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RESEARCH ARTICLE

Thermal and acoustic characterization of nanofibrous polymeric structures for insulation applications

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Abstract

Nanofibrous structures are engineered materials for high-end applications. The impact of electrospinning settings on the thermal and acoustic properties of polyurethane (PU) nanofibrous structures is examined in this research. The excellent sound-absorbing properties of PU make it a versatile material that may be used in a variety of acoustic applications. The study focuses on how PU nanofiber morphology, such as fiber diameter and volume fraction, is affected by varying ambient conditions. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are used to examine the stability and thermal behavior of PU nanofibers. The findings show that raising the fiber volume fraction improves thermal stability and changes the way PU nanofibers behave thermally. PU nanofiber webs provide efficient sound absorption in low and intermediate frequency ranges according to the study's analysis of the sound absorption coefficients. According to the results, PU nanofiber webs may offer novel approaches to noise control, especially in situations where acoustic panel insulation is needed with no weight penalty.

1. Introduction

The remarkable qualities of polyurethane (PU) nanofibers have led to a wide range of engineering applications [1]. PU nanofibers are useful in the important areas such as acoustic panel insulation in architectural design, automotive industry for interior noise control, reinforced materials for mechanical engineering, civil engineering for vibration dampening, textile engineering for advanced fabrics, and biomedical engineering for drug delivery systems [1-8]. PU nanofibers contribute to the development of lightweight and effective materials for noise control in car interiors, serve as efficient sound absorbers in architectural designs to enhance acoustical comfort in buildings, and are employed in civil engineering projects to reduce noise and decrease vibrations since they absorb sound [2,3,6]. Moreover, composites can be improved mechanically by adding PU nanofibers, which makes them appropriate for a range of mechanical engineering uses [5]. PU nanofibers are also used in drug delivery systems in biomedical applications due to their controlled release capabilities [8].

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For acoustic applications, polyurethane (PU) has proven to be a highly effective and adaptable material. It is the perfect option for many different acoustic solutions because of its exceptional sound-absorbing qualities. PU has demonstrated its value in improving acoustical comfort in a variety of applications, including architectural design, car interiors, and acoustic panels [9-11]. Because of its versatility, light weight, and effective sound-dampening properties, it's become a preferred material for building more comfortable and silent rooms [10]. The usage of PU in acoustic applications is growing as a result of continued research and innovation, providing encouraging answers to problems with noise control and acoustic design.

There is a lot of interest in fibrous materials with improved low- and medium-frequency sound absorption capabilities. The relationship between the sound absorption coefficient and fiber surface area is highly significant. For instance, due to the increase in relative density and friction, larger specific surface areas of submicron and nanoscale fibers and nanofibers greatly improve sound absorption coefficient, especially in the lower frequency range [12]. Consequently, research into the possible use of electrospun nanofibers as nanoscale sound absorbers has been conducted recently. Kalinova [13] examined the possible applications of electrospun polyvinyl alcohol (PVA)-based nanofibrous membranes as sound absorbents. The researcher concentrated on estimating the resonance frequency of these membranes using measurements of transmission loss and sound absorption coefficient. Additionally, Jirsak et al. [14] showed that even at lower frequencies, coated specimens with nanofibrous layers had a sound absorption coefficient that is noticeably larger than that of plain specimens. It was also mentioned that the lower frequency sound absorption was induced by the resonant nanofibrous membrane's oscillation.

The electrospinning process involves the formation of ultrafine fibers through the application of high voltage to a polymer solution or melt, leading to the elongation and subsequent solidification of the polymer jet. This method offers precise control over the fiber morphology, diameter, and alignment, making it suitable for various applications [15]. In order to fabricate polymeric nanofibrous structures successfully and with maximum efficiency, it is essential to optimize various processing parameters related to the technique [16]. Studies have been done on how certain system and process variables, such as flow rate, distance from the collector, and solution concentration, affect the size and morphology of nanofibers [17, 18]. Temperature and humidity have great impact on the spinning process [19].

Understanding the thermal properties of PU nanofibers is crucial for optimizing their performance and expanding their utilization in applications. Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) are widely used techniques for investigating the thermal behavior and stability of polymers [20]. The morphology of polyurethane nanofibers plays a crucial role in determining their thermal properties, including thermal conductivity, melting and glass transition temperatures, and thermal stability [21]. The melting and glass transition temperatures of polyurethane is influenced when it has a nano-scaled structure. Higher fiber volume fractions can affect the degree of crystallinity and phase transitions, leading to changes in the thermal behavior of the material. Moreover, the percentage of fiber material in nanoweb can impact the thermal stability of polyurethane nanofibers. A higher fiber volume fraction may provide better mechanical reinforcement and reduce the chances of fiber combination, enhancing the material's thermal stability under heat exposure [22].

The work conducted examines the detailed analysis of the thermal and acoustic characteristics of polyurethane (PU) nanofibrous structures, emphasizing the impact of various electrospinning parameters on the mentioned properties. In order to provide a comprehensive understanding of the thermal behavior, phase transitions, and stability of PU nanofibers, it was focused on the results obtained from DSC and TGA analyses. Furthermore, the evaluation of sound absorption coefficients advances the study goal of producing a nanofiber-based material appropriate for use in insulation applications.

The novelty of this study lies in its significant contributions to the field of engineering applications, specifically in the areas of thermal insulation and acoustic design with polyurethane (PU) nanofibrous structures. Through a methodical examination of the impact of electrospinning parameters on the thermal and acoustic characteristics of PU nanofibers, this research provides novel understandings into customizing nanofiber structure to improve performance in real world engineering applications.

2. Experimental study

2.1. Materials

From PU polymer, nanofibrous polymeric structures were produced. The polymer utilized was PU, which has a molecular weight of 2000 g/mol, and the solvent employed was dimethylformamide. Tetraethyleneammonium Bromide salt was added to solutions at a concentration of 1% wt to increase conductivity and productivity [23]. Solutions were made at an 18% wt PU concentration.

2.2. Methods

The needleless (roller) electrospinning technology was utilized to fabricate nanofibrous polymeric structures. A slowly revolving cylinder is partially submerged in a polymer solution in roller electrospinning (Fig. 1). The collector is typically grounded while the polymer solution is connected to a high voltage source. Because of the rotation of the roller during the electrospinning process, polymer solution is brought to the surface of the device. With the right level of high voltage, a large number of Taylor cones form on the roller surface at once and result in the production of nanofibers. Next, the nanofibers are moved in the direction of the collector [14].

As was mentioned in the literature part, ambient conditions, especially relative humidity and temperature, affect both production process and membrane morphology of the PU polymer. Therefore, relative humidity and temperature were changed while the other process parameters were set the same. For the two samples produced, distance between electrodes and voltage were set 15 cm and 60 kV. For the first sample, relative humidity (%) and temperature (°C) were set to 30 and 10, respectively, and for the second one, relative humidity (%) and temperature (°C) were set to 20 and 18, respectively.

Scanning electron microscopy (SEM) was used to analyze the structures from electrospun nanofibers to assess their fiber diameter and morphology at a 5k magnification. By utilizing Image J software 100 measurements were taken to calculate the nanofiber diameters.

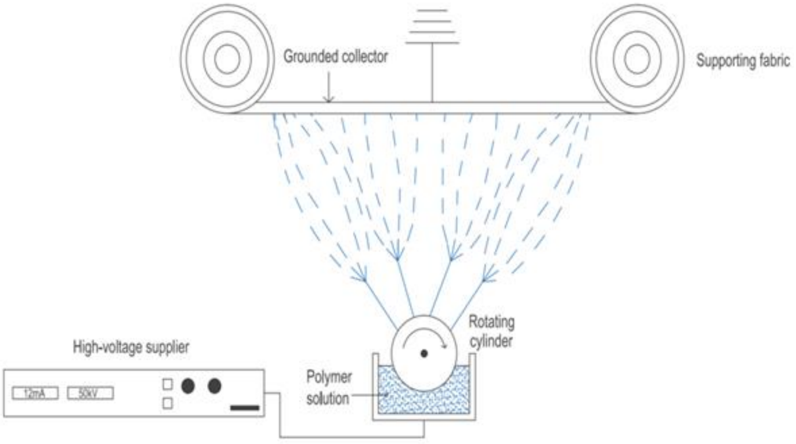


Fig. 1. Needleless electrospinning

DSC was used to investigate the thermal characteristics of nanofibrous membranes. Materials were heated at a rate of 10 °C/min from 25 °C to 450 °C, after which the samples were cooled at a rate of 10 °C/min to 25 °C. Samples were heated to 450 °C at a rate of 10 °C per minute after waiting one minute at 25 °C, and then they were cooled to 25 °C.

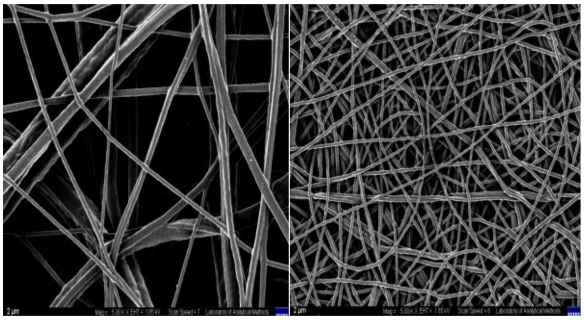
Weight/mass change and the rate of weight change as a function of temperature, time, and environment are measured by thermogravimetric analysis (TGA). TGA analysis was carried out in air moving at 10 °C/min between 25 and 700 °C.

Sound absorption coefficient was measured by Testsens impedance tube in accordance with the ISO 10534 standard.

3. Results and discussion

As may be seen from the SEM images presented in Fig. 2, it is evident that ambient conditions affect the morphology of PU nanofibrous structures, especially in terms of fiber diameter and fiber volume fraction value.

Fiber diameters of PU_1 and PU_2 nanofibers were measured as 300 nm and 200 nm, and fiber volume fraction (%) values are 30% and 75%, respectively. When the humidity decreases and the temperature increases, nanoweb consisting of finer fibers and higher fiber volume fraction (%) is obtained.



(a) (b)

Fig. 2. SEM images of a. PU-1 and b. PU_2 (magnification is 5k)

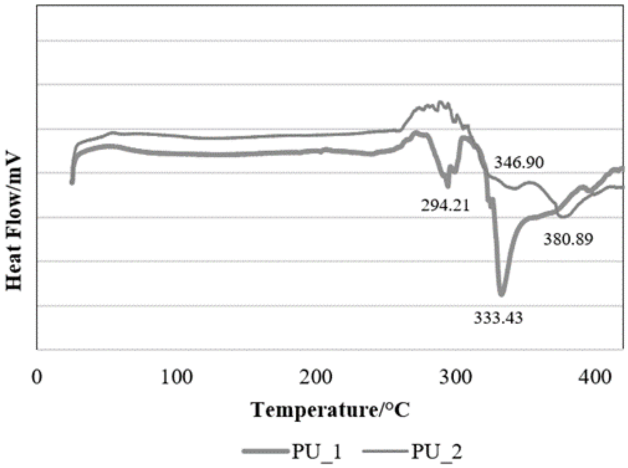


Fig. 3. DSC graphs of PU-1 and PU_2A

Fig. 3 displays the PU electrospinning fibers' DSC thermograms. DSC thermograms of both PU_1 and PU_2 show quite similar characteristics beyond 300°C. However, PU_1 indicates two different endothermic peaks at 294 and 333°C. On the other hand, in the PU_1, the presence of an endothermic peak observed at 346 °C, means that PU_1 sample shows lower crystal behavior. Moreover, PU_1 represents high enthalpy compared with PU_2. A significant bond enthalpy indicates that a considerable amount of energy is necessary to rupture such a bond in the structure. Increased enthalpy signifies that heat had to be assimilated during the formation of the substance, resulting in a higher-energy compound. Compounds with high energy levels tend to exhibit greater reactivity and, consequently, lower stability. Conversely, lower enthalpies follow the opposite trend [24]. As seen in the graph, the stability of the nanofiber webs increases with the increase in the fiber volume fraction value.

The TGA graphs are displayed in Figs. 4 and 5. The graphs display how the samples' weight changes as the temperature rises. A dramatic fall in sample weight begins at the onset temperature, which is seen in the graph.

As can be seen in Fig. 4 and 5, the degradation temperatures of the PU_1 and PU_2 nanofibers are 273 °C and 283 °C, respectively. Polyurethane's main decomposition peak shifted to 283 °C with producing finer fibers web with high fiber volume fraction. This fact shows that unstable nanofibrous web begins to degrade at lower temperature.

The measured sound absorption coefficients (α) per 1/3 octave band are reported in the Table 1.

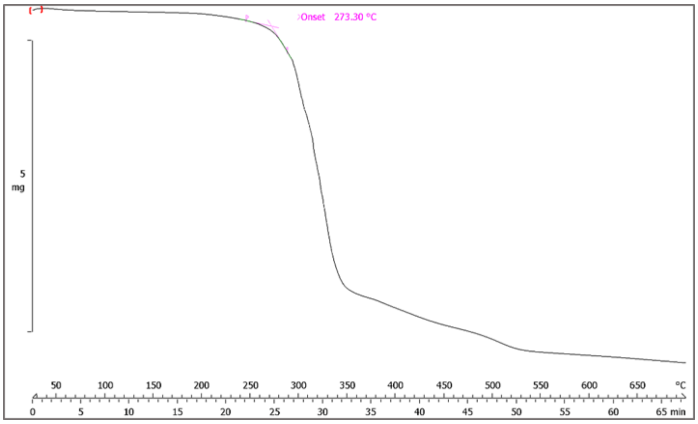


Fig.4. TGA graph of PU_1

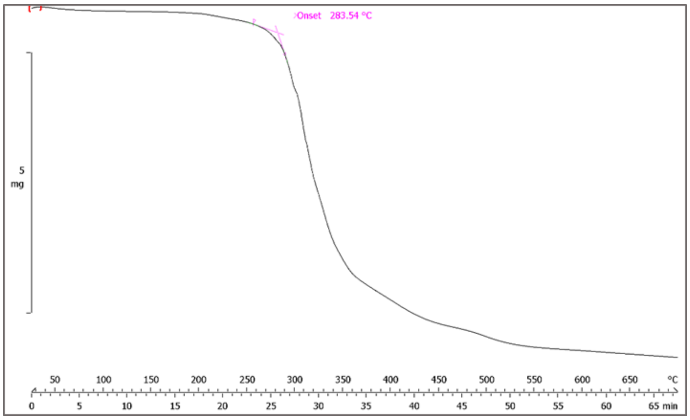


Fig. 5. TGA graph of PU_2

Table 1. 1/3 octave frequency sound absorption measured

Frequency [Hz]	PU_1	PU_2
63	0.0328	0.0702
80	0.0519	0.0216
100	0.0186	0.0185
125	0.0469	0.0379
160	0.0187	0.0273
200	0.0301	0.0269
250	0.0333	0.0325
315	0.0332	0.0289
400	0.0379	0.0386
500	0.0356	0.0344
630	0.0323	0.0302
800	0.0427	0.0712
1000	0.0489	0.2234
1250	0.1844	0.1276
1600	0.0803	0.7934
2000	0.0891	0.3227
2500	0.7212	0.2522
3150	0.0913	0.1391
4000	0.2598	0.4488
5000	0.3541	0.5438
6300	0.3996	0.6429

As may be seen in Table 1, PU_1 nanofibrous structure has the first absorption peak at 1250 Hz while PU_2 nano structure has its first peak at 1000 Hz. The second resonance frequency of PU_1 nanofibrous structure is 2500 Hz while for PU_2 it is 1600 Hz. The resonant frequency is defined as the frequency at which the transfer function reaches its maximum value. The sound absorption of the nanofibrous polymeric structures decreases after reaching their peak values. Having absorption peaks is a characteristic behavior of structures in the form of membrane absorbers. As the fiber volume fraction increased and fiber diameter decreases, the first resonance absorption frequency of nanofibrous polymeric structure moves to a lower frequency. The PU_2 nanolayer's uniform fibrous structure and high number of nanofibers in its morphology provide a higher surface area, which aids in the absorption of sound waves through friction. The behavior of the PU_1 nanofibrous layer's sound absorption is lower. There are fewer nanofibers in a consistent area with larger pore diameters in the PU_1 nanofiborus membrane's shape which might have made it easier for the sound waves to pass through the structure due to the large pore size.

4. Conclusion

The effects of the ambient conditions, relative humidity and temperature, used in nanofiber production on structure and morphology of the nanoweb structures were examined. The results showed that as the ambient conditions varied, the average fiber diameter and fiber volume fraction also altered. Additionally, PU_2 displayed less bead formation and a more uniform morphology. DSC analysis showed that with increasing fiber volume fraction of nanofibrous webs, the endothermic curves' peaks changed toward the high temperature, and the enthalpy decreased as well. TGA analysis showed that with decreasing fiber volume fraction, the degradation temperature shifted to lower temperature.

The acoustic findings of this study showed that PU nanofibrous structure exhibit good sound absorption in low and moderate frequency ranges (250-2000 Hz) where humans are highly sensitive to noise. Sound absorption coefficient values reached up to 0.8 with no weight or thickness penalty for the 1000 Hz–2000 Hz frequency range which are important for interior panel insulation. Conventional textile materials cannot achieve such enhancements without weight penalty. As a result, the developed nanofibrous structures hold out as a creative solution to address the challenges related to noise management in many applications, especially in terms of reinforced material for acoustic panel insulation.

The results of this work on PU nanofibrous structures offer potential avenues for many engineering applications, especially in the mechanical and civil sectors. Increased fiber volume fraction has been shown to improve thermal stability, which has implications for civil engineering applications where better thermal qualities are essential. Besides, PU's lightweight nature makes it an even more desirable material for mechanical components and construction, providing a special blend of thermal stability and sound absorbing capacity without the usual weight penalties associated with insulation materials.

This work comprehensively examines the impacts of the electrospinning settings on PU nanofibrous structures, offering a novel viewpoint for engineering applications. The research contributes to the basic understanding of how environmental factors affect nanofiber shape and offers useful technical insights that may be used to solve specific engineering problems related to thermal insulation and acoustic design in various applications.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability statement

No new data were created or analyzed in this study.

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