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Mechanical recycling of foam from end-of-life mattresses by AIR-LAY process for the production of new mattresses with a fully circular approach

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ABSTRACT

A novel method for the recycling of end-of-life mattresses foam, using an AIR-LAY process which employs a bi-component fiber as a binder for the polyurethane foam, have been developed and optimized. This method permits to obtain materials with the same density of the starting foam (25 kg/m^3) and with a significantly lower density with respect to that obtainable with the rebonding process (above 70 kg/m^3) that uses isocyanates to bond the foam particles. The obtained recycled foams have been tested by mechanical compression and recovery tests showing that compression values of 3.7 KPa, similar to that of the mattress foam (3.0 KPa), can be achieved using 20 % of bi-component fibers as binders and a density of 35 kg/m^3. On the contrary, only 3 times stiffer and denser materials can be obtained using the rebonding technology, thus making them not suitable for application in mattresses. On the basis of the results of the optimization tests a set of mattresses containing a layer of the recycled foams have been prepared. The results of the tests on the prepared mattresses have shown that they have the same compression behavior, recovery time and durability (after 30,000 cycles of compression) of a standard mattress without the recycled layer, thus proving that a fully circular approach in the recycling of the foam of the mattresses is possible using the AIR-LAY process.

Introduction

The world mattresses market has been continuously expanding for many years and it was worth € 24 billion in 2017 with an expected grow to € 37 billion in 2024, with a replacement time that is attested, depending on the country, between 8 and 10 years (Statista, 2017). The types of mattresses most commonly used (i.e. springs, latex and polyurethane (PU) based) differ from country to country, with a trend towards the growth of PU and hybrid mattresses, which combine different components with an estimated average composition of 45 % springs, 42 % PU and 11 % latex (CalRecycle - California Department of Resources Recycling and Recovery, 2012). Reliable estimates about the number of mattresses discarded each year can be derived from systematic surveys made at the level of individual countries. On this basis it is possible to estimate that about 450 million mattresses are in use in the EU with a replacement rate of about 9 % per year, leading to about 40 million/year and over 700 million tons/year of dismissed mattresses (Cordella and Wolf, 2013). Only a small part of them is recycled, while the majority becomes waste and ends up in landfills or in incinerators. The environmental impact is substantial and derive primarily from the nature and quantity of the materials involved and therefore from the resulting consumption of resources (Percival et al., 2022). Other aspects, such as high volumes due to the low density of foams, make the management of mattress waste not easy as regards both logistics and delivery to incineration plants (Trainer, 2004). Nevertheless, at the moment, neither policies nor specific regulations on the end-of-life of mattresses have been defined at European level. Even the Ecolabel criteria, recently renewed, do not contain prescriptions on the end-of-life and recycling. It only generically refers to these topics in terms of eco-design criteria. *"The manufacturer shall demonstrate that the mattress can be dismantled for undertaking repairs and replacements of worn-out parts, upgrading older or obsolete parts, and separating parts and materials for its potential recycle"*

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(Bojczuk, 2012). However, several European countries have developed national policies and strategies for a circular economy approach for mattresses. In particular, France has implemented an effective policy, based on the Extended Product Responsibility (EPR), involving a vast collection network and a series of industrial plants for the disassembly of the mattresses and for the recycling of the components. Other significant experiences are underway in the UK, Holland and Belgium (Ademe, 2014).

Of the different components of mattresses, the metal and textile components can be directed to the recycling industries that are already operational, while there is no supply chain capable of recycling the post-consumer PU deriving from used mattresses.

Polyurethane based thermoplastic materials and foams amounts to about 7.7 % of the global plastic demand. End-of-life PU generates significant amounts of waste since only 29.7 % of it is recycled. While 39.5 % is recovered through energy recovery processes and 30.8 % of the total waste is landfilled (Gadhave et al., 2019). The natural slow decay of PU materials and their poor disposal management create a severe hazard to environmental pollution when these materials are dumped after use (Scheirs, 1998). Moreover, incineration, that is the main option actually applied, lead to the generation of gas that contribute to the greenhouse effect and pollute the environment (Garrido et al., 2016). For these reasons, the various recycling technologies for mechanical and chemical recycling of PU materials have greatly contributed to improve the overall sustainability of polyurethanes in recent years (Europur Association, 2016).

Currently, the most widespread mechanical recycling technology of flexible polyurethane foams that has found application on an industrial scale is the rebonding technique, which is almost only used for the recycling of pre-consumer flexible polyurethane waste (Guo et al., 2022). In the rebonding process the shredded polyurethane foam waste with dimensions of about 1 cm is mixed with the monomers or prepolymers used for the production of soft polyurethane foams, which are generally based on diphenylmethane diisocyanate (MDI) and polyols (ester or ether based). The main limit of this process is the minimum obtainable density, which generally exceeds 60 kg/m^3 (Kemona and Piotrowska, 2020). This aspect does not favor the application in the field of mattresses in which a density of 25 kg/m^3 is needed (Ademe, 2014). Therefore, this process has been only used to produce foams for other applications (e.g. thermal insulation and construction) (Zia et al., 2007). In the Netherlands, RetourMatras has built 4 partially automated mattress treatment plants, capable of separating the different types of components and sending them for recycling. The plants have the capacity to process 400,000 mattresses/year. Other processes that recycle mattresses by rebonding are Recyc-Matelas (France) (Ademe, 2014) and Matras Recycling Europe (The Netherlands) (Ademe, 2013). The other option for PU recycling that can be applied to mattresses is chemical recycling. This method is characterized by processes that allow to generate new raw materials, in particular polyols, to be used for the production of new PU. The glycolysis process, that is the most used, consists of a reaction of the urethane groups present in the polymer with a glycol, carried out at high temperature and in the presence of a suitable catalyst, which leads to the formation of a liquid product, consisting mainly of the original polyol and low molecular weight oligomers (Wu, & Chang, 2002). This product is reusable in quite high percentages together with virgin polyol for the synthesis of new materials or can be used as a fuel (Zia et al., 2007). To date, chemical recycling for this type of waste is a technology that still needs optimization and further development in order to overcome many obstacles such as (Manžuch et al., 2021):

- The types of polyurethane foams treated are limited since the quality of the PU entering the recycling plant it is not always good enough to ensure process effectiveness and efficiency.
- The aromatic part of PU polymers cannot be recycled and therefore is discarded or used for energy recovery.
- The glycolysis process needs high energy consumption.
- Polyols need to be re-polymerized to produce the recycled foam thus a significant amount of energy is needed to afford new PUs.
- Medium-large sizes of plants and continuous processing are needed to meet economies of scale.

These elements have meant that chemical recycling is the exclusive prerogative of the same large companies that produce raw materials for PU or of chemical companies connected to them (Manžuch et al., 2021). However, this type of recycle is particularly attractive in case of recycling of multi-materials components that cannot be recycled with the traditional mechanical recycling techniques (Korniejenko et al., 2021).

Recently, a new approach based on AIR-LAY technology has been developed for the mechanical recycling of PU foams with the aim to overcome the problems related to the rebonding and to the chemical recycling processes. The AIR-LAY technology is based on the use of bonding bi-component fibers and is usually applied at industrial level to create non-woven fabrics (e.g. absorbent paper, filters, etc.) and to recycle materials of different nature (e.g. fabric, wood, paper scraps). The fiber binder is generally formed by an outer layer made of a low melting temperature polymer (e.g. polyethylene, PE) that permits, upon heating above its melting temperature, the melt-bonding with the material to be recycled and an inner polymer with higher melting temperature (e.g. polypropylene, PP) that maintain the mechanical properties of the fiber during heating. The AIR-LAY system is based on the use of air flows to homogeneously distribute the material and the binder, which are then heated and pressed to obtain a single stable material. The process takes place continuously and consists of a series of successive phases (Fig. 1) such as the shredding of the input material, the homogenization of the material, the deposition of the material through air flows, the heating in a hot air oven, the compression and the cutting. Another element that guarantees flexibility to this technology is the possibility of varying the operating conditions, in order to obtain different values of thickness and density of the final product. In particular, by changing the parameters of the air flows, the temperature of the oven and the pressure of the roll mill, it is possible to obtain materials with different thicknesses, from 5 mm to 20 cm. Depending on the operating conditions, the density can also vary, with minimum values of 20 kg/m^3, thus overcoming the problems of the rebonding process for which the minimum density obtainable using polyurethane foams is above 60 kg/m^3. Moreover, the same AIR-LAY plant can be parallelly used for the recycling of the fabrics of the external part of the mattresses for the production of non-woven fabrics (Pourdeyhimi Behnam, 2007).

Nowadays, there are few cases of application of the AIR-LAY technology for the recycling of EOL mattress components (RetourMatras, 2021). In particular, a company called Secondly is developing and exploiting recycling processes of EOL mattresses with this technology (Europur Association, 2016).

Although the recycled polyurethane panels produced by AIR-LAY process using PU waste have been used for producing materials for some market applications, such as construction, automotive, thermal-acoustic insulation and sport cushioning, they have not been tested for the production of new mattresses (Sylvain et al., 2017) and there are no specific scientific studies that describes the characteristics of the obtained materials. The hypothesis that we wanted to address with the present study was that a fully circular approach could be achieved for the recycling of mattresses with an optimized AIR-LAY process. Moreover, there are no studies that compare the rebonding and AIR-LAY technologies for the recycling of PU foams and for the production of recycled products. For these reasons, the overall purpose of this study has been the optimization of the AIR-LAY process for the mechanical recycling of the foam of end-of-life mattresses, its comparison with the rebonding process and the evaluation of the optimal mechanical properties of the recycled material for its use in the bedding sector in order to achieve a fully circular scenario.

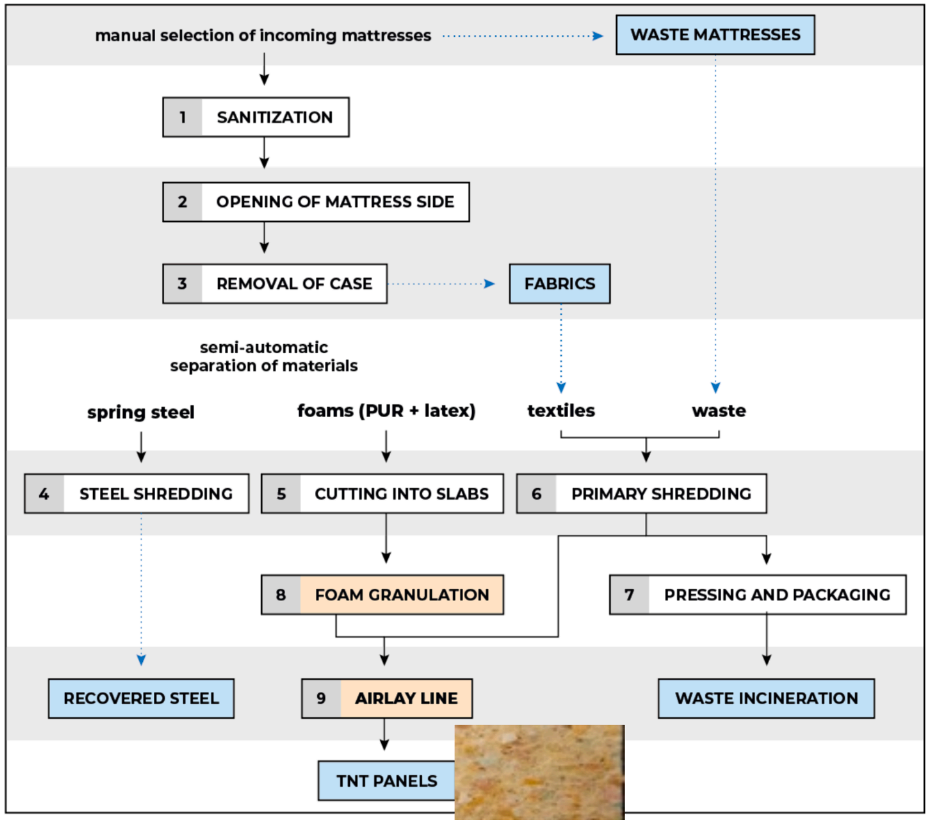

Fig. 1. Overall pathways of end-of-life processes for the different components of mattresses by air-lay process.

Materials and methods

Materials

The post-consumer foam used to assess the AIR-LAY process was obtained from post-consumer mattresses collected by the multiutility company Hera Group (Bologna, Italy) as part of its municipal waste management activities.

Considering the different types of mattresses containing foam and the variability of density and hardness of the foams, a set of 25 randomly sampled mattresses was selected.

The composition of the foam was determined using FTIR analysis using a Perkin Elmer Spectrum One FTIR spectrophotometer with ATR detector and the density was measured according to ISO 845 norm.

Intraloc™ bi-component fibers have been purchased from Fiber-Visions AS (Denmark). 6 and 12 mm long fibers with a linear density of 1.7 dtex have been used. They are made of an inner core of polypropylene (PP) and an outer layer of polyethylene (PE).

Rebonded foams from end-of-life and new mattresses have been obtained using a rebonding machine made by TEC MAC srl (Italy) and have been made using a 10 % (w/w) of polyurethane pre-polymer based on methylene diphenyl diisocyanate (MDI). The foam has been compressed with a piston and cured with steam at 150 °C, until the required density has been achieved and maintained under pressure for 12 h.

Chemical and physical characterization

Differential scanning calorimetry (DSC)

Thermal properties of PP/PE fibers have been evaluated by differential scanning calorimetry (DSC). DSC measurements have been performed by a DSC PerkinElmer Pyris 1 instrument, using 8 ± 2 mg of sample and purging the chamber with nitrogen at 20 mL min^{-1}. The machine has been coupled with an Intracooler 2P cooling system and calibrated with indium at a heating rate of 10 °C/min.

The sample has been first heated from 40 °C to 200 °C at 20 °C min^{-1} in order to erase the previous thermal history. After a 1 min isothermal step at 200 °C, cooling cycle has been conducted at 10 °C min^{-1} to 40 °C. The sample has been kept at 40 °C for 1 min. Finally, the sample has been reheated to 200 °C at 10 °C min^{-1}.

Scanning electron microscopy

The morphology of all mattresses has been investigated using a TESCAN MORA3 FEG-SEM. Each specimen has been mounted on carbon tape and the cross sections have been covered by a 10 nm thickness gold layer. The obtained surfaces have been observed with the SEM operating in low-vacuum conditions.

Recycling process of mattresses foams by the AIR-LAY process

The AIR-LAY recycling process has been performed on a pilot plant built by Cormatex srl (Prato, Italy) that is able to produce continuous panels of 1 m width, with a maximum thickness of 30 cm and a maximum density of 60 kg/m^3 with an output of 100 kg per hour.

The mattress recycling plant permits to perform the following three main steps:

1) A separation phase, where all the different materials forming the mattresses are divided (textiles, latex, PU foam, metals) and prepared for the recycling process. It is composed by the following sections: sanitizing of the mattresses; cutting on the external mattress perimeter; peeling of the outer casing; tearing of textile rag; PU waste granulation. 25 mattresses have been dismantled and the foam homogenized in a storage box before the AIR-LAY process.
2) The AIR-LAY forming section, the core of the PU recycling process, consisting of:

- Fiber opening and blending section. In the opening and blending section bi-component fibers made of PP/PE are added to the waste material. PET fibers have also been added in some tests.
- Horizontal AIR-LAY formation section which allows the mixing of the previously stored materials, a uniform distribution of the material and a horizontal stratification of the fibers.
- Heat setting section that stabilizes the panel in the final shape (composed of an oven, a cold roll mill, a cooling system, a connecting conveyor belt). The oven temperature is between 140 and 160 °C in order to melt the external layer of the bi-component fibers. The transit time in the oven varies from 30 to 60 sec. The roll mill force is up to 5 tons and its clearance and force have been adjusted according to the final product thickness to be targeted.

3) The cutting and the storage of the finished product, consisting of an automatic fork palletizer for panels.

The samples obtained by AIR-LAY process have been named by the letter **A**, followed by a number for each combination of fibers amount and type, density and eventual presence of PET fibers. The samples obtained by rebonding have been named with the letter **R** followed by a number depending on the source of the starting material (from end-of-life or from production waste).

Mattresses preparation

3 mattresses of 180 mm thickness have been prepared by an industrial manufacturer using a standard production procedure using layers of different density and thickness. Two of them, with the same structure of a commercial one (chosen as a reference), contained an inner part comprising a layer of 40 mm of a foam made of recycled materials from end-of-life mattresses produced by AIR-LAY process.

Mechanical characterization

Compression tests have been performed according to ISO 3386-1 at 40 % compression recording the load as a function of compression using a Instron 4465 mechanical testing instrument with a strain rate of 1 mm/min at 23 °C and 50 % relative humidity. The tests have been also repeated for 50 cycles and the final compression load at 40 % and residual deformation were recorded (Fig. 2). The tests have been repeated 3 times on 3 different samples and the results averaged.

The foams have also been compressed at 50 % of their initial height and kept for 60 min at 50 % compression. The height of the samples has been measured after 1, 5 and 10 min from the removal of the load and the recovery of the initial height has been plotted versus time. Foam hardness has been evaluated according to UNI EN ISO 2439 Method B. Tests according to UNI EN ISO 1798 have also been performed on foams in order to determine the elongation and load at break of the foams. Residual deformation after compression has been measured according to UNI EN ISO 1856 Method A. All tests have been performed in triplicate and the results averaged.

Durability tests have been performed on a mattress made with a recycled foam layer and on the reference mattress according to ISO 1957:2012. A load of 1400 N has been applied for 30,000 cycles with a frequency of 16 cycles per minute.

All tests have been performed at least 2 weeks after the preparation of the materials.

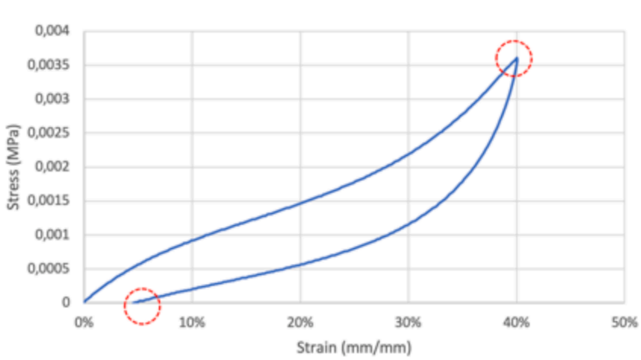

Fig. 2. Hysteresis curve of compression tests according with ISO 3386-1 with highlighted in red the point at which the compression load at 40 % and final deformation are measured. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Results and discussion

Bi-component fibers characterization

The fibers made of PP/PE have been characterized by DSC analysis to determine the melting temperature of the two components of the fibers. From the DSC thermogram in Fig. 3 it is possible to notice that there are two single melting temperatures endotherm peaks, one at 130 °C ascribable to the outer polyethylene part and one at 165 °C ascribable to the polypropylene inner core. Therefore, it is clear that, by heating the fibers at a temperature comprised between the two melting temperatures, it is possible to melt only the external PE part, while keeping in the solid state the inner core, thus maintaining the dimensional stability of the fiber. In this way, the molten external part act as a binder between the parts to be recycled, like a hot-melt adhesive. Once the final material is cooled, the fibers connect mechanically and durably the parts of the final material, making it possible to re-use it in a new shape. On the basis of these results, the temperature used in the oven of the AIR-LAY process has been of 150 °C. In this way it was possible to avoid the melting of the inner PP core of the fibers.

Mattress foam characterization

The FTIR analysis of the foam samples obtained from the mattresses confirm that they are all composed of polyurethane-based materials since they are characterized by the peaks at 3345–3380 cm^{-1} (N-H stretching vibration), at 1727 cm^{-1} (stretching vibration of urethane C=O bond) and at 1600 cm^{-1} (C=O stretching band of urea linkage). Mattresses with at least one layer of viscoelastic memory foam have been not used in this work since they can affect the results depending on the amount of memory foam present. Moreover, they are used in a lower amounts with respect to standard PU foams (CalRecycle - California Department of Resources Recycling and Recovery, 2012). Nevertheless, the AIR-LAY and rebonding recycling techniques can be also used in principle for the recycling viscoelastic memory foams. Future studies will be performed on this type of material to determine the mechanical characteristics of the recycled memory foams.

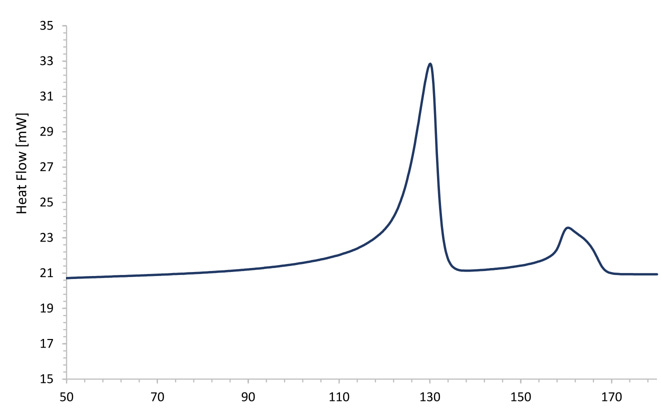

Fig. 3. DSC first heating thermogram of bi-component fibers.

All the mattresses used in this work were made of a single piece of PU foam with a density varying from 23 to 28 kg/m^3. Since the densities of the foams slightly vary from mattress to mattress a set of 25 different mattresses was used and the resulting foam was homogenized in a stirred tank before the AIR-LAY processes. It was not possible to have clear indications on the usage time of the EOL mattresses, but it could be assumed to be approximately of 8–10 years that according to the literature is the average usage time of mattresses (Statista, 2017).

AIR-LAY process

The fibers and the grinded foam to be recycled have been mixed in a

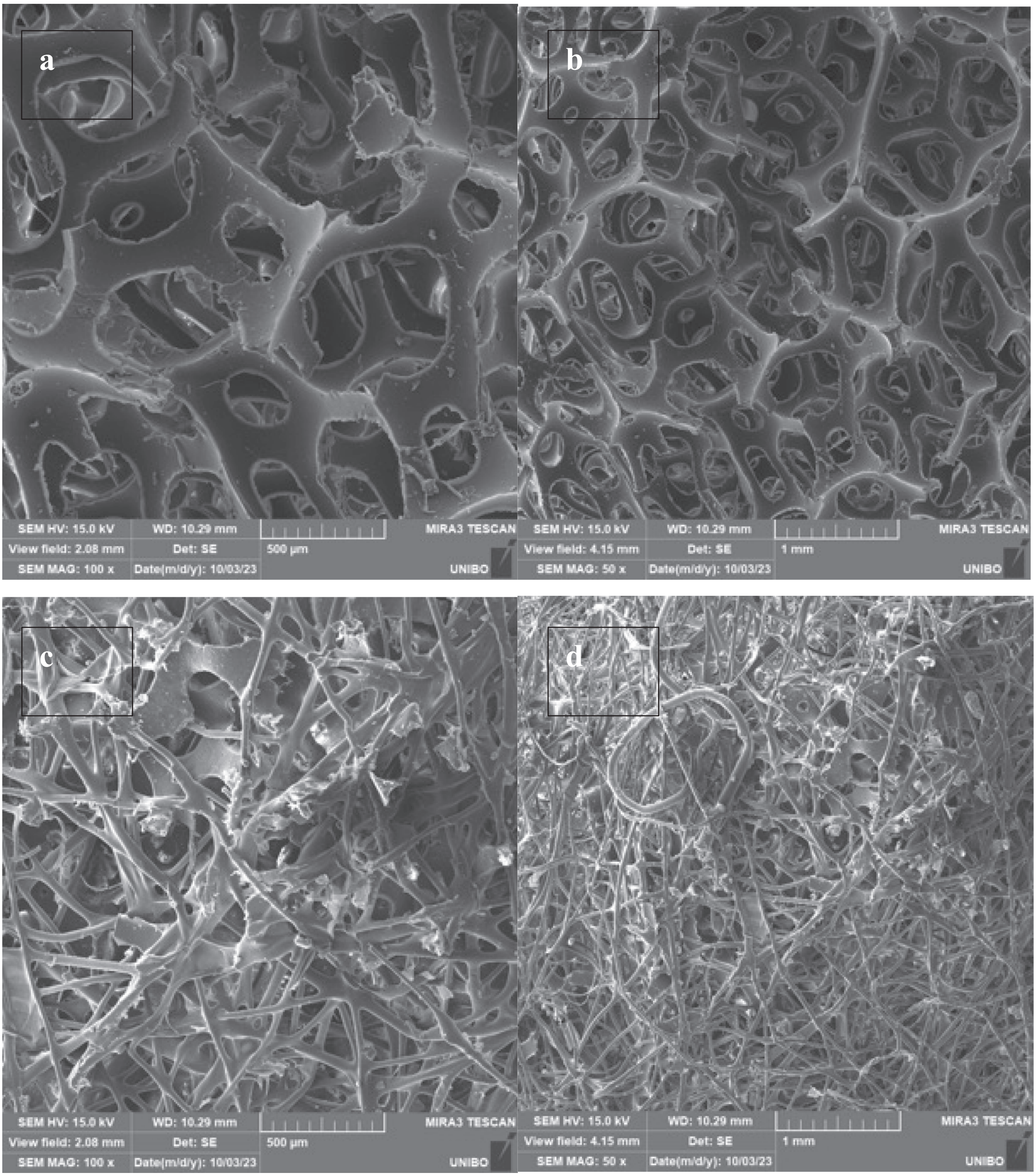

Fig. 4. SEM micrographs of the starting foam (a at 100X and b at 50X magnification) and of the material obtained from the AIR-LAY process with 20 % w/w fibers (c at 100X and d at 50X magnification).

vertical tunnel where have been homogenized using air fluxes and then deposited on a conveyor belt able to create a layer of uniform thickness of the material. The mixed fiber/foam layer was then heated in an oven and compressed with a roll mill to obtain the final material. All the process parameters have been tuned according to the target properties of density and thickness, in order to obtain a homogenous and dimensionally stable final material. In particular, the residence time and temperature in the oven are key points to achieve an efficient bonding between the fibers and the foam. However, the temperature and residence time must be kept below a certain limit in order to avoid the degradation of the foam and/or the melting of the inner core of the fiber. On the basis of the DSC analysis previously reported an oven temperature of 150 °C was used.

A first set of AIR-LAY tests have been conducted with 20 % (w/w) of bicomponent fibers of 6 mm length, analyzing the adhesion (by tensile tests) of the fibers with the foam and the presence of degradation on the final material in order to define the best residence time of the heating process. A good adhesion was considered when the tensile tests give a break of the foam and not of the interface with the fibers, as observed by optical microscopy. The results of the tensile tests have shown that a residence time of 45 in the oven at 150 °C give rise to good adhesion, while shorter times are not sufficient to achieve good adhesion properties. The SEM micrographs (Fig. 4c and 4d) show that the fibers maintain their dimensional stability, confirming that after 45 s in the oven the inner PP core is not melted. The SEM micrographs also show a good mixing of the fibers (Fig. 4c and 4d) with the grinded foam that has an open cell morphology (Fig. 4a and 4b).

The samples have been first characterized by compression at 40 % of the initial height according to ISO 3386-1. The tests have been repeated for 50 cycles, measuring the load at 40 % and the residual deformation after removal of the load as an indication of the elastic recovery of the foam. A sample of a foam from and end-of-life mattress has been used as comparison. This sample has been chosen as it has the mid values among the materials of 25 different mattresses analyzed and recycled and has a density value in line with that of commercial mattresses (25 kg/m^3).

The analysis of the curves of the reference sample and of the recycled material with the same density (sample A1) shows a significant difference in the shape of the compression curve (Fig. 5). For the reference foam it can be noticed, in accordance with the literature (Mane et al., 2017), a classical shape of an open cell foam (as evidenced in SEM micrographs in Fig. 4a) with a first steep linear section (due to the elastic behavior) followed by a plateau (due to buckling of the cells) and then a steeper section where densification occurs. On the contrary, a more linear behavior, without the plateau due to buckling of the cells, can be observed for the recycled material. This can be ascribed to the fact that the deformation between 10 and 30 % of compression mainly occurs due to the deformation of the fibers (that are the main interconnection between the foam parts as evidenced in SEM micrographs in Fig. 4c) and not of the cells, with a more linear trend. Moreover, it can be observed that the steepness of the curve in the first elastic region is higher for the reference foam with respect to the recycled material. This can be ascribed to the higher flexibility of the fibers with respect to the foam (due to their lower thickness, as evidenced in SEM micrographs in Fig. 4) and for this reason the recycled material can be more easily compressed in the first 10 % of compression. Another important aspect that can be noticed is that at every cycle the curve does not return to the initial shape, and a deformation is present when the compression force is released. This is more significant for the recycled material, with a more pronounced shift of the curves of the following cycles toward larger deformations. This means that the overall behavior of the recycled material is more viscous with respect to the non-recycled foam that has a more elastic behavior. This difference can be again ascribed to the fact that the entire material of the mattress is made of a continuous polyurethane foam (as evidenced by SEM micrographs), while in the case of the recycled material the particles of foam are bridged by flexible fibers that are not able to return to the starting shape in a short period of time.

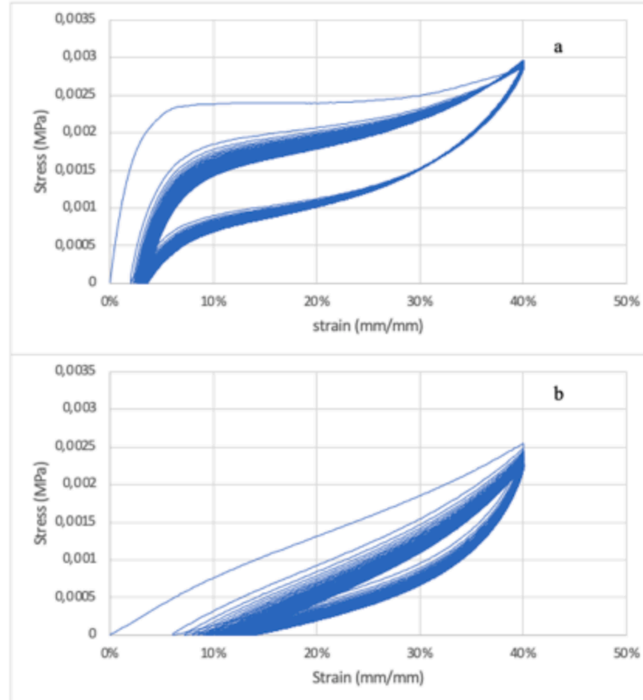

Fig. 5. Cyclic compression curves of the reference foam from end-of-life mattress (a) and of sample a1 made by air-lay with 20 % bi-component fibers (b).

All the recycled materials have a similar shape of the load/strain curves.

AIR-LAY process optimization

The characteristic of the products of the AIR-LAY process strictly depends on the type and amount of the bi-component fibers and on the compression after heating of the agglomerate. In order to assess the best process to produce new mattresses from end-of-life mattresses, a series of tests have been performed, changing the following parameters:

- Density of the final foam.
- Amount of bi-component fibers.
- Length of the bi-component fibers.
- Presence of other fibers.

The pressure applied by the roll mill was adjusted to achieve the desired densities of the final materials. The amount of material to be deposed on the conveyor belt was changed in order to obtain samples of the same height (40 mm) with different densities.

The data obtained changing the final density, fiber type and amount and by the addition of PET fibers are reported in Table 1. Comparing samples with the same amount and type of fibers but different densities (A1, A4, A5, A6) it can be observed that, as expected and according to the literature (Alzoubi et al., 2011), the increase in density makes the compression load higher. The data in Table 1 also show that a density of 35 kg/m^3 (sample A4) is needed to achieve a compression load that is similar to that of the starting foam. Nevertheless, the increased density does not have a significant effect on the residual deformation after 1 and 50 cycles since the observed differences lie in between the standard deviation of the tests. This indicates that the higher compression exerted by the roll mill to achieve the higher densities does not improve the adhesion of the fiber with the foam particles but only compress more the material that upon cooling is maintained in a more compressed state at higher density.

Comparing the effect of the fiber amount (sample A1 with 20 % and

Table 1
Properties of the materials obtained by air-lay process.

Sample	Density (kg/m^3)	Fiber amount (w/w)	Fiber length (mm)	PET fiber (w/w)	Compression load at 40 % (KPa)	Compression load at 40 % after 50 cycles (KPa)	Deformation after 1 cycle (%)	Deformation after 50 cycles (%)
Reference	25	no	–	no	3.0 ± 0.2	2.9 ± 0.2	2 ± 1	4 ± 1
A1	25	20 %	6	no	2.5 ± 0.2	2.2 ± 0.2	7 ± 2	18 ± 3
A2	25	5 %	6	no	1.5 ± 0.1	1.3 ± 0.1	10 ± 2	20 ± 3
A3	25	20 %	6	20 %	1.7 ± 0.1	1.6 ± 0.1	7 ± 2	12 ± 3
A4	35	20 %	6	no	3.7 ± 0.2	3.4 ± 0.2	6 ± 2	14 ± 3
A5	50	20 %	6	no	5.0 ± 0.3	4.2 ± 0.3	7 ± 2	16 ± 3
A6	70	20 %	6	no	8.1 ± 0.3	7.5 ± 0.3	7 ± 2	15 ± 3
A7	25	20 %	12	no	1.8 ± 0.1	1.6 ± 0.1	7 ± 2	14 ± 3
A8	25	5 %	12	no	1.5 ± 0.1	1,3 ± 0.1	10 ± 2	18 ± 3

sample A2 with 5 %) it is possible to observe that the use of a lower content of fibers decreases the stiffness of the material and also gives a larger residual deformation after the release of the compression load. This behavior has been ascribed to the lower number of bridges between the foam particles for the sample A2 with respect to the sample A1 due to the lower amount of bonding fibers.

Comparing sample A1 (6 mm long fibers) with sample A7 (12 mm long fibers) it is possible to observe that the use of longer fibers decreases the compression load at 40 % but does not have a significant effect on residual deformation. This can be ascribed to the higher flexibility exerted by the longer fibers. The addition of PET fibers (A3) decreases the compression load.

A series of tests have been performed by compressing the foam at 50 % of the initial height for 60 min and then measuring the deformation at 1, 5 and 10 min after the removal of the load in order to determine if this decrease in elastic recovery was only time-dependent or permanent. It can be highlighted (Fig. 6) that all samples except sample A2 return to the initial shape at least after 10 min after the removal of the load. The reason why the material obtained in test A2 is not able to get back to its initial shape, even after 60 min, can be ascribed to the lower amount of fibers used (5 % w/w) that create less bridges between the foam particles. For this reason, the force that is applied between the bridging fibers and the foam is higher with respect to the cases when more fibers are present. This higher force can cause a detachment of the fiber from the foam during compression, causing an irreversible deformation. However, this has not been observed in the other case in which 5 % fibers have been used (sample A8). This difference can be due to the fact that in this second case the fibers are longer (12 mm vs 6 mm) and therefore can bridge more foam particles at the same time, thus increasing the number of bridges between the foam particles. This is also confirmed by the fact that the use of 20 % (w/w) of longer fibers (12 mm) in sample A7 permits a faster recover (5 min) of the initial shape respect to the use of 6 mm long fibers (sample A1) (See Fig. 7).

Fig. 7. Foam obtained by rebonding process of pre-consumer foam waste.

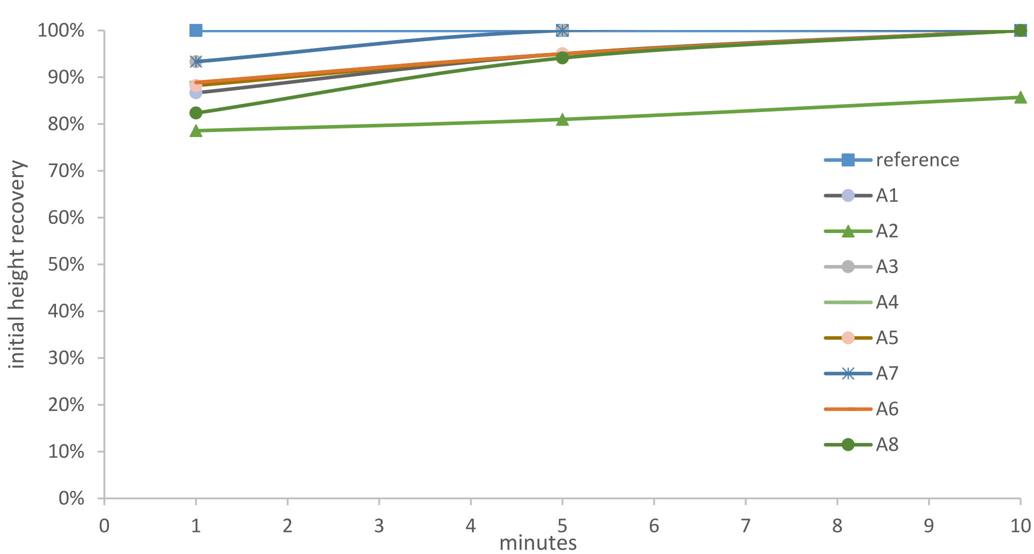

Fig. 6. Return to initial height after 60 min of compression at 50 % deformation.

Characterization of recycled foams obtained by rebonding

Recycled foams obtained by rebonding process are already widely used for the recycle of pre-consumer waste of foams (Guo et al., 2022). This method is generally performed in batch conditions using a polyurethane pre-polymer that act as a binder. Once the binder and the grinded foam are mixed together, they are poured in a closed vessel and maintained under pressure and temperature for several hours until the binding action of the pre-polymer is completed. Since this process is performed under pressure, the final material obtained has generally a significantly higher density than that of the starting foam (Kemona and Piotrowska, 2020) The results reported in Table 2 are in agreement with the previous literature on rebonding (Kemona and Piotrowska, 2020), showing that a 3 times higher density is obtained compared to that of the starting foam due to the compression needed to achieve a good adhesion between the foam particles. In this work, we have used as a reference for the AIR-LAY process a commercial rebonding process developed for the recycle of PU foams using 10 % w/w of binding agent that permits to achieve the lower density for this type of process (70 kg/m^3) while having good adhesion between the grinded foam particles. Since this process is already commercial and widely used, in this paper we have not optimized the process, but only obtained some samples to be compared with those made by the AIR-LAY process. The SEM micrographs (Fig. 8) show that the grinded foam is bonded by parts of PU with a complex morphology, partially with small pores and partially in bulk.

The compression tests of the rebounded foams show curves (Fig. 9) with a shape in-between that of the standard foam and of the materials obtained with the AIR-LAY process. In particular, in this case a small change in the steepness of the curve is observed at about 10 % compression. This indicates that the material does not behave as a standard foam with a plateau between 10 and 30 % compression. This intermediate behavior can be ascribed to the fact that the bonding material in this case is not a fiber but is a polyurethane with a hardness different with respect to that of the starting foam.

A lower residual deformation is observed compared to the AIR-LAY material due to the more elastic behavior of the PU used to bond the foam particles with respect to the fibers used in the AIR-LAY process. Nevertheless, in all cases the return to the initial shape is achieved in 10 min as for most of the AIR-LAY samples.

The comparison of the rebonded materials obtained with different starting foams, show similar results for the materials obtained from recycled mattresses (R1) and from pre-consumer waste of mattresses production (R3). The material R2 has a higher compression load at 40 %. This was ascribed to the higher stiffness of the starting material.

Comparison of foams from AIR-ALY and rebonding processes

The samples obtained from AIR-LAY with 20 % fibers at different densities (samples A1, A4, A5 and A6) and the samples obtained using the rebonding process (samples R1, R2 and R3) have been then further analyzed with a set of more detailed tests used to characterize foams to be used for mattresses production. In particular, tensile tests (UNI EN ISO1798), measure of hardness (UNI EN ISO 2439 method B) and measure of residual deformation after compression (UNI EN ISO 1856 method A) have been performed (Table 3).

The results show a higher load at break in tensile tests for samples obtained with the AIR-LAY process with respect to those obtained from the rebonding process and to the reference foam. This is a clear indication that the bonding of bi-component fibers is very effective in keeping the foam particles together. On the contrary, the elongation at break follows an opposite trend with rebonded samples having a higher elongation at break. This indicates that the interface that keeps the grinded foam particles is softer and more ductile for the rebonding process with respect to that of the AIR-LAY process.

The hardness at different compression values (25 %, 40 % and 60 %) is often used to evaluate the comfort and performances of foams to be used for mattresses (Fang and Shen, 2023). The graph in Fig. 10 of the hardness at 3 different compressions, shows that sample A1 and A4 present values closer to the reference material (that are in line with data reported in the literature (Fang and Shen, 2023) for PU foams for mattresses) and that the samples with higher densities (A6, R1, R2 and R3) have also higher hardness, especially at 65 % compression since those materials due to their higher densities reach the densification at lower compression values. For this reason, samples A1 and A4 have been chosen for the production of mattresses. However, due to the slower elastic return and residual deformation of the recycled materials, the recycled materials have not been used for the entire mattress, but only for a single layer.

Production and tests on mattresses

A set of full-size single mattresses of 180 mm height has been prepared and tested. The mattresses, prepared by an industrial manufacturer, in 2 cases presented a layer made of 40 mm of recycled foam by AIR-LAY process (Fig. 11). In particular, an A1 and an A4 layer have been added to the mattress on the basis of previous tests. The choice of these two recycled foams is due to the fact that they have the closer compression values compared to that of the reference foam.

The results obtained in compression and hardness tests (Table 4) show that the addition of an A4 layer slightly increase the compression load at 40 % while the A1 layer, that is softer, decreases the compression at 40 % load. Similar trend has been obtained analyzing the hardness at 40 % (Fig. 12). In all cases the return to initial shape after compression of 50 % for 60 min occurs in 10 min. These results indicates that by tuning the density of the recycled material it is possible to obtain the same characteristics of the standard mattress.

Durability tests have been performed on the mattress made with A4 layer and on the reference mattress to determine the effect of use on the final properties and comfort (Hänel et al., 1997) according to ISO 1957:2012. A load of 1400 N has been applied for 30,000 cycles with a frequency of 16 cycles per minute. In both cases no breakage or damages on the mattress were observed after 30,000 cycles in the external part and in the internal part where the recycled material was present.

The load/displacement curves have been analyzed at the beginning and at the end of the 30,000 cycles by taking into consideration the steepness of the compression curve at 210 N, 275 N and 340 N, reporting the average of these values (H) and the rigidity index (Hs) that can be obtained from the following formula:

$$\mathrm{Hs} = 10^*\left(1 - e^{-(\mathrm{Ka}+\mathrm{b})}\right)^4$$

Table 2
Properties of foams obtained by rebonding process.

Sample	Density (kg/m^3)	Source of foam used	Compression load at 40 % (KPa)	Compression load at 40 % after 50 cycles (KPa)	Deformation after 1 cycle (%)	Deformation after 50 cycles (%)	Recovery time after 50 % compression (min)
R1	73	End-of-life mattress	9.5 ± 0.4	8.7 ± 0.4	5 ± 1	11 ± 2	10
R2	73	Pre-consumer waste general purpose foam	12.3 ± 0.4	11.4 ± 0.4	4 ± 1	10 ± 2	10
R3	70	Pre-consumer waste mattress foam	8.9 ± 0.4	8.4 ± 0.4	4 ± 1	10 ± 2	10

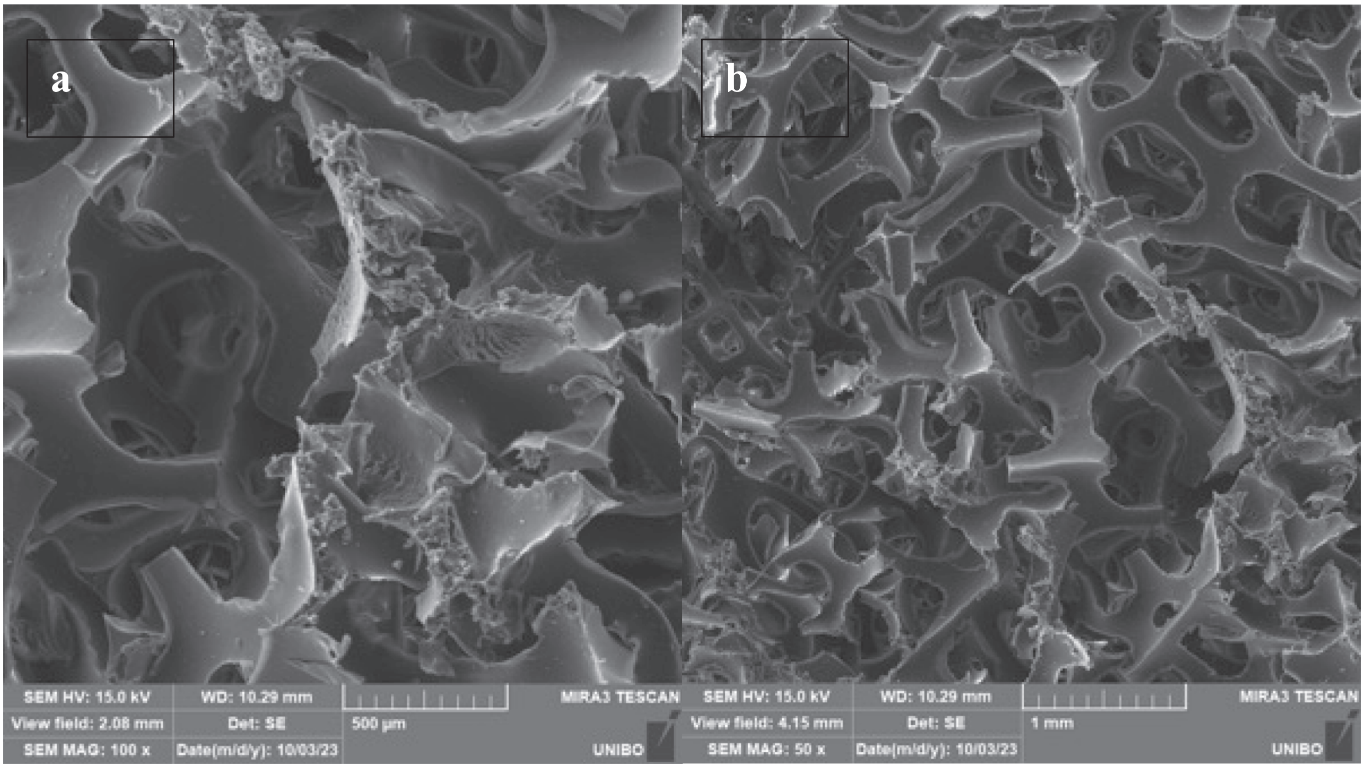

Fig. 8. SEM micrographs at 100X (a) and 50X (b) magnification of rebonding foam from pre-consumer waste.

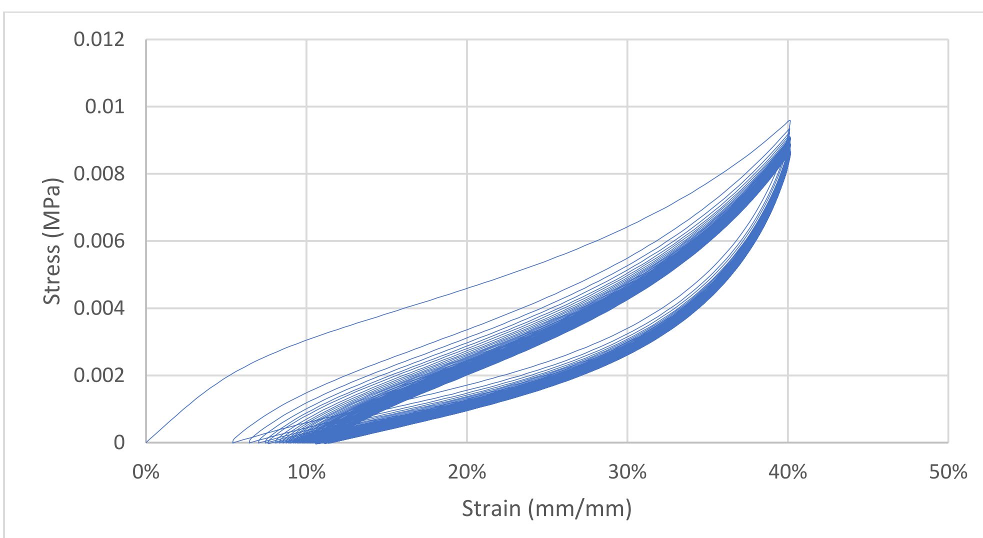

Fig. 9. Compression test of run R1.

Table 3
Characterization of foams for mattress production.

Sample	Density (kg/m^3)	Compression load at 40 % (KPa) ISO 3386-1	Recovery time after 50 % compression (min)	Load at break (KPa) UNI EN ISO 1798	Elongation at break (%) UNI EN ISO 1798	Residual deformation UNI EN ISO 1856 Method A (%)
Reference	25	3,0 ± 0.2	1	60 ± 10	80 ± 5	10 ± 3
A1	25	2,5 ± 0.2	10	170 ± 10	35 ± 5	46 ± 5
A4	37	3,7 ± 0.2	10	90 ± 10	45 ± 5	40 ± 5
A5	54	5,0 ± 0.3	10	130 ± 10	40 ± 5	40 ± 5
A6	68	8,1 ± 0.3	10	180 ± 10	30 ± 5	30 ± 5
R1	73	9,5 ± 0.4	10	30 ± 10	60 ± 5	34 ± 5
R2	73	12,3 ± 0.4	10	40 ± 10	70 ± 5	35 ± 5
R3	70	8,9 ± 0.4	10	50 ± 10	90 ± 5	30 ± 5

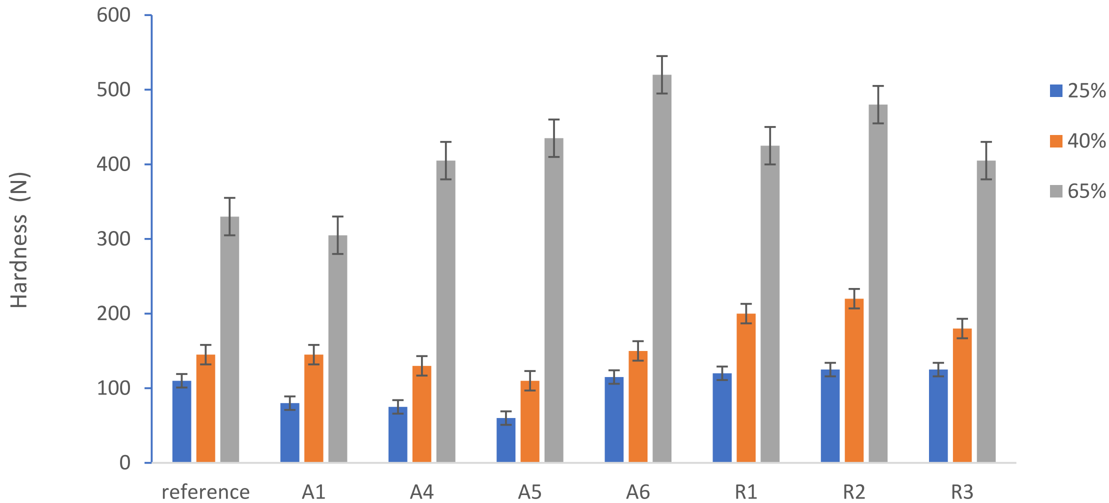

Fig. 10. Hardness (N) UNI EN ISO 2439 method B at 25 %, 40 % and 65 % compression.

Fig. 11. Mattress with an air-lay layer.

Table 4
Characteristics of the mattresses.

Sample	Composition	Compression load at 40 % (KPa) ISO 3386-1 (KPa)	Recovery time after 50 % compression (min)
M 1	without AIR-LAY layer	2,7 ± 0.2	10
M 2	With A4 layer	2,8 ± 0.2	10
M 3	With A1 layer	1,9 ± 0.2	10

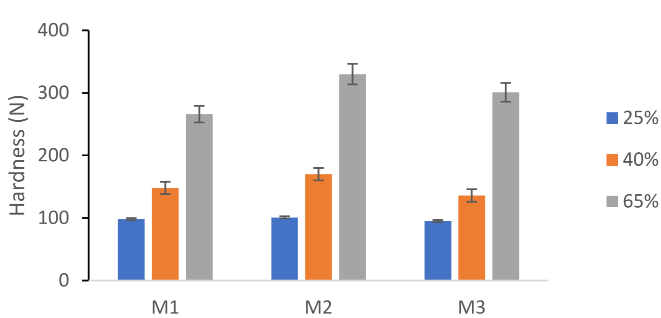

Fig. 12. Hardness according to UNI EN ISO 2439 method B at 25 %, 40 % and 65 % compression of mattresses.

Where:

A is the area below the load/displacement compression curve

K is A/H

a = $5.92*10^{-4}$

b = 0.148

The results in Table 5 show that the variation of the H value and of the Hs value are always below 0.3 N/mm after 30,000 cycles. The norm indicates a threshold value of 1.5 N/mm for Hs, that is well above the value observed for the mattress with the recycled part. Moreover, a very similar height variation (7.5 for M1 vs 7.6 mm for M2) was observed. Again, this value is well below the threshold values of the norm that is 10 mm plus the 5 % of the initial height of the mattress (in the present case 19 mm overall). All the data obtained show that the mattress with the recycled material have similar properties with respect to the standard one, with values that permits their use and commercialization as mattresses, that in the case of the mattress produced in the present work have a high level of rigidity (9.2 on a 1–10 scale).

Conclusions

A novel method for the recycling of end-of-life mattresses foam has been performed by using an AIR-LAY process that employs, as a binder, a bi-component fiber with a low melting temperature on the outside of the fiber that permits, upon heating, the bonding of the grinded foam to be recycled. This method allows to obtain materials with the same density (25 kg/m^3) of the recycled foam and with a significantly lower density with respect to that obtainable with the rebonding process (above 70 kg/m^3) that is, at the moment, the most used method for the recycling of PU foams. Indeed, a fully circular process for mattresses recycling is not feasible using the rebonding technique since this process affords foams with a density that is generally at least 3 times higher than that of the starting foams, not allowing its use for the production of mattresses due to the high weight of the foam.

The AIR-LAY recycling process has been optimized, by changing the process parameters (amount and type of the bi-component fibers, temperature, pressure and addition of other fibers) in order to obtain a material with the characteristics needed for the production of new mattresses. In particular, using 20 % of 6 mm bi-component fibers and a density of 35 kg/m^3 it has been possible to achieve a compression value at 40 % of 3.7 KPa, similar to that of the starting foam (3.0 KPa).

The comparison of the optimized materials obtained with the AIR-LAY process with the materials obtained by rebonding process shows a higher load at break in tensile tests for samples obtained with the AIR-LAY process. This is a clear indication that the bonding of the bi-

Table 5
Results of durability tests on m1 and m2 mattresses.

	Initial						After 30,000 cycles					
	C1 (N/mm)	C2 (N/mm)	C3 (N/mm)	H (N/mm)	Hs	Height (mm)	C1 (N/mm)	C2 (N/mm)	C3 (N/mm)	H (N/mm)	Hs	Height (mm)
M1	4.7	4.0	3.4	4.1	9.2	182.3	4.3	4.0	4.2	4.0	9.2	174.8
M2	4.8	3.5	4.1	4.1	9.2	181.7	4.7	3.2	3.6	3.8	9.4	174.1

C1 = steepness of the curve at 210 N.
C2 = steepness of the curve at 275 N.
C3 = steepness of the curve at 340 N.
H = (C1 + C2 + C3)/3.

component fibers is very effective in keeping the foam particles together. The materials obtained by rebonding all have a significantly higher (approx. 3 times) compression load at 40 % with respect to that of the foam used for mattresses and to those of the materials obtained by AIR-LAY process due to the high compression needed during the process to achieve good adhesion between the foam particles. The return to the initial shape after prolonged compression is the same for materials obtained from rebonding and AIR-LAY processes and is always longer compared to that of the starting foam and for this reason the recycled material cannot be used alone for the production of new mattresses.

On the basis of the results of the optimization tests we have prepared a set of mattresses containing a layer of the recycled foam that have the same compression behavior, recovery time and durability (after 30,000 cycles of compression) of a standard mattress without the recycled layer, thus proving that a fully circular approach for the recycling of the foam of the mattresses is possible using the AIR-LAY process.

The method here presented for the recycling of mattresses foam can be applied to other end-of-life foams and, on the basis of the results of the optimization process, the properties of the recycled materials can be tailored to match other industrial applications such as for example thermal and acoustic insulation.

The LCA and Techno-Economical analysis of the process will be presented in a following paper that will take into consideration all the steps from cradle to grave of the recycling process of the PU foam of mattresses.

CRediT authorship contribution statement

G. Liberati: Writing – review & editing, Writing – original draft, Methodology, Investigation. **F. Biagi:** Writing – review & editing, Investigation, Data curation. **A. Nanni:** Validation, Investigation, Data curation. **M.F. Parisi:** Writing – original draft, Investigation, Data curation. **L. Barbaresi:** Validation. **L. Querci:** Validation. **S. Ceccarelli:** Validation, Methodology. **M. Regazzi:** Supervision, Methodology. **A. Bonoli:** Validation, Investigation, Data curation. **M. Colonna:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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