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RESEARCH

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Influence of the polyester non-wovens production type on their thermal and flammability properties

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Abstract

In recent years, non-wovens have become the main segment of textile production because they can find applications in different areas. Thermal insulation properties, fire resistance, and flexibility make them cost-effective and efficient insulation panels for buildings. This paper aims to study the influence of the production method and surface treatment on the thermophysical characteristics and behavior under direct fire of two polyethylene terephthalate non-woven fabrics. The fibers have been bonded with polyacrylate adhesive or thermal and coated with silicone. Infrared spectroscopy, optical microscopy, and thermal analyses were applied to compare the non-wovens' morphology, composition, and thermal properties. It founds that the non-woven polyester with acrylic additives and adhesive bonding has a higher thermal conductivity value and high flammability with complete combustion. In contrast, thermosetting siliconized polyester materials have limited flammability with limited droplet release. The silicone-based finish protects the polyester fibers leading to self-extinguishing and stopping the complete combustion of the sample.

Keywords: Non-wovens, Thermal insulation, Flame retardant, Thermal conductive coefficient

Introduction

Thermal insulation is a substantial element in ensuring energy efficiency in building construction. Polymers have been of great interest for this purpose due to their excellent properties, such as waterproof, anti-corrosion, wear resistance, anti-seismic, lightweight, good strength, sound, heat, and electrical insulation [1]. Polystyrene (PS), polyurethane (PU), and polyvinyl chloride (PVC) in the foam form are already found the wide application as thermal insulation materials in the building industry [2]. Despite their exceptional characteristics, some problems are the reason for continuing research on perfect thermal insulation. The studies have focused on improving their brittle and fracture resistance, recycling the polymer waste, use of renewable raw materials [3]. The other requirements are a uniform pore structure, mechanical strength, climate ageing durability, microbial resistance, the ability to regulate the thermal insulation level, resistance towards water, and freezing/thawing cycles. Other properties are fire resistance without smoke and toxic gases during burning. The materials must be able to be cut and adapted on the construction site and be cost-effective [4].

Textile insulation products from virgin or recycled materials have many advantages and comparable properties with other insulation materials [5]. In many applications, the non-wovens are preferred to the conventional woven and knitted fabrics due to their properties and easy making, combining high productivity with lower cost. Non-woven production technology allows easy recycling of fiber waste [6]. A cheap resource used as textile waste has an environmental and economic effect [7].

Recovery of industry-generated waste has been an extremely pressing issue in recent years because waste has a serious impact on the ecological balance of the Earth [7]. The protection of the environment, as well as the new circular economy development tendencies, made it possible to examine various new ways to utilize waste—domestic, construction, or industrial—be it as a raw material for a new production, a heat source (RDF, SDF), or as a component in various building materials.

A promising area is the textile waste utilization from the light industry, listed in Directive 2008/98/EC on waste and repealing certain directives [8] and Commission Decision of 3 May 2000, and fully fitting into the "Roadmap to a Resource Efficient Europe". According to the United States Environmental Protection Agency [9], ordinarily only about 15% of all textile waste is recycled. These available free resources are suitable for the production of cheap insulation materials.

Polyester fibers are the most widely used non-wovens and have the potential to be 100% recyclable. Polyester (PET) is a thermoplastic synthetic polymer from which almost 52% of all textile fibers are produced [10–13]. However, only 13% of it is subject to subsequent recycling [13]. There are already many studies that present the merits of this material for the production of thermal insulation [6, 14–18].

The main application of PET is for light non-woven products in the form of wadding, auxiliary sewing materials, cushion stuffing, filters, medical patches, masks etc. [13] As a textile material, PET has several advantages - good mechanical properties, moisture resistance, resistance to temperature and light, as well as good chemical resistance to solutions of acids and bases at room temperature. The main disadvantage is its low hygroscopicity, due to which it is difficult to dye and is highly prone to static electricity [10, 19]. Polyester belongs to the so-called moderately flammable fibers that are more difficult to ignite. As the other synthetic polymers (e.g., acrylic, nylon), PET tends to melt and drip, sometimes self-extinguishing upon removal of the ignition source [20]. The flame retardant properties of PET non-woven fabrics can be improved by using relatively non-flammable fibers but also by application of additives in finishing [21, 22]. The coatings on the fibers can prevent flame propagation and improve resistance to irradiative heat flux exposure [23]. The presence of inorganic additives like silica derivates can form protective glassy layers that could insulate the inner layers from further decomposition. Silicones have been used successfully as a flame retardance addition, thanks to their high thermal stability, minimal sensitivity to external heat flux, low heat release rate, and low toxic gas generation during combustion [21, 24].

The current paper presents specific test results aiming to determine the basic thermophysical characteristics and behavior under direct fire of PET samples which are obtained by different production methods and are a waste product from the textile industry. The aim is to establish whether these non-wovens are suitable for and meet the requirements for being used as building thermal insulation materials.

Experimental

Materials

The subject of the study is two non-woven fabrics obtained from polyester fibers with different coating and production technologies (adhesive or thermal bonding). Five probes cut into a square shape (side 25 cm) were tested from each non-woven. The fabrics' properties are given in Table 1.

Methods

Morphological analysis of samples conducted by a light optical microscopy

The structure of the tested samples was defined using a Metam LV41 light microscope. Various techniques have been applied—dark field and polarized light, aiming a better fiber visualization.

FTIR analysis

For the characterization of the studied non-woven fabrics, mATR-FT-IR analysis was applied. The spectra were obtained from an infrared Fourier transform spectrometer (IRAffinity-1, Shimadzu), equipped with a diffuse-reflectance attachment (MIRacle Attenuated Total Reflectance Attachment). Measurements were done using a spectral range of 600–4000 cm^{-1}. This allows for the application of instrumental non-invasive analysis to determine the non-wovens production method and decide on the further processing ensuring their new, enhanced properties.

Differential thermal and thermogravimetric analysis (DTA and TGA)

The simultaneous thermal analysis TGA was carried out with STA PT1600 TG-DTA/DSC analyzer (LINSEIS Messgeräte GmbH, Germany) at a heating rate of 10°C/min between room temperature and 600 °C under an air atmosphere.

Thermal properties measurement

The thermal properties of the samples were measured using the ISOMET 2114 instrument, which is based on the modified transient plane source (MTPS). The measurement accuracy is ± 5%. The averages of 10 measurements for each sample were taken, and the mean values of the thermal properties were calculated. The following parameters are defined: thermal conductivity (k), volumetric heat capacity (c_p), and thermal diffusivity (α) [25, 26].

Table 1 Samples description

Name	Type of non-woven	Joining techniques	Weight, g/m^2	Fabric density, kg/m^3	Thickness, cm
Sample 1	Polyester fibers bonding with polyacrylate dispersion	Adhesive bonding	150	8,45	2
Sample 2	Thermally bonded polyester fibers with silicone coating	Thermal bonding	150	7,90	2

Infrared camera visualization

The behavior of the tested materials under thermal impact is examined on a specially built experimental installation. All test specimens are subjected unilaterally to a heat flux generating a temperature of $T = 60$ °C. The heat source is located at a 30-cm distance from the test samples. The heat field is 12 × 15 cm.

The samples are photographed with a FLIR 60Ebx infrared camera to visualize the heat field distribution. Infrared images are taken after different periods of short-term exposure to heat—0 min, 3 min, and 5 min.

Flammability testing

A flammability test by the BDS EN ISO 6941: 2006 standard is performed. The method of the edge ignition is applied. A burner is placed perpendicularly, in the middle of the front side of the test specimens. The length of the flame is 40 mm and is fed by propane gas. The axis of the burner to the vertical plane of the lower sample end is at an angle of 30°. The distance between the end of the burner and the lower end of the sample is 20 mm. All the tested samples (dimensions 25 cm × 12.5 cm) are conditioned under a standard atmosphere at a temperature of 25 °C and relative humidity of 65%. The test is performed under standard conditions with fire duration of 5 s.

Results and discussion

Morphology of non-wovens

The test specimens were made from polyester fibers with a smooth surface and nearly circular cross-section (Fig. 1). The fibers in sample 1 have a shiny and transparent surface, and the fibers in sample 2 have a matte surface with good polarizing ability. Both samples of test materials have a high degree of transparency due to their low density.

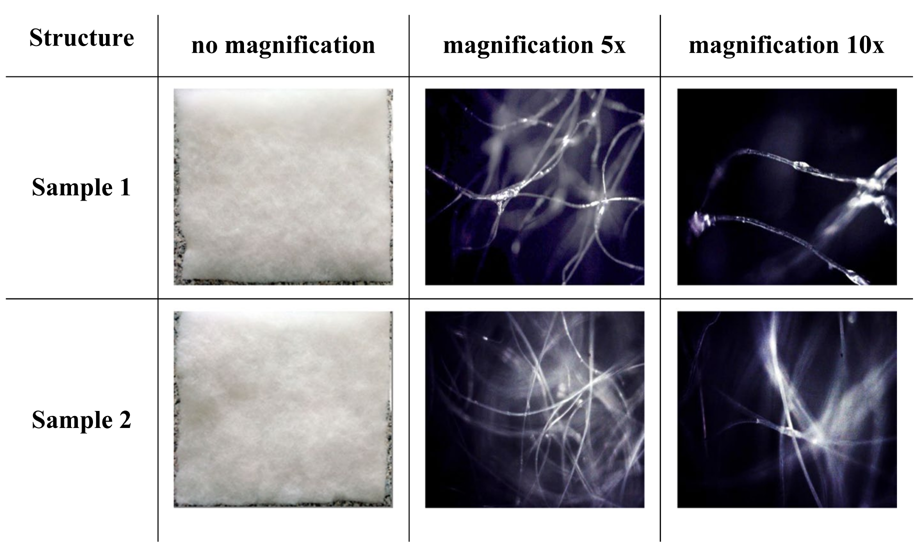

Fig. 1 Structures of the non-wovens at different magnifications

Infrared analysis

Figure 2 shows the infrared spectra of the non-woven fabrics sample 1 and sample 2 in the range from 1800 cm^{-1} to 600 cm^{-1}. The polyester fibers in the sample 2 have been thermally bonded and coated with silicone. The blue arrows in Fig. 2A) show the

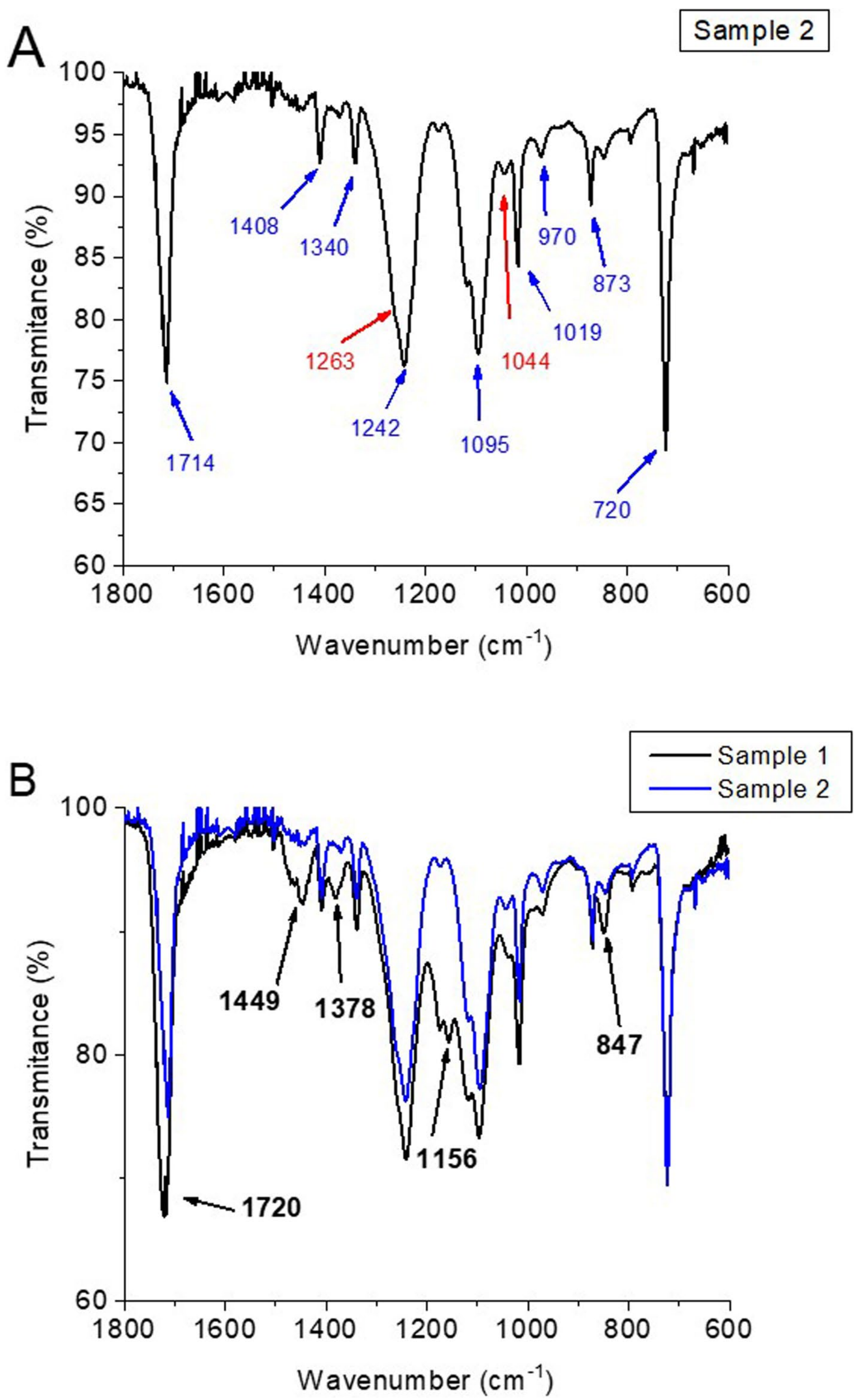

Fig. 2 FT-IR spectra. **A** Sample 2. **B** Comparison of sample 1 and sample 2

characteristic bands of polyester functional groups and values of their maxima. The stretching vibration of C=O in either group was characterized by a strong band of 1714 cm^{-1}. The 1408 cm^{-1} band shows a vibration of the aromatic ring, and the 1340 cm^{-1} one of the C–H bonds. The stretching vibrations appear at 1242 cm^{-1} (C–O bond in –O–C=O), at 1095 cm^{-1} (indicates the presence of C–O in O–CH_2), at 1019 cm^{-1} due to C–O–C, and at 970 cm^{-1} (C–O bond). The C–C and C–H vibrations from the benzene ring in the polyester appear at 873 cm^{-1} and 723 cm^{-1}. It is difficult to distinguish the main characteristic bands for the silicone coating because they coincide with the typical bands for polyester. In the Fig. 2A) two bands are pointed with red arrows. The presence of Si–(CH3)3 is confirmed by the absorption peaks at 1263 cm^{-1} and it appears in the spectrum as a shoulder of the peak with a maximum at 1242 cm^{-1}. A low-intensity peak appears at 1044 cm^{-1} due to the Si–O–Si connection.

In Fig. 2B, the infrared spectra of both samples are compared. In sample 1, the polyester fibers have been bonded by polyacrylate adhesive that is well visible in its IR spectrum. The band intensity of 1720 cm^{-1} is increased due to the presence of C=O groups. The bands with the intensity of 1449 cm^{-1}, 1378 cm^{-1}, and 847 cm^{-1} are assigned to the C–H bond, respectively from CH_3, CH_2–CO, and CH_2 groups. The transmittance bands with the intensity of 1156 cm^{-1} are ascribed to C–O–C.

Thermal degradation behavior of non-wovens

The thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) curves of both non-woven PET fabrics in air are shown in Fig. 3A, B, respectively. The fabrics' thermal degradation has three stages. The first weight loss stage is at around 225–340 °C for sample 1 and around 225–380 °C for sample 2. This stage is associated with the process of moisture removal absorbed from the air. Therefore, the second main weight-loss percentage stage starts for sample 2 at a higher temperature than for sample 1 and ends at 450 °C for both samples. The weight loss for sample 1 is 78% and 74% for sample 2 because polyester fibers become thermal stable after their coating with silicone. During the third stage, for both fabrics, the weight decreases gradually. The remaining residues at 600 °C for sample 2 (11.27%) are higher than for sample 1 (9.60%). These results show better thermal stability of sample 2 because the silicone coating protects the polymer fibers.

The DTG curves give detailed information about the ongoing processes. They allow pointing precisely the number of thermal degradation stages and the temperature of maximum degradation rate T_{max}. The height of the DTG picks shows the rate of mass decomposition kinetics [27]. Figure 3B displays the T_{max} of each degradation stage of non-wovens. For sample 2, two or even three processes can point in the region between 450 °C and 600 °C. For sample 1, the critical weight loss stage is more complex and probably combines several successive processes.

Figure 4 shows the differential thermal analysis (DTA) of sample 1 and sample 2. Fabric thermal decomposition in the air begins with an exothermic process that ends at 227 °C, followed by an endothermic process, represented by a narrow peak with a maximum of 255 °C for sample 2 and a broad peak for sample 1. These peaks in the DTA chart are related to the first step of weight loss in the TGA curve and may be associated with the dehydration process. Also, a small peak is observed in the DTG graph

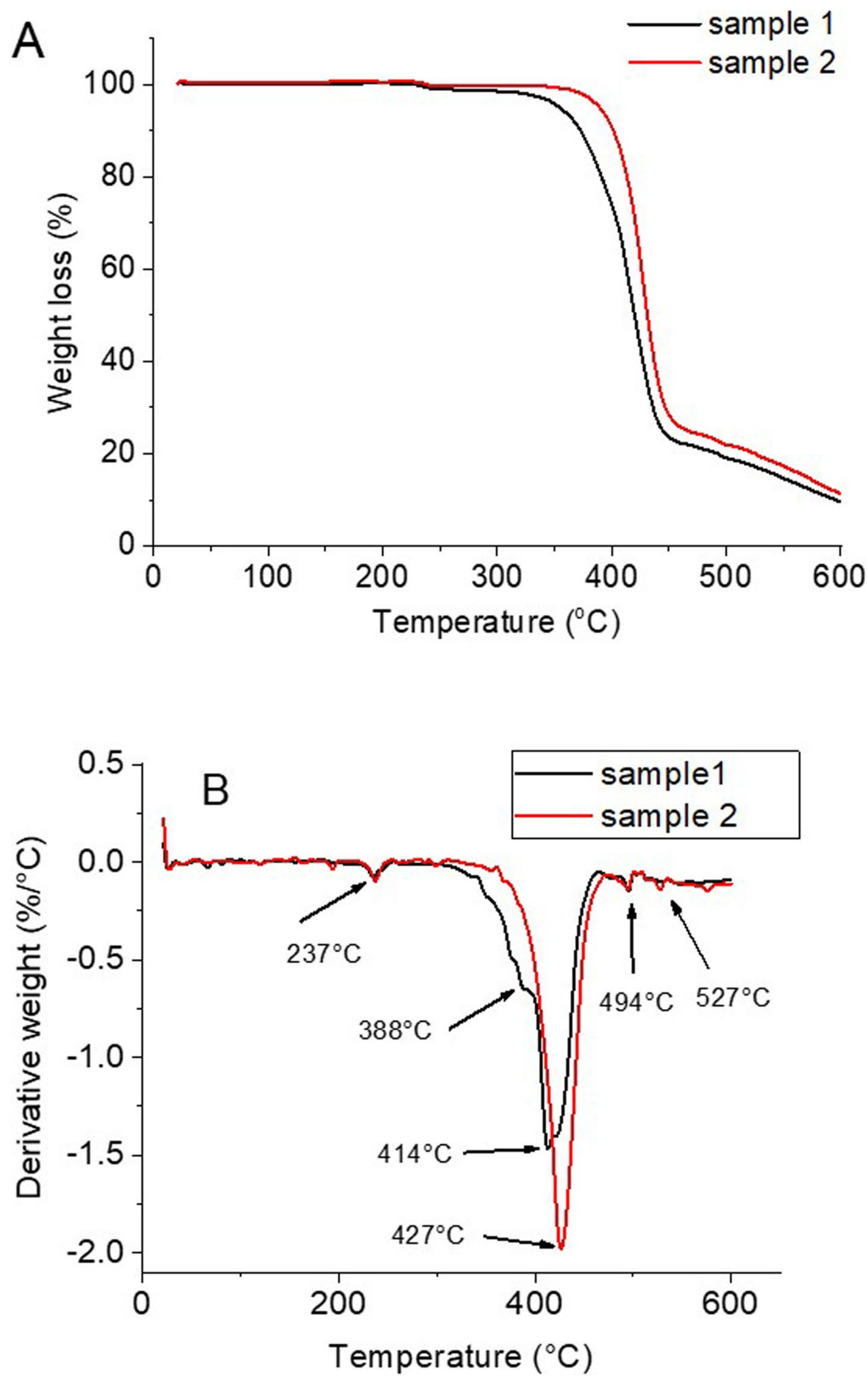

Fig. 3 Thermal degradation behavior for non-wovens. **A** TGA diagrams. **B** DTG diagrams

in this temperature range. Next, the chemical transformation continues as exothermic combustion reactions. Significant weight loss in TGA (Fig. 3A) and peaks in DTG curves (Fig. 3B) were observed at this temperature range, indicating the degradation of polyester fibers. After that, the exothermic process continues faster for sample 1 and ends at

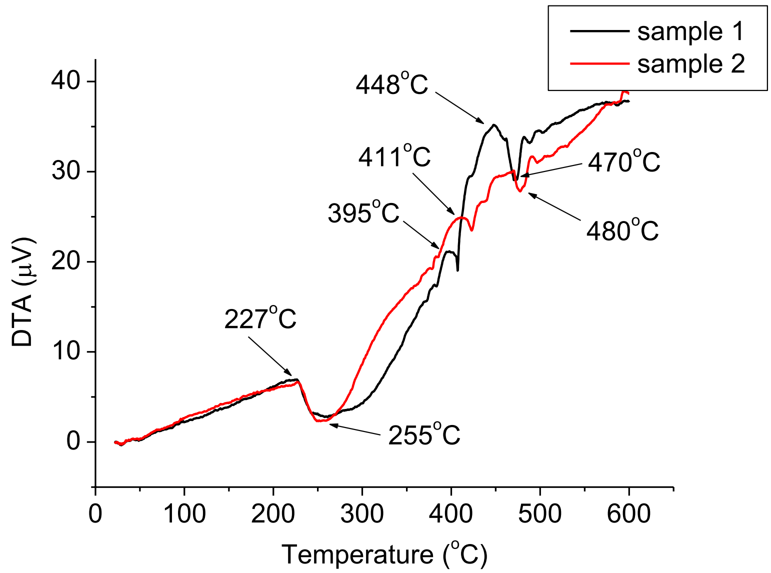

Fig. 4 Differential thermal analysis (DTA) of the sample 1 and sample 2 in air (heating rate of 15 °C/min)

448 °C. This temperature coincides with the end of the second stage in the TGA curve. Next, the endothermic peaks appear with a maximum of 470 °C and 480 °C accordingly for sample 1 and sample 2. Subsequently, the exothermic conversion of the materials continues with further heating.

Thermophysical study

Table 2 presents the results of the thermophysical study of the tested non-woven materials. Both samples have a very similar coefficient of thermal conductivity; therefore, they have similar thermal insulation properties. The results are analogous to those of other authors [27–31]. The non-woven fabrics' thermal insulation properties are comparable to those of foamed polymer insulators such as polystyrene, polyurethane, polyvinyl chloride, and others [32]. The specific heat capacity for both materials is high. This makes them good thermal insulators. The heating of the material will be slow. Only a greater heat amount would lead to a temperature change. However, sample 1 has a lower heat capacity value. Therefore, they have less ability to accumulate heat and have a better thermal conductivity compared to sample 2. Sample 1 shows a more than 20% higher value of thermal diffusivity than sample 2. The non-woven fabric bonded by a polyacrylate dispersion has a higher temperature than the thermally bonded non-woven

Table 2 Thermal properties of the non-woven fabrics

Name	Thermal conductivity[a] k, (W/mK)	Volumetric heat capacity[a] c_p, (J/m^{3}K)	Thermal diffusivity[a] α, (m^2/s)	Specific heat resistance[b], R, m.K/W
Sample 1	0.0393 ± 0.00057	$0.0630.10^6 \pm 0.0015.10^6$	$0.6250.10^{-6} \pm 0.0116.10^{-6}$	25.44
Sample 2	0.0403 ± 0.00059	$0.0816.10^6 \pm 0.0020.10^6$	$0.4937.10^{-6} \pm 0.0092.10^{-6}$	24.81

[a] Measured

[b] Calculated $R = 1/k$

fabric with a silicone coating. This is crucial for their flammability as sample 1 would have better flammability compared to sample 2.

The infrared imaging of the studied materials (Fig. 5) shows a very similar thermal behavior and an identical heat field distribution. Despite their different heat storage capacity, during the short-term heat exposure, the studied materials reach very similar maximum temperatures in the range of 75–82 °C for sample 1, and the range of 78–82 °C for sample 2. The registered temperature difference between the two surfaces in the sample 1 is averagely $\Delta T = 10$ °C, and in the sample 2–averagely $\Delta T = 8$ °C.

The uneven distribution of the thermal field proves the stochastic and uneven distribution of the fibers, and therefore their uneven density in the studied objects, which is a result of the production technology. The local density of the samples directly affects their thermal behavior.

The conducted burning test proves that the polyester fibers processing in non-woven fabric production has an enormously strong influence on their flammability. The results are presented in Figs. 6 and 7.

Series 1 samples are ignited at the time of the fire application and develop intense combustion lasting up to 10 s after its removal. The combustion is also accompanied by an intensive melting, smoke emission, and formation of many liquid burning drops. The samples have a specific yellow flame and burn completely within 25–30 s of the test start.

Series 2 samples are ignited at the time of the fire application but have limited combustion. The duration of the residual combustion is about 12 s. The silicone coating of the fibers leads to a sparse separation of individual liquid burning droplets. Combustion is also accompanied by intense melting and smoke. The sample is partially burned with a 50% loss of the test area. Charring of the burnt edges is registered. The sample burns slowly with a yellow flame.

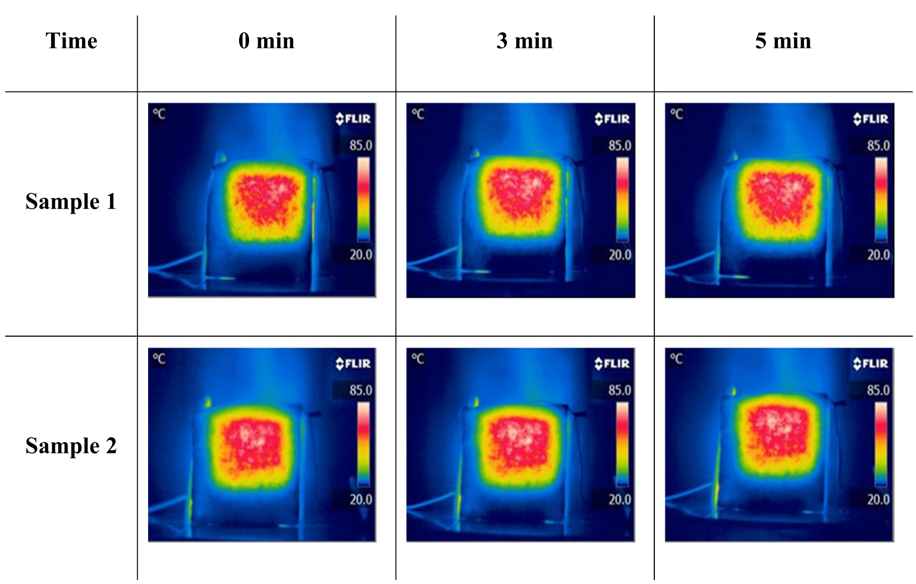

Fig. 5 Infrared images of the studied samples

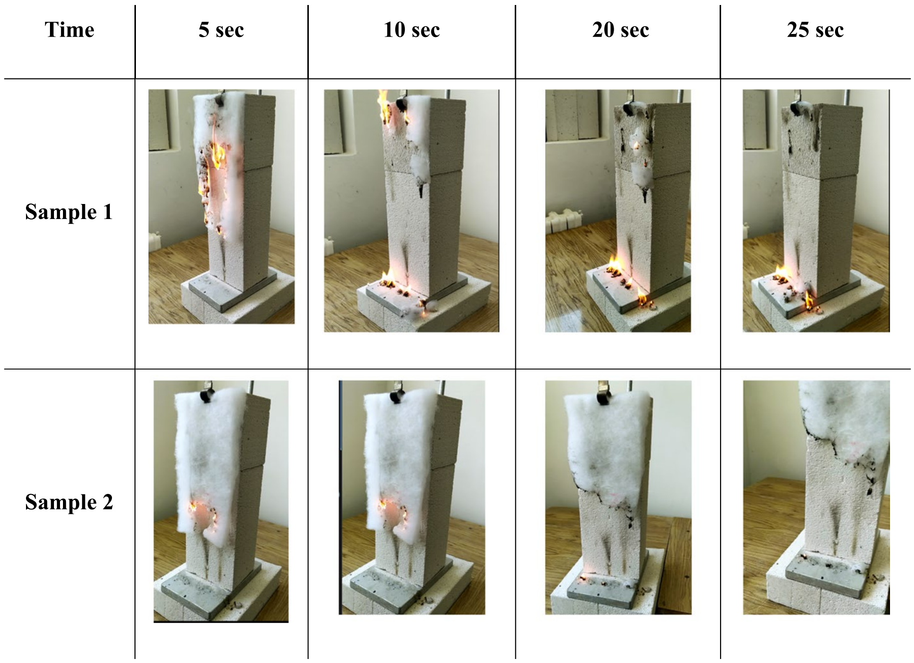

Fig. 6 Burning time (in seconds) of the samples after flame removing

Conclusions

The studied polyester non-wovens have distinguished thermal insulation properties ($k \approx 0.04$ W/m.K) comparable to the other materials (polystyrene foam, polyvinyl chloride foam, and polyurethane foam) traditionally used in construction thermal insulation. They have the same weight and thickness with a modest difference in their density and different method of production, which, however, affects their thermophysical characteristics.

The non-woven polyester with acrylic additives and adhesive bonding has a higher thermal conductivity value and high flammability with complete combustion. In

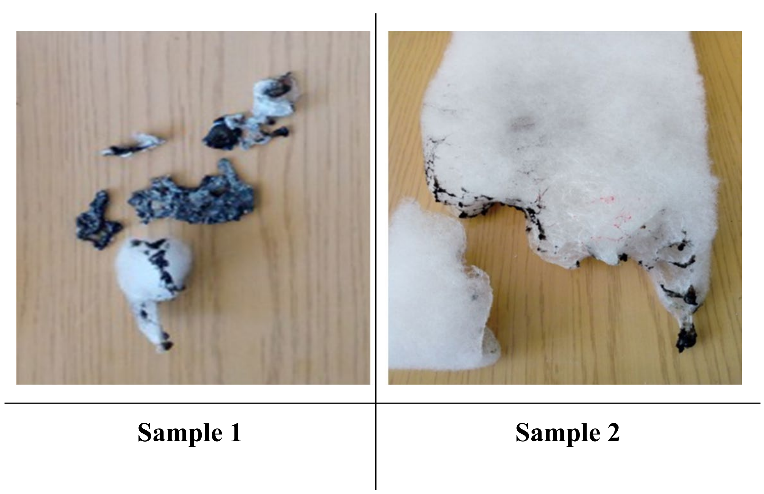

Fig. 7 Remainders of the tested materials after the flammability test

contrast, thermosetting siliconized polyester materials have limited flammability with limited droplet release.

Polyester fibers with silicone coating have better thermal stability than polyester fibers without it, which has been established and proven by carried out tests.

The research continues with the siliconized thermally bonded polyester non-woven fabrics and their suitability as a thermal insulation material in construction.

Abbreviations

PET Polyester
MTPS Modified transient plane source
RDF Refuse-derived fuel
SDF Solid recovered fuel
FT-IR spectrum Fourier transform infrared spectrum

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Not applicable.

Authors' contributions
RPS and PZ study conception and design. RPS, PZ, and DS C contributed to the data collection analysis and interpretation of the results. RPS, PZ, and DS contributed to the draft manuscript preparation and review. The authors read and approved the final paper.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no competing interests.

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