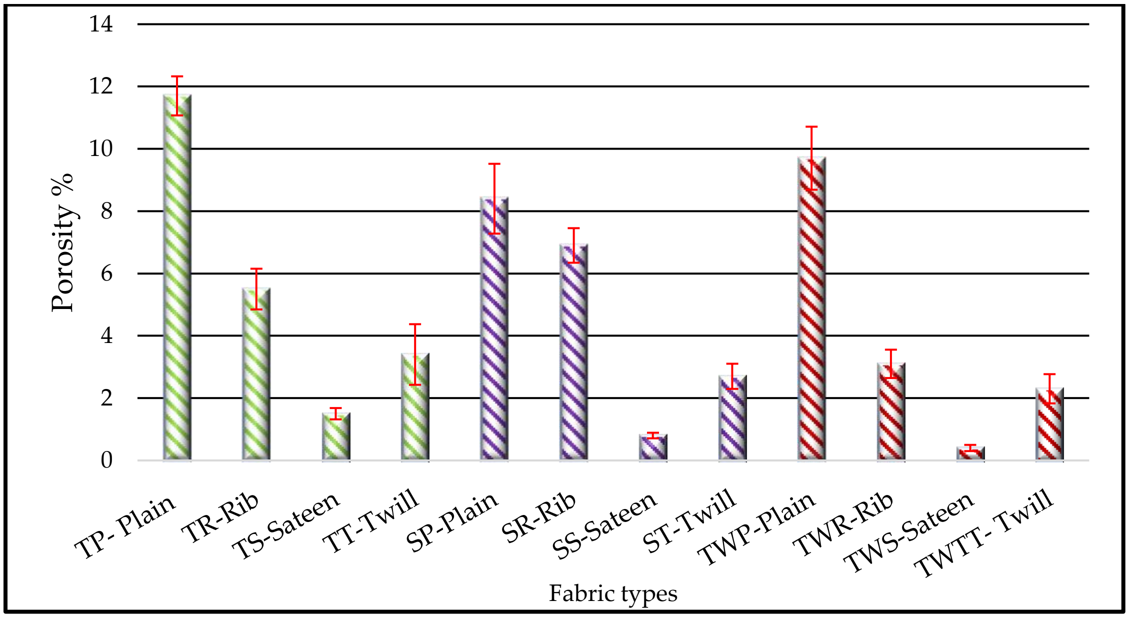


Figure 38. Twelve woven fabrics porosity results.

The plain fabric has a dense interlacing pattern compared to other weave structures. As the degree of interlacing increased, the number of pores between the warp and weft threads increased. This porous gap created an optimal surface for sound waves to enter the structure. As a result of the friction between sound waves and specific fibers within the yarn structure, there is the potential to convert sound waves into energy at that time. Inversely, when the yarn floating in the fabric structure rises, simultaneously, the number of pores is reduced (Figure *39*). This phenomenon may occur as a result of the weave type. Consequently, the relationship between NRC and the fabric's porosity revealed that TP, SP, and TWP fabrics have highly porous surfaces (relative to other fabrics) and high

NRC values (Figure 36). Generally, the higher number of pores (at optimum) in woven fabric facilitates the penetration and absorption of sound waves within the fabric's structure.

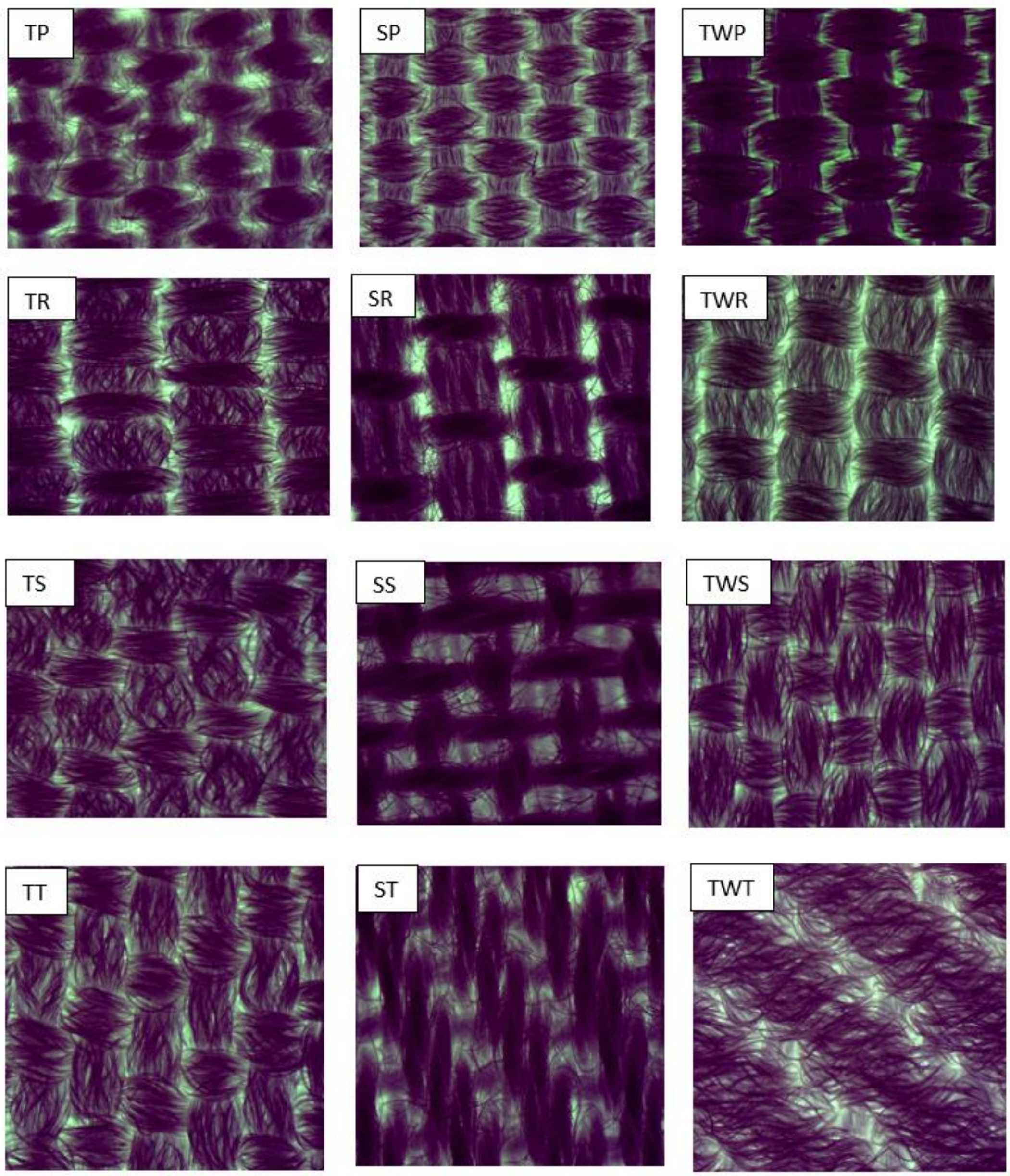


Figure 39. Woven fabric porosity surfaces that are shown with thresholded area.

Fabric roughness and its relationship with the sound absorption coefficient

The surface structure with which sound waves interact is one of the properties that determine or can be used as a prediction of the acoustic characteristics of a material. The roughness test was carried out in both directions (warp and weft), from which the mean value was derived. Plain weave structures: TP, SP, and TWP, have the lowest roughness relative to other weaves (Figure 40). Also accompanied by rib fabric structures TR, SR, and TWR. This phenomenon may have been related to the degree of the fabric's interweaving. The roughness of the fabric decreased as the number of warp and weft interlacements increased.

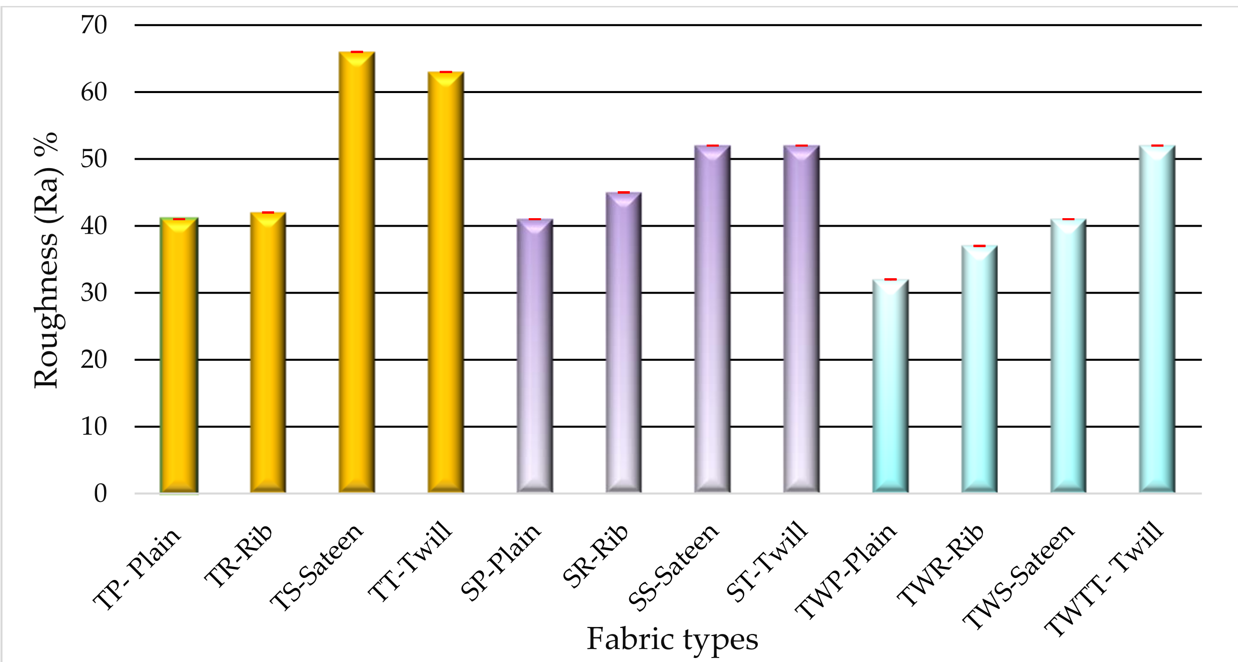


Figure 40. Fabric roughness properties

This characteristic is illustrated by the roughness values (Ra) (Figure 40) of plain fabrics in comparison to those of other weave types. The comparison of yarn types reveals that fabrics manufactured with twisted yarn are less rough than those made with other yarn types. The fabrics TP, SP, and TWP (single fabric with nonwoven and airgap) exhibited high noise reduction coefficient and low surface roughness compared to other types of fabric. In contrast, the triple-woven fabric TS had the highest NRC and surface roughness (Figure 36). This finding implies that as the number of woven fabrics increases, the effect of fabric roughness on sound absorption capabilities becomes negligible.

The study's results suggest that the high sound absorption of the single-layer woven fabric can be attributed in part to its relatively low fabric roughness. Additionally, the possibility of wave scattering from the surface may be raised by the increasing roughness of the fabric's surface. Due to this effect, the fabric will be less able to muffle surrounding noise. Therefore, surface roughness must be taken into account during the production of sound barrier materials to optimize sound absorption.

4.4 Conclusion of the Chapter

This study examines the sound absorption efficiency of three woven fabric variants: only woven fabric (variant I), woven fabric with nonwoven fabric (variant II), and woven fabric with airgap (variant III). Each variant of the investigation is composed of single, double, and triple layers of woven materials. For comparison, the sound absorption coefficient presented with the noise reduction coefficient results. In addition, the influence of fabric physical properties, including porosity, PES fiber content, and surface roughness, on the sound absorption coefficient of woven fabrics was investigated. The following are the main conclusions of this chapter:

- ✓ In general, the sound absorption coefficient of the I variant (only woven fabric) exhibits poor sound absorption properties, and as a result, the results are insignificant. In contrast, with the exception of plain fabrics, the sound absorption coefficient of all II variants (woven fabric with nonwoven) that consist of nonwoven fabrics at higher frequencies (1600 to 2500 Hz) ranges between 0.9 and 1 (α). Similarly, as the number of woven fabric layers increases, the sound absorption coefficient (α) of plain fabrics decreases in variant II (TWP) and variant

III (woven fabric with airgap) (TP, SP, and TWP). However, the plain fabric shows a higher coefficient at low frequencies (200-1000 Hz) than others.

- ✓ Fabrics included in variant I (only woven fabric) cannot be used as an absorber material because of noise reduction coefficient (NRC) is less than 0.2. Compared to fabrics made from staple yarn, which have a lower NRC for variant II (woven fabric with nonwoven) and III (woven fabric with air gap), the NRC for textured and twisted yarn is higher and comparable. According to the results of versions II and III, plain fabrics have a higher capacity for sound absorption than other fabric forms, especially single-layer woven fabric and double-woven plain fabric (TP). Woven fabric with nonwoven fabric (variant II) achieves a significant noise reduction compared to the first (I) and third (III) variants. The III variant (woven fabric with air gap) produces results that are centered. They are significantly higher than the I variant (only woven fabric); however, lower than the II variant.
- ✓ Fabrics with low surface roughness, such as TP, SP, and TWP, have a higher NRC performance. This phenomenon is closely related to the likelihood of surface wave scattering as a result of an increase in surface roughness. In addition, plain fabric shows a higher fiber content, and porous surfaces, on the other hand, have a higher absorption coefficient than weave structures such as rib, sateen, and twill.
- ✓ Combining woven and nonwoven materials improves sound barrier characteristics in multiple ways. The first objective is to enhance the sound absorption of both fabrics. Second, woven fabrics have high mechanical properties, and integrated materials with woven fabrics may outperform nonwoven alone in terms of mechanical properties. As a final point, the aesthetic value of these combined materials can be enhanced by incorporating intricately woven fabrics as the front layer.

5. OPTIMIZATION OF POROUS SOUND ABSORPTION PERFORMANCE

The previous chapter presented the outcome obtained from impedance tube measurement of different layers of woven fabrics and a combination of woven and nonwoven fabrics as well as woven fabrics with the addition of an air gap. The outcome shows significant results that give further clues for investigating woven fabrics with different conditions. In general, the improvement in sound absorption at low frequencies for single-layer plain fabrics combined with nonwovens or air gaps is a hint that these kinds of materials could be used to make low-sound absorbers. Therefore, as part of the study, this chapter utilized woven fabric that showed high sound reduction at low frequencies in previous studies and combined it with various weave structure combinations, nonwoven fabric, and air gap measurement configurations. Furthermore, selective measurements and materials used are given to enhance the absorption coefficient properties of the porous materials.

5.1 Materials

The preceding parts presented ways to verify woven fabrics' sound absorption using nonwoven fabric and air gap combinations. It also demonstrated the sound absorption efficiency of woven fabrics by independently measuring their efficiency using an impedance tube. In addition, distinct variant measurement methods, such as single, double, and triple layers with the same fabric type, were also investigated. As a continuation of the study, this section employed row material selected fabric types based on their sound absorption effectiveness and fabric characteristics that were measured and analyzed in the previous sections. The selected materials are formed from drawn textured yarn (DTY) of dtex 167×2 (f 32), and three different weave structures were selected: plain (TP), sateen (TS), and twill (TT). In addition, three fabric structures were utilized, such as rib (SR), sateen (SS), and twill (ST), which were created from staple yarn with a yarn count of 20×2 tex. Furthermore, the nonwoven fabric Figure 24 used in this section of the study is the same as used in the previous section of Materials 4.1.

5.2 Methods

The method for analyzing the acoustic properties of multilayer fabrics and fabric characteristics measuring methodologies are described as follows.

Using the transfer function method, the sound absorption coefficient of multilayer fabrics was determined. According to PN-EN ISO 10534-2:2003 [78], the sound absorption coefficient (α) of porous materials in the frequency range of 80–5000 Hz was tested. Each sample was examined three times in the impedance tube, and the mean values were calculated. A material's sound absorption coefficient ranges from 1 (full absorption) to 0 (no absorption). At the Lukasiewicz Research Network-Textile Research Institute in Lodz, Poland, all experimental acoustic tests were undertaken. In previous tests and analyses (in chapters three and four), the sound absorption (reduction) performance at low frequencies of plain fabrics made with textured yarn (TP) was higher than that of plain fabrics made with staple and twisted yarn. Therefore, in this chapter, we can see the measurements combining textured yarn plain fabrics (TP) with additional fabrics and different weave structures as multi-layers to maximize the sound absorption performance of porous material, specifically at low frequencies Table 8. Therefore, the sound absorption coefficient (α) was evaluated using three different measuring techniques.

Table 8. Fabric measurement setting and fabric combination [99]

Measurement plan	Yarn type	Number of fabric layers and weave type	Sample code
Nonwoven layout	Textured	Triple sateen (3TS) Double plain (2TP) Triple twill (3TT) Nonwoven (N)	3TS+2TP+N+A 3TS+N+2TP+A 3TT+2TP+N+A 3TT+N+2TP+A
Without and with an air gap	Textured, Staple	Plain (TP) Sateen (SS) Twill (ST) Rib (SR)	TP+SR+N, TP+SR+N+A TP+ST+N, TP+ST+N+A TP+SS+N, TP+SS+N +A
Woven fabric layout	Textured	Triple plain (3TP) Triple sateen (3TS) Nonwoven (N)	3TP+N+3TS+A 3TS+N+3TP+A

- ✓ The first plan was to examine the impact of nonwoven fabric layouts on the absorption performance of multilayer fabrics (Table 8). Figure 41 (ab) illustrates the location of the nonwoven fabric with multilayers of woven fabric with an air gap (A). In this section of the investigation, three distinct weave structures of fabric were used, such as two layers of plain (2TP), three layers of twill (3TT), three layers of sateen (3TS), and a single layer of nonwoven fabric (N).

- ✓ The second plan examines the role of air gaps in multilayer porous sound-absorbing materials. Porous materials were measured both without and with an air gap to enable comparison. The fabric varieties and combinations are shown in Table 8 between the nonwoven fabric and solid plate of impedance, the tube was set at a 30-mm air gap. Figure 42 (ab) shows the fabric setting within the impendence tube.

- ✓ The other research part assessed woven fabric layouts on the sound absorption characteristics of the fabric. The research consists of three layers of plain fabric (3TP), three layers of sateen fabric (3TS), and one layer of nonwoven fabric (N). In addition, an air gap (A) is set between the woven fabric and the solid plate of the impedance tube (Table 8). Figure 43 (ab) depicts the sample arrangement within the impedance tube.

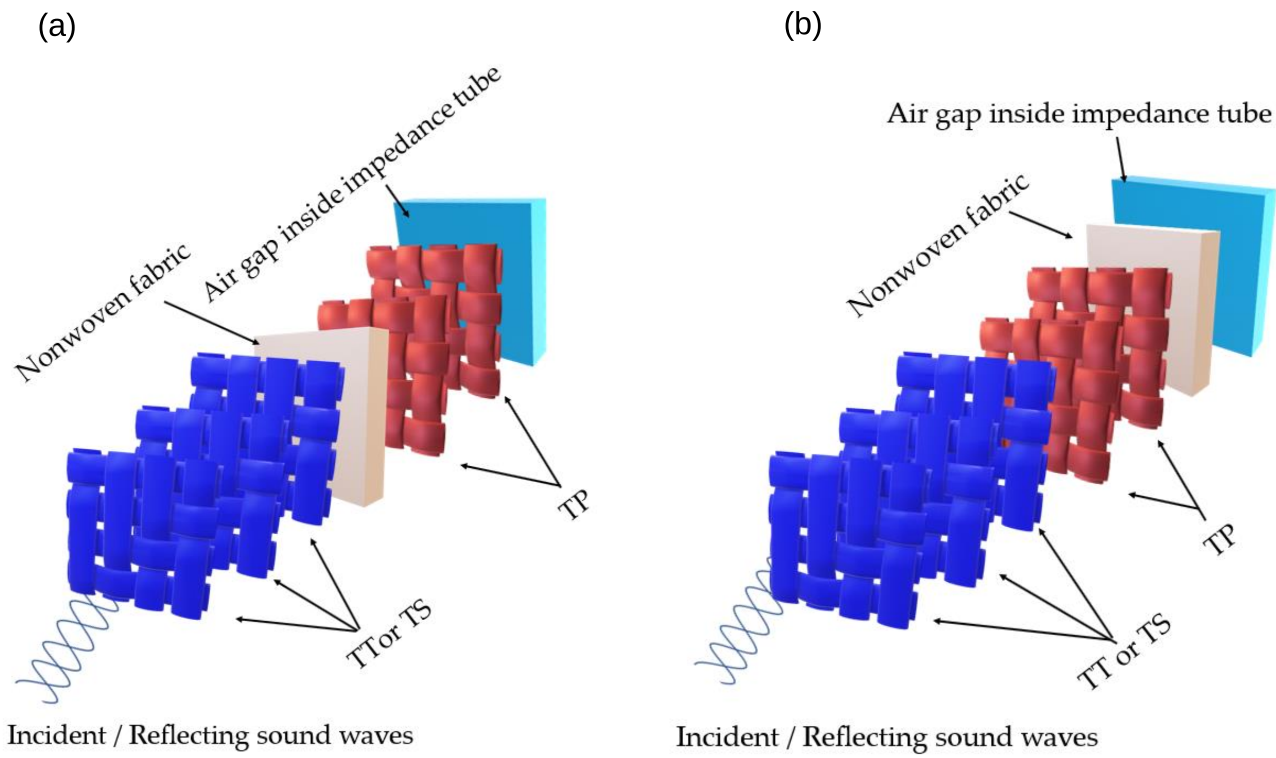


Figure 41. Samples layout inside impedance tube, (a) nonwoven fabric layout between multilayer of two different woven fabrics, (b) layout of a nonwoven fabric between multilayer different woven fabrics, and an air gap.

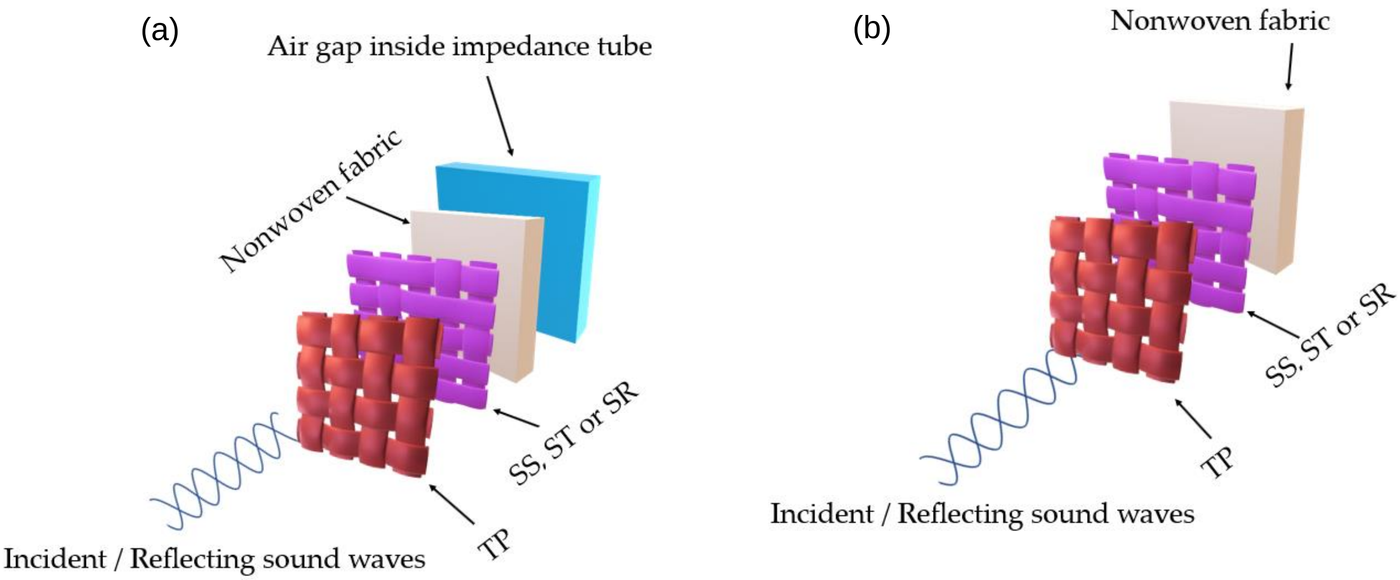


Figure 42 Samples layout inside impedance tube; - (a) fabrics arrangement with an air gap, (b) fabrics arrangement without an air gap.

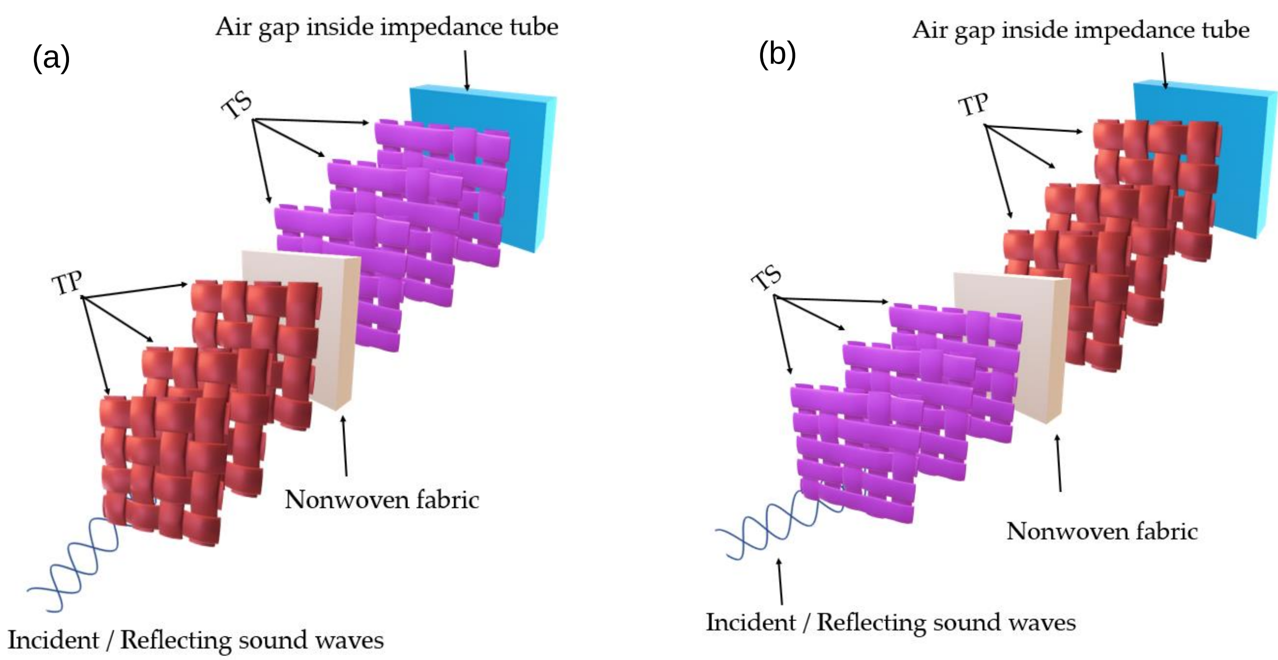


Figure 43. Samples layout inside impedance tube; - (a) plain fabric (TP) layout in front of nonwoven and sateen (TS) fabrics, (b) plain fabric (TP) layout between nonwoven fabric and air gap.

X-ray micro-computed tomography (SkyScan 1272; Bruker, Kontich, Belgium) was utilized to measure fabric porosity under the following scanning conditions: the source of X-rays has a current of 200 μA, voltage of 50 kV, and a pixel size of 6.4 μm. The image was rotated 180° with a rotation step of 0.2°, and no filter was selected. The samples were prepared with 2 cm × 1cm (Figure 44), and the testing was performed on a surface area of 3 mm x 3 mm. Micro-CT is based on the absorption of X-rays by the tested material and permits the microscale assessment of an object's interior structure.

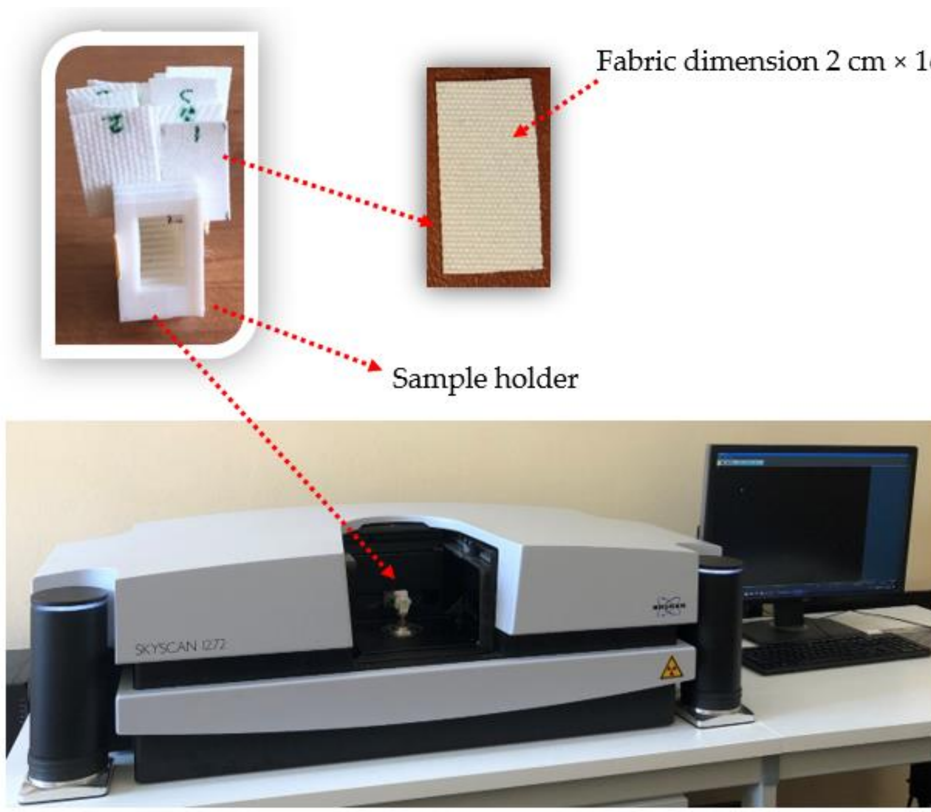


Figure 44. X-ray micro-computed tomography for fabric porosity testing

During testing, it is possible to distinguish different phases of X-ray absorption (such as pores or other spaces and parts of the tested object), define their shape, surface, volume, and spatial orientation within the material, and thus determine the porosity and properties of the pore structure based on the sample surfaces. In Table 4, fabric characteristics such as yarn density, mass per unit area, and fabric thickness are presented.

Besides, according to PN-EN ISO 9237:1998 the air permeability tests were done at a pressure drop of 100Pa on a fabric surface of 20 cm^2 [85]. The measurements were conducted on single and multiple layers woven fabrics Table 9. During the measurement, the fabric was arranged in accordance with the standard.

5.3 Results and Discussion

Previous chapters described the investigation performed on the fabric's acoustic properties, which were comprised of three types of polyester yarns, including twisted, stapled, and textured (PES) yarns. Plain, rib, twill, and sateen were the fabric’s weave structures that were formed from the three types of yarn. The sound-absorbing capabilities of 12 woven fabrics were evaluated in relation to their yarn and weave parameters. In general, the results indicate that yarn properties and interlacement structure have a significant impact on defining the acoustic performance of fabrics.

As a continuation of the previous study [98-99] and taking the main results as the starting point for this research, the results are presented in this chapter for further investigation. One of the findings of a prior study was that plain fabric absorbs sound well at low frequencies. At higher frequencies than other weave structures, the effect was not as long-lasting. In addition, weave structures such as rib, sateen, and twill showed higher sound absorption at higher frequencies than plain fabric. Furthermore, it was demonstrated that the combination of nonwoven and woven fabric produces higher sound absorption than either material used alone as a sound absorber.

Therefore, in this study, a variety of fabrics with different weave structures was utilized to obtain continuous absorption outcome at both low and high frequencies. This was done to maximize the porous materials' sound absorption capabilities. This study investigates the effects of both the layout of the porous material (woven and nonwoven) and an air gap when employing multilayer porous materials. In addition, the relationship between the performance of the samples' absorption coefficient and the fabric's characteristics, such as porosity and air permeability, is presented. Furthermore, the noise reduction coefficient (NRC) is provided to evaluate the efficacy of sound absorption between various sample packages of fabric. Calculation formulas and description of NRC can be found in Section "4.3.3 Noise Reduction Properties of Porous Fabrics". This chapter provides the NRC in percentage form for sample comparison.

5.3.1 The Influence of Nonwoven Fabric Layout on Porous Fabric Sound Absorption Performance

This section of the experiment includes woven and nonwoven fabrics as well as an air gap. Experiments were performed with different layouts of nonwoven fabrics, using woven fabrics as a reference, to understand the influence of nonwoven fabric layouts on the sound absorption performance of porous materials.

The results of the experiments indicate that samples consisting of nonwoven fabric sandwiched between two different multilayered woven fabrics (3TS+N+2TP+A and 3TT+N+2TP+A) have the highest absorption coefficient (α) (0.9–0.8) between 400 and 3150 Hz. Moreover, the samples consisting of woven fabrics on the front and nonwovens at the back (3TS,2TP+N+A, 3TT,2TP+N+A) had an absorption coefficient capability of 0.8 (α) at 400 and 3150–4000 Hz (Figure 45).

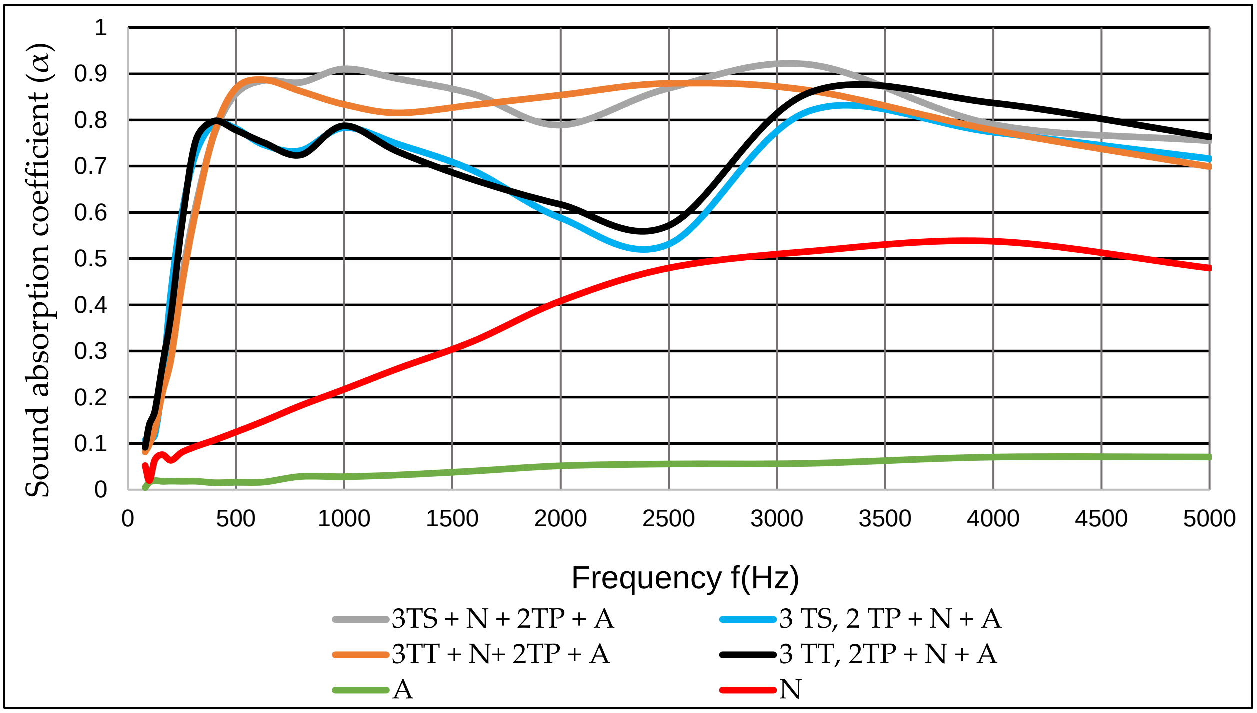


Figure 45. Sound absorption differences depend on the layout of the nonwoven fabric.

Similar design samples or those including similar arrangements of materials, 3TS+N+2TP+A and 3TT+N+2TP+A, as well as 3TS+2TP+N+A and 3TT+2TP+N+A, did not show different findings for sound absorption. In addition, this result was verified with Post-Hoc static analysis with no significant difference between the samples result. However, the sample composed of a nonwoven fabric sandwiched between two woven fabrics (3TS+N+2TP+A and 3TT+N+2TP+A) demonstrates a considerable increase in the sound absorption coefficient of the fabrics.

The NRC of samples containing nonwoven fabric between the fabrics (3TS+N+2TP+A) is 75%, which is greater than the NRC of samples containing nonwoven fabric between the air gap and plain fabrics (3TS, 2TP+N), which is 69%. Likewise, the NRC of sample package 3TT+N+2TP+A (75%) is higher than that of sample package 3TT+2TP+N (69%).

Comparing similar sample layouts, the NRC determined that comparable results were obtained. The NRC for samples 3TS+N+2TP+A and 3TT+N+2TP+A was therefore 75%. In addition, samples 3TS, 2TP+N+A, and 3TT+2TP+N+A exhibit comparable NRC results of 69%.

As a sound wave propagates from one fabric phase to the next, it meets various porous structures and porosity distributions, which act as impediment properties of single and multilayer porous materials. Table 9 includes the single fabric porosity results.

Each porous material used has different porosity sizes, distributions, and shapes. As the sound wave travels through the material, the friction between each porous surface causes it to lose energy. Therefore, it is feasible to conclude that the arrangement of porous acoustic materials can impact their absorption performance and the air permeability results. According to Table 9, the air permeability of samples of nonwoven fabric sandwiched between woven fabrics is low (3TT+N+2TP and 3TS+N+2TP). In contrast, front samples composed of woven materials (3TT+2TP+N and 3TS+2TP+N) exhibit high air permeability. There is an inverse correlation between sound absorption and air permeability. Samples with low air permeability exhibit superior sound absorption and vice versa.

Table 9. Fabric properties of single and multilayer porous materials.

Fabric type	Porosity (%)	Air permeability (mm/s)	Sample type	Air permeability (mm/s)
TP	60	95.3	3TP+N+3TS	5
TS	58	453.1	3TS+ N +3TP	3.9
TT	55	419.6	3TS+ N +2TP	7.3
SS	58	608.3	3TS+2TP+ N	33
ST	53	418	3TT+N+2TP	5.9
SR	47	424.9	3TT+2TP+N	28.3
Nonwoven	97	9284.4		

5.3.2 The Role of Air Gap in Maximizing the Performance of Multilayer Porous Fabric's Sound Absorption Coefficient

Plain fabric (TP) and nonwoven fabric (N) were employed as base materials in this part. Twill (ST), rib (SR), and sateen (SS) fabrics from staple yarn were used in addition to the influence of air gap attributes. The arrangement of fabrics inside the impedance tube is displayed as base materials to determine the impact of weave and yarn characteristics, as well as in Figure 42.

Figure 46 (a) shows that the combinations of different weave structures (TP+SR+N, TP+ST+N, and TP+SS+N) do not show significant differences in results.

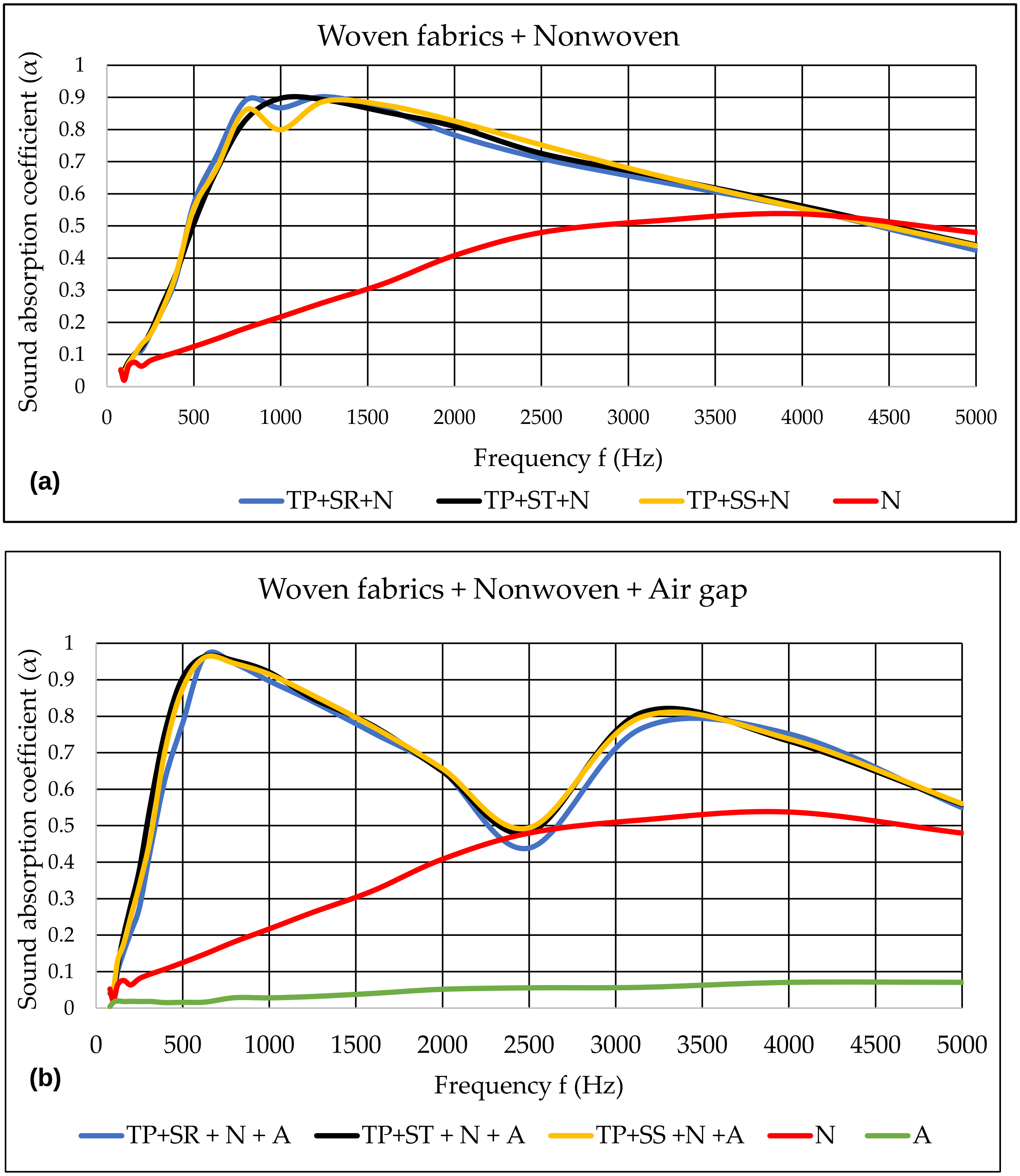


Figure 46. Multilayer fabrics sound absorption coefficients (α): a) double-woven fabric with nonwoven fabric and b) double-woven fabric with nonwoven fabric and an air gap.

This data suggests that the various weave combinations utilized responded similarly to sound incidence. The highest sound absorption coefficient (α) was found for all materials between 0.8 and 0.9 at 800 to 1600 Hz.

Figure 46 (b) illustrates that the addition of an air gap enhanced the coefficient (α) of all samples (TP+SR+N+A, TP+ST+N+A, and TP+SS+N+A). Furthermore, the absorption at low and medium frequencies increased significantly compared to samples collected without an air gap (Figure 46a). However, the results did not persist at higher frequencies.

The incident sound waves that travel through the multilayer acoustic material without being absorbed face additional impedance in the air medium prior to hitting the solid plate and being reflected back into the layered porous materials. Furthermore, due to the friction between the air particles and the sound waves, the sound waves become weaker, resulting in faster dissipation of the incident wave in the multilayer acoustic material.

The air gap generally improved sound absorption, particularly at low- to medium-frequency ranges. The sound absorption coefficients (α), for instance, at 500–1000 Hz, samples TP+SS+N+A, TP+ST+N+A, and TP+SR+N+A range between 0.90 and 1. However, at 800 Hz, the absorption of all fabric begins to decrease. Comparing samples measured with and without an air gap reveals that the NRC percentages are different. The NRC of samples with an air gap versus those without an air gap is therefore provided as follows: TP+SS+N+A versus TP+SS+N has an NRC of 70%/57%; samples TP+ST+N+A versus TP+ST+N have an NRC of 71%/59%; and samples TP+SR+N+A versus TP+SR+N have an NRC of 65%/60%. The NRC of packages without air gaps are comparable, and there is no significant difference between their results.

5.3.3 Optimization of Porous Sound Absorption using Plain Fabric

This section presents the influence of the number of plain fabrics on the sound absorption properties of multilayer porous fabrics using different fabric weave structures, such as plain and sateen. The results of an evaluation of the sound absorption of two different fabric weave structures combined with nonwoven fabric and, in addition, a 30 mm air gap were used for the evaluations.

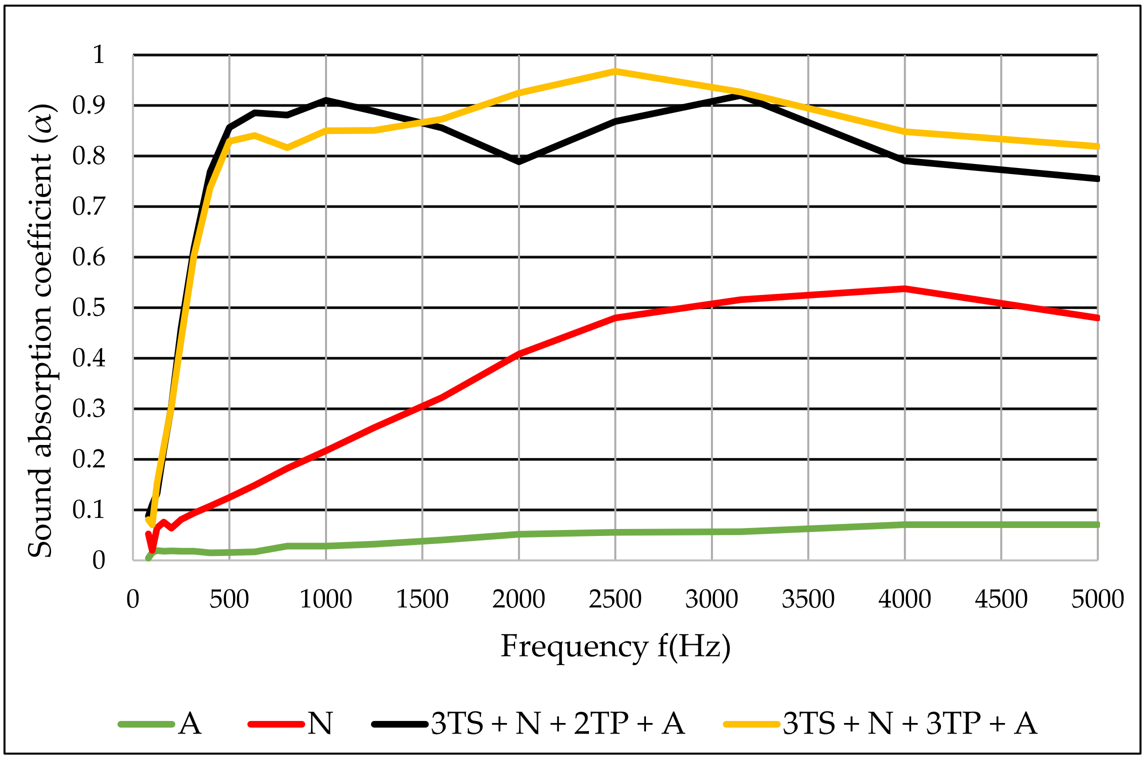


Figure 47. The sound absorption comparison based on the number of plain fabric layer difference.

Considering the findings of the preceding sections, this study part evaluated their sound absorption properties with two layers of plain fabrics (2TP) and three layers of plain fabrics (3TP) with the combination of a triple layer of sateen fabrics (3TS). The selection of these weave structures is based on the results demonstrated in the preceding sections, namely, that plain fabrics exhibit high sound absorption at lower frequencies and sateen fabrics show high sound absorption at higher frequencies. To maximize the sound absorption performance of porous materials, a combination of plain and sateen fabric is used as a multilayer, along with an air gap and nonwoven.

Apart from the difference in the number of layers on plain fabric, the measurement setting, layout arrangement, and types of material used in both tests were the same. However, the findings shown in Figure 47 and the NRC results for samples 3TS+N+2TP+A (75%) and 3TS+N+3TP+A (76%) are very similar. The results that increase the number of plain fabric layers in multilayers is an insignificant factor in increasing sound absorption at low frequencies when the number of plain fabrics is increased.

With increasing the layer count of plain fabric, the sound absorption at higher frequencies, specifically at 1500 Hz, increases in comparison. However, the absorption result for lower frequencies is high within both samples. In addition, the result demonstrated with both samples can be considered a remarkable result that was obtained, with continuous absorption results from a low to a high range of frequencies compared to the results that were obtained in chapters two and one. This result fills the research gap regarding porous absorption limitations at lower frequencies.

The other part of the research focused on the fabric layout. The evaluation results of the sound absorption of two different fabric weave structures, plain and sateen, fabricated from textured PES yarn, are presented in Figure 48. Both samples used the same nonwoven and air gap measurement parameters. However, the result of the absorption coefficient fluctuated considerably as the position or layout of the materials changed within multi-layer porous materials.

Both samples exhibit enhanced low-frequency sound absorption. As shown in Figure 48 demonstrates a package of samples made of a triple layer of plain fabrics on the front, nonwoven fabric in the middle, and consequently, a triple layer of sateen fabric and air gap at the end (3TP+N+3TS+A) exhibited higher sound absorption at low frequencies (approximately 0.9 coefficient). However, as frequency increases, the result decreases, also 64% of NRC result is demonstrated. Figure 43 (ab) shows details of the sample arrangement within the impedance tube.

When the plain (3TP) fabrics were positioned behind samples or between nonwoven and the air gap (3TS+N+3TP+A) and sateen fabric set on the front conversely, the sound absorption at higher frequencies increased (Figure 48). Only the sample consisting of plain fabrics (3TP) in the rear of the other samples (3TS+N+3TP+A) demonstrates consistent absorption results, with NRC of 76%, and the absorption coefficient (α) ranges from 0.8 to 1 from 400 to 5000 Hz.

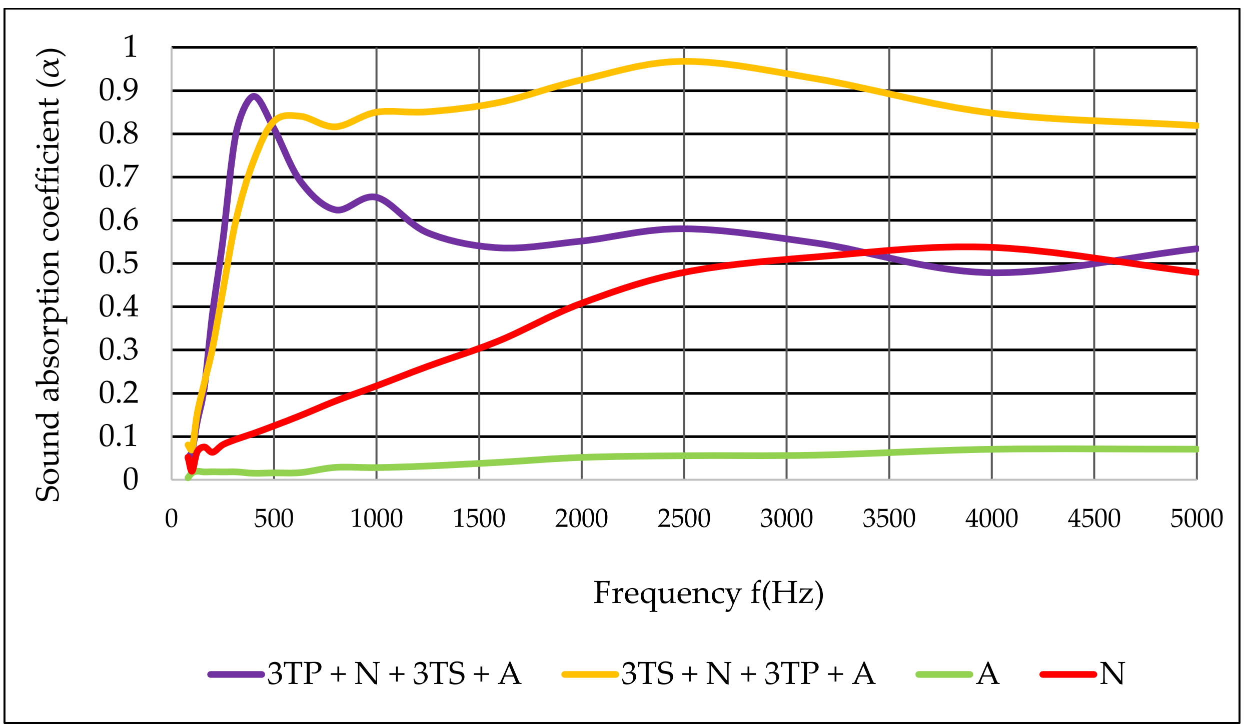


Figure 48. Woven fabric layout, sound absorption performance of fabrics versus frequencies.

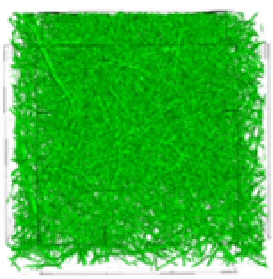
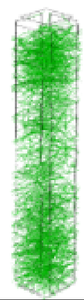
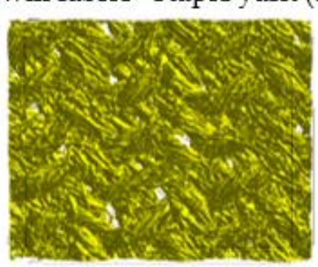
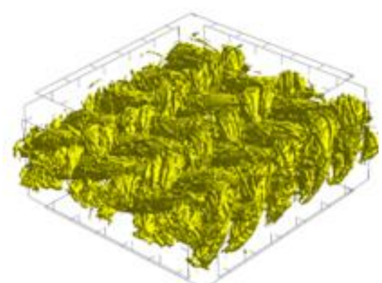
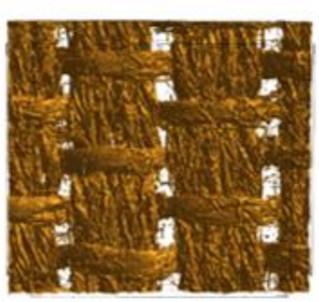
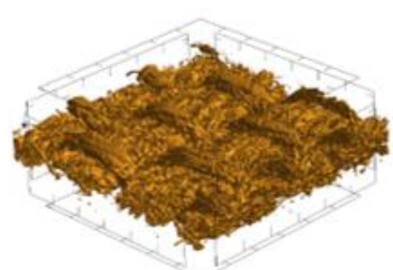
In terms of the physical characteristics of fabrics, plain (TP) weave structures include dense interlacing. The weave structure is shown in Figure 49 (TP) as transparent, open porous surfaces. This open, porous region increases the probability that sounds waves enter and facilitate their propagation through the fabric.

The plain fabrics (3TP) in the front and sateen fabrics behind (3TP+N+3TS+A) increase the probability of low-frequency penetration via open porous structures. This process boosts the fabric's sound absorption of long wavelengths. Furthermore, when plain fabrics are sandwiched between nonwoven and air gaps, (3TS+N+3TP+A) simultaneously increases absorption at higher frequencies. In this phenomenon, the possibility of a reduction in sound waves can be noticed in two ways. First, it could be dependent on the wave energy. Due to energy loss induced by friction between the sound wave wall and porous wall, the propagation of sound incidence waves through the thickness of the materials decreases with time.

Consequently, the probability of residual weak sound incident wave absorption by the open, porous portions of the plain fabric increases. Secondly, due to the high open porous area of plain fabric, sound waves reflected from a solid plate can easily permeate the open porous structure.

The sateen structure (1/4 (3)) consists of four weft strands floating over a single warp yarn. Consequently, the degree of interlacement is smaller than that of plain (1/1) fabric, and this feature gives a loose and soft surface structure to the fabric. In addition, the sateen (TS) porous surface result of 58% is equivalent to that of the plain (TP) fabric (60%). (Table 9). However, as depicted in Figure 49 (TS), the sateen fabric structure shows yarn over-float, which causes the porous surface to appear different and to be concealed by the fabric's top surface.

The results of the air permeability test indicate that samples with a plain structure on the back of fabrics (3TS+N+3TP) have a lower air permeability than samples that have plain fabric on the front of other fabrics (3TP+N+3TS). The results of the air permeability test corroborated the results of the acoustic test. In other words, the result for air permeability is inversely correlated with the coefficient of sound absorption (α) of the samples.

Fabrics top view	3D fabric structure
Nonwoven 	Thickness of nonwoven fabric 
Twill fabric –Staple yarn (ST) 	
Rib fabric – Staple yarn (SR) 	

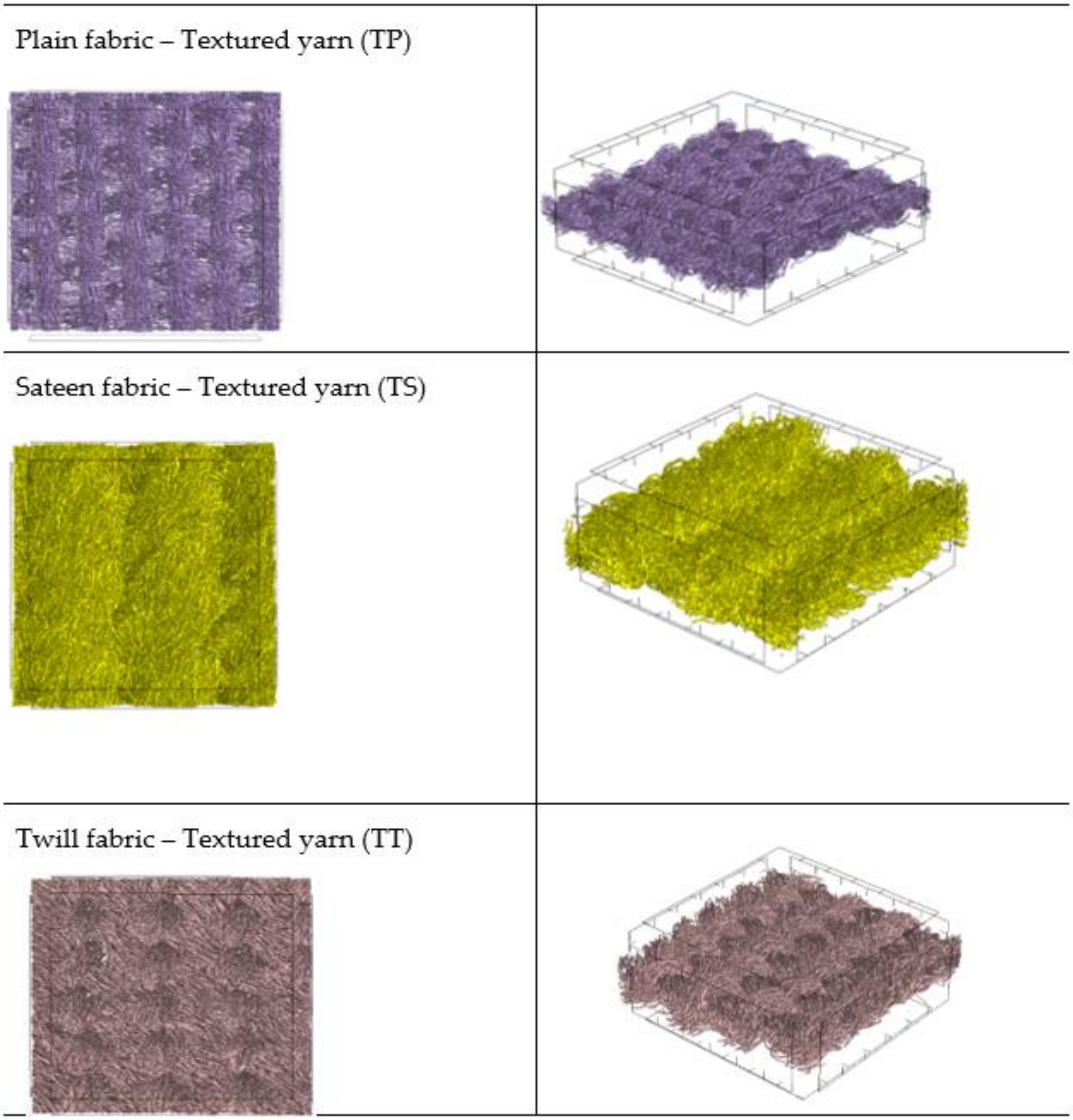


Figure 49. Micro-computed tomography, three-dimensional fabric surface, and porous surface topography (surface area of 3 mm x 3 mm).

5.4 Conclusion of the Chapter

Based on the previous chapter results and utilizing selective materials, this part of the study focused on optimizing the sound absorption performance of multilayer porous fabrics, mainly using a woven fabric, on achieving persistent and high sound absorption capabilities from low to high-frequency ranges. In addition, the effects of fabric arrangement on absorption coefficient efficiency and air gap presence on the acoustic performance of multilayer porous materials were investigated. The main conclusions drawn are listed as follows:

- ✓ The layout of nonwoven fabrics relative to woven fabrics considerably affects the absorption result. In addition, the sample that consists of nonwoven fabric between triple layers of sateen fabric and double layers of plain fabric (3TS+N+2TP+A and 3TT+N+2TP+A) exhibits higher sound absorption between 400 and 3150 Hz than those with woven fabric on the front and nonwoven fabric at the back (3TS+2TP+N+A and 3TS+2TP+N+A).
- ✓ The number of fabric layer additions or thicknesses doesn't show any significant result regarding increasing sound absorption.
- ✓ The other layout analysis used plain (3TP) fabrics. The sample consists of a plain (3TP) fabric layout on the rear set of the triple layer of sateen fabric (3TS) and nonwoven fabric in the middle of the two woven fabrics (3TS+N+3TP+A), which improved the sound absorption performance. On the other hand, sound absorption at low frequencies was high when three layers of plain fabric (3TP) were placed in the front (3TP+N+3TS+A). However, the result does not persist for mid- and high-frequency levels. 3TS+N+3TP+A demonstrates superior sound absorption at low to high frequencies compared to other samples. In general, the sound absorption performance of multilayered porous materials improved below 500 Hz, and between 400 - 5000 Hz, with increasing and consistent sound

absorption coefficients of 0.8–1 (α) outcome observed. Consequently, these materials can be acoustic in environments with low- to medium-frequency sounds.

- ✓ Based on the X-ray micro-computed tomography result for porosity, the TP fabric has a more porous surface than the other fabrics. Due to the open structure of plain fabric (TP) (between fibers as a result of yarn characteristics and the interlacement points), the propagation of incidence waves traveling through the fabric increases. This phenomenon enables the sound absorption performance of the samples to vary based on the arrangement and number of plain fabric layers.
- ✓ The addition of an air gap to a multilayer of porous materials improves the absorption coefficient at low and medium frequencies. In addition, the advantages of introducing an air gap with multilayer porous material can be categorized into two groups. First, it improves the fabric's absorption performance at low and medium frequencies. Additionally, it reduces the need for extra porous material, which has substantial economic benefits.

6. SUMMARY AND RECOMMENDATION

The study's overall findings and recommended measures are presented below:

1. The research evaluated the influence of yarn characteristics on the fabrics' sound-absorbing materials.
   - ✓ The woven fabrics were prepared using polyester yarn as a staple, twisted, and textured yarn. By using only polyester yarn, this research was able to determine the influence of yarn characteristics on the efficiency of acoustic materials.
   - ✓ The outcome shows that the fabrics formed from textured yarn exhibited higher sound absorption in the anechoic chamber acoustic sound reduction measurement. The linear density of textured yarn (Tex) is apparent between the two yarns. Due to the formation of the textured yarn, the fabric's fuzziness and bulkiness distinguish it from other commonly used yarn types. Therefore, it is impossible to determine physical characteristics such as twist, hairiness, and yarn evenness. The advantage of the bulkiness of the yarn is that it increases the possibility of wave propagation through the fabric; this phenomenon increases sound reduction.
2. Evaluation of the influence of woven fabric interlacement characteristics on sound absorption efficiency of the fabrics.
   - ✓ The fabric weaving structure or interlacement influence on the potential of sound absorption was verified with two different acoustics measurement methods. In the anechoic chamber, an outstanding result was obtained by plain fabric. Also, this result verified with the impedance tube that the sound absorption of plain fabric is higher at lower frequencies as a comparison. The other weave structures of woven fabrics show very comparable results within fabrics.

- ✓ The physio-mechanical characteristics of the single-layer fabric show that the air permeability of woven fabric and the sound absorption phenomena of the fabric are inversely related. The porosity of the materials shows that fabrics such as plain fabric with higher porous surface show simultaneously higher sound reduction properties. The roughness of the material is directly related to the fabric's sound absorption performance. As a result, shows fabric relatively low fabric roughness index indicates high sound reduction. This result supported the second hypothesis of the study, which stated that the surface roughness of the woven fabric influences its ability to absorb sound.
- ✓ The fabrics that show high sound reduction simultaneously contain higher fiber content in the fabric, such as plain fabric.

3. Determined the influence of incidence sound wave angle on the fabric absorption performance.

   - ✓ The sound reduction efficiency of different fabrics depends on the sound source angle settings. This phenomenon is proven by measuring angles at 0° and 45° in an anechoic chamber room measurement. The results show fabrics measured at 0° demonstrated a higher reduction coefficient than those measured at 45°.

4. Determined the sound absorption of similar multilayer woven fabrics.
   - ✓ The sound absorption coefficient obtained from the impendence tube indicates that only single-, double-, and triple-layer woven fabrics are low.
5. Determined the sound absorption of woven fabrics up to three layers of similar weave structures with the addition of nonwoven fabric.
   - ✓ The combination of woven and nonwoven fabric shows increasing and obtaining high sound absorption in fabrics sateen, rib, and twill at higher

frequencies. On the other hand, plain fabric shows high sound absorption at lower frequencies as a comparison and decreases the efficiency as increasing of frequencies.

6. Determined the sound absorption of woven fabrics up to three layers of similar weave structures with the addition of an air gap.
   - ✓ In terms of sound absorption, the result of combining an air gap with woven fabric is comparable to the result of combining woven and nonwoven fabric. Furthermore, it shows increasing in sound absorption at lower frequencies as a comparison of woven fabric with nonwoven fabric results.
7. The influence of nonwoven fabric layout on porous fabric sound absorption performance.
   - ✓ To fully comprehend the effectiveness of porous materials, it is essential to understand the layout effect on absorption performance. For instance, samples composed of nonwoven fabric sandwiched between two different multilayered woven fabrics, which are triple layers of sateen and two layers of plain fabrics, as well as a sample package containing triple layers of twill fabric and double layers of plain fabric (3TS+N+2TP+A and 3TT+N+2TP+A) have the highest absorption coefficient (α) (0.9–0.8) between 400 and 3150 Hz. On the other hand, the samples composed of woven fabrics on the front and nonwovens at the back (3TS+2TP+N+A, 3TT+2TP+N+A) demonstrate an absorption coefficient capability maximum of 0.8 (α) at 400 and 3150–4000 Hz. As a result, the absorption coefficient is lower than the sample that consists of nonwoven fabric sandwiched between woven fabrics.
8. The significance of air gap in multilayer porous fabric acoustic performance
   - ✓ The air gap enhanced sound absorption, especially at low- to mid-frequency ranges. At 500–1000 Hz, the sound absorption coefficients (α) for samples packages of plain fabrics in addition to sateen and nonwoven fabrics with an

air gap (TP+SS+N+A), plain with twill fabrics in addition to nonwoven fabric and an air gap (TP+ST+N+A), and plain and rib fabrics with nonwoven fabric and an air gap (TP+SR+N+A) range between 0.90 and 1. At 800 Hz, the absorption of all fabrics begins to diminish.

9. Optimizing porous sound absorption using plain fabric

- ✓ The attempt to maximize the performance of porous materials falls on; fabrics formed from textured yarn, as a result of obtained higher absorption performance than staple and twisted yarn fabrics. As well as from utilized woven fabrics, the plain fabric was selected due to its high absorption coefficient performance at low frequencies. Furthermore, the sateen weave structure obtains high sound absorption at higher frequencies. In addition, the nonwoven fabric enhances the absorption performance by setting in the middle of multilayer woven fabrics. Also, airgap is used to increase sound absorption at low frequencies.
- ✓ The result indicated that the fabric combination of three layers of sateen fabric, three layers of nonwoven fabric, and three layers of plain fabric with the air gap (3TS+N+3TP+A) demonstrated higher sound absorption performance from low to high frequency (400 to 5000 Hz), with NRC of 76% and the absorption coefficient ranges from 0.8 to 1 (α).
- ✓ Besides, the study investigated the influence of a number of layers and layouts of plain fabric. The layer number difference shows insignificant results between the sample that consists of 2TP (double layer of plain fabric) and 3TP (three layers of plain fabric). This result contradicts the secondary hypothesis, which states that the absorption performance of multilayer woven fabrics increases with the number of layers.
- ✓ The difference in layout indicates that the sample 3TP+N+3TS+A has high sound absorption at low frequencies but not at higher frequencies. On the

other hand, when the 3TP layout between the nonwoven and air gap (3TS+N+3TP+A), the sound absorption increases and shows consistent absorption results. This significant result puts us one step ahead in the scientific gap concerned with the porous material's sound absorption limitation.

CONCLUSION

The study's objective was to develop a fabric-based acoustic material that improves the acoustic performance of porous fabric through the internal weave geometry, yarn properties, and the arrangement of fabric assemblies. The main outcomes of the investigation are as follows:

- ✓ The investigation performed in an anechoic acoustic chamber concerning the sound reduction performance of fabrics at 0° and 45° angles demonstrates that the fabrics measured at 0° incidence angle have high sound reduction than 45° incidence angle. In addition, the results of sound reduction vary based on the type of yarn and weave structure used to create the fabric. Consequently, the plain weave structure exhibited superior sound reduction compared to the rib, sateen, and twill weave structures. Fabrics formed from textured yarn generally result in higher sound reduction than fabrics formed from other yarn types.
- ✓ The second verification of acoustic investigation was conducted in an impedance tube with a frequency range of 80 –5,000 Hz. Fabrics with similar weave structures were measured as single, double, and triple layers, with a combination of nonwoven and air gaps. With a noise reduction coefficient (NRC) of less than 0.2, the acoustic test for only woven fabric with different layers reveals low absorption. In addition, the sample, which consists of a woven fabric with an air gap, exhibits a higher sound reduction coefficient between 0.04 and 0.56. As a result, except for

the sateen and rib weave structures formed from staple yarn, the fabrics can be categorized as useful acoustic materials. The outcomes of combining woven and nonwoven fabrics can be categorized as high-performance absorber materials. The NRC of the nonwoven fabric cannot be classified as an acoustic material because the result is below 0.2. In contrast, single-layer plain fabric with nonwoven fabric and single-layer plain fabric with an air gap indicates a higher sound absorption coefficient and specifically high absorption at lower frequencies than other results.

- ✓ The primary hypothesis of the study, "woven fabric increases the level of sound absorption at low frequencies in the porous material," was verified by utilizing combinations of different weave structures consisting of three layers of sateen fabric, nonwoven fabric, three layers of plain fabric, and an air gap (3TS+N+3TP+A). The combination of porous materials improved low-frequency absorption while also obtaining a high and consistent range of sound absorption from low to high (400-5000Hz) frequencies and a high NRC of 76%.
- ✓ The porous materials layout has a significant impact on the performance of acoustic materials. Therefore, when developing multilayer woven fabric acoustic material, consideration must be given to the layout setting of porous materials. Additionally, the use of porous material, particularly with a high proportion of woven fabric, increases the mechanical properties and durability of the material. In the acoustic industry, the possibility of choosing woven fabric over nonwoven fabric is wide as a result of the aesthetic value of the woven designs' versatility.

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