



Coatings with recycled polyvinyl butyral on polyester and polyamide mono- and multifilament yarns

Rike Brendgen, Carsten Graßmann , Thomas Grethe, Boris Mahltig, Anne Schwarz-Pfeiffer

Received: 9 April 2020 / Revised: 23 November 2020 / Accepted: 30 November 2020
© The Author(s) 2021

Abstract Polyvinyl butyral is used in safety glass interlayers, mainly in car windshields. Legislative regulations require a recycling of cars after their lifetime and therefore also their safety glass. This causes the availability of recycled polyvinyl butyrate (r-PVB) originated from safety glass interlayers. Due to deteriorated optical properties, such as the transparency, and unknown amounts of plasticizers, it is challenging to reuse the recycled material in new windshields. Therefore, it is of particular interest to find new fields of application for r-PVB, such as the usage as a textile coating. In this research, r-PVB was investigated as a material for yarn coating. Polyester and polyamide mono- and multifilament yarns were coated continuously with solely a polymer dispersion and with mixtures of crosslinking agent and polymer dispersion. Crosslinked r-PVB coatings showed enhanced properties toward abrasion and chemical resistance. Coatings without the crosslinking agent showed a diminished abrasion resistance and could be washed off with ethanol. Mechanical properties of the monofilaments were influenced by the r-PVB coating in

general. However, varying concentrations of the crosslinking agent did not affect the mechanical properties.

Keywords Yarn coating, Crosslinked PVB, Mechanical properties, Polymer recycling

Introduction

Textiles are often coated not only for decorative reasons but also to create functional and enhanced properties like flame retardancy, easy-care surfaces, water and oil repellence, and antimicrobial properties.¹ A widely used polymer for textile coatings in outdoor applications, such as for tarpaulins or sunscreens, is polyvinyl chloride (PVC). It is often plasticized with different phthalates, which are considered to have a potential influence on the endocrine system.² Furthermore, these products are often incinerated at their end of life, which leads to the production of chlorinated by-products requiring a cost-intensive treatment of exhaust fumes. An alternative polymer, which can be considered for these applications due to its lower environmental impact, is polyvinyl butyral (PVB). PVB is one of the most important representatives of polyvinyl acetals and belongs to the group of thermoplastic polymers. The production of PVB is based on polyvinyl alcohol (PVA). It originates from the condensation of PVA with n-butyral aldehyde in the presence of an acidic catalyst, leading to a random terpolymer containing butyral and hydroxyl side groups with a small amount of acetate units. The PVB structure is built up of approximately 81% polyvinyl butyral, 18–23% polyvinyl alcohol, and less than 1% polyvinyl acetate as illustrated in Fig. 1. The exact composition of the polymer and its properties are determined by the production process.^{3,4}

R. Brendgen, C. Graßmann (✉), T. Grethe,
B. Mahltig, A. Schwarz-Pfeiffer
Research Institute for Textile and Clothing, Niederrhein
University of Applied Sciences, Webschulstraße 31, 41065
Mönchengladbach, Germany
e-mail: carsten.grassmann@hs-niederrhein.de

R. Brendgen
e-mail: rike.brendgen@hs-niederrhein.de

T. Grethe
e-mail: thomas.grethe@hs-niederrhein.de

B. Mahltig
e-mail: boris.mahltig@hs-niederrhein.de

A. Schwarz-Pfeiffer
e-mail: anne.schwarz-pfeiffer@hs-niederrhein.de

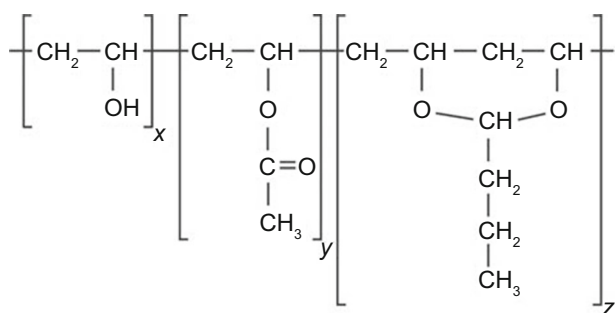


Fig. 1: Chemical structure of PVB with the three different building blocks: polyvinyl alcohol ($x \sim 0.2$); polyvinyl acetate ($y < 0.01$); and polyvinyl butyral ($z \sim 0.8$)

The polymer is typically used in applications where strong chemical bonding, optical transparency, and good adhesion on surfaces are required. Due to these characteristics, it is often placed between two sheets of glass resulting in a laminate for car windshields with both excellent optical and shatterproof mechanical properties.⁵ PVB sheets for glass lamination processes are mostly supplemented with 20–25 wt% of plasticizer. It is often plasticized with butyl ricinoleate, dibutyl sebacate, glycerol trisebacate, triethylene glycol bis-(2-ethyl hexanoate), or castor oil.^{6,7}

Besides its use in automotive and safety glass, PVB is also used in several textile-related niches in research and also in industrial application processes, some of which are described below.

Even though PVB was already investigated as a blending material in polyethylene terephthalate (PET) films, it is a rather uncommon polymer for textile coatings. Few examples of PVB coatings on textile structures exist.⁸ For instance, PVB was investigated as a polymer matrix for UV absorbing coatings on fabrics.⁹ Also, blends with inorganic nanoparticles to produce antibacterial yarns by electrospinning are reported.¹⁰ Precoats and backings for floor coverings were also investigated as potential PVB applications in the textile field. By extrusion or dispersion coating, the polymeric material can be applied as a precoat to the pile-forming textile in order to secure the pile yarns. The backing functions as a cushioning material that compresses and recovers when loaded and released. It may consist of recycled PVB, virgin PVB, or a combination thereof.¹¹ An early textile application of PVB was for use in military ponchos, in which two fabrics were bonded together by PVB.¹² However, this interlayer would not be considered as a coating now. PVB was later used as a coating on nylon fabrics for the same purpose and also as sealant for seams.¹³ Ultimately, these techniques were replaced by polyurethane coating.¹⁴ A niche application of PVB is the conservation of historic clothing.¹⁵

Besides application in the textile field, PVB is also used to fabricate electrodes for electrochemical analysis. In a study of Guinovart et al. from 2014, a solid-contact reference electrode for potentiometry that was

made of a PVB, Ag/AgCl, and NaCl membrane mixture, drop-casted onto a glassy carbon substrate, was described. This demonstrated a new approach to build a reference electrode using a hydrophilic membrane that performed with a great stability to changes in solution concentration, light, pH, and redox potential.¹⁶

Commercial applications can only be found to a limited extent in the patent literature. A flame retardant and, at the same time, antibacterial coating for textiles was described in CN000105421064A, while approximately 20% of the coating consists of PVB, together with an isocyanate crosslinker and sodium tripolyphosphate as the presumably flame-retardant component.¹⁷ The antibacterial effect is most likely achieved by adding silver components. Surgical swabs are described in FR000002166738A5, where the fibrous material is impregnated with different water permeable polymers to prevent loosening of the swab fibers in the operation area. However, since PVB shows a significant hydrophobicity, it may be applied only blended with other polymers, acting mostly as an additional binder.¹⁸

The above-described applications used virgin PVB. Due to the massive accumulation of unused windshields of scrapped cars, some companies specialize in recovering PVB from windshields. This is in line with the existing guidelines for the waste treatment of cars in the European Union, which impose the necessity to recycle most materials used to reduce landfills.

During the recycling of windshields, the glass must be separated from the PVB interlayer. Therefore, the PVB film can also be recycled, which is an established process.^{5,19,20} The properties of the recycled material are determined by the material used, and solid impurities like dust and glass fragments must be separated prior to the recycling process.²¹ Using recycled PVB (r-PVB) in car windshields is difficult and only successful when mixed with the virgin polymer because the PVB sheet degrades during its lifetime and during the recycling process. Thus, the exact amount of plasticizer in the recycled resin and molecular weight of the polymer are not known due to elimination and degradation reactions.⁵ Therefore, the recycled material needs to be blended with up to 40 wt% virgin PVB for use in safety glass laminates as well as carpet backings and leather composites.^{11,22,23} To our knowledge, recycled PVB formulations are scarcely used for other textile applications so far.

Against this background, we applied recycled PVB-blends on synthetic yarns as a coating material. Yarn coating is far less represented but might offer some advantages for certain applications. As stated by Uddin, textile appearance and haptics are changed when a fabric is coated. The coating covers the characteristic cavities that result from the woven or knitted structure and often forms a clearly visible second film on the substrate. Using coated yarns and processing them for fabric manufacture, the resulting product will maintain the typical textile structure,

while the composite material still leverages both components.²⁴ Yarn coating is also useful to realize a specific structure or pattern along the yarn.²⁴ In this case the coated yarn can easily be embedded in the textile structure, e.g., by embroidering of the functionalized yarn, which is often found in smart textile production.

For larger quantities, a technically simple method of immersion (dip) coating is used, where the substrate is dipped and pulled vertically out of the solution in the coating bath.²⁴ The uptake mainly depends on the viscosity, the solid content of the coating material, and the process speed. This allows the surplus of coating dispersion on the substrate to drip back into the reservoir by gravity. This procedure is also used for yarn coatings but only for small pieces in a batch process.²⁵

In this work, we employed a continuous dip coating process, where the yarn is pulled horizontally through the coating bath and extracted at 45°, while the surplus is removed with a scraper and allowed to drip back from that scraper into the reservoir.

Materials and methods

Materials

A colorless polyester monofilament (diameter 220 μm) was purchased from Monofil Technik GmbH (Hennef/Sieg, Germany), and a white polyamide 6.10 monofilament (diameter 220 μm) was obtained from Dr. Karl Wetekam & Co. KG (Melsungen, Germany). A polyester multifilament (16 tex) was provided by Benecke-Hornschuch (Weißbach, Germany), and a polyamide multifilament (18 tex) was obtained from Gütermann (Gutach-Breisgau, Germany).

Recycled PVB dispersion TC-100 was obtained from Shark Solutions (Waregem, Belgium). The blocked isocyanate containing crosslinking agent RucoCoat FX 8041 was kindly provided from Rudolf-Chemie (Gertsried, Germany).

In order to distinguish between the different coating formulations easily, inorganic color pigments were added, named Helizarin[®] (BASF Ludwigshafen, Germany).

Coating dispersions and process

The coating dispersions were prepared by mixing the PVB dispersions with different amounts of crosslinking agent as shown in Table 1. To distinguish the amount of crosslinking agent in the coating solution easily, a color code by adding color pigments was established, as also denoted in Table 1.

The coating process is shown in Fig. 2. The substrate runs through a yarn brake and is immersed into the coating solution before entering the drying tower. The

Table 1: Used PVB coating dispersions with increasing amount of added crosslinking agent

PVD dispersion (g)	Crosslinking agent (g)	Color code
50.00	0.00	Gray
45.00	5.00	Red
40.00	10.00	Yellow
37.50	12.50	Purple

The mentioned color code is related to the added color pigment to identify the finally produced coated yarns

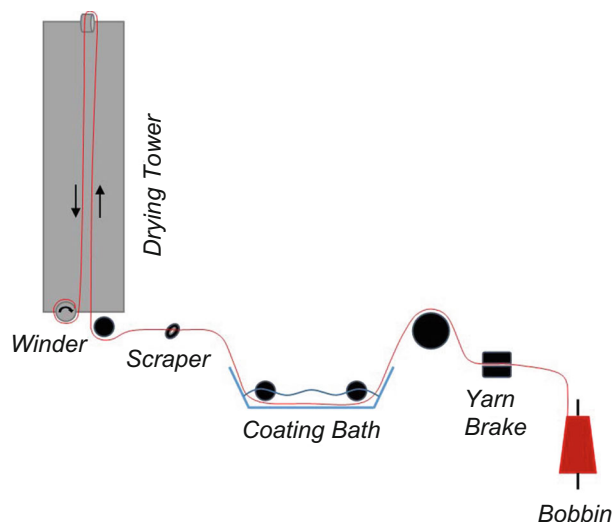


Fig. 2: Scheme of coating process. Yarn runs from right to left

process parameters are as follows: Distance between the two immersing rolls was set at 8.0 cm, the height of the drying tunnel (FMP Technology, Erlangen, Germany) was 2.0 m, and all experiments were carried out at a speed of 50 cm/min.

Analytics

Microscope and scanning electron microscope

All coated yarns were examined with a VHS-600 digital microscope from Keyence. This microscope enables magnifications between 20 and 200 times. For the current experiments, 150 times magnification was used. Scanning electron micrographs were recorded with TM 4000 Plus tabletop SEM from Hitachi.

Tear strength and maximum elongation

The tear strength and maximum elongation of the filaments were investigated with a ZwickRoell tensile tester according to DIN EN ISO 2062. The length of the multifilament yarns was 50 cm, while the length of

tested monofilament yarns was reduced to 20 cm due to their maximum elongation. In some cases, the maximum position of the tensile tester was exceeded when longer filaments were measured. To calculate the mechanical properties, the values of five samples were averaged.

Surface energy

The surface energy of the coated and uncoated filaments was determined using a drop shape analyzer DSA-25 from Krüss. Droplets of water and diiodomethane with a volume of 0.5 µL were analyzed.

Coating weight

The coating weight was determined by weighing five pieces of exactly one meter each and calculating the arithmetic average.

Coating durability in ethanol

PVB is known to be easily soluble in alcohols, especially ethanol. The solubility of the coating in this solvent was determined using a Soxhlet extraction apparatus. The extraction was conducted over 4 h, and the extract was determined gravimetrically after

removing the solvent in vacuum (10 mbar at 40°C). The values given in Table 2 were calculated in percentage of dissolved coating material. Also, the amount of dissolved substances in the pristine filaments was determined.

Fastness to abrasion

The coating’s abrasion resistance was investigated qualitatively using a modified Martindale abrasion test with 100 Martindale cycles on the basis of DIN EN ISO 12947. The filaments were wrapped twice around the screws of the Martindale fabric holder as shown in Fig. 3. The test was performed with the standard test fabric as the counterpart rubbing with a load of 9 kN over the substrates. Due to little weight changes, the treated filaments were compared to untreated filaments under the microscope.

Thermoanalysis

For thermoanalysis, free standing films of all four r-PVB/crosslinking agent combinations were obtained by coating of glass slides. After drying and crosslinking, the polymer film was removed from the slides and shredded into small pieces, which were then analyzed. Differential scanning calorimetry (DSC) of all polymers was performed with a DSC Q200 from TA

Table 2: Chemical and physical properties of filaments coated with r-PVB

Filament type	Material	Amount of crosslinking agent	Coating weight (mg/m)	Dissolved in ethanol	Tear strength [cN/tex]	Maximum elongation (%)	Surface energy (mJ/m)
Monofilament	PA	Uncoated	–	–	n.a.	n.a.	–
		0%	6.1	100%	52 [± 0.4]	23 [± 0.9]	20.9
		10%	4.8	11.1%	52 [± 0.4]	25 [± 0.9]	21.02
		20%	4.3	7.4%	52 [± 0.6]	25 [± 1.2]	19.2
		25%	4.1	7.0%	52 [± 0.6]	26 [± 1.4]	18.86
	PES	Uncoated	–	–	37 [± 0.9]	60 [± 8.0]	–
		0%	4.8	100%	37 [± 0.7]	58 [± 3.9]	26.65
		10%	4.5	7.5%	38 [± 1.2]	59 [± 3.5]	22.51
		20%	4.1	5.1%	38 [± 1.0]	60 [± 2.0]	21.66
		25%	3.9	5.1%	38 [± 0.9]	61 [± 5.9]	16.39
Multifilament	PA	Uncoated	–	–	45 [± 0.3]	29 [± 1.0]	–
		0%	14.5	100%	58 [± 1.4]	35 [± 3.0]	26.78
		10%	13.5	10.4%	58 [± 1.3]	36 [± 2.9]	21.79
		20%	13.2	10.1%	58 [± 1.0]	40 [± 1.7]	20.91
		25%	13.0	10.0%	58 [± 1.1]	42 [± 2.4]	17.96
	PES	Uncoated	–	–	31 [± 6.7]	15 [± 2.1]	–
		0%	16.0	100%	44 [± 0.9]	19 [± 0.9]	25.51
		10%	14.1	17.6%	44 [± 1.1]	21 [± 1.8]	25.43
		20%	13.5	13.7%	44 [± 0.8]	22 [± 2.2]	21.33
		25%	12.0	8.6%	44 [± 1.2]	24 [± 2.1]	21.28



Fig. 3: Modified Martindale abrasion test for r-PVB-coated yarns

Instruments. All samples were measured in a hermetically sealed aluminum pan. Measurements started at 40°C, and samples were first cooled down rapidly to 0°C (not shown in diagrams). After cooling, the DSC measurement was performed at a heating rate of 10 K/min between 0°C and 200°C. Additionally, thermogravimetric measurements (TG) of all samples were performed in an open aluminum pan with a STA 2500 Regulus from Netzsch under argon atmosphere.

Spectroscopy

Free standing films produced using the same parameters for the yarn coatings were analyzed by ATR-FTIR spectroscopy with a Varian 3100-FTIR Excalibur Series equipped with a Golden Gate ATR unit. The films were produced in analogy to the method described for the thermoanalysis.

Results and discussion

All filaments were coated successfully with aqueous r-PVB dispersion in a dip coating process. A simple installation with rollers for immersing the yarn into the coating bath was built. The yarn was pulled out of the coating dispersion at an angle of 45°. Surplus coating dispersion was stripped off with a scraper. The coating speed was controlled by the winder, which was equipped after the drying tunnel. The drying temperature was set to 160°C. This temperature was chosen to activate the crosslinking reaction by de-blocking the isocyanate groups which usually occurs at temperatures above 120°C.

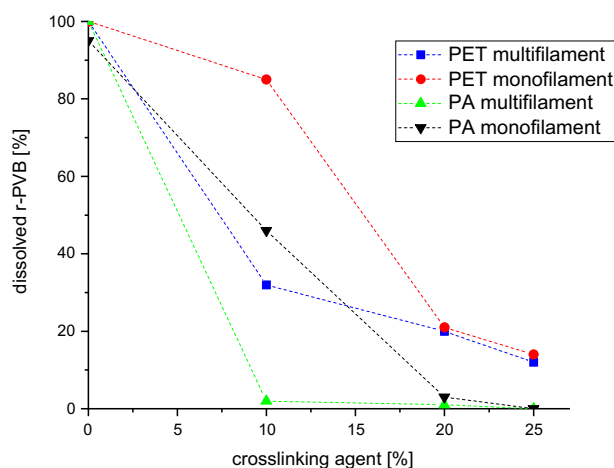


Fig. 4: Influence of crosslinking agent amount on coating stability, shown as dissolved PVB by ethanol extraction as a function of crosslinking agent concentration

Coatings on the monofilament yarns resulted in a thin layer of r-PVB on the outside of the yarn, whereas coating multifilament yarns led to the agglutination of the single filaments that built up the yarn.

Coatings on monofilament yarns show a thin and smooth appearance across all coating dispersions. The amount of crosslinking agent exhibited no influence on the coating structure. In the micrograph of PA monofilament with 10 wt% crosslinking agent, indentations by the transportation rolls are slightly visible.

The results of the coating weight measurements are given in Table 2. Generally, coatings with a higher amount of crosslinking agent show a lower coating weight. This can be explained by the reduced solid content in the coating dispersions with 10, 20, and 25 wt% crosslinking agent. The total solid content of the mixed coating dispersion decreases with increasing amount of crosslinking agent due to the lower solid content in the crosslinking agent of 32% compared to 48% in the r-PVB dispersion.

It can also be observed that the coating weight of the multifilament yarns is higher than that of the monofilaments. This result can be explained by a higher specific surface area of multifilaments; all single strains that make up a multifilament are covered with the coating dispersion and capillary forces exist between them, whereas the monofilaments are built up by just one single strain.

The coating weight on all mono- and multifilament yarns is nearly linearly related to the crosslinking agent amount in the dispersion. Small deviations can be attributed to a nonregular coating thickness along the yarn.

Due to its good solubility in alcohol, the coating stability was examined via a Soxhlet extraction process using ethanol. The results are shown in Table 2 and Fig. 4. The amount of crosslinking agent in the coating dispersion shows a substantial impact on the coating durability. Without crosslinking agent, the r-PVB

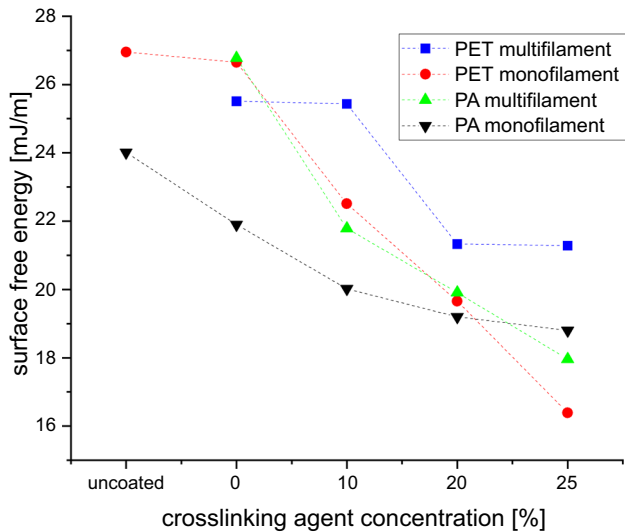


Fig. 5: Free surface energy of coated filaments



Fig. 6: Micrographs of PA monofilament yarn after coating (left) and after Martindale abrasion test (right). Colors are according to table (Color figure online)



Fig. 7: Micrographs of PET monofilament yarn after coating (left) and after Martindale abrasion test (right). Colors are according to table (Color figure online)

coating is dissolved completely during Soxhlet extraction.

The addition of only 10% crosslinking agent already leads to a distinctly higher durability of PVB coating for most of the investigated yarn types. Increasing the amount of crosslinking agent enhances the coating durability a little further. However, a sophisticated coating durability with a loss of less than 1 wt% could only be observed for the PA multifilament.

The surface free energy is complicated to determine on yarns, especially on multifilament yarns.²⁶ In general, yarns have a curved surface, which makes an accurate drop casting on the yarn surface difficult. Moreover, the increase in capillary forces in the multifilament yarns influences the affinity to water by overcoming the surface free energy. Hence, the droplet was directly absorbed by the untreated multifilament so that no conclusion about the surface free energy can be stated here.

All coated substrates were, however, measurable and demonstrate that with increasing amount of crosslinking agent in the coating dispersion, the surface free energy can be reduced marginally (Fig. 5). The coated substrates can be classified as being hydrophobic, as their surface free energy is lower than that of their wetting agents. Polar interactions contribute mostly to the coating's free surface energy. This contribution is reduced by the increasing amount of crosslinking agent, which can be explained by the reaction of the crosslinking agent with free OH groups to urethane, reducing the amount of these polar groups in the coating.

Dried rubber, like r-PVB coating without crosslinking agent, could be removed from all substrates during 100 Martindale cycles. To ensure a higher durability of the coating, a crosslinking agent was added in three different amounts. Adding crosslinking agent to the coating dispersion leads to better abrasion resistance on the filaments.

As is clearly visible in the micrographs (Figs. 6, 7, 8, 9), the samples containing little to no crosslinking agent (pink and gray samples) are not covered by a

colored coating in the case of the monofilaments or are characterized by protruding filament ends and loosened filament strands in the case of the multifilament yarns after 100 cycles of standardized abrasion. In contrast, the coating of the samples containing a higher amount of crosslinking agent (yellow and purple) shows little wear. The damaged multifilament yarns indicate that external filament strands come loose and tear during the abrasion. This shortcoming can be overcome by increasing the amount of crosslinking agent in the coating solution, which facilitates a better adhesion between the single filament strands. The SEM micrograph of the samples in Fig. 10 reveals that there is a thin polymer layer around the monofilament yarns resulting in uniformly looking surfaces. However, scratches of the guide rollers can lead to small defects in the coating layer. The multifilament yarns are glued together, resulting in a surface totally made of r-PVB and crosslinked r-PVB, respectively. However, the shape of this yarn looks irregular on a small scale in the SEM micrographs. The coating reduces or even cancels completely the capillary forces between the filaments, which explains why the wettability of all coated



Fig. 8: Micrographs of PA multifilament yarn after coating (left) and after Martindale abrasion test (right) filament yarn after coating

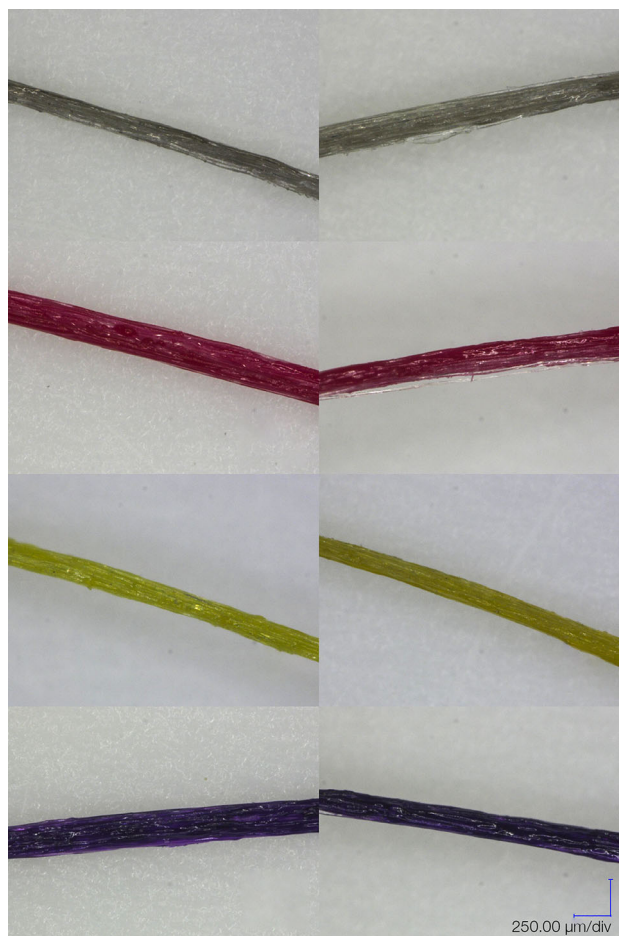


Fig. 9: Micrographs of PET multifilament yarn after coating (left) and after Martindale abrasion test (right). Colors are according to table (Color figure online)

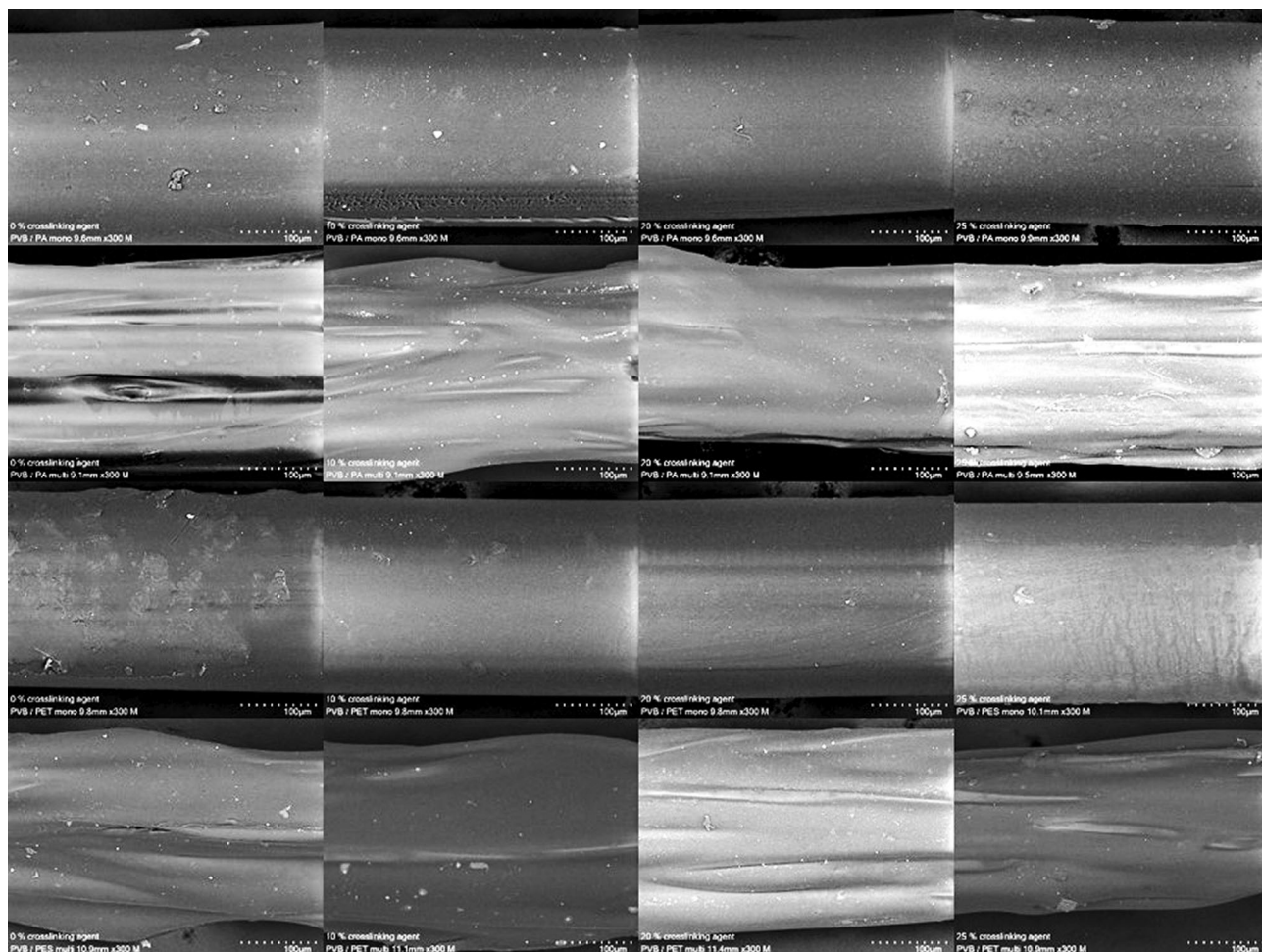


Fig. 10: SEM micrographs of coated mono- and multifilament yarns. From left to right: coatings with increasing crosslinking agent amount. Line 1: PA monofilament

multifilament yarns could have been measured. The amount of crosslinking agent does not influence the visual impression of the yarns in the micrographs.

For the FTIR investigations, it is noticeable that a strong band at 1690 cm^{-1} appears after crosslinking the polymer with an isocyanate (Fig. 11). This can be attributed to urethane groups, which are formed by the reaction of the unblocked isocyanate and alcohol groups. The intensity of this band increases with increasing amount of crosslinking agent. The formation of urethane groups through this reaction is also supported by a decreasing ratio of hydroxyl valence vibration at 3450 cm^{-1} . While the differences in the C–H region at $2800\text{ to }3000\text{ cm}^{-1}$ are probably of artificial origin, due to slightly different penetration depths, light refraction, and scattering across the different materials, the peak at 1430 cm^{-1} shows the emergence of an additional peak, similar to the above mentioned peak at 1690 cm^{-1} . However, the increase in peak height with crosslinking agent occurs in different ratios in both peaks, giving rise to the idea that with increasing crosslinking agent concentration, different

reactions or even side reactions are triggered. It can therefore also be considered that other compounds like plasticizers are able to react with the crosslinking agent.

The maximum elongation of multifilament yarns was slightly influenced by the coating. Coated multifilament yarns (24% maximum elongation for polyester and 42% for polyamide) have a higher maximum elongation than the untreated yarns (15% maximum elongation for polyester and 29% for polyamide), whereby merely the coating itself, irrespective of its crosslinking agent concentration, is accountable for that increase. The same effect cannot be observed for the monofilament yarns since there is only a thin coating layer on top of the filament that does not influence the mechanical behavior in the same way as it does with the completely wetted multifilament yarns. The coating layer is much thicker and penetrated the multifilament yarns so that single strands were bonded together by the r-PVB polymer. The differences in the morphology of the substrates might also explain the tenacity results. Accordingly, these results show an increase in tenacity

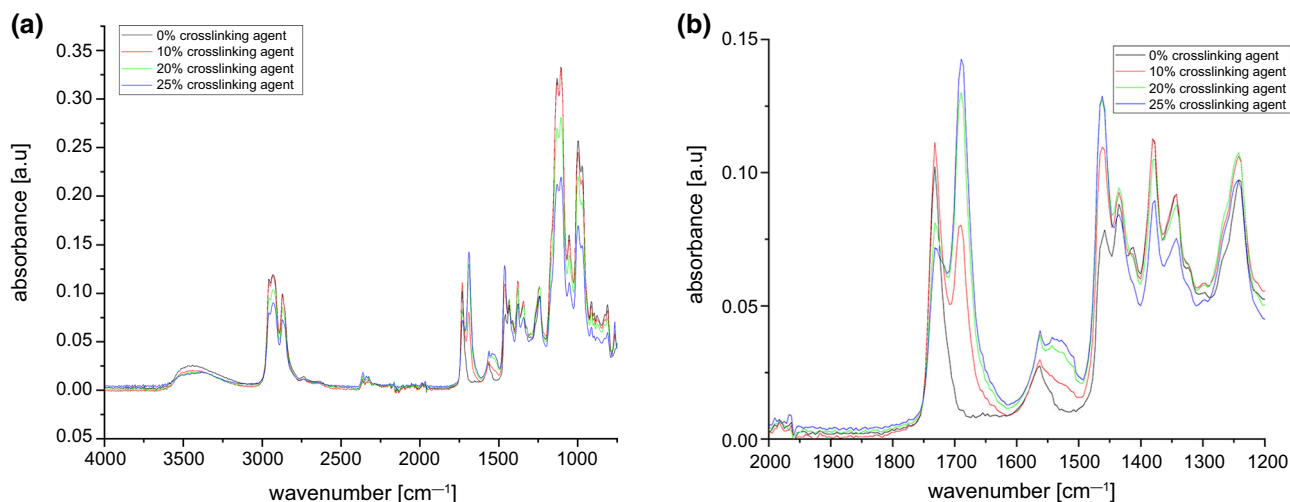


Fig. 11: (a) FTIR spectra of r-PVB and crosslinked samples; (b) the region between 2000 and 1200 cm^{-1} is enlarged on the right side

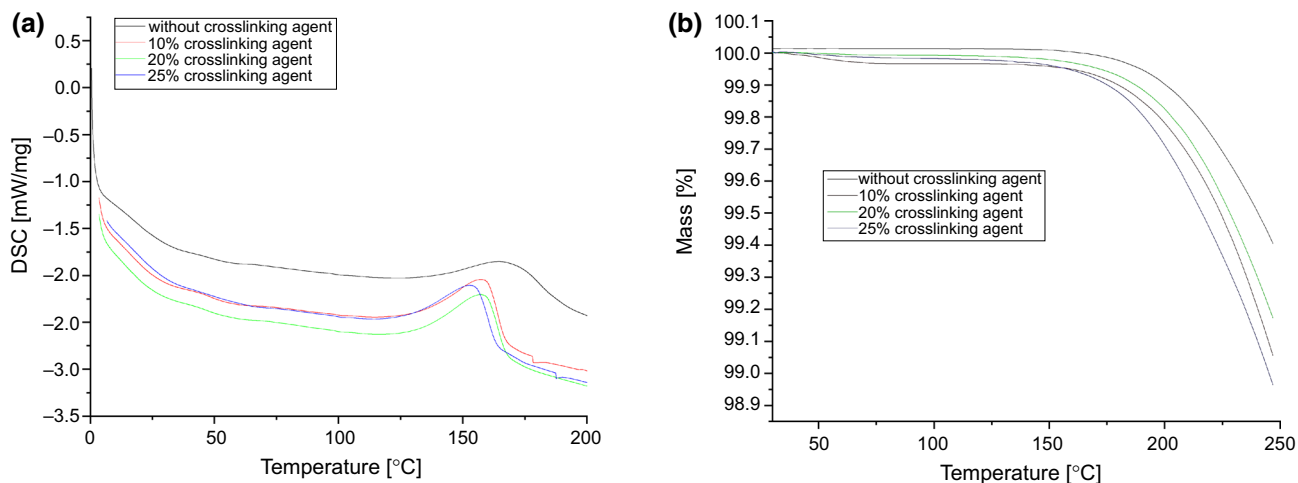


Fig. 12: (a) Results of DSC measurements of r-PVB and crosslinked r-PVB between 0 and 200°C; (b) result of TG and measurements of r-PVB and crosslinked r-PVB

for the multifilament samples containing crosslinking agent regardless of its concentration.

The glass transition temperature of unplasticized pristine PVB is found to be between 63 and 73°C according to Dhaliwal and co-workers.³ The exact value depends on the molecular weight distribution of the polymer chains and the ratio of alcohol, acetate, and acetal groups. The herein used r-PVB dispersion contains several not fully known additives, and the main component beside PVB was the plasticizer, triethylene glycol bis(2-ethylhexanoate). Furthermore, the molecular weight distribution of the recycled polymer extends over the range between 34 and 385 kDa. DSC and TGA measurements of the cross-linked polymers were performed in the temperature

range between 0 and 200°C and are depicted in Fig. 12. The glass transition temperature of the noncrosslinked sample could be found around 20–22°C.

However, all samples show a broad signal for the glass transition temperature, which cannot be identified well. It is believed that the crosslinked polymers have the glass transition occurring in a wide range between 20 and 50°C. The exothermic signal at around 160°C shifts to lower temperature with increasing crosslinking agent amount in the polymer; therefore, this can be tentatively attributed to a decomposition of r-PVB. The most rigid, i.e., the sample with 25% crosslinking agent, has the lowest decomposition temperature, whereas the sample without crosslinking agent, in which the polymer chains are allowed to

move more freely, shows a much higher decomposition temperature. The small endothermic signals in the curves for polymers with 10 and 25% crosslinking agent are believed to be artifacts due to the measuring method in a sealed aluminum pan. Additionally, thermogravimetric measurements were performed in an open aluminum pan between 20 and 250°C. The results are depicted in Fig. 12b. These results show a clear correlation of decomposition reaction for all polymer samples. The temperature, where the samples start to lose weight, coincides with the DSC measurement and drops with the crosslinking degree.

Conclusions

It was shown that a recycled material, of which huge amounts are accumulated due to the recycling process of safety glass, can be used in textile coatings. This contributes to the reduction of waste and to a resource-saving handling of raw materials. Crosslinked r-PVB can be used as a coating agent for polyester and polyamide mono- and multifilament yarns by using a dip coating process. The coating weight decreased with higher amounts of crosslinking agent due to the reduced solid content in the dispersion. The measured coating weight correlates to the respective amount of crosslinking agent in the coating dispersion, concluding that the filaments can be coated evenly and can be applied in a homogeneous layer. The mechanical properties of the filaments were primarily determined by the yarn properties, whereas the coating itself has rather little effect on maximum elongation. Tenacity, however, could be improved by the coating and depends on crosslinking, though the amount of crosslinking agent is not decisive for the increase in the breaking force. Crosslinking agents were added successfully to enhance the durability of the coating as demonstrated by the abrasion resistance testing. The increasing amount of crosslinking agent in the coating dispersion also influences the water repellence as the surface free energy was reduced, which indicates that the coated yarns became more hydrophobic.

In future research the coatings may also be functionalized by adding, for example, UV absorbers, flame retardants, and antimicrobial finishing. Also, it is necessary to investigate the eligibility of such functionalized yarns in the production of fabrics by weaving or knitting processes.

Acknowledgements The work was co-financed by the Collective Research Network (Cornet) and supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) and Flanders Innovation & Entrepreneurship—Agentschap Innoveren & Ondernemen, under the support code 213 EBG. The project “Coating applications for recycled PVB

(CarPVB)” was a joint project of FILK (Freiberg, Germany), FTB (Mönchengladbach, Germany), and Centexbel (Ghent, Belgium).

Funding Open Access funding enabled and organized by Projekt DEAL.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Paul, R, “Functional Finishes for Textiles: An Overview.” In: Paul, R (ed.) *Functional Finishes for Textiles*, pp. 1–14. Woodhead Publishing, Oxford (2014)
2. Nguyen, T, Jung, E, Yang, H, Hyun, S, Choi, K, Jeung, E, “Potential Endocrine Disrupting Effects of Phthalates in In Vitro and In Vivo Models.” *J. Emb. Trans.*, **25** (4) 207–213 (2010)
3. Dhaliwal, AK, Hay, JN, “The Characterization of Polyvinyl Butyral by Thermal Analysis.” *Thermochim. Acta*, **391** 245–255 (2002)
4. Nguyen, FN, Berg, JC, “The Effect of Vinyl Alcohol Content on Adhesion Performance in Poly(vinyl butyral)/Glass Systems.” *J. Adhes. Sci. Technol.*, **18** 1011–1026 (2004)
5. Tupý, M, Měřínská, D, Kašpárková, V, “PVB Sheet Recycling and Degradation.” In: Achilias, D (ed.) *Material Recycling—Trends and Perspectives*, pp. 133–150. InTechOpen, London (2012)
6. Smith, P, Bewisher, A, Ruggles, C, “Polyvinyl Butyral Dispersions.” Patent Application US20180009914A1, 2018
7. Mistler, RE, Bianchi, E, Wade, B, Hurlbut, J, “Evaluation of an Environmentally Friendly Plasticizer for Polyvinyl Butyral for Use in Tape Casting.” In: Ohji, T, Singh, M, Salem, J, Zhu, D (eds.) *Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials: Ceramic Engineering and Science Proceedings*, Volume 28, Issue 7. <https://doi.org/10.1002/9780470339718.ch4> (2009)
8. Takeshita, Y, Kamisho, T, Sakata, S, Sawada, T, Watanuki, Y, Nishio, R, Ueda, T, “Mixed Powder Coating Film Using Thermoplastic Polyester and Its Alkaline Resistance.” *J. Coat. Technol. Res.*, **10** 503–514 (2013)
9. Grethe, T, Schwarz-Pfeiffer, A, Graßmann, C, Engelhardt, E, Feld, S, Guo, F, De Vrieze, M, Mahltig, B, “Polyvinylbutyral (PVB) Coatings for Optical Modification of Textile

- Substrates.” In: Mendez-Vilas, A (ed.) *Polymer Research: Communicating Current Advances, Contributions, Applications and Educational Aspects*, pp. 36–45. Formatex Research Center, Badajoz (2018)
10. Yalcinkaya, F, Komared, M, “Polyvinyl Butyral (PVB) Nanofiber/Nanoparticle-Covered Yarns for Antibacterial Textile Surfaces.” *Int. J. Mol. Sci.*, **20** 4317 (2019)
 11. Randall, BS, Evans Jr., PD, Hammel, WJ, “Polyvinyl Butyral Backed Floor Covering.” US Patent Application 2005/0249911A1, 2005
 12. Technical Abstracts, United States. Office of the Quartermaster General. Military Planning Division, 11 (1943) 594
 13. Babers, FH, “Sealing of Seams and Hydrostatic Test Requirements in Specifications.” Technical Report 67-89-CM, Clothing and Organic Materials Laboratory US Army, Natick, Massachusetts, 1967
 14. Damewood, JR, “Direct Coated Polyurethane Fabrics.” *J. Coated Fabrics*, **5** 219–224 (1976)
 15. Cruickshank, P, Sáiz Gómez, V, “An Early Gut Parka from the Arctic: Its Past and Current Treatment.” *Proceedings of Scraping Gut and Plucking Feathers: The Deterioration and Conservation of Feather and Gut Materials, ICON Ethnography Group Conference*, University of York, October, 6th, 2009
 16. Guinovart, T, Crespo, GA, Rius, FX, Andrade, FJ, “A Reference Electrode Based on Polyvinyl Butyral (PVB) Polymer for Decentralized Chemical Measurements.” *Anal. Chim. Acta*, **821** 72–80 (2014)
 17. Chen, L, Ma, J, Yan L, Zhou, M, “Flame-Retardant Antibacterial Coating for Textile Fabric.” Patent CN000105421064A, 2016
 18. Roescheisen, “Surgical Swab—With a Fluid Permeable Coating Preventing the Core Fibres from Felting Off.” Patent FR000002166738A5, 1973
 19. Farel, R, Yannou, B, Ghaffari, A, Leroy, Y, “A Cost and Benefit Analysis of Future End-of-Life Vehicle Glazing Recycling in France: A Systematic Approach.” *Resour. Conserv. Recycl.*, **74** 54–65 (2013)
 20. Tupý, M, Mokrejs, P, Merinska, D, Svoboda, P, Zvonicek, J, “Windshield Recycling Focused on Effective Separation of PVB Sheet.” *J. Appl. Polym. Sci.*, **131** 39879 (2014)
 21. Knapčíková, L, Radchenko, S, Duplák, D, Hatala, M, “Advanced Materials Based on the Recycled Polyvinyl Butyral (PVB).” *2nd EAI International Conference on Management of Manufacturing Systems*, November 22–24, Starý Smokovec, Slovakia, 2017
 22. Valera, TS, Dermarquette, NR, “Polymer Toughening Using Residue of Recycled Windshields: PVB Film as Impact Modifier.” *Eur. Polym. J.*, **44** 755–768 (2008)
 23. Ambrósio, JD, Lucas, AA, Otaguro, H, Costa, LC, “Preparation and Characterization of Poly(vinyl butyral)-Leather Fiber Composites.” *Polym. Compos.*, **32** 776–785 (2011)
 24. Uddin, AJ, “Coatings for Technical Textile Yarns.” In: Alagirusamy, R, Das, RA (eds.) *Technical Textile Yarns*, pp. 140–184. Woodhead Publishing, Cambridge (2010)
 25. Shim, BS, Chen, W, Doty, C, Xu, C, Kotov, NA, “Smart Electronic Yarns and Wearable Fabrics for Human Biomonitoring Made by Carbon Nanotube Coating with Polyelectrolytes.” *Nano Lett.*, **8** 4551–4557 (2008)
 26. Gassan, J, Gutowski, VS, Bledzki, AK, “About the Surface Characteristics of Natural Fibres.” *Macromol. Mater. Eng.*, **283** 132–139 (2000)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.