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Investigation of Sound Absorption Characteristics of Textile Materials Produced from Recycled Fibers

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Abstract

Excessive sound causes growing public well-being problems and significant environmental contamination in our daily life. Generally, most of the noise problems are difficult to be treated at source, and the reduction of noise emission is usually achieved through the use of noise isolation processes. In recent times, nonwovens as one of the most common textile products have become valuable sound absorption materials. These materials are used as sound absorbers, sound diffusers, noise barriers, and sound reflectors. For sustainable development of the textile industry, solutions for both decreasing waste and reducing noise have been searched for years. Due to the good sound absorbing properties, recycled materials are becoming an attractive option to traditional materials for practical purposes. In this study, the measurement methods of acoustic characteristics of textile materials are explained, and the sound absorption features of nonwoven fabrics made from both pure and recycled polyester and polypropylene fibers are compared.

Keywords: sound absorption, acoustic textiles, textile material, sustainability, recycled fibers

1. Introduction

With the rising number of new technologies, daily noise pollution is becoming a growing public health problem along with the severe environment pollution affecting the life comfort, especially in big cities. The noise being exposed for a long time makes communication difficult, distorts concentration, and lowers quality of life, that is, health hazard. The World Health Organization (WHO) defines noise pollution as a worldwide problem influencing the health of numerous individuals. The most common reactions are headaches, fatigue, tension, body aches, sleep disturbances, and other problems related to stress. There are also studies showing the relationship between high blood pressure, vascular spasms, and heart attack associated with prolonged exposure to noise [1–3].

It is crucial to have appropriate living conditions for the people staying at homes and the workers to work well in the industries. Hence, in order to eliminate the problems faced by the people, the noise pollution needs to be decreased or removed. Transportation systems, machines, and constructions are the causes for the outdoor noise pollution, while interior noise can be produced by means of inside actions,

performances, and operating electrical-powered equipment. Both outdoor and indoor noise pollutions are damaging for the people and animals. According to the ISO 25267 standard, sound pressure levels in living room, kitchen, and bedroom are recommended to be lower than 30, 40, and 20 dB, respectively. Subjecting to a noise level of 85 dB and higher for a long time can lead to increased blood pressure, raised stress level, and long-lasting hearing injury [4, 5].

Materials used for controlling the noise can be generally categorized as those appropriate for treatment at source, those for declining along the noise path, and those for receiver treatment. The classification can be done by absorbing materials, scattering or altering the sound energy on impact; barrier materials, blocking the sound waves; vibration isolation, damping the materials for reducing radiated sound; and silencers and passive and active materials, quelling the sounds [6].

Generally, it is not possible to handle most of the noise problems at source, and the decrease in noise emission is mostly undertaken by noise isolation systems. Active and passive noise control methods are available for noise control. Active noise control is the total noise reduction process using a secondary audio resource, while passive noise control is supplied by sound absorbers and sound insulation materials. Active sound control is managed by using complex digital signal processing techniques to delay the harmful sound waves [7]. Sound absorption is made in passive control method, and knowing acoustic properties of these absorbent materials is helpful for determining the suitable usage fields of the products such as sound barriers, walls, and road surfaces [8].

The performance of insulation materials should be evaluated in terms of multiscale principles, respecting physical features, protection level of health and environment, and applicability as building elements and their cost. The basic requirements on insulating products are good thermal and sound insulation characteristics. Noise reduction coefficient of 0.5–0.9 and thermal conductivity coefficient of 0.030–0.045 W/mK are the main characteristics of the most conventional insulating materials [9].

Nonwoven textile materials are widely used for sound insulation and absorption applications due to their porous structure in recent times. These materials are used as sound absorbers, sound diffusers, noise barriers, and sound reflectors. For the sound transmission through friction, the sound wave should penetrate into the absorbent material. The loss of sound energy in textile materials is influenced by various physical issues such as fiber type, fiber diameter, material thickness, density, bonding method, air resistance, and porosity. The nonwoven surface forms a large inner surface in the form of a flexible fiber skeleton of a fabric composition, providing these required physical conditions [3, 10, 11].

For sustainable development of the textile industry, solutions for both decreasing waste and reducing noise have been searched for years. Caused by the reduction of ecological supplies and the rising costs of waste removal, the recycling or reprocessing of textile waste is becoming progressively significant all over the world in terms of economy, environment, and sustainability [12, 13]. Both natural and synthetic fibers together with recycled materials are used to construct textile-based acoustic materials. The use of textile surfaces produced from recycled materials has spread to a wide range of areas, and its use as sound insulation material has also become widespread.

In this study, recycling nonwoven materials are considered in terms of sound insulation characteristics; the measurement methods of acoustic features of textile materials are explained; and the sound absorption properties of nonwoven fabrics produced from both pure and recycled polyester and polypropylene fibers are compared.

2. Recycling of textile materials

The growth of worldwide population, the rapid development of technology, the change of living standards and fashion trend, the improvement in marketing activities, and reduced time that the clothing is used before disposal result in serious increment in textile production and consumption. Along with these key factors for the rapid development in the textile industry, an overconsumption of clothing and an extreme use of resources and energy have started to become crucial problems and significantly responsible for the generation of textile waste as well.

In order to reuse the textile articles, the end-of-life textiles should be collected separately from the remaining waste, and reusable and nonreusable clothing have to be separated from each other. Textiles intended to be used in the second-hand market should be cleaned, dried, and not worn. According to Directive 2008/98/EC (European Parliament and Council of the European Union, 2008), recycling means any recovery action in which waste materials are reprocessed into products, materials, or substances for the original or other purposes. This description separates recycling from reuse required preparation by the word reprocess. Recovery, on the other hand, denotes any operation, either processing waste by replacing materials used to fulfill a function, or replacing waste being prepared to fulfill that function, in the plant or in the wider economy [14, 15].

Textile wastes released in and after the production of textile products have a large volume, and their disposals have become one of the most important threats to the ecological system. Apart from this, the raw materials used in this process are natural and limited resources; high water consumption and water pollution from this process as well as high energy consumption and the resulting carbon emissions have exceeded 1.2 billion tons per year [16]. Shortage of natural resources and increase of raw material cost have increased the importance of recycling. Due to the environmental troubles, the uses of biodegradable and recyclable material in many products become significant [5]. Theoretically, 97% of textile waste can be recycled [9]. In addition, waste storage areas are decreasing, and all these factors have created a serious threat to the environment and increased awareness in global world. As a result, the concepts of “recycling” and “sustainability” have gained great importance in the textile industry and have been among the priority state policies in the world.

Recycling in textiles can be defined as using the waste materials as raw resources to produce new products. According to the production flow of the new product produced by recycling textile wastes, recycling is evaluated in two groups such as open loop recycling and closed loop recycling. Open loop recycling characterizes the usage of recycled material in different purposes from the used material, whereas the closed loop recycling is the production of the used materials in the same product [17].

Textile recycling material can be also categorized into two groups such as pre-consumer and post-consumer wastes. Pre-consumer waste contains materials from the various production stages of textile industries, and these wastes are remanufactured for the automotive, aeronautic, home building, furniture, mattress, coarse yarn, home furnishings, paper, apparel, and other industries. Post-consumer waste is described as any type of discarded garment or household articles, which are worn out, damaged, outgrown, or have gone out of fashion. The post-consumer textiles are “opened” mechanically or chemically so as to return it to a fibrous form, and they can be able to process new products for renewed consumption [18].

Textile recycling technologies are realized in four different processes. Primary recycling is the recycling of a product to its initial state. In secondary recycling,

waste is included in a different application area than its original form and transformed into a new product having lower levels of physical, mechanical, and chemical properties. In tertiary recycling, pyrolysis occurs by turning gas into simple chemicals or fuels by gasification and hydrolysis. The fourth recycling process is realized by utilizing the heat released by incineration of solid wastes. The recycling method of the fibers differs on the type of fibers, for instance, synthetic fibers are chemically recycled, whereas all others are mechanically recycled [19]. Recycling of synthetic fibers such as polyester and polyamide is included in primary recycling technologies and is evaluated within the scope of the “closed loop recycling” class. Today, the most applied recycling is “open loop recycling,” which belongs to the secondary recycling technology class [13, 20].

Since recycled materials demonstrate good sound absorbing characteristics, these materials are becoming an interesting alternative to typical materials for functional applications. Acoustic barriers and acoustic ceilings, passenger vehicle noise absorbers, and wall claddings are some of the implementation of noise control functions of the nonwoven fabrics. Nonwoven fabrics made from recycled fibers are having more advantageous in terms of environmental pleasantness compared to traditionally utilized polyurethane foams produced by environmental harmful manufacturing methods and cannot be recycled [21]. Lower product cost, good processing, and environmental protection are some of the benefits of using recycled polyester nonwovens compared to conventional sound absorbers. Former studies about the noise absorption of nonwovens have indicated that the noise absorption coefficients of these materials in the high frequency range ($f > 2000$ Hz) are equivalent to that of the traditional sound absorbers such as rockwool and glass fiber [22].

3. Sound absorption characteristics of textile materials

3.1 Acoustic textiles

The definition of sound is a pressure change in air, water, or similar elastic medium, which can be perceived by the ear as a stimulus of hearing. Loudness and tone are two aspects of sound. Loudness is defined as the sound pressure expressed in decibel (dB), and tone is defined as the sound frequency expressed in Hertz (Hz). Human ear is not sensitive to all the sound frequencies, and depending on its frequency and intensity, the sound may or may not be audible to the human ear. The range of 20–20,000 Hz is the audible sound frequency for humans [4].

As the material or item is vibrated, the sound is created. These vibrations spread in solid, liquid, or gas medium in a waveform from the emitter to the receiver. Therefore, a sound wave is the transfer of energy radiated by a source material or an object into the medium as it travels. A sound wave is considered by its frequency, wavelength, and amplitude. The wave properties can change according to the interaction of sound waves with the receiver’s surface and the properties of the receiver’s object. The sound wave can be absorbed, transmitted, reflected, refracted, and diffracted from the surface [5].

The classic solution to the problem of noise pollution is to remove the noise from the source; however, it is not always possible to remove it in this way. Thus, noise isolation methods are usually used for the reduction of noise emission. For this purpose, two types of methods are used, defined as sound absorption and sound insulation, as shown in **Figure 1**. In sound absorption, air particles rub inside the insulating material, and with the conversion of the sound kinetic energy into heat energy, the sound power is reduced. Therefore, sound absorption refers to the absorption level of the sound from the sound source in the environment of the

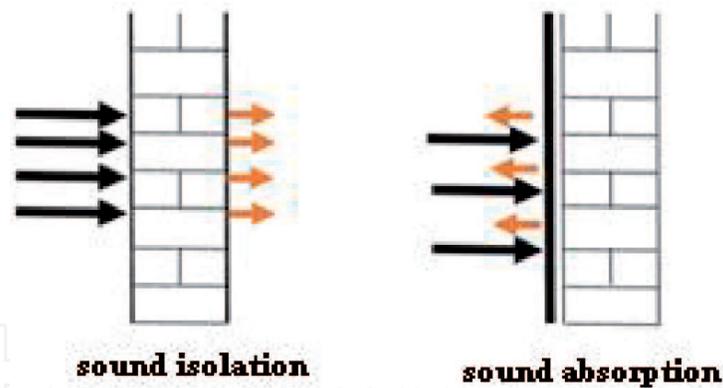


Figure 1.
Sound isolation and absorption [23].

source. Since frictional and momentum losses and heat fluctuation occur as the sound goes through the sound absorbing material, these are the essential reasons of the acoustic energy loss [2, 10].

Sound insulation deals with the transmission of sound between the adjacent rooms. Sound transmission loss indicates the sound insulation ability of a material and is denoted as the difference between the transmitted sound power and the sound power level of the incident wave [24]. An applying barrier to prevent transmission is the main principle. Materials that have high density such as thick glass, solid, metal, and brick are used for this aim [5].

Sound absorptive materials are known as the materials reducing the acoustic energy of a sound wave as the wave passes through it. They are usually used to soften the acoustic environment of a closed volume by reducing the amplitude of the reflected waves [25]. There are three types of absorbers: porous absorbers, membrane absorbers, and resonance absorbers. Inside the porous absorbers, sound transmission occurs in such a way that viscous and thermal effects cause acoustic energy to be dissipated. They are usually fuzzy, fibrous materials such as textiles, mineral wool, curtains, clothing, carpets, and certain types of foam plastic. As the sound energy penetrates into the material on hitting the surface, the sound-absorbing effect is obtained. Generally, since the required thickness is large with porous textile absorbers, obtaining adequate absorption at low frequencies is difficult. Membrane absorber is basically a flat box, 100–200 mm deep, installed in the wall with a thin sheet of plywood or similar on the front and with a light mineral wool filling the box cavity. Resonance absorber takes the form of perforated plaster-board, perforated metal corrugated sheets, and metal boxes. The working principle of the resonant absorbers is dissipating acoustic energy with structure vibration. Resonance absorbers are usually efficient in a thin tunable low-frequency band, whereas the porous absorbers are good for mid-to-high frequency range [26, 27].

Even though all materials absorb a part of incident sound, acoustic material term is used, especially for materials providing high values of absorption for the specific application fields. The acoustic materials are used in various applications such as in building construction; transportation; industries for specific purposes; such as concert rooms, schools, theaters, recording studios, lecture halls, and so forth. In recent days, acoustic textiles as acoustic materials are critical for the reduction of noise pollution.

The sound intensity, sound pressure levels, and sound classification systems can be used to assess the performance of the acoustic structure. Sound absorption defines the energy amount absorbed by the material and stated as sound absorption coefficient (α) ranging between 0 and 1, where 0 means no absorption and 1 means the highest or total absorption. The higher coefficient expresses lower reverberation

time. The reverberation time is the time lag, in seconds, measured for the sound to decay by 60 dB in a space after a sound source has been stopped. The noise reduction coefficient is the average absorption coefficients of an acoustic material at a typical frequency set of 250, 512, 1024, and 2048 Hz defined according to the tube type and acoustic measuring instrument used for the tests [5, 24].

Nonwoven materials are ideal materials for sound insulation and sound absorption applications in order to decrease sound pollution in the environment due to their fibrous structure and high total surface area [28]. Areal density (mass), porosity, volumetric density, tortuosity, particle size distribution, and thickness constitute significant physical properties of nonwoven fabrics for acoustic applications. Acoustic ceilings, noise reducing quilts, and noise proof barriers are some of the applications of nonwoven fabrics serving as noise absorption elements. A wide variety of studies on the acoustic properties of nonwoven products are available, which some of them are given in the following paragraphs.

Lee and Joo investigated the usage of the recycled polyester nonwovens as a sound absorber instead of conventional materials such as glass wool and rockwool by using a two-microphone impedance tube. Nonwoven having more fine fiber was found to be better at contacting the sound wave due to more resistant characteristic. The nonwoven absorber having an unoriented web in the middle layer had a higher noise absorption coefficient (NAC) than the ones having entirely oriented web structure, but the difference was insignificant. The panel resonance effect had contributed to increase the noise absorption coefficient. In the case of coating structure, the panel promoted the NAC in low- and middle-frequency regions, but reverse effect was obtained in the high frequency region by the coincidence effect [22].

Na et al. measured the sound absorption features of the fabric-nonwoven system produced by adding a microfiber fabric to a layer of 15-, 30-, and 45-mm nonwoven by reverberation chamber method. The results revealed that the fabrics made from microfibers were quite advantageous compared to the conventional fabrics of the similar thickness or weight in terms of sound absorption characteristics [29].

Tascan and Vaughn studied the effects of total fiber surface area and fabric density on needle punched nonwovens. It was reported that the needle punched nonwoven fabrics produced from polyester fibers having octalobal and trilobal cross-sectional shape had better sound insulation results than the nonwoven fabrics produced from round fibers. Moreover, nonwovens with finer fibers in various cross-sectional shapes had better sound absorption and insulation than the ones made from coarser fibers. Fabric density and total fiber surface area in needle punched nonwoven fabrics were found to be in the tendency of improving fabric sound insulation [28].

Sengupta searched the effect of fabric type, density, the number of layers, source intensity, the distance of fabric from the receiver, the distance of the fabric from the sound source, and fiber type on the sound reduction of various needle-punched nonwoven fabrics. A sound insulation box was used for measurement. It was found that higher area density was one of the reasons of higher sound reduction. A negative correlation between the area density and bulk density of needle punched nonwoven and sound reduction was determined. Moreover, maximum sound reduction among jute, polypropylene, polyester, and other jute-polypropylene blended (3:1 and 1:3) nonwovens was obtained by jute-polypropylene (1:1) blend [30, 31].

Küçük and Korkmaz tested eight different nonwoven composites produced from various blends. Sound absorption properties, weight per unit area, thickness, and air permeability parameters of the samples were measured. An increase in sound absorption properties of the material was determined along with the increase in thickness and the decrease in air permeability. About 70% cotton and 30%

polyester nonwoven supplied the best sound absorption coefficient in the mid-to-high frequency ranges. It was revealed that the increase in the amount of fiber per unit area caused an increase in sound absorption of the material. The results indicated that acrylic and polypropylene addition into a cotton and polyester fiber mixture increased the sound absorption properties of the composite in the low- and mid-frequency ranges [3].

Recently, recycled nonwovens have become important sound absorption materials. Some of the studies related to sound absorption characteristic of the recycled nonwoven surfaces are given in the following paragraphs.

Seddeq et al. searched the acoustic properties of the nonwovens produced from recycled natural fibers blended with synthetic fibers and studied PET/cotton-wool (70/30), PP/cotton-wool (80/20), cotton/PET (50/50) blends and 100% jute fibers in the range of 422–561 g/m² and 2.53–5.64 mm. At high frequencies (2000–6300 Hz), nonwoven samples had high sound absorption coefficients, whereas at low frequencies (100–400 Hz), low sound absorption coefficients were obtained, and at mid frequencies (500–1600 Hz), better sound absorption coefficients were found. The increased thickness of nonwovens improved the sound absorption coefficients of the materials at all frequency ranges [10].

Carvalho et al. studied qualitative analysis of the acoustic insulation behavior of various thermo-bonded nonwoven fabrics. Nonwoven fabrics were produced from mineral wool and recycled fibers, containing a mixture of polypropylene, cotton, acrylic, and polyester. Some samples were laminated with aluminum foil. Thermo-bonded nonwovens with high thickness value and laminated with aluminum foil displayed better sound reduction performance than the other single-layered nonwovens made from recycled fibers. They showed better performance than the nonwovens made from mineral wool as well [32].

Manning and Panneton studied the acoustic properties of post-consumer and industrial recycled fiber absorbers. Three different shoddy samples, needle-punched mat, thermally bonded mat, and resin-bonded mat, were compared in the study. A lower noise absorption coefficient value of 0.20 was obtained at low frequency (0–1000 Hz) for all samples. The results showed that the noise absorption coefficient values of the samples in frequency range of 0–4000 Hz were similar to each other [33].

Rey et al. designed novel green sound absorbing materials as a part of noise barriers. They used recycled textile materials and nontoxic binder fibers to manufacture the eco-materials. Acoustic characterization of noise barriers was measured in a small-scale reverberation room designed for the testing of small samples. New materials used in noise barrier prototypes performed very well in accordance with the international standards. The performance of them was comparable with those of commercially available noise barriers made of typical sound absorbing materials [34].

Patnaik et al. studied the sound insulation properties of needle-punched samples produced from waste wool and recycled polyester fibers (r-PET) for building industrial applications. Waste wool fibers were mixed with r-PET fibers in 50/50 proportion to prepare needle-punched mats, and their acoustic properties were evaluated with other performance properties. Nonwoven mats were produced from waste wool fibers that are coring wool (CW) and Dorper wool (DW); r-PET fibers; and blended r-PET fibers in 50/50 proportion with these fibers (DWP, CWP). Good sound absorption properties in the overall frequency range (50–5700 Hz) were obtained for all nonwoven samples. The sound absorption was lower at low frequencies (50–1000 Hz) and increased from medium (1000–2000 Hz) to high frequency range (200–5700 Hz) for all the samples. The lowest noise absorption coefficient value was 0.61 for r-PET, and the highest was 0.75 for DWP for all frequency ranges.

DWP presented higher α value than CWP due to the presence of longer fiber length. It was stated that sound absorption depends on thickness of the material among other factors. They also determined that the r-PET/wool mats (DWP, CWP) could absorb more than 70% of the incident noise in the overall frequency range [35].

Kalebek investigated acoustic behavior of needle-punched nonwoven fabrics produced from recycled PES fibers for the automotive industry. The physical properties such as density, thickness, weight per unit area, air permeability, tensile strength, and elongation were measured and compared to each other. The fabric mass per unit area and the thickness of the needle-punched nonwoven fabrics were found to be positively effective on the sound insulation. Additionally, it was observed that higher air permeability caused higher sound transmission and, as a result, lower sound insulation [30].

3.2 Measurement methods of acoustic absorption properties of materials

There are various standards related to test procedures for determination of acoustic features of textile materials. In terms of standards, sound absorption properties of nonwovens can be defined in different parameters such as sound absorption coefficient, transmission coefficient, reflection coefficient, sound transmission loss, air-flow resistivity, and sound power ratio. Some of the commonly used standards are as follows: ISO 354:07 Acoustics—measurement of sound absorption in a reverberation room; ISO 11957:2009 Acoustics—determination of sound insulation performance of cabins (laboratory and in situ measurements); ISO 10534-1:96 Acoustics—determination of sound absorption coefficient and impedance in impedance tubes—Part 1: method using standing wave ratio; ISO 10534-2:98 Acoustics—determination of sound absorption coefficient and impedance in an impedance tube—Part 2: transfer-function method; ASTM E2611-19 Standard test method for measurement of normal incidence sound transmission of acoustic material based on the transfer matrix method; ASTM E1050-19 Standard test method for impedance and absorption of acoustic materials using a tube, two microphones, and digital frequency analysis system; and ASTM C423-17 Standard test method for sound absorption and sound absorption coefficients by the reverberation room method.

The impedance tube method and alpha cabinet methods, which are used in experimental part, will be explained in detail in the following paragraphs.

3.2.1 Measurement of acoustic absorption characteristics by impedance tube method

One of the methods mostly utilized to determine the sound absorption coefficients of textile surfaces is the ISO 10534-2 double microphone impedance tube method. The sound pressure difference with the help of a microphone placed in the impedance tube is measured. The sound is created by the signal generator in the apparatus to define the sound absorption coefficient and transmitted through the impedance tube. The performance of the material is examined by the software.

The measurement principle of the impedance tube method depends on measuring the reflected sound wave and calculating the sound absorption coefficient from the surface impedance value and transfer function. Obtaining the surface impedance and sound absorption coefficient values in one measurement for each frequency generates the advantage of this method [36].

During the measurement, sound is generated by the sound source, and the receiving decibels are evaluated by the decibel meter with and without the sample, and subsequently, the sound insulation by the fabric samples is calculated [37]. The tube is produced by rigid, transparent, or opaque materials to limit the sound within

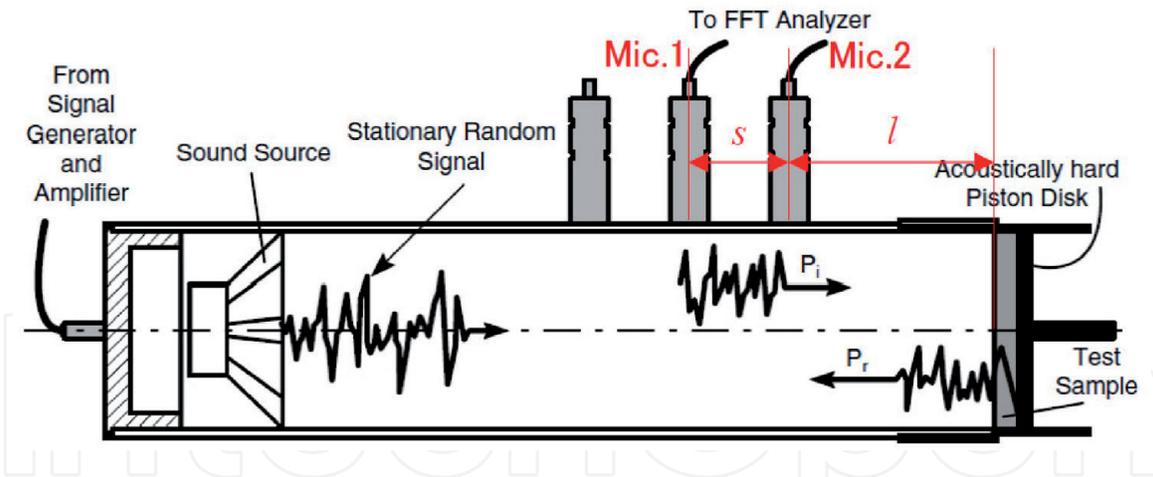


Figure 2. Impedance tube sound absorption measurement method [41].

the tube along one direction toward the direction of transmission. Consequently, it simplifies the three-dimensional wave equations to one-dimensional wave equation. The sample size is small compared to reverberation method [38].

In the impedance tube arrangement schematically shown in **Figure 2**, first, the test sample is attached at one end of the impedance tube, and the signal characterizing the voice is generated by the software of test system. Plane waves are created in the tube by sound source emitting random or pseudo-random cycle, and pressure is measured at two places close to the sample. Then, the signal passing across the amplifier is transformed into a planar progressive sound wave in the tube through the speaker. The transfer function between two microphones is a ratio of the pressure values measured separately from the two microphones. The transfer function is related to the value of the reflection factor and the value of the sound absorption coefficient of that frequency (R) is obtained from this factor [36]. The frequency scale is based on the diameter of the tube and the gap between the two microphones. With the impedance tube method, the sound absorption coefficient values of the materials can be measured in the frequency range of 50 Hz to 6.4 kHz.

The normal incidence reflection factor is computed by Eq. (1).

$$r = |r| e^{j\phi_r} = \frac{H_{12} - H_1}{H_R - H_{12}} e^{2jk_0x_1} \quad (1)$$

where r is a reflection factor of normal incidence; x_1 is the distance between the sample and the further microphone location; j is the square root of minus one; k is $2\pi f/c$ (m^{-1}); ϕ_r is the phase angle of the normal incidence reflection factor; H_{12} is the transfer function from microphone one to two, defined by the complex ratio $p_2/p_1 = S_{12}/S_{21}$; and H_R and H_I are the real and imaginary part of H_{12} .

The sound absorption coefficient (α) is calculated by Eq. (2) [39, 40]:

$$\alpha = 1 - |r|^2. \quad (2)$$

3.2.2 Measurement of acoustic absorption characteristics by alpha cabinet method

ISO 354 and ASTM C423-17 standards explain the measurement method of sound absorption by the reverberation room. In reverberation room, reverberant sound field closely approaches a diffuse sound field. This approach occurs, when the source is on, that is the stable condition and also after the sound source

is stopped, which is defined as decomposition condition. The room is isolated adequately to keep outside noises and structural vibrations from impeding during the measurements (ASTM C423-17).

Reverberation room is naturally large empty room having long reverberation times. The volume of the room is higher than 200 m³, and it has nonparallel wall and ceiling sides. An exactly truly reverberant room is designed such that energy from a noise source is diffused throughout the room to keep the sound pressure level the same everywhere. Absorption coefficients of a material can be computed with and without the material by measuring reverberation times in a reverberation room [42].

There are different types of cabinets used to measure acoustic sound absorption characteristics on the market. Some of the cabin examples are as follows: Rieter Alpha Cabin Instructions: Technical Note 591; Toyota Engineering Standard: test method for acoustic materials, TSL0600G; Renault Test Method: fibrous and cellular material sound absorption in diffuser field, D49-1977-B; and the design of small reverberation chambers for transmission loss measurements [36].

The name of alpha cabinet comes from the name of the sound absorption coefficient “alpha,” and their structure is like a miniature reverberation room (**Figure 3**). During the measurements, the relative humidity in the alpha cabinet is 55%, and the temperature is set at 25°C. Before testing in the alpha cabinet, it is necessary to compare the noise levels in the cabinet with the background noise levels from outside (motor noise and electrical noise), while the speakers are in operation. The difference between these levels should be at least 45 dB. Alpha cabinets are quite similar to the reverberation rooms (**Figure 4**).

Sabine’s reverberation formula is used for determining the material absorption coefficients with the help of reverberation rooms and is still commonly accepted as a very practical evaluation method for the reverberation time in rooms. Sabin is a unit of sound absorption in square meter, indicating the area of open window. The main principle of the method is that sound energy moving in the direction of an open window in a room will not be reflected at all; however, it entirely disappears in the open air outside. The same effect will be obtained if the open window would be replaced with 100% absorbing material in the same sizes [45].

The Sabine formula is applied for the sound absorption coefficient measurements, and the coefficient is analyzed by taking the difference between the resonance times of the sampled and nonsampled measurements in the cabinet [36].

$$\alpha = \frac{0.163 \times V}{S} \left(\frac{1}{TR} - \frac{1}{TR_0} \right) \times C \quad (3)$$

where V is the cabinet volume, S is the sample area, TR is the sound receiving time with the test sample inside the cabinet, TR_0 is the sound receiving time without the test sample inside the cabinet, and C is the cabinet correction coefficient.

Sabine also derived a definition for the time, T , of the residual sound to decay below the audible intensity, starting from 1,000,000 times higher initial amount given in Eq. (4).

$$T = 0.161 V/A \quad (4)$$

where V is the room volume in m³ and A is the total absorption area in m² [45, 46].

The noise reduction coefficient (NRC) is calculated by deriving the arithmetic mean of the absorption coefficients in the 250, 500, 1000, and 2000 Hz 1/3-octave frequency bands. This number is rounded to the nearest multiple of 0.05. The zero



Figure 3.
Twin mini reverberation cabinets [43].

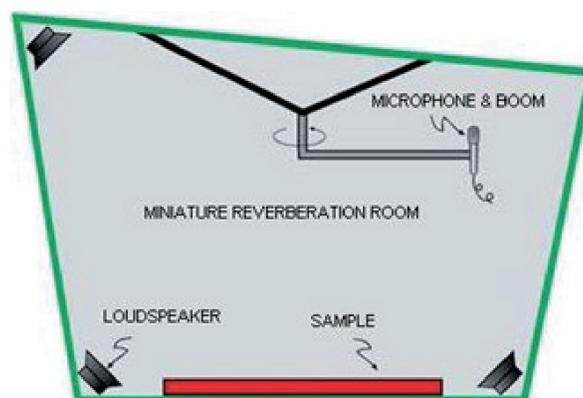


Figure 4.
Alpha cabinet measurement arrangement [44].

value of NRC indicates the perfect reflection. The NRC value 1 means that the perfect absorption happens. Reverberation room techniques can also be used to measure this parameter [5].

When studies carried out in the literature are examined, it can be concluded that impedance tube measurements and alpha cabinet measurements do not give comparable results, as also found in this study. Therefore, correlation analysis between the results is not necessary.

4. Experimental part

Today, while studies on new sound insulating materials continue intensively, the usage of recycled products in this area is also increasing. Recycling technology provides environmental, social, and economic benefits. With environmental awareness and increased sensitivity to sustainability, recycled materials provide significant advantages for sound insulation.

In this study, nonwoven materials produced from conventional polyester (PES), mechanically recycled polyester (rm-PES), recycled polyester (r-PET), polypropylene (PP), and recycled polypropylene (r-PP) were compared with each other in terms of their sound absorption characteristics [47]. In **Figure 5**, photographs of the samples are given.

Supplying the raw materials and producing the nonwoven fabrics were carried out in a Turkish company working especially on recycled products. The processes

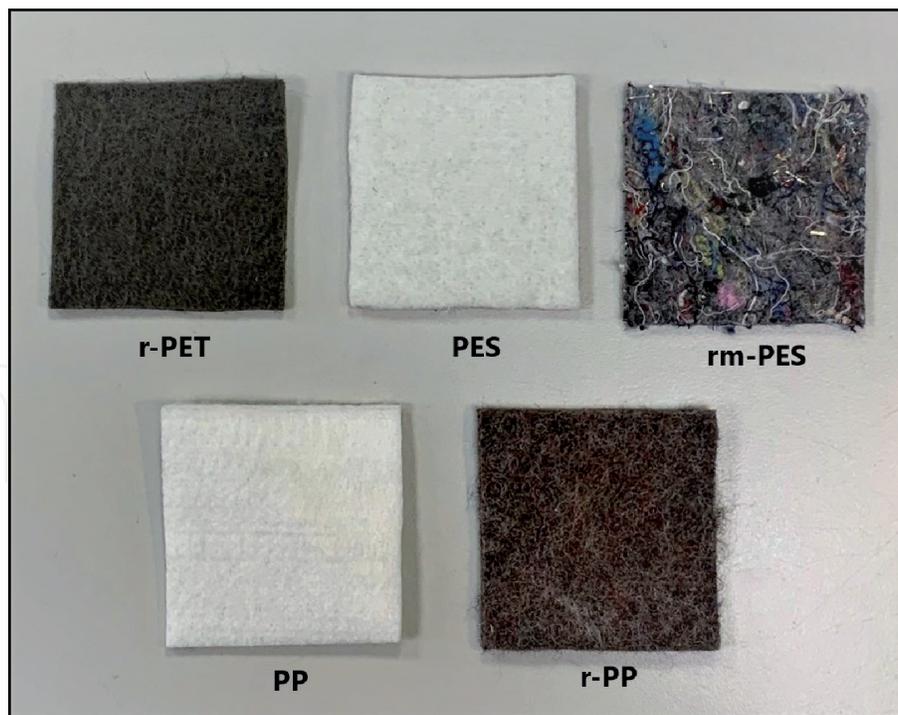


Figure 5.
Photographs of the samples used in experimental.

applied for the mechanically recycled polyester and polypropylene fibers were as follows: the collected waste fabrics were cut with guillotine cutting machine and then shredded into pieces with particles of a suitable size. Then, the pieces were weighted on an electronic balance and blended in a vertical mixing blender. Carding process was applied to break down the big fiber bundle to the small size. Two-time carding process was applied to get uniform web formation, and then, the fine opener was used.

r-PET fibers provided by using r-PET flakes gained from PET bottles were used in this study. The common method of fiber production is as follows: at first, PET bottle wastes are separated from the other wastes; then, they are broken into flakes, washed, and dried before the spinning process of the fiber. In this method, r-PET fibers are acquired by transforming PET chips by the melt fiber drawing method [17].

The nonwoven fabric samples were produced by needle-punching technology. The webs were fed to a needling loom to produce nonwoven surfaces. Softness, bulkiness, conformability, fibrousness, and high strength characteristic without binder usage make the needle-punched nonwoven fabrics unique among the other nonwovens.

Before the physical tests, nonwoven samples were conditioned in standard atmospheric conditions ($20 \pm 2^\circ\text{C}$ temperature, $65 \pm 4\%$ relative humidity). The mass per unit area was determined in accordance with the ISO 9073-1 standard, and thickness measurements of the materials were carried out according to the ISO 9073-2 standard using SDL Atlas fabric thickness gauge. Air permeability test was conducted according to the EN ISO 9237 standard by using Textest FX 3300 air permeability meter at 200 Pa pressure difference and 20 cm^2 measurement areas.

Two methods were applied to measure sound absorption properties of the samples: alpha cabinet and impedance tube methods. Nonwoven textile products supplied within the scope of the study were tested by using alpha cabinet according to the Renault D49-1977-B standard. The cabinet volume was 6.44 m^3 , and the total surface area was 22.2 m^2 . The surface area of the test specimens was 1.12 m^2 ; the

height of the microphone from the ground was 0.88 m; and the height of the sound source was 0.20 m. The frequency measurement range was set at 400–10,000 Hz. Three Brüel and Kjaer 2669 model microphones were used.

Impedance tube method was also used to measure the sound absorption coefficients of the samples according to the EN ISO 10534-2 method. The frequency was set from 100 to 1600 Hz. The test was carried out by three test samples randomly taken from nonwoven fabrics.

The structural properties and air permeability values of five different nonwoven surfaces used in the study are given in **Table 1**.

As air permeability results of nonwoven fabrics are examined, the surface produced from r-PP material has the highest air permeability, whereas the lowest air permeability value belongs to mechanically recycled polyester surface.

The test results obtained from the impedance tube method are given in **Figure 6**. According to the results, at low frequencies between 100 and 400 Hz, it can be clearly seen that r-PP, rm-PES, and r-PET surfaces have higher sound absorption coefficient values than the conventional PES and PP fabrics. This is an important point that recycled textile surfaces can be suggestible as sound insulation materials in low frequency band gap (100–400 Hz) as an alternative to the conventional fibers. In addition to this, r-PP material has the highest sound absorption coefficient (over 0.50) among the other recycled products since its lower density and porous structure create a higher friction surface. As the performance at the mid frequencies (400–1600 Hz) is analyzed, only PP, r-PP, and rm-PES fabrics have sound absorption coefficient over 0.50. Therefore, these surfaces can be suggested for sound insulation materials to be used at mid frequencies.

Compared to conventional polypropylene, r-PP indicates better sound absorption characteristics for all frequencies. It is associated with the micro voids in the recycled material caused by the inhomogeneity [48].

The acoustic absorption test results of the textile surfaces according to the alpha cabinet method are given in **Figure 7**.

Measured parameter		100% PES	100% r-PET	100% rm-PES	100% PP	100% r-PP
Mass per unit area (g/m ²)	Mean (\bar{X})	550	596	519	509	500
	Standard deviation (SD)	8.14	12.10	27.27	10.92	4.81
	CV (%)	1.48	2.03	5.25	2.15	0.96
Thickness (mm)	Mean (\bar{X})	4.04	2.95	3.17	3.60	4.55
	Standard deviation (SD)	0.16	0.09	0.30	0.10	0.10
	CV (%)	3.93	2.89	9.46	2.67	2.28
Air permeability (l/m ² s)	Mean (\bar{X})	1136	1270	600	875	1536
	Standard deviation (SD)	57.71	116.40	112.13	148.66	69.14
	CV (%)	5.08	9.17	18.66	17.01	4.50
Fabric density (g/cm ³)	Mean (\bar{X})	0.136	0.202	0.164	0.141	0.110

Table 1.
Properties of nonwoven fabrics used in the study.

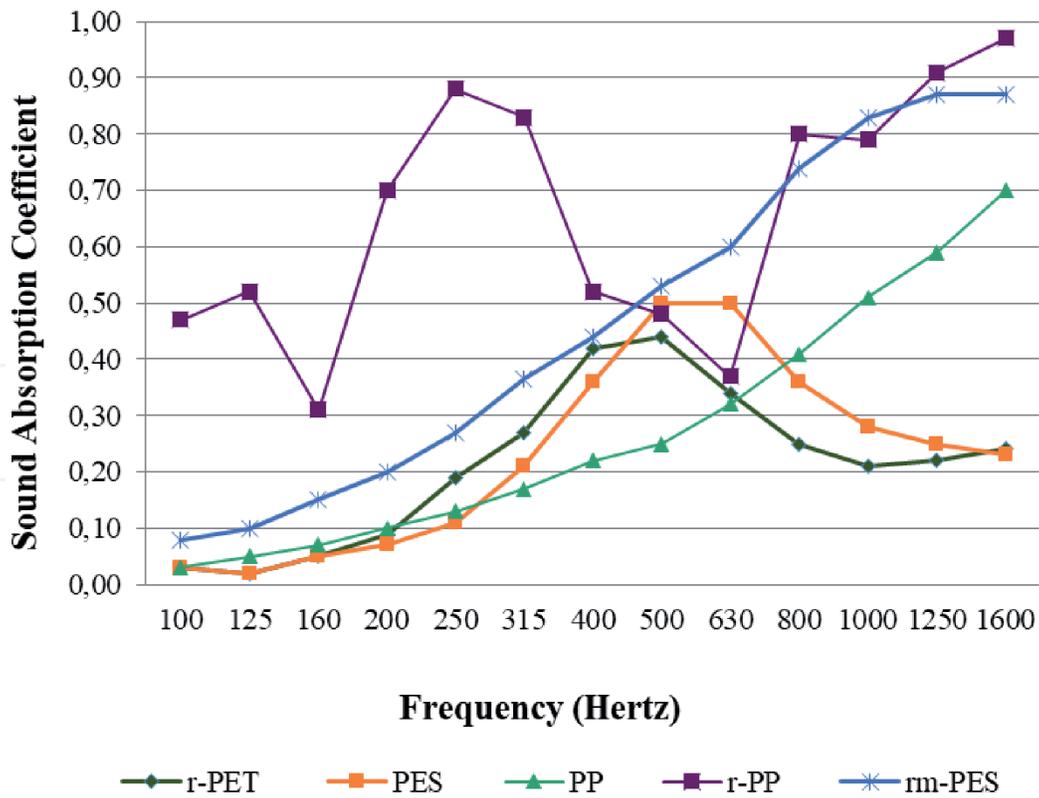


Figure 6. Sound absorption coefficients based on the impedance tube method.

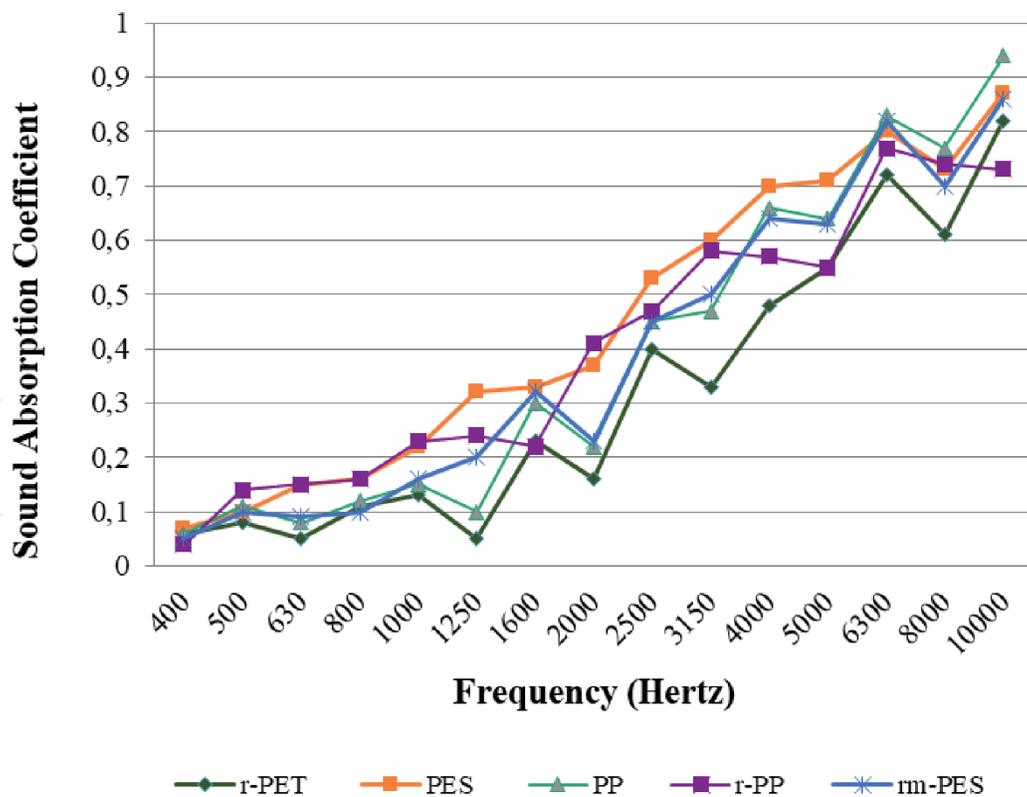


Figure 7. Sound absorption coefficients based on alpha cabinet method.

Materials can be tested at a wide frequency band in case of their sound absorption properties. In this study, the tested frequency range is 400–10,000 Hz. According to **Figure 7**, between 400 and 1600 Hz, sound absorption coefficients of all nonwoven

surfaces are close to each other and are lower than 0.35. Over 2500 Hz frequency, which is a high frequency level, sound absorption coefficients of the nonwovens are over 0.5, which supply a better sound insulation property and can be an alternating insulation material for the industry.

In this study, acoustic absorption coefficients were measured according to two different sound measurement methods. The results obtained from the alpha cabinet and the impedance tube methods complement each other and give the idea for the performance and comparability of the materials at different sound frequencies. For obtaining the required results, the choice of the appropriate method is crucial. The impedance tube method is mostly suitable in order to develop new materials, while a reverberation room test is more relevant to design acoustic adjustments of the space [49]. Moreover, reverberation rooms are often preferred since they give closer results to the actual working conditions of the material by means of the random incidence excitation. However, the tests in impedance tube allow obtaining the additional information about the characteristic acoustic impedance of the sample [50].

5. Conclusion

Along with the growing population, noise has become one of the major problems of everyday life, affecting our quality of lives and, in some cases, our health. As the studies on reducing the noise generation continue, new solutions are being searched on systems that allow absorbing more quantities of the present disturbing noise. Within this scope, many different technical textile materials are produced, which are closely related to building construction, automotive, and machinery industries. The use of these high-performance products is becoming increasingly widespread in terms of technical specifications. However, in today's competitive conditions, products that can compete in terms of cost are more preferred in the market. Recycled surfaces are one of these preferred products. In addition to the price advantage, waste materials are transformed into usable products by recycling, which is completely an environmentally friendly production that provides sustainability.

In this study, characteristics of conventional polyester and polypropylene non-woven insulation materials commonly used in the market and the nonwoven fabrics produced from recycled materials were compared. When the test results were examined, it was concluded that the recycled materials used in sound insulation area had very successful competitive performance when compared with the conventional materials. They had the qualifications supplying the expectations in terms of sound insulation when produced in enough thickness value.

Insulation materials are used, especially in areas where sound insulation is desired (e.g., children's houses, hospitals, entertainment places, and automotive sector) and in civil engineering area. In addition, it is a good application area for recycled materials to supply a sustainable world, to increase the environment friendly approach, and to evaluate the waste materials in a technical field. By the year 2019, price of PP fiber in the market is about 3.2 \$/kg, 1.6 \$/kg for r-PP fiber, about 1.6 \$/kg for 100% PES and r-PET fibers, and 1.2 \$/kg for rm-PES fibers. In the scope of economy, it can be foreseen that recycling materials will provide an important advantage for both producers and consumers.

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