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Acoustic Response of Aerogel Fiber Nonwovens: The Contribution of Fiber Crimp

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ABSTRACT

This study investigates the impact of fiber crimp on the acoustic performance of nonwoven structures fabricated from aerogel fibers. Aerogel fibers were produced via wet spinning followed by supercritical CO_2 drying, then either uncrimped or thermally crimped. These fibers were blended with polypropylene, carded into webs, and consolidated through needle punching. The sound absorption of the nonwovens was evaluated using an impedance tube across a wide frequency range. Crimping led to a modest yet notable increase in absorption, particularly at higher frequencies, due to increased bulk, porosity, and fiber entanglement. Double-layered samples further showed superior performance over a broader frequency spectrum, underscoring the combined effects of fiber morphology and layer architecture. These insights provide guidance for developing lightweight porous composites for noise reduction applications.

Aerogel Liflerinden Elde Edilen Dokusuz Yüzey Yapıların Akustik Tepkisi: Lif Kıvrımının Katkısı

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Anahtar Kelimeler
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Akustik dokusuz yüzeyler
Ses Yalıtımı
Lif kıvrımı
Akustik tekstiller

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ÖZ

Bu çalışma, aerogel liflerinden üretilen dokusuz yüzey yapıların akustik performansı üzerinde lif kıvrımının etkisini araştırmaktadır. Aerogel lifleri, ıslak eğirme ve ardından süperkritik CO_2 kurutma yoluyla üretilmiş, ardından termal kıvrıma tabi tutulmuştur. Bu lifler polipropilen ile karıştırılmış, tülbent halinde taranmış ve iğneleme yoluyla sabitlenmiştir. Elde edilen dokusuz yüzeylerin ses emilim özellikleri, geniş bir frekans aralığında bir empedans tüpü kullanılarak değerlendirilmiştir. Bulgular, aerogel liflere verilen kıvrımın, özellikle daha yüksek frekanslarda, ses emilim katsayısında dikkate değer bir artışa yol açtığını göstermektedir. Bu iyileşme, hava akış direncini ve ses enerjisi dağılımı için kullanılabilir yüzey alanını artıran bir hacme ve gelişmiş gözenekliğin oluştuğuna işarat etmektedir. Ayrıca, çift katmanlı numuneler, daha geniş bir frekans spektrumunda önemli ölçüde üstün akustik performans göstererek, lif morfolojisi ve katman mimarisinin sinerjik etkilerinin altını çizmiştir. Bu bilgiler, gürültü azaltma uygulamalarına yönelik gelişmiş hafif gözenekli kompozitlerin geliştirilmesi için yol gösterici olmuştur.

1. INTRODUCTION

Noise has become an inevitable byproduct of modern life and technological progress, exerting numerous adverse effects on human health, including hearing loss, sleep disturbances, stress, fatigue, and cardiovascular disorders [1,2]. Moreover, it poses a significant threat to biodiversity [3]. According to the World Health Organization (WHO), noise pollution ranks among the most critical environmental issues impacting public health [4]. In Europe, industrial activities [5], transportation and air traffic [1], construction, social gatherings [6], and the food and entertainment industries have collectively re-established noise as a pressing concern. Consequently, strategies aimed at mitigating noise pollution have become increasingly vital.

Ensuring acoustic comfort in transportation systems (such as aircraft, automobiles, and trains) as well as in indoor environments has emerged as an essential component of modern living standards. Among the various approaches to achieving indoor acoustic control, the development and application of sound-absorbing materials stand out. These materials are fabricated from a wide range of raw inputs, including mineral- or polymer-based, natural or synthetic constituents. Fiber-based systems are particularly advantageous due to their lightweight nature, cost-effectiveness, and superior sound absorption capabilities, primarily attributed to the interconnected porous air voids between fibers [7]. The acoustic performance of fibrous porous materials fundamentally stems from the dissipation of sound wave energy through vibration and friction within both the fibers and the surrounding air [8].

In recent years, aerogel-based fiber materials have garnered growing attention due to their lightweight characteristics, high specific surface area, and intrinsic porosity, offering exceptional potential for sound insulation applications. In particular, polyacrylonitrile (PAN)-based aerogel fibers exhibit low density and a porous internal structure, enabling efficient sound energy absorption. Employing these fibers in nonwoven fabric form provides additional benefits, such as ease of production and uniform surface morphology.

Nonwoven structures occupy a distinctive position within sound-absorbing systems due to their fibrous architecture. Their extensive surface areas combined with micro-scale pores make them highly effective for sound insulation. Furthermore, the random arrangement of fibers not only enhances sound absorption but also facilitates more uniform distribution of acoustic energy across the material [9]. However, the acoustic performance of nonwoven surfaces depends on both the microstructural properties of the fibers and their macroscopic arrangement. In this context, imparting crimp to fibers emerges as a critical strategy for improving sound absorption. Crimp refers to the deviation of a fiber from a straight axis, resulting in a wavy or irregular shape, typically characterized by the number of crimps per unit length or the extent of fiber straightening under tension [10].

Beyond its impact on yarn quality, uniformity, and strength during spinning processes [11], crimp significantly increases the bulk of carded webs, facilitates drafting, and enhances the loft of nonwoven structures [12]. The increased inter-fiber distances introduce additional air pockets within the material, which contribute to greater reflection and attenuation of sound waves, thereby improving absorption. Moreover, crimp restricts fibers from lying flat, promoting volumetric stability and yielding a denser overall structure [13,14]. The degree of crimp retention during processing is also crucial; fibers with identical initial crimp levels may exhibit different bulk, elasticity, and air permeability characteristics depending on subsequent processing conditions [15,16].

Certain inherent limitations of synthetic fibers, such as low moisture regain and inadequate thermal insulation, can be partially mitigated by introducing crimp, which effectively traps air between fibers, enhancing both thermal and acoustic performance. Typically, crimping is achieved using a stuffer box method prior to cutting fiber bundles into staple lengths, with crimp frequency exerting a direct influence on the final product's properties. Loose nonwoven fibrous layers have consequently found extensive application in the automotive and construction sectors, driven by increasing demands for sound and thermal insulation [17].

The influence of fiber arrangement and pore structure on sound absorption is well documented. Ibrahim et al. reported that increasing the thickness of fibrous materials significantly enhances low-frequency sound absorption [18]. Similarly, Fahy and Walker, along with Ver and Beranek, emphasized that flow resistance, porosity, air permeability, and fiber crimp are key determinants of the acoustic behavior of textile-based materials [19,20]. Moreover, reducing fiber diameter has been shown to improve sound absorption. For instance, Koizumi et al. demonstrated that decreasing fiber diameter leads to higher sound absorption coefficients, with micro-denier fibers exhibiting particularly pronounced effects [21]. Likewise, Lee et al. found that reducing polyester fiber diameter to 1.25 dpf increased airflow resistance, thereby enhancing acoustic performance [22].

Against this backdrop, the present study investigates the impact of fiber crimp on the acoustic properties of nonwoven surfaces produced using PAN-based aerogel fibers with a diameter of 20 µm, processed via a thermal crimping method. Nonwoven samples of varying areal densities and needling intensities were fabricated, and their acoustic performance was comprehensively evaluated. This study hypothesizes that introducing crimp to aerogel fibers will enhance the sound absorption of nonwoven structures by increasing porosity and tortuosity.

2. MATERIALS AND METHODS

2.1. Materials

This study primarily used polyacrylonitrile (PAN)-based aerogel fibres and polypropylene (PP) fibres. The PP fibres had a fineness of 6.7 dtex, a length of 80 mm, and were commercially sourced. The aerogel fibres were produced in the laboratory with a diameter of 30 micrometres, then cut to a length of 80 mm for use in producing nonwoven fabrics.

2.2. Inducing Crimp in Fibers

Thermal crimping was applied to the aerogel fibers to enhance their volumetric properties and improve the acoustic performance of the resulting nonwoven fabrics. The crimping process involved exposing the drawn aerogel fibers to a hot air flow at 130°C for 45 seconds, followed by rapid cooling. This treatment caused irregular bending along the fiber axis, resulting in permanent crimp formation. Consequently, the surface area and volume of the fibers increased, contributing to the formation of more air voids in the nonwoven fabrics produced in subsequent steps, thereby enhancing sound absorption capacity. The temperature and duration parameters applied during the crimping process were determined based on the thermal behavior of PAN fibers were maintained within ranges recommended in the literature [10].

Figure 1. Imparting crimp to aerogel fibers

2.3. Production of Nonwoven Fabrics

2.3.1. Web Formation

The initial step in the production of nonwoven fabrics is web formation. For this purpose, a laboratory-scale carding machine (Mesdan Card) was employed. This equipment consists of a wide conveyor belt, two feeding rollers, three pairs of stripper and worker rollers, a fancy clearer, and an oscillating mechanism that strips the web from the card clothing and transfers it to the collecting drum, enabling the production of webs with desired thickness.

Initially, production was carried out using only PP fibers; subsequently, a homogeneous blend of aerogel and PP fibers was prepared and carded. During this stage, both the homogeneity of the fiber blend and the structural characteristics of the webs after needling were evaluated. The carded web was subjected to needle punching to enhance surface stability and promote fiber bonding [Figure 2].

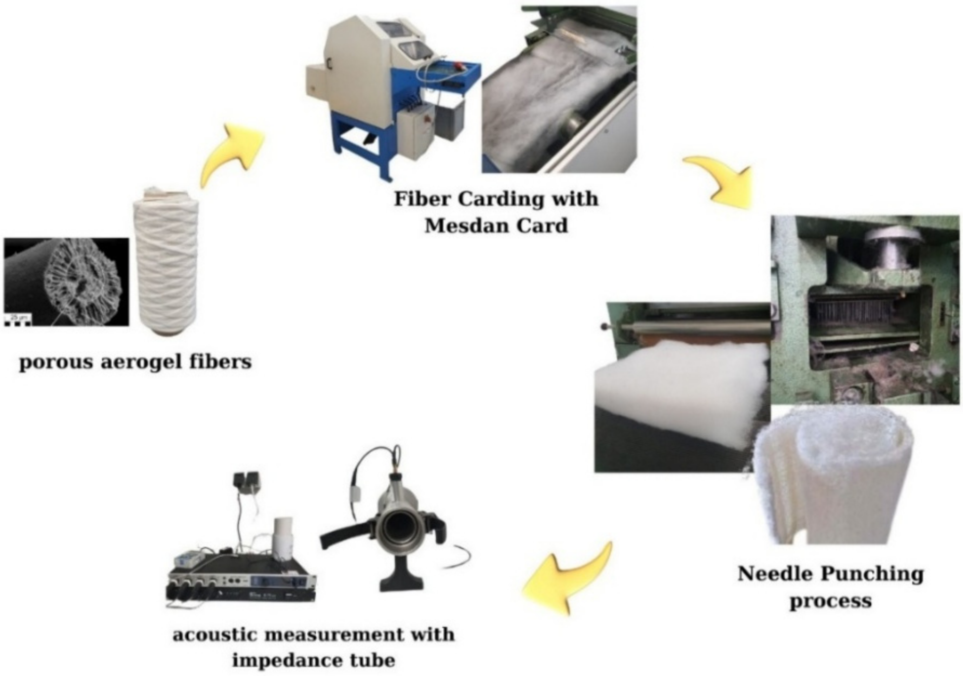

Figure 2. Material production flow diagram

2.4. Experimental Design

Nonwoven fabrics were produced by blending aerogel fibers and polypropylene (PP) fibers at basis weights of 500 and 1000 g/m², as specified in the experimental design. Samples were prepared with fiber blends consisting of 40% aerogel, 60% PP. The samples produced using crimped aerogel fibers were evaluated comparatively against those produced with uncrimped fibers.

In the experimental design, samples coded as 1C, 1CR, 1K, 1KC, 2C, 2CR, 2K, and 2KC are given in Table 1. The codes which starts with '2' refer to the double layer versions of corresponding '1' series samples.

Table 1. Preliminary experimental design plan

Exp.	Sample Code	Gram Weight (g/m²)	Aerogel (%)	PP (%)	Total fiber amount (gr)	Aerogel amount (gr)	PP amount (gr)	Crimp Value
1	1C	500	40	60	250	100	150	Non-crimped
2	1CR	500	40	60	250	100	150	Crimped
3	1K	1000	40	60	500	200	300	Non-crimped
4	1KC	1000	40	60	500	200	300	Crimped
5	2C	1000	40	60	500	200	300	Non-crimped
6	2CR	1000	40	60	500	200	300	Crimped
7	2K	2000	40	60	1000	400	600	Non-crimped
8	2KC	2000	40	60	1000	400	600	Crimped

The fibers, which were combed into fabric, were fixed in place using the needling method on a needling machine. An LBM 6 type needling machine manufactured by Oskar Dilo KG Maschinenfabrik was used. In all samples in the test plan, the needle length was set to 3 inches (approximately 76 mm), the stitch depth to 2.5 units (according to the machine scale), and the impact depth to automatic mode (standard setting). Needling density is 75 punches/cm².

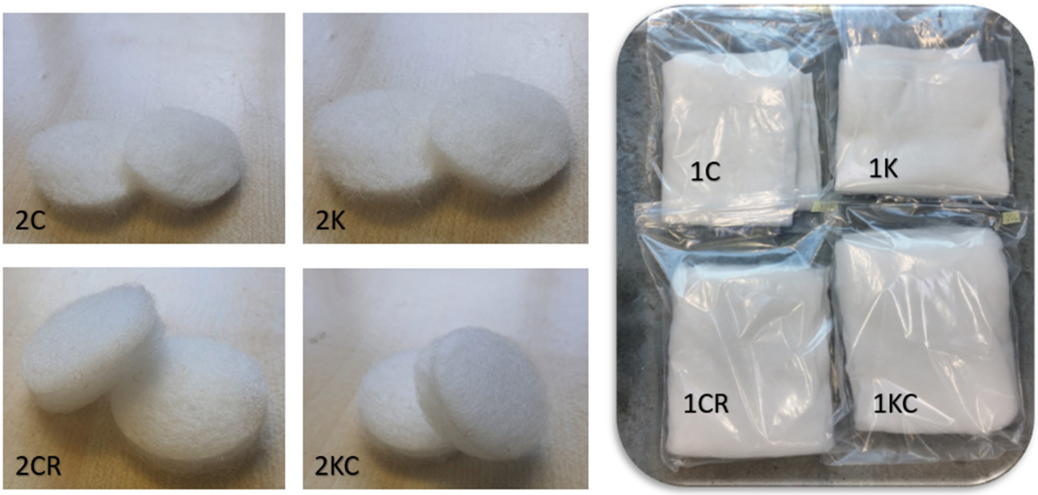

Figure 3. Nonwoven samples produced from crimp and non-crimp fibers

2.5. Morphological Characterization

The morphology of both crimped and uncrimped fibers, as well as the nonwoven fabrics produced from these fibers, was examined using scanning electron microscopy (SEM). SEM analyses provided detailed evaluation of the surface properties of the fibers and the structural changes following crimping. In particular, the relationship between fiber diameter and crimp structure was analyzed through images obtained at 50 µm magnification. The crimp characteristics were qualitatively verified via SEM imaging, which revealed enhanced fiber undulations post-crimping.

2.6. Acoustic Performance Measurements

All acoustic measurements were conducted at the Aachen TFI laboratories using a Siemens-brand impedance tube. The measurements followed the DIN EN ISO 10534-2 standard, which specifies the determination of the normal incidence sound absorption coefficient of sound-absorbing materials using an impedance tube equipped with two microphones and a frequency analysis system.

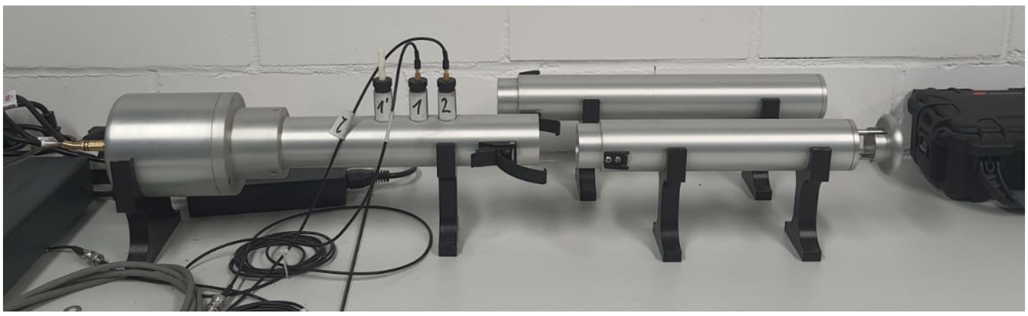

Figure 4. Sıemens mark impedance tube at TFI

Figure 5. Preparation of samples for acoustic measurement

3. RESULTS AND DISCUSSION

First, Table 2 presenting the basic physical properties of the samples, including thickness, porosity, and basis weight, is provided. Subsequently, the morphological images obtained from SEM analyses and the acoustic performance results are presented and discussed sequentially.

All parameters listed in Table 2 were calculated by applying the calculation procedures and formulas outlined below.

The bulk density of the fabric (d, g/cm³) was determined using the mean measured mass per unit area (M, g/m²) and thickness (t, cm) as follows: [23]

$$d = \frac{M}{t} \quad (1)$$

The fiber volume fraction (FVF, %) expresses the volume occupied by fibers relative to the full volume of the fabric. This value is obtained by the ratio of fiber volume to the overall fabric volume [24]

$$FVF = \frac{M}{t\,x\,\rho_f} \quad (2)$$

In this formula, M represents the measured mass per unit area (g/cm²), t is the fabric thickness (cm), and ρ is the density of the fiber blend (g/cm³). The density of the component fibers was derived using a weighted average, following the method described in [26]

$$\rho_f = w_p\rho_p + w_v\rho_v \quad (3)$$

Here; w_p and w_v define weight fraction of pp and aerogel fibers (%), respectively. ρ_p is the density of pp fiber (0,67g/cm3) and ρ_v is the density of aerogel fiber (0.003g/cm3).

Porosity = (1-FVF)x100

Table 2. Physical properties of the nonwoven samples

Exp.	Sample code	Material weight (gr)	Surface area (cm²)	Thickness (cm)	Bulk density (g/cm³)	Areal weight (g/cm²)	Bulk density (g/cm³)	Fiber volume friction (FVF)	Porosity (%)
1	1C	19,8	400	0,912	0,05428	0,049	0,05427	0,13461	86,53861
2	1CR	20,1	400	0,924	0,05438	0,050	0,05438	0,13487	86,51212
3	1K	40,4	400	1,956	0,05164	0,101	0,05163	0,12806	87,19345
4	1KC	40,1	400	0,946	0,10597	0,100	0,10597	0,26282	73,71713
5	2C	39,9	400	1.876	0,05317	0,099	0,05317	0,13187	99,98681
6	2CR	40,3	400	1,886	0,05341	0,100	0,05341	0,13248	86,75100
7	2K	81,2	400	3,92	0,05177	0,203	0,05178	0,12843	87,15632
8	2KC	80.5	400	1,907	0,10555	0,201	0,10553	0,26173	73,82632

The acoustic performance of nonwoven fabrics produced from both crimped and uncrimped fibers was evaluated. SEM images of the fibers and the corresponding nonwoven fabric samples were obtained before and after the crimping process (Figure 6).

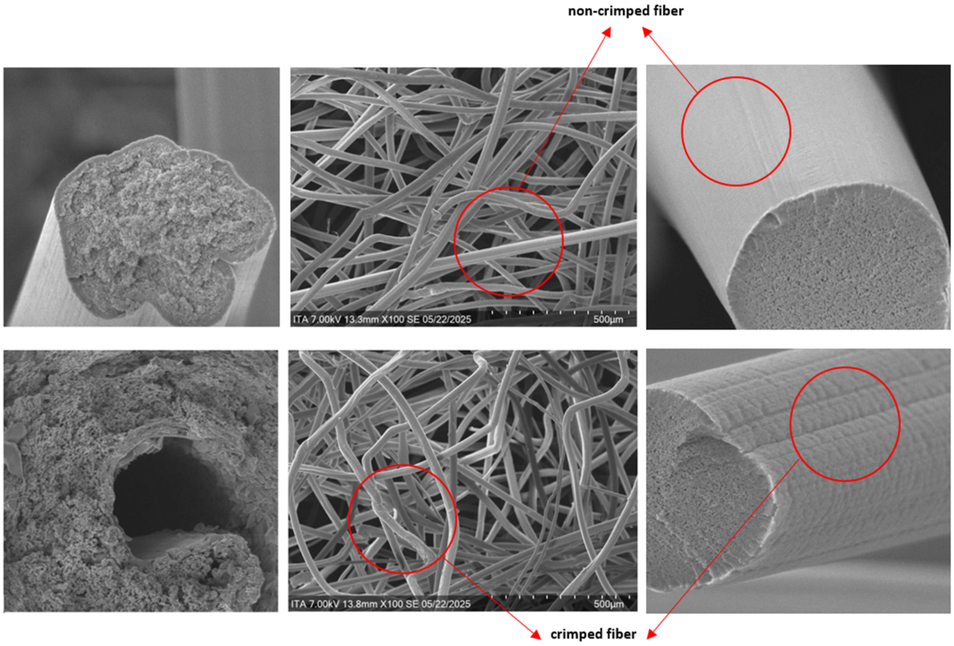

Figure 6. SEM anaylses of fiber and nonwoven sample: noncrimps fiber and nonwoven (above), crimp fiber and nonwoven (below)

The images provided an important reference for assessing whether the internal porous structure of the fibers was compromised after crimping and for visually confirming the morphological prominence of the crimp. Based on these observations, it was concluded that the crimping process did not damage the internal structural integrity of the fibers; rather, in some areas, it introduced increased irregularity in the porous structure, leading to variations in sound absorption. SEM analysis illustrated more pronounced fiber waviness in crimped samples, indicating increased tortuosity and potential for higher acoustic dissipation paths.

In this study, the effects of basis weight and crimping (imparting waviness to the fibers) on the sound absorption performance of nonwoven fabrics produced from aerogel and PP fibers were systematically investigated. The findings are discussed in detail below.

The sound absorption coefficients (α) of the produced nonwoven fabrics were evaluated with respect to the crimp condition of the fibers. Comparative analyses were conducted over the frequency range of 100 Hz to 5000 Hz, with samples produced from both crimped and uncrimped fibers tested under identical manufacturing parameters.

Incorporating crimp into the fiber structure significantly impacted the internal architecture of nonwoven fabrics, directly influencing their acoustic behaviour. Crimped fibers created a network in nonwoven surface that was more irregular, tortuous and spatially expanded, increasing the number of fiber–air interfaces and enhancing the propagation pathway of incident sound waves. As a result, crimped samples demonstrated enhanced sound energy dissipation, particularly within the middle to high frequency range. This is consistent with earlier findings indicating that fiber waviness modifies essential structural properties, such as porosity and volumetric density, thereby affecting the acoustic performance of nonwoven materials [26,27].

Changes in base weight have also significantly affected the acoustic properties of the samples. Increasing the base weight from 500 g/m² to 1000 g/m² and then to 2000 g/m² reduced the pore volume and increased fibre entanglement, thereby creating more compact fibre structures within the material. These morphological changes in the production of nonwoven surfaces have been observed to encourage multiple reflections and viscous friction by allowing sound waves to pass through longer and more complex internal paths. Consequently, samples produced at higher base weights demonstrated noticeably higher sound absorption capabilities, particularly at high frequencies where pore complexity plays a dominant role in acoustic attenuation.

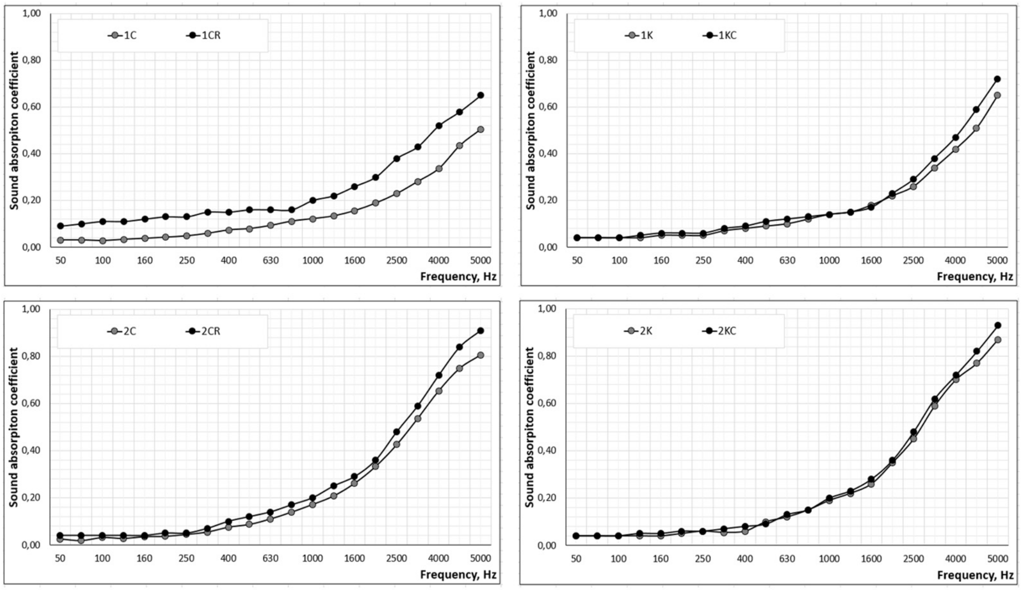

Figure 7. Sound absorption coefficient of samples with different crimp levels and basis weights across 100-5000 Hz.

Direct comparison of crimped and non-crimped samples of identical basis weight further highlights the positive impact of crimping. The crimped fibers formed a more convoluted internal geometry, enhancing scattering, reflection and frictional losses within the structure. This improvement was most evident in the mid-to-high frequency region, demonstrating that fiber morphology is a critical determinant of acoustic performance in aerogel-based nonwovens.

The combined effects of basis weight, crimping and layering showed that the 2KC sample, which was produced with a total basis weight of 2000 g/m² and crimped fibers, exhibited the most compact structural characteristics. This specimen had the highest bulk density (0.105 g/cm³) and fiber volume fraction (0.26), and the lowest porosity (73.8%). These properties are indicative of a densely packed fiber network. This microstructure enhances the material's ability to dissipate acoustic energy, particularly within frequency ranges where internal friction and scattering are dominant. These properties highly suggest that the 2KC sample is capable of achieving the highest sound absorption coefficients.

As shown in Table 2, the bulk density values for 1C, 1CR, 1K and 1KC ranged from approximately 0.051 to 0.106 g/cm³. Double-layer samples exhibited similar patterns, with 2CR and 2KC consistently showing higher densities and FVF values than non-crimped ones. Samples produced from crimped fibers, particularly 1KC and 2KC, showed pronounced increases in both bulk density and fiber volume fraction, confirming their more consolidated and compact internal architecture. These structural parameters closely align with their superior expected performance in sound absorption, particularly at medium and high frequencies.

Overall, the results clearly demonstrate that nonwoven fabrics produced with higher basis weights and crimped aerogel fibers exhibit significantly enhanced acoustic absorption. The combination of increased fiber mass, reduced porosity and a more intricate internal fiber arrangement makes these materials strong candidates for high-performance acoustic insulation applications, particularly in systems requiring lightweight yet effective sound absorption. Similar studies on alternative insulation materials are also available in the literature [28,29].

4. CONCLUSIONS

All results in this study show that the acoustic behaviour of aerogel–polypropylene (PP) nonwoven surfaces can be significantly impacted by various structural factors, particularly basis weight and the incorporation of crimped fibers. As basis weight increased, the fabric structure became more consolidated, creating more complex airflow paths inside the material and enabling the samples to absorb more sound at medium and high frequencies. Crimped fibers also played an important role, creating a more irregular and entangled network that encouraged additional friction and scattering of sound waves.

The samples produced with both a higher basis weight and crimped fibers, such as the 2KC sample, stood out due to their compact internal structure and notably better acoustic response. These results suggest that carefully adjusted aerogel-based nonwovens with specific fiber morphology could be promising candidates for use in areas requiring lightweight yet effective sound absorption, including interior building applications.

Future studies could examine how different crimp levels, alternative aerogel–polymer blends and changes in needling or fiber ratios might further improve the acoustic behaviour of similar nonwoven structures. Exploring these parameters could provide a more detailed understanding of how to fine-tune the material for specific performance requirements.

5. ACKNOWLEDGMENTS

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