sustainability

Article

Usage of Recycled Technical Textiles as Thermal Insulation and an Acoustic Absorber

Anna Danihelová [1], Miroslav Němec [2], Tomáš Gergeľ [3], Miloš Gejdoš [4,*], Janka Gordanová [1] and Patrik Ščensný [1]

1 Department of Fire protection, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T.G. Masaryka 24, 960 01 Zvolen, Slovakia; danihelova@acoustics.sk (A.D.); gordanova.janka@gmail.com (J.G.); scensnypatrik@gmail.com (P.S.)
2 Electrical Engineering and Applied Mechanics, Department of Physics, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T.G. Masaryka 24, 960 01 Zvolen, Slovakia; nemec@tuzvo.sk
3 National Forest Centre, Forest Research Institute, T.G. Masaryka 22, 960 01 Zvolen, Slovakia; gergel@nlcsk.org
4 Logistics and Amelioration, Department of Forest Harvesting, Faculty of Forestry, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia
* Correspondence: gejdos@tuzvo.sk

Received: 17 April 2019; Accepted: 20 May 2019; Published: 24 May 2019

Abstract: The sound absorption coefficient is a commonly used parameter to characterize the acoustic properties of materials. The fire performance of construction products has to be evaluated on the basis of their reaction to fire performance. The evaluation of the reaction to fire performance for the flammable construction materials which are in Class E reaction to fire is based on the ignitability test and the thermal test using the radiant heat source. For this study, nine types of STERED® products, which were made from the recycled automotive technical textiles, were chosen in order to evaluate their ability for sound absorption and the reaction to fire. The fire performance was evaluated on the basis of the relative mass loss in the radiant heat source test; the ignitability in accordance with ISO 11925-2, the possible appearance of flame, duration of flame, and the glowing during the single flame source test. The sound absorption of nine products was rated on the basis of the sound absorption coefficient and the noise reduction coefficient. The measurement was performed using the transfer function method in accordance with ISO 10534-2. From the nine tested types of STERED® products, the product Senizol AT XX2 TL 60 had the lowest mass loss at thermal loads up to 700 °C and it fulfilled the conditions for Class E reaction to fire. This product had the highest noise reduction coefficient of 0.81 and a high absorption coefficient for frequencies ranging between 500 Hz and 2000 Hz. The STERED® product Senizol AT XX2 TL 60, as well as Senizol AT 22 TL 50, Senizol AT 40 TL 25, Senizol AT XX4 TL 50 and Senizol AT XX4 TL 10 with a sound absorption coefficient α of between 0.80 to 0.95 and corresponding NRCs from 0.66 to 0.81, these STERED® products can be classified according to ISO 11654 into the sound absorption classes A and B.

Keywords: technical textiles; waste; recycling; ignitability; mass loss; sound absorption coefficient; noise reduction coefficient (NRC)

1. Introduction

Recycling industrial textiles reduces the need for raw materials and consequently any negative environmental impacts. The prerequisite for functional recycling is a system that recovers textiles efficiently with regard to environmental considerations. Recycling is a precondition for a circular economy, i.e., materials can be recycled, returned back to the economy and used again. At the beginning of 2017, the European Parliament adopted a report stating that waste recycling should reach 70%

by 2030. At present, less than 50% of the waste in the EU is recycled; the European Parliament considers that unsatisfactory [1]. The recycling of metal, paper or glass is currently well underway, but there are assortments of waste whose recycling is not so profitable. These are mainly textiles when recycling of textiles stands only 20% of high-volume wastes. Nowadays, however, there has been increasing pressure to increase the recycling share of these materials as well. The increasing cost of waste management, as well as lack of space for landfill, is probably the cause of growing interest in recovering waste as either material or energy [2]. There is an increasing variety of products that have been produced by using recycled material as the main raw material. One of these materials is also textile waste from cars. In the automobiles, fibers are used in different forms of textile materials such as circular knitted, warp knitted, woven and nonwoven structures. Fibers are also used as a component in multi-layer composite structures. Textile products used in automobiles are expected to fulfill different performance requirements regarding the application area [3].

This waste consists of synthetic fabrics (carpets and upholstery) from end-of-life vehicles and offcuts from new car production.

Considering the fact that textiles are used as insulation material in the construction industry, the possibility of using recycled textiles is evident. This is a fabric that comes from processing old vehicles. Directive 2000/53 of the European Parliament and of the Council determined for all EU Member States the obligation to re-evaluate up to 95% of the mass of an old vehicle by 2015 [4]. This requirement is difficult to fulfill. Therefore, the reuse of such waste is highly desirable. Djordjevic and Avramovic report that the automotive industry produces large quantities of textile waste. It has prospective uses as thermal and acoustic insulation in lightweight structures and can lead to the saving of more than 100 million EUR across Europe [5]. The reuse of waste from technical textiles will contributes to the fulfillment of the Directive of the European Parliament and of the Council EU no. 2012/27/EU on energy efficiency and 7th EAP—the new general Union Environment Action Program to 2020 [6,7].

Zeinab et al. dealt with heat transfer through various types of nonwoven fabrics that was used as a thermal insulation layer. They studied the dependence of the thermal conductivity on the thickness and the density of the insulation panels made of the polyester and the polypropylene fibers. Zeinab et al. concluded that, based on the measured value of the thermal conductivity ($\lambda = 0.033\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$) of the recycled textile materials investigated, the selected nonwovens were suitable for use as a thermal insulation material [8].

Hadded et al. studied the recycled textile materials in terms of the thermo-physical characteristics (the thermal conductivity and the diffusivity). Their research results showed that the values of both studied thermo-physical characteristics fulfilled the requirement laid for the thermal insulation. It means the recycled textile materials have competitive thermal properties and can be used as an alternative to commercial thermal insulation materials (the extruded polystyrene or mineral wool) in construction [9].

As is evident from the above mentioned, the researchers dealt mostly with the investigation of the thermal insulation characteristics of the recycled technical textiles. However, from the point of view of their use in construction, the fire-technical and acoustic characteristics of the materials are also very important [10]. For that reason, the tests of the reaction to fire test must show the material's behavior when exposed to a direct flame of ignition. Considering the possibilities of using the materials tested by us, it is of the great importance to quantify the effect of the high temperatures on their thermal degradation. In our experience, the thermal degradation of the material can be assessed by monitoring mass loss as a response to radiant heat. The high mass loss indicates the extent of the damaged of material when exposed to radiant heat during the fire [11].

Automotive textiles are produced from the synthetic, natural and recycled fibers to provide the thermal and acoustical comfort. Reintroduced into a specific manufacturing process, textile boards will be used in making multilayered composite materials, thermal insulation materials and interior cladding [12]. Therefore, it makes sense to find out the ability of the materials made from recycled technical textiles to absorb sound energy. The sound absorption properties of investigated materials can be characterized by a sound absorption coefficient and noise reduction coefficient.

There are several of insulation materials made from recycled technical textiles (they differ in density, proportion of natural fibers, polypropylene, polyester, polyamide and polyurethane fibers, as well as by the fiber length). In this work, the fire performance and the acoustic characteristics recycled textile materials are presented. The most appropriate material from the acoustic and fire-protection perspective was chosen to compare with commercially used insulation materials (polystyrene and polyurethane foam).

2. Materials and Methods

Samples were prepared from the nine various products made from the recycled technical textiles [13]. The input material consisted of certified synthetic textile normally used for manufacturing textile components in the automotive industry. Some of the material content may also include the textile fibers produced from recycled tires. The products with a common name (STERED®) varied in material composition and density [14]. The STERED® products consist of polypropylene (PP), polyamide (PA), polyester (PET) and the other materials also include polyethylene (PE), and polyurethane foams (PUR) as well as cotton, wool and inert materials (e.g., talc) [15]. Individual types of STERED® products differ in the percentage representation of the individual components which are mentioned above. These STERED® products are moisture and mold resistant, they have a high mechanical resistance and they fulfill requirement pertaining to hygiene and health safety [16].

Our experiment was divided into two parts. In the first part of the experiment, the reaction to of the nine STERED® products the fire (Figure 1), based on the results of two tests, was rated. In the second part of the experiment, the sound absorption coefficients α (-) and the noise reduction coefficients (NRC) of the tested samples were established.

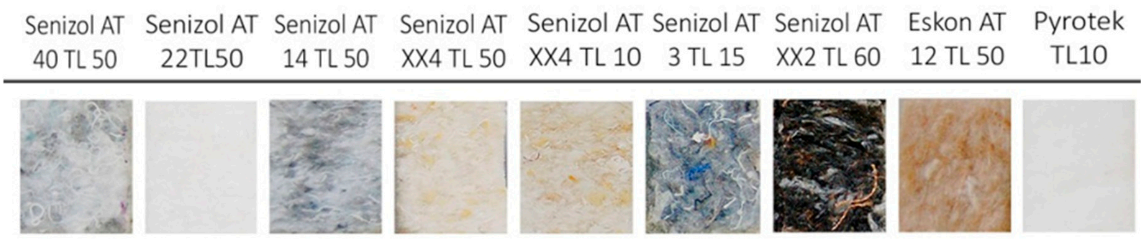


Figure 1. STERED® products.

The non-standard thermal test using a radiant heat source was performed to determine the relative mass loss of material, and the ignitability of the materials subjected to direct impingement of a small flame was investigated via the ignitability test [17]. The test samples were prepared from all the nine STERED® products. Prior to testing, all samples were conditioned in the laboratory at a temperature of (20 ± 2) °C and a relative humidity of (55 ± 5)% to reach the same equilibrium moisture of all tested samples. All tests were carried out in these laboratory conditions in accordance with the test method requirements. The shape of the test samples depended on the experimental method used. The samples with dimensions of (50 × 40 × 50) mm were used for the thermal test using a radiant heat source. For the ignitability test, the samples were prepared from the STERED® product the Senizol AT XX2 TL 60, which had the lowest mass loss at the thermal loading and the highest sound absorption coefficient. The samples were prepared also from polystyrene and polyurethane foam to compare their ignitability with STERED® product the Senizol AT XX2 TL 60. The dimensions of all test samples for the ignitability test (Figure 2) were (250 × 90 × 30) mm.

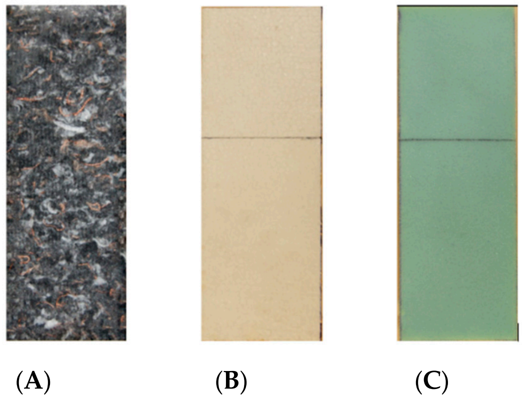


Figure 2. Test samples (**A**)—Senizol AT XX2 TL 60, (**B**)—polystyrene, (**C**)—polyurethane foam.

The aim of this test was to determine the ignition of the sample and the flame spread over the main surface area and across the edge. The flame application time was 15 s, and the test was terminated 20 s after the removal of the flame. The same procedure was done for all materials tested by us (all belonging to the fire reaction class E).

For obtaining the sound absorption coefficient α (-) and the noise reduction coefficient (NRC) the transfer function method was used [18]. The samples for this second part of the experiment were of a cylindrical shape having a radius 100 mm and the height 50 mm.

2.1. Thermal Test Using a Radiant Heat Source

The thermal test using the radiant heat source is considered to be a non-standard testing method. This method was applied in the model test of burning. The diagram of the test equipment is shown in Figure 3. The test sample was placed on a metal stand at a variable distance h from the thermal infrared (in our test h = 30 mm). The 1000 W ceramic infrared heater emitted radiation at a wavelength of 3–6 µm. The operating temperature was within the interval (300–750) °C. Its efficiency was about 85% in a properly designed system. The analytical Sartorius Basicplus type BDBC 200 scales (included in class 1 accuracy) were used to detect the mass loss.

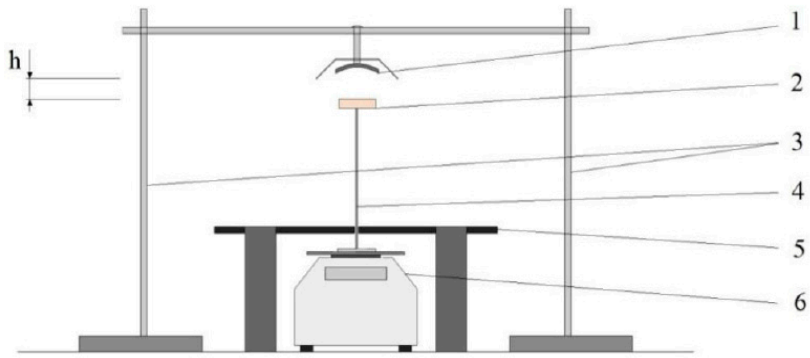


Figure 3. Scheme of test equipment [19] 1—ceramic infrared heater, 2—test sample, 3—metal frame, 4—sample holder, 5—scales protection, 6—analytical scales.

In our test, the infrared ceramic heater was preheated to an operating temperature for 10 min before the test procedure. After reaching the desired operating temperature, the samples were successively inserted into the test equipment. Before the test, and during the test, the mass of each sample was recorded every 10 s. The relative mass loss in the monitored intervals was calculated according to Equation (1).

$$m_{r,t} = \frac{m_0 - m_t}{m_0} \cdot 100 \quad (1)$$

where: $m_{r,t}$ (%)—relative mass loss in the period of time t; m_0 (kg)—sample mass before the test; m_t (kg)—sample mass in the period of time t (s).

Simultaneously, the occurrence of flame burning of the sample was monitored as well as the flame retardation time and extinction time. If the sample was burning, even after 10 min, it was necessary to remove the sample from the holder to manually extinguish it.

2.2. Determination of Sound Absorption Coefficient in Impedance Tube

The sound absorption coefficient (SAC) describes the efficiency of the material or its surface to absorb the sound. The amount of sound energy which is absorbed can be defined as the ratio of sound energy absorbed to the sound energy incident [12,20]. It can be described by Equation (2).

$$\alpha = \frac{E_i - E_r}{E_i} = \frac{E_a}{E_i} \tag{2}$$

where: α (-)—the sound absorption coefficient; E_i (J)—the energy of the incident wave; E_r (J)—the energy of the reflected wave; E_a (J)—the absorbed sound energy.

The measurement of the sound absorption coefficient α (-) was run in compliance with the standard ISO 10534-2 [18] in an impedance Kundt tube via the transfer function method. The impedance tube is an acoustic duct used to measure the normal sound absorption coefficient of the test sample.

In the transfer function method, plane waves are generated in the Kundt tube by the sound source. The decomposition of the interference field is achieved by the measurement of sound pressures (p_1 and p_2) at two fixed positions of microphones mounted on the wall of the Kundt tube. The sound pressures p_1 and p_2 were used to calculate three transfer function. The transfer function for the incident wave alone H_I, the transfer function for the reflected wave alone H_R and the transfer function H_{12} for the total sound field [21]. The sound reflection factor r (-) can be determined according to Equation (3).

$$r = \frac{H_{12} - H_{\mathrm{I}}}{H_{\mathrm{R}} + H_{12}} \cdot \mathrm{e}^{2jk_0x_1} \tag{3}$$

where: k_0—a complex wave number; x_1—the distance sample to the far microphone; j—the imaginary unit. The sound absorption coefficient α(-) for the plane wave can be calculated according to Equation (4).

$$\alpha = 1 - |r|^2. \tag{4}$$

In our experiments for the determination of the normal incidence sound absorption coefficient of the STERED® products a two-microphone impedance tube Type 4206 was used as shown in Figure 4. The Kundt impedance tube comprised the two impedance tubes: one with a diameter 100 mm was used for measuring the low frequencies (between 50 Hz and 1.6 kHz) and the other with a diameter 30 mm was used for measuring the high frequencies (between 500 Hz and 6.4 kHz).

The measuring equipment consisted of several components: Bruel and Kjaer impedance tube Type 4206, Bruel and Kjaer power amplifier Type 2706, the LAN module-XI Brüel and Kjær Type 3560-B-030 with two active inputs and personal computer (PC) with Pulse software.

Figure 4. Kundt impedance tube Type 4206 and STERED® samples.

Before any measurements were taken, a transfer function calibration was performed. To be successful, calibration of both transfer functions have to be symmetric about a horizontal axis x across the frequency spectrum. Then, the samples were gradually inserted at one end of the impedance Kundt tube. The sound source was inserted at the opposite end of the tube and thus a standing wave was formed. This frequency range was chosen because the frequencies 250 Hz–2 kHz are the most important for the speech communication, the frequencies 100 Hz–1 kHz give the suitable evaluation of the usability of STERED® products as a sound absorption material, which would aid in improvement in the acoustic comfort of an indoor environment [22].

For the measurement, the samples from the nine types of STERED® materials were prepared. The densities of these materials were (25–224) kg·m^{-3} (Table 1). The thickness of all samples was 50 mm. The environmental data during measurement; the air temperature was 21 °C and the relative humidity was 65%. The noise reduction coefficient was determined by calculating the mean value from four one-third octave values of the sound absorption coefficient (250 Hz, 500 Hz, 1000 Hz and 2000 Hz) and rounding the result to the nearest 0.05.

Table 1. Density (ϱ), sound absorption coefficient (α) and noise reduction coefficient (NRC) of STERED® products.

Serial Num.	Samples	ϱ (kg·m^{-3})			α (-)			NRC
f (Hz)			200	250	500	1000	2000	
1.	Escon AT 12 TL 50	25	0.05	0.13	0.26	0.51	0.73	0.43
2.	Senizol AT 40 TL 50	26	0.05	0.18	0.43	0.81	0.95	0.64
3.	Senizol AT 40 TL 25	42	0.03	0.26	0.66	0.98	0.98	0.79
4.	Senizol AT 22 TL 50	44	0.09	0.29	0.68	0.98	0.97	0.80
5.	Senizol AT XX4 TL 50	48	0.05	0.24	0.58	0.95	0.99	0.76
6.	Senziol AT XX2 TL 60	61	0.13	0.40	0.82	0.93	0.90	0.81
7.	Senizol AT XX4 TL 10	140	0.11	0.27	0.65	0.77	0.80	0.66
8.	Pyrotek TL 10	223	0.16	0.26	0.38	0.56	0.65	0.51
9.	Senizol AT 3 TL 15	224	0.14	0.24	0.37	0.52	0.57	0.47

2.3. The Reaction to Fire Test

The reaction to the fire test was carried out according to standard ISO 11925-2 [17]. This ignitability test is used for testing of building materials for the classes reaction to fire B, C, D and E [23]. According to this test, the sample is subjected to direct impingement of a small flame. The test was carried out in a combustion chamber into which the test samples were placed. These were exposed to the effects of a small flame for 15 s. The testing sample was fixed vertically in the required position by the holder. The flame was brought into contact with the specimen at an angle of 45°and the correct distance between the burner edge (flame peak) and the sample surface was adjusted via the use of a distance measurement device. The flame height was adjusted to (20 ± 1) mm via the burner valve. After the adjustment of the parameters, the burner moved horizontally until the flame reached the preset contact point with the testing sample. When the sample was touched by the flame, the time device was triggered and after 15 s the burner was moved away. The test sample was left in the combustion chamber for another 20 s. In the case of sample burning, the process was terminated. The test samples were affected by the flame in two ways; acting on the main surface and on the lower edge of the sample. The flame application point was either 40 mm above the bottom edge of the surface exposure or at the center of the width of the edge exposure (for products with a total thickness above 3 mm). In the laboratory, the following conditions were maintained: a temperature of (23 ± 5) °C and a relative humidity of (50 ± 20)%. During the test, we investigated: if a sample had been ignited; if the top of the flame reached a height of 150 mm above the flame attachment point and the time at which it was observed.

During the test, the physical behavior of the testing sample was compared. For example the presence of smoke, the color of the smoke, the dripping of the molten material, and whether the test material has self-extinguishing capability.

3. Results and Discussion

The average total mass loss of each tested material when the sample was exposed to a radiant heat source is represented in Figure 5. The average time (t_{fl}) of a flame appearance as well as the average flame time (t_{bur}) for each material in the logarithmic scale is presented in Figure 6.

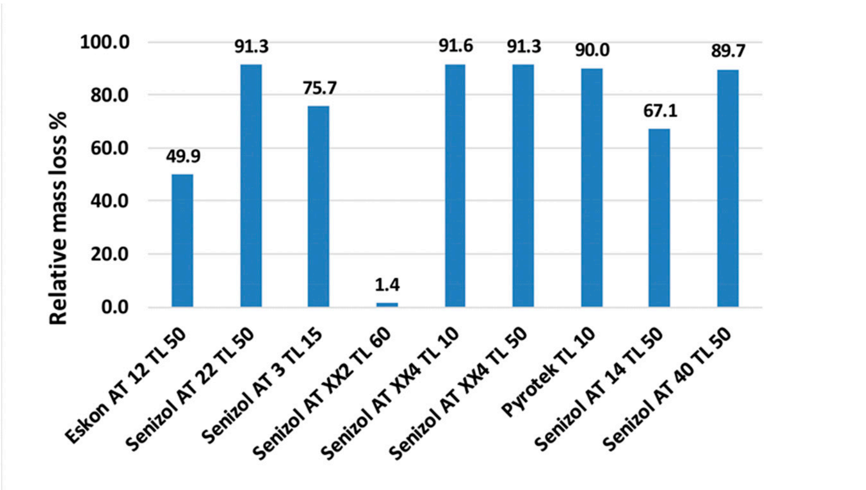


Figure 5. Mass loss of all tested materials.

From Figure 5, it is obvious that the STERED® product Senizol AT XX2 TL 60 had the lowest mass loss (1.4% on average). Immediately after exposure of sample to the radiant heat source, the surface of the material began to melt and a melt formed about 40 s. Until the end of the test, white smoke was released from the material in small amounts and the mass of the samples gradually decreased. The greatest relative mass loss of all nine STERED® products was observed at Senizol AT XX4 TL 50, Senizol AT 22 TL 50 and Senizol AT XX4 TL 1 (91.3%–91.6%). These results are consistent with the results of Oremusova and Hudakova [24]. Oremusova and Hudakova that discovered (via the use of the cone calorimeter method) that the mass loss of various textile materials exceeded 95%.

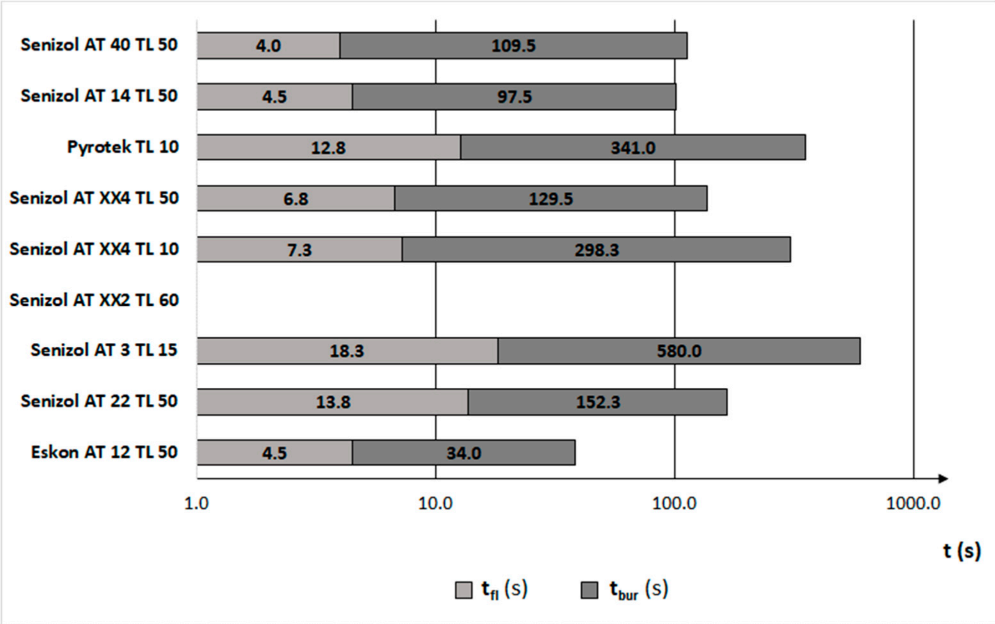


Figure 6. Flash time t_{fl} and flame burning time t_{bur} of tested products.

Almost all the investigated samples of STERED® products burned with the flame burning. The flameless combustion occurred only in the case of the Senizol AT XX2 TL 60 (Figure 6). That explains why this product had the smallest mass loss. We deduce that the flame burning did not occur because the original technical textile may have included the flame retardants in its manufacture. The flame retardants are commonly added to the textile fabrics to reduce flammability [11,25,26].

The results of measuring the sound absorption carried out on the all STERED® products samples are presented in Table 1. This table contains the average sound absorption coefficients, the noise reduction coefficients (NRC) and the densities of all nine types of STERED® products.

It is apparent (Table 1) that the highest value of NRC was found for Senizol AT XX2 TL 60 (0.81). High values of NRC also have been reached for products Senizol AT 22 TL 50 (0.80), Senizol AT 40 TL 25 (0.79) and Senizol AT XX4 TL 50 (0.76). These products have a high ability to absorb unwanted sounds and block noise from traveling to adjacent areas. It appears that the sound absorption depends upon the STERED® product composition, surface structure and density. They can be rated as the best from the point of view sound absorption.

Tiuc et al. [27] measured the sound absorption of polyurethane insulating materials with varying proportions of recycled textile. The highest NRC of 0.59 was achieved for material marked as 60 PRF. This material consists of rigid polyurethane foam (60%) and recycled textile waste (40%). The density of this material was approximately 60 kg m^{-3} (as compared to Senizol AT XX2 TL 60, ϱ = 61 kg m^{-3}).

In addition, Korenkova [28] measured the sound absorption of the textile materials (wool, duffel, fleece and manchester) but only with a thickness of several mm. The highest value of NRC was measured for the fleece with a density of 67.4 kg m^{-3}.

On the basis of our results, it can be said that almost all of the investigated STERED® products can function as highly efficient acoustical absorption materials as well as, for example, wood fiber boards, which are used as light-weight partition structures [29]. Namely, the maximum sound absorption coefficient of wood fiber boards (from 0.51 to 0.99) of the same thickness (50 mm) as Senizol AT XX2 TL 60 was observed at frequencies between 500 and 2000 Hz.

The results of the ignitability test of the STERED® product Senizol AT XX2 TL 60, polystyrene and polyurethane foam are given in Table 2.

Table 2. Ignitability test results of Senizol AT XX2 TL 60, polystyrene and polyurethane foam.

Senizol—exposing the flame to the surface						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	After the flame was applied, the material ignited briefly with a luminous flame, then after removing the source of the flame it extinguished after 20 s and the surface remained melted. The sample released a dense black smoke during burning. After the flame died, the smoke became white. The material did not drip during burning and did not fall out pieces of it.					
Senizol—exposing the flame to the edge						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	After the source was attached, the sample began to burn with a luminous flame and released a dense black smoke. After the flame source was removed, we had to artificially extinguish the sample after 20 s. The material did not fall off and dripped. The 150 mm limit has not been reached.					
Polystyrene—exposing the flame to the surface						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	After the flame was applied, the sample started to melt at the flame application point, and after an average of 7 s has ignited and then extinguished. Particles did not fall from the material and also did not drip away. Smoke was not produced.					
Polystyrene—exposing the flame to the edge						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	After the flame was applied, the sample started to melt at the application site. Ignition occurred after an average 6 s time period and was then was extinguished. The material did not disintegrate and did not drip. Smoke was not produced.					
PUR foam—exposing the flame to the surface						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	The sample burned with a luminous flame after applying the source. On average, the flame died after 8 s. The material did not disintegrate or drip. A sticky liquid layer formed on the burning surface, which coagulated after an average time period of 5 s.					
PUR foam—exposing the flame to the edge						
Sample number	**1**	**2**	**3**	**4**	**5**	**6**
Flame application time (s)	15	15	15	15	15	15
Occurrence of ignition	yes	yes	yes	yes	yes	yes
Reaching a flame height of 150 mm above the attachment point	no	no	no	no	no	no
Sample behavior during the test	After the flame was applied, the sample began to burn. The sample's flame died after an average time period of 9 s. Grey smoke emanated from the sample during the burn. The material did not disintegrate or drip.					

Figure 7 shows the relative mass loss for each tested material. A pair of the columns show the relative mass loss when exposed to the flame on the edge (first column of the pair) and exposed to the flame to the surface (second column of the pair). It is clear from Figure 7 that polystyrene reached the lowest relative mass loss and the recycled textile reached the largest relative mass loss. This is probably due to the fact that recycled textile does not have the ability to self-extinguish. It burned during the entire duration of the test (20 s). Polystyrene and polyurethane foam burned for under 10 s.

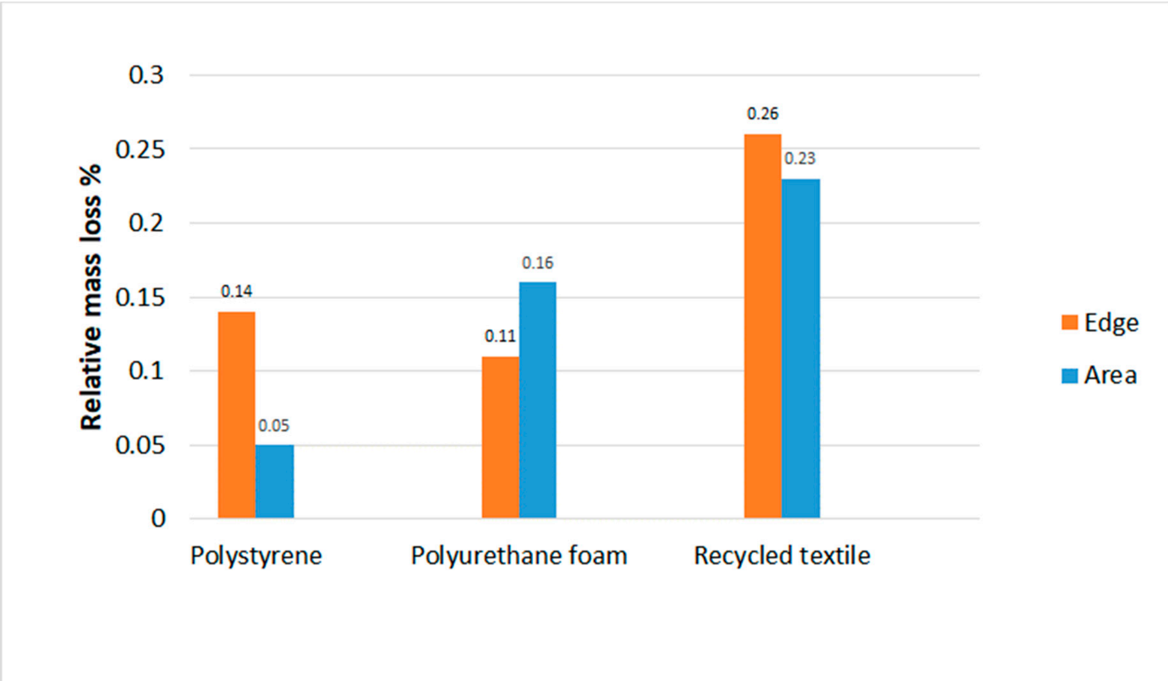
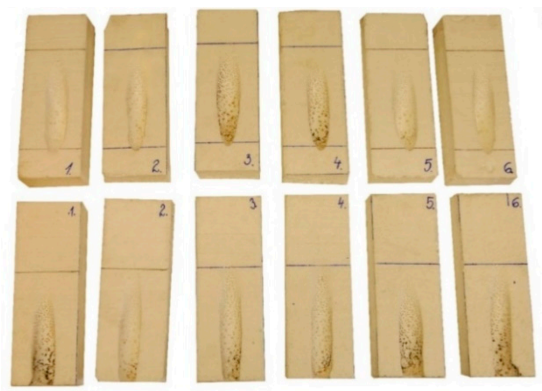


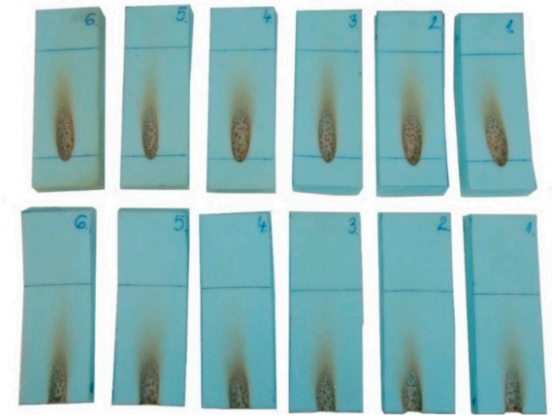
Figure 7. Evaluation of relative mass loss during the ignitability test.

In order to classify a product into the class E of reaction to fire performance, it must comply the following [17]: the flame spread must not exceed 150 mm in the vertical direction from the application point of the test flame within a given time. From the results of the ignitability test, it is clear that although the samples were ignited during the test, the flame did not reach over 150 mm (Figure 8) within the 20 s duration of the test. Thus, it can be stated that STERED® product Senizol AT XX2 TL 60 can be included in the class E reaction to fire performance as well as polystyrene and polyurethane foam.

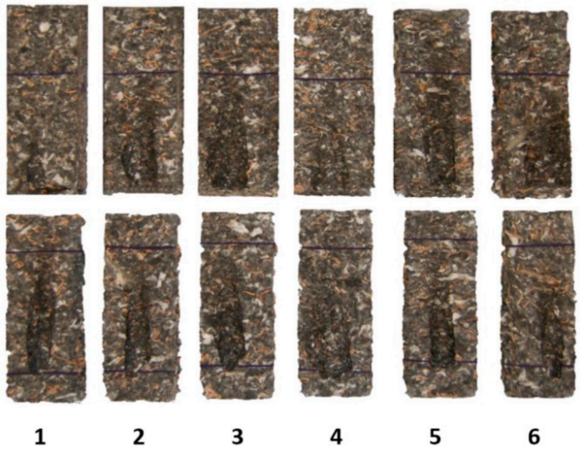


(**A**)

Figure 8. *Cont.*



(**B**)



(**C**)

Figure 8. Polystyrene (**A**), polyurethane foam (**B**) and Senizol AT XX2 TL 60 (**C**) after ignitability test.

4. Conclusions

The primary purpose of insulation in buildings is focused on the thermal side [30,31], but often an insulation material will be chosen for its ability to perform several functions at once. In addition to thermal insulation and soundproofing, it is important that fire protection is included in these functions. In this paper, the acoustic properties and the reaction to fire of nine STERED® products manufactured from recycled automotive technical textiles are introduced. These products are a good solution for reducing the automotive technical textiles waste because their reuse helps to reduce the negative environmental impact.

In the first part of our research, the reaction to fire performance and sound absorption of STERED® products were studied. The evaluated parameters were the mass loss and the noise reduction coefficient of these products.

The results show that STERED® Senizol AT XX2 TL 60 achieved the lowest mass loss (an average of 1.4%). The same product also had the highest value of the noise reduction coefficient (coefficient value of 0.81 at the density of 61 kg m^{-3}). It can be seen that for the frequencies 500 Hz–2000 Hz four of other types of STERED® products had similarly high sound absorption coefficients (above 0.60) and high noise reduction coefficients above 0.70 (Senizol AT 22 TL 50 (0.80), Senizol AT 40 TL 25 (0.79), Senizol AT XX4 TL 50 (0.76) and Senizol AT XX4 TL 10 (0.66)). The sound absorption coefficients of the above mentioned five STERED® products were in the range from 0.80 to 0.99 and according to ISO 11,654 [32], they can be rated as Class A and B absorbers. However, the non-standard thermal test showed markedly worse results of the fire performance of Senizol AT 22 TL 50, Senizol AT 40 TL 25, Senizol AT XX4 TL 50 and Senizol AT XX4 TL 10 as in the case of Senizol AT XX2 TL 60.

From these results is clear that Senizol AT XX2 TL 60 manufactured from the recycled automotive technical textiles meets the conditions for inclusion in the class E reaction to fire, along with the other two tested materials (polyurethane foam and polystyrene). STERED® products Senizol AT XX2 TL 60 and also Senizol AT 22 TL 50, Senizol AT 40 TL 25, Senizol AT XX4 TL 50 and Senizol AT XX4 TL 10 have a high sound absorption ability. More than 60% of the sound energy from waves from the frequency intervals 125, 250, 500, 1000, 2000 Hz entering into these materials will be captured.

The results reveal that the recycled automotive technical textile waste can be a suitable alternative to the commonly used building insulation materials.

Author Contributions: Conceptualization M.N.; methodology J.G.; validation, P.S.; formal analysis, M.G.; resources T.G.; writing—original draft preparation. T.G.; writing—review and editing, A.D.

Funding: This work was supported by VEGA Nr. 1/0031/18 Optimization of technological and work processes and risk assessment in the production of forest biomass for energy purposes; KEGA 009TU Z-4/2017 Building of the progressive and experimental laboratory for innovative forms of education in the study program Fire Protection and Safety; APVV-17-0583.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. North Holding AD. Recent Tendencies in Recycling. Available online: https://nordholding.bg/en/news-en/recent-tendencies-recycling/ (accessed on 2 October 2018).
2. Voncina, B. Recycling of textile materials. *MDT Recycl.* **2016**, *1*, 1–37.
3. Saricam, C.; Okur, N. Polyester Usage for Automotive Applications. In *Polyester-Production, Characterization and Innovative Applications*, 1st ed.; Camlibel, N.O., Ed.; IntechOpen: Zagreb, Croatia, 2018; pp. 69–85.
4. European Parliament. *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End-Of Life Vehicles*; European Parliament: Bruxelles, Belgium, 2000.
5. Djordjevic, D.; Avramovic, B. New insulation material produced by auto-textile waste recycling–Izoretex. In *Contemporary Achievements in Civil Engineering*; Birografika MB: Subotica, Republika Srbija, 2015; pp. 29–35.
6. European Parliament. *Directive 2012/27/EU of the European Parliament and of the Council of October*; EP: Bruxelles, Belgium, 2012.
7. European Parliament. *Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013*; EP: Bruxelles, Belgium, 2013.
8. Zeinab, S.; AbdeL-Rehim, Z.S.; Saad, M.M.; El-Shakankery, M.; Hanafy, I. Textile fabrics as thermal insulators. *Autex Res. J.* **2016**, *6*, 148–161.
9. Hadded, A.; Benltoufa, S.; Fayala, F.J. Thermo physical characterisation of recycled textile materials used for building insulating. *Build. Eng.* **2016**, *5*, 34–40. [CrossRef]
10. Rubino, C.; Liuzzi, S.; Martellotta, F.; Stefanizzi, P. Textile waste in building sector. A review. *Model. Meas. Control B* **2018**, *87*, 172–179. [CrossRef]
11. Ozcan, G.; Dayioglu, H.; Candan, C. Application of flame-retardant products to knitted fabric. *Indian J. Fibre Text. Res.* **2006**, *31*, 330–334.
12. Iaşnicu, I.; Vasile, O.; Iatan, R. The analysis of sound absorbing performances for composite plates containing recycled textile wastes. *UPB Sci. Bull. Ser. D* **2016**, *78*, 213–220.
13. STERED in House. Available online: http://www.stered.sk/stered-v-dome?lang=en (accessed on 25 September 2018). (In Slovak).
14. Discover the world of STERED . . . (Objav svet STEREDu . . .). Available online: http://www.stered.sk/uvod (accessed on 25 September 2018). (In Slovak).
15. The Unusual Thermal and Sound Insulation STERED®. Available online: http://www.stered.sk/wp-content/uploads/2014/09/serial-PSS-Stered.pdf (accessed on 25 September 2018). (In Slovak).
16. Danihelová, A.; Bubeníková, T.; Bednár, M.; Gergel, T. Acoustic properties of selected thermal insulation materials and their contribution to pollution of environment. *Akustika* **2018**, *30*, 35–41.
17. The International Organization for Standardization (ISO). *ISO 11925-2: Reaction to Fire Tests. Ignitability of Products Subjected to Direct Impingement of Flame. Part 2: Single-Flame Source Test*; ISO: Geneva, Switzerland, 2010.

18. The International Organization for Standardization (ISO). *ISO 10534-2: Acoustics-Determination of Sound Absorption Coefficient and Impedance in Impedances Tubes. Part 2: Transfer-Function Method*; ISO: Geneva, Switzerland, 1998.
19. Gergeľ, T.; Kamenská, V.; Oravcová, J.; Kačíková, D.; Danihelová, A.; Němec, M. Potential of recycled fabric utilization in terms of fire protection and acoustics. In Proceedings of the International Conference Fire Protection, Safety and Security, Zvolen, Slovakia, 3–5 May 2017; Majlingová, A., Veľková, V., Eds.; TU in Zvolen: Zvolen, Slovakia, 2017; pp. 57–63.
20. Deaconu, M.; Toma, A.C.; Dragasanu, L.I.; Mihai, D. Comparative study of sound absorption coefficient determination using FEM method and experimental tests on Kundt's tube. In Proceedings of the AIP Conference Proceedings, Roma, Italy, 5 June 2017; Ntalianis, K., Ed.; AIP Publishing: Roma, Italy, 2017; pp. 1–6.
21. Danihelová, A.; Čulík, M.; Mitterová, I. Evaluation of selected properties of Krupinit. In Proceedings of the 4th International Conference on Applied Technology, Leuven, Belgium, 15–16 September 2016; Chmelík, V., Hartman, P., Rychtáriková, M., Eds.; The Katholieke Universiteit: Leuven, Belgium, 2016; pp. 81–86.
22. Kusno, A.; Sakagami, K.; Okuzono, T.; Toyoda, M.; Otsuru, T.; Mulyadi, R.; Kamil, K.A. Pilot Study on the Sound Absorption Characteristics of Chicken Feathers as an Alternative Sustainable Acoustical Material. *Sustainability* **2019**, *11*, 1476. [CrossRef]
23. British Standards Institution. *EN 13501-1:2018. Fire Classification of Construction Products and Building Elements. Part 1: Classification Using Data from Reaction to Fire Tests*; BSI: London, UK, 2018.
24. Orémusová, E.; Hudáková, M. Coating textiles based on natural and synthetic fibers evaluated by the cone calorimeter method. In *Proceedings of the 5th International Scientific Conference Security–Quality–Reliability*, 1st ed.; TUKE: Košice, Slovakia, 2011; pp. 201–206.
25. Lewin, M.; Weil, E.D. Mechanism and modes of action in flame retardancy of polymers. In *Fire Retardant Materials*; Horrocks, A.R., Price, D., Eds.; Woodhead Publishing Limited: Cambridge, UK, 2001; pp. 31–68.
26. Muralidhara, K.S.; Sreenivasan, S. Thermal Degradation Kinetic Data of Polyester, Cotton and Polyester-Cotton Blended Textile Material. *World Appl. Sci. J.* **2010**, *11*, 184–189.
27. Tiuc, A.E.; Vermeşan, H.; Gabor, T.; Vasil, O. Improved sound absorption properties of polyurethane foam mixed with textile waste. *Energy Procedia* **2016**, *85*, 559–565. [CrossRef]
28. Kořenková, M. Dependence of Acoustic Absorption on the Layer Thickness of Selected Textile Materials. Master's Thesis, Tomas Bata University in Zlín, Zlín, Czech Republic, 2010.
29. Jochim, S.; Čulík, M.; Puškár, A.; Danihelová, Z. Sound reduction index of multi layered walls for wooden constructions. *Akustika* **2017**, *27*, 18–27.
30. Igaz, R.; Krišťák, L.; Ružiak, I.; Gajtanska, M.; Kučerka, M. Thermophysical Properties of OSB Boards versus Equilibrium Moisture Content. *BioResources* **2017**, *12*, 8106–8118.
31. Krišťák, L'.; Igaz, R.; Ružiak, I. Applying the EDPS Method to the Research into Thermophysical Properties of Solid Wood of Coniferous Trees. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 1–9. [CrossRef]
32. The International Organization for Standardization (ISO). *ISO 11654: Acoustics. Sound Absorbers for Use in Buildings. Rating of Sound Absorption*; ISO: Geneva, Switzerland, 1997.