This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003893

CIrcular SUstainable FLOor coverings

Grant Agreement number: 101003893

D4.13 Report Circular Flooring Pilots Evaluation

Author(s):	Ine De Vilder (Centexbel), Ansgar Paschen (TFI), Shaun Wadsworth (CFA), Joran Moyson (BIG), Geert Coudenys (UNILIN), Giampaolo Brugnoni (Aquafil)
Internal reviewers:	Ansgar Paschen, TFI Sandra Tapin-Lingua, FCBA
Contractual delivery date:	28/02/2025
Actual delivery date:	30/04/2025
Version:	V1.0
Dissemination level[1]:	PU

[1] PU: Public
RE: Restricted to a group specified by the consortium
CO: Confidential, only for members of the consortium; Commission services always included

Document history

Version	Date	Change	Author
V0.1	3/2/25	Initial version for review	CTB, TFI, BIG, UNILIN, AQUAFIL
V0.2	11/4/25	Second version for review	UNILIN
V1.0	30/4/25	Final version	CTB

Abbreviations

ACR	Aquafil Carpet Recycling machine
ACS	Aquafil Carpet Separation machine
CaO	Calcium Oxide
$CaCO_3$	Calcium Carbonate
CFA	Contract Flooring Association
cTextile	Circular textile
cLaminate	Circular laminate
CV	Cushion Vinyl
D	Deliverable
DPP	Digital Product Passport
EoL	End of life
EoW	End of Waste
FITA	Flooring Industry Training Association
HDF	High Density Fiber Board
LVT	Luxury vinyl tile
MDF	Medium Density Fiber Board
PA6	Polyamide
PET	Polyester
PO	Polyolefin
PP	Polypropylene
PSA	Pressure Sensitive Adhesive
PVC	Polyvinyl chloride
TPO	Thermoplastic polyolefine
Wt%	Weight %

Table of contents

Index of figures

Index of tables

Executive summary

CLaminate

The goal of the pilot line was to build a pilot line that demonstrates the feasibility to recycle EoL laminate flooring and use this as a raw material in the production of new laminate flooring.

The recycling of EoL laminate flooring is happening in two consecutive steps:

1) First the wood fibers are extracted from the EoL laminate and these fibers are used in the production of new HDF core boards. The pilot line for this has been constructed in the MDF/HDF factory of Unilin in Bazeilles, France.
2) In a second step, these HDF core boards including recycled fibers are used in the production of new laminate flooring. This is happening in the production facility in Wielsbeke, Belgium. This step did not require any adaptation nor development, because the quality requirements for the HDF baseboards were met by these HDF baseboards with recycled content.

The building of the pilot line in Bazeilles started a few months ahead of the CISUFLO project's start and it has been modified and optimized several times in the course of the project in order to meet the goals. Issues where detected with contaminants coming from the recycled material such as coatings, small undefibered lumps, etc., which was in the end solved by installing a novel cleaning machine.

The results of the pilot line development and the recycling process have proven to be satisfactory. The recycled fibers that come coming out of the defibring process can be used to produce good quality HDF and MDF products that comply with customer requirements and the norm (EN622-5). This has been demonstrated in 2 ways:

- Small boards samples have been produced on lab scale using 100% recycled fibers coming out of the pilot line. The quality of these samples proved good quality of the recycled fibers.
- The same fibers were injected on semi-industrial scale in the MDF production. Because the capacity of the pilot line is limited, only levels of recycled fibers in the range of 3 to 5 weight % have been demonstrated. The resulting MDF/HDF quality testing showed no negative impact on the mechanical quality of the boards (internal bond, modulus of elasticity, swelling etc.).

CTextile

- Monomaterial concept

A monomaterial broadloom carpet consisting out of recycled PA6 piles, a PP primary backing, a PO based precoat (applied via powder scattering) and a PA6 secondary backing has been produced without issues. Installation trials have been performed, showing that the tackifier adhesive has most potential for easy uplift. A room has been fitted with the carpet using the tackifier, and was in use for 5 months. The use of a 'hairy' PA6 felt as backing has created issue around the joints as the loose fibres contaminated the adhesive at those spots (due to repeated uplifting during installation). It was shown that the installation goes smoother when the secondary backing is smooth, and does not contain loose fibres. The offcuts and the end-of-life carpet have been chemically recycled, and could both be converted to caprolactam without problems. RFID tags have been assessed during the lifetime of the carpet, and some signals were lost after a while.

- Separation layer concept

The separation layer concept was tested with the main focus on carpet tiles which is to be expected to be an important application for this principle. It could be shown that a reasonable pile fixation was achieved using a thermobonding process and coating of the separation layer on the backside is possible. Applied separation layers are: I) a thermoplastic PO triggerable by heat and II) a recycled polymer triggerable via solvent. The conventional secondary backings (bitumen and PO) can easily be applied. Separation tests were performed on lab scale to assess the potential of this concept. When using the recycled polymer separation layer, the bitumen backing can be delaminated using an alcohol, the polyolefin backing can be delaminated in acidic environment. Using heat to separate shows potential, but more finetuning is needed to have the correct temperature frame.

- Mechanical recycling

To address the textile flooring waste that is currently produced, considering that all circular solutions will not affect recyclability of currently disposed carpets for a long period of time (carpets lifetime ranges between 5 to 20 years), a practical and viable solution must be identified now. In the last year, mechanical dismantling was investigated, as it seems an interesting approach that is giving promising results at lower operational costs. A newly developed technology was tested on different kind of products from different partners, also external to the project, ranging from carpet tiles, broadloom carpets and rubber mats.

It is not easy to draw general conclusions about the results, because each product behaves differently, and sometimes also the lifetime of the carpet influences its dismantling and separability. However, the new technology being developed (ACS, Aquafil Carpet Separation) helped identifying some design-for-recycling insights regarding material and construction methods. Remarkable examples are the addition of a brittle precoating layer that acts as a separation layer, or a weaker primary backing of polypropylene instead of polyester.

The streams obtained from carpets recycling can vary, but all have one thing in common: they can’t reach the required purity for the end-of-waste classification. This means that further purification steps are required, according to the desired purity needed for the reintroduction of such materials in the production process. Some preliminary tests were done with positive results, but at the moment the process is still distant from an industrial uptake.

CVinyl

Cushion vinyl:

- Current process

The introduction of micronized cushion vinyl as recycled content has been tested in the current plastisol coating process. Trials showed that it is possible to use micronized material as recycled content but due to a lack of technical feasibility it was not possible to reach a recycled content of higher than 2-3 w%.

By using bio-circular PVC instead of virgin PVC in one product range, a significant carbon footprint reduction could be achieved.

- Alternative technologies

Research was conducted into two alternative technologies: extrusion and calendering. By using these technologies, a higher amount of recycled content can be added than using the current technology. Both technologies have shown promise but the focus has mainly been on developing a qualitative formulation of the recycled PVC granules.

Luxury Vinyl Tiles (LVT):

The full replacement of virgin PVC by recycled PVC was tested using material coming from post-industrial and post-consumer sources like window profiles. The use of only recycled PVC showed good results and shows that it is possible to manufacture LVT without the use of virgin PVC.

1. Introduction

Within the CISUFLO project several pilots have been conducted to assess the circularity of floor coverings:

- Pilot 1: the production of circular floor coverings, being laminate, vinyl (LVT and vinyl flooring) and textile based flooring (carpet and carpet tiles)
- Pilot 2: sorting of flooring waste
- Pilot 3: separation of multilayered flooring
- Pilot 4: laminate recycling into MDF and HDF
- Pilot 5: PVC recycling into LVT and cushion vinyl
- Pilot 6: full circular carpet

The link between the different pilots and the value chain of a flooring can be seen in the picture below.

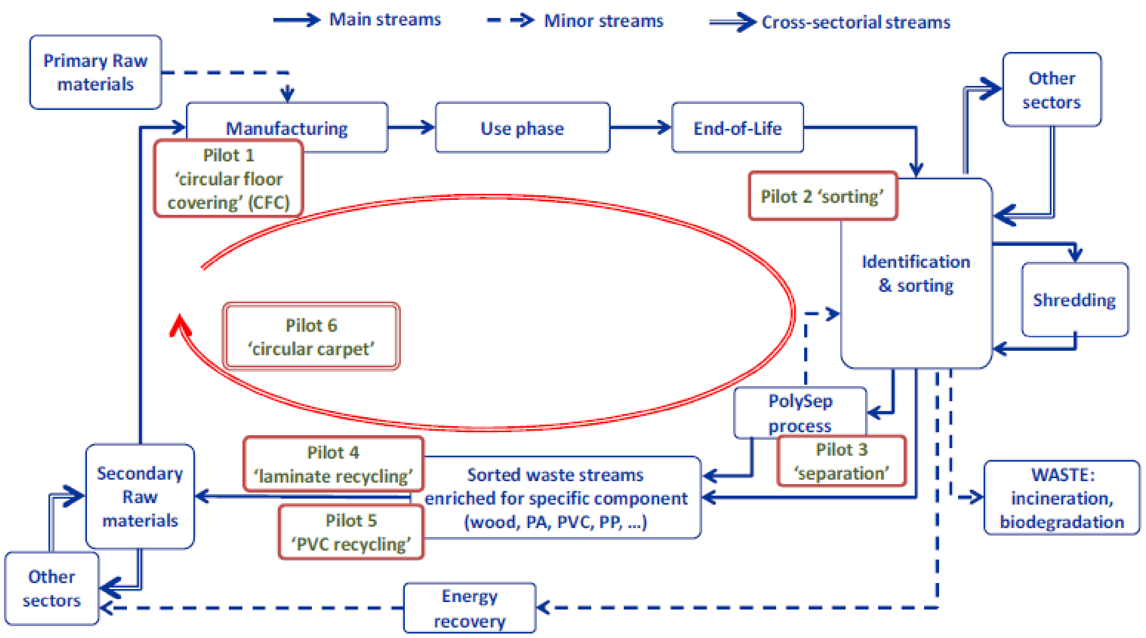


Figure 1: Overview of the pilots along the flooring value chain

This report will contain a summary of the activities performed in those pilots, and the obtained results. These findings have been analysed, serving as basis for guidelines to the flooring sector on how to produce and install circular flooring, and how to sort and recycle at end-of-life.

This report has been drafted as part of work package 4, task 4.6 – Evaluation of the pilots.

2. Laminate flooring

The recycling of EoL laminate into new laminate consists of 2 stages: first the extraction of the wood fibers out of the EoL laminate and the production of new core board (HDF) using a % of these recycled fibers. This HDF is then used as a baseboard to produce new laminate flooring.

The pilot line only deals with the recycling of wood fibers and using them to produce new HDF baseboard (see further). The production of new laminate flooring is no part of this pilot line.

The pilot consists of the following building blocks:

- Feeding section to supply the material to the steaming section
- Steam treatment: the defibring process, which is a batch process
- Buffer box: to store fibers to have a buffer to be able to inject fibers continuously
- Fiber cleaning: remove unwanted contaminants in the fiber flow
- Fiber injection: adding the recycled fibers into the production line of new MDF/HDF

Figure 2: Process flow laminate recycling and reuse.

2.1. Recycling of EoL laminate

The recycling of EoL laminate is based on a steam explosion process. This process, that is well known in other industries, has been adapted to the disintegration of EoL laminate and the extraction of the wood fibers.

The first step is to shred the EoL material into smaller pieces (chips) of typically a few cm in size. A batch of these chips is then introduced into a high pressure steam cooker. Once the material is in the vessel, the lids are closed and high pressure with saturated steam is applied during a couple of minutes. This will heat up the material and allow the steam to penetrate in the chips till the core. The final step of this defibring process is to release the steam pressure very quickly by opening a big valve. During this depressurization, the steam expands and 'explodes' the material from the inside.

This results in good quality wood fibers mixed with flakes from the coatings, that are part of the build-up of a laminate flooring (see Figure 3). The output is used in replacement of virgin fibers in the production of MDF/HDF.

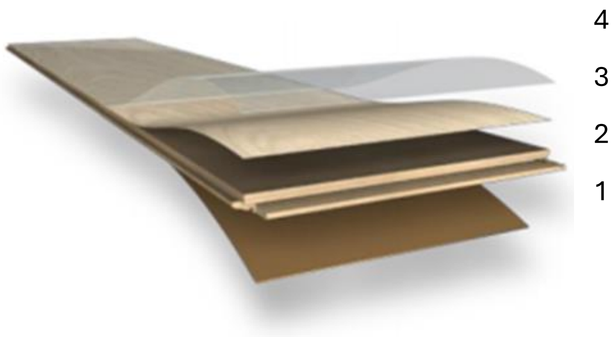


Figure 3: Laminate flooring build-up : 2 = HDF 1,3,4 = resin impregnated paper layers

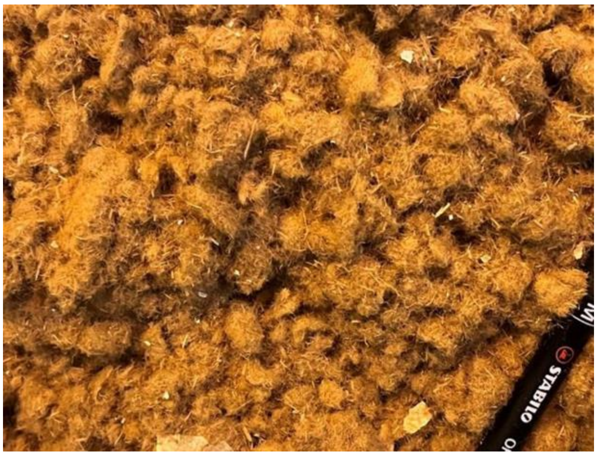


Figure 4: Recycled fibers from EoL laminate flooring containing coating flakes (white)

2.1.1. Defibering by steam explosion

During the project, the optimum process settings of the high pressure steam process have been determined. The process has a few parameters that can be varied:

- Pressure: this is the most important parameter. This is the pressure that is used during the heating of the chips.
- Time: this parameter is the time that the material remains in the vessel at high pressure. A trade-off between time and pressure has can be made. Higher pressure allows to shorten the treatment time and as such improve the capacity of the pilot line. And vice versa: lower pressures require longer treatment times.
- Speed of depressurization: the faster, the better for the defibering yield.

Out of the tests it can be concluded that using pressures above 10 bar is a good setting to obtain good yield, good fiber quality and good throughput.

The fibers that come out of this process are of very good quality: the fiber surface is unharmed by the process. The fibers are slightly darker than fibers produced by virgin wood, depending on the process settings. This is no problem for the applications, because the MDF/HDF board is – in almost all cases - fully covered by a coating (paint, melamine paper, lacquer, etc.).

Putting more energy into the material (higher pressures or longer treatment times) increases the darkening effect.

Figure 5: Left) Optical microscope of recycled fibers showing smooth and intact fibers surface, Right) Left: virgin fibers - Right: recycled fibers

2.1.2. Cleaning of the fibers

The first developments were based on recycling the internal reject of the factory. This is pure MDF/HDF: uncoated and not contaminated. During the testing of such material, good quality fibers were obtained and it was first believed that a cleaning step would not be necessary. The general idea was: 'the chipped MDF/HDF goes into the process and good fibers come out' when the process settings are correct.

This assumption however was wrong because there always seems to be a small fraction of material that is poorly defibrated and that can be found as lumps (bigger or even quite small) in between the fibers. These lumps can originate from material that was not chipped to the right size (too big), by the fact that the glue content or composition was different, by the steam that did not treat the whole chip homogeneously.

Figure 6: Fiber lumps (left) and effect of such a lump in a HDF board (X-section) (right)

In case these lumps are not removed, they end up creating bumps at the surface of the produced boards.

As a consequence, at an early stage in the project, a cleaning step was introduced and a wind sifter was inserted into the pilot line. In a later stage of the project, when also EoL material was recycled, this cleaning step will also remove foreign materials (pieces of plastic, metal, etc…), wood pieces and contaminants from the recycled fiber flow.

2.1.3. Production of new HDF/MDF

Two methods have been explored to assess the fibers from this recycling process:

1) On lab scale in the range from 0 to 100 wt% of recycled fibers
2) Industrially, with the pilot line, in the range of 3 to 5 wt% of recycled fibers

The lab scale tests revealed no problems with the fiber quality. Even boards produced with 100% recycled fibers did not show worse quality than fibers from virgin wood. The different process settings (pressure, time) have been compared and all settings yielded good boards with only minor differences in the characteristics. Therefore it was decided to carry out further tests on the pilot line in order to get more statistical relevant information.

The steam explosion step is a batch process that produces more than 1 m³ of fibers per batch. A batch lasts a few minutes to be processed and therefore a lot of m³ of fibers are produced every hour of testing. The choice has been made to recycle as much as possible these fibers, even during the development of the steaming process, by using them in the regular production of MDF/HDF and not disposing them. The consequence is that during the course of the project, quite considerable volume of fibers has already been recycled and injected into the production of new MDF/HDF. This has put quite some pressure on the execution of the testing because the quality of the produced boards needed to remain guaranteed.

Fibers leaving the steam explosion process are stored into a buffer box. Starting from this box, the fibers are dosed, pass through the cleaning step and are injected into the production line in a continuous flow in replacement of virgin fibers (replacement 1:1).

2.1.4. Problems encountered during the setup/engineering of the pilot line

A lot of effort was spent on the process to get to the best conditions of pressure and treatment time to get a good yield of the process. However, most of the manpower in this part of the project had to go to the development of the machines and the interconnection between the different parts of the installation. The pilot line started with a simple setup that only allowed to do a few batches before it needed to be stopped because of fibers blocking valves and because of the fact that there was a 'carpet' of several centimetres of fibers on the floor of the hall. This starting situation has been modified and improved till the situation of Jan 2025. See Figure 7 and Figure 8 to see the evolution of the pilot line.

Several rebuilds have been done in order to:

- Improve the reliability of the pilot line
  - replacement of pressure relief valve by another type
  - redesign the seals of the in- and outfeed of the steam vessel
  - redesign of the mechanical arm in the steam vessel
- Improve the ergonomics
  - replace the open belt conveyors by screw transport in order to keep the fibers into the system
  - automatic feeding of the line instead of manual feeding
- Improve the safety of the installation
  - spark detection and automatic fire extinction
  - prevent steam leaks by modification of seals
  - add flushing system to the dead zones in the vessel (avoid smouldering fibers)
- Improve the performance of the pilot line
  - twice replacement of the cleaning equipment to improve the cleaning performance

This list is not exhaustive but lists the most important modifications.

2.1.5. Overview of the obtained results

In summary, the pilot line brings the following results:

- The goal, a capacity of 1 ton per hour, has been largely met. Even 1.4 ton per hour is possible in a continuous way.
- 3 to 5 wt% of recycled fibers have replaced virgin fibers in the production of MDF and HDF without impact on the mechanical characteristics of the boards. As the output of regained fibres from the pilot plant is much lower than the production speed of novel MDF/HDF, only low amounts can be added to guarantee a constant infeed into the fibreboard production line.

- The yield of the defibring process is > 90% and typically > 95% in weight (fibers out/chips in)
- The process can deal with the majority of MDF/HDF products currently on the market. It can not recycle some types of glues like high melamine UF and pMDI.
- Recycling of EoL material and more specifically EoL laminate flooring is demonstrated.
- Over 1000 tons of recycled wood fibers have been produced in the course of 2024 on the pilot in order further optimize, tune, improve the pilot line and its process. These recycled fibers have been used in the production of new MDF/HDF.

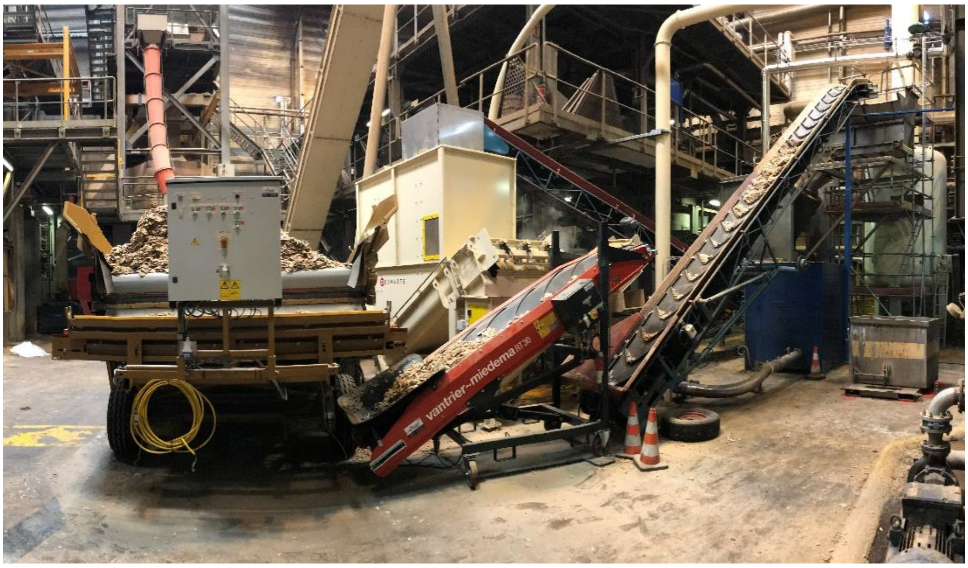


Figure 7: Pilot line July 2021

8

Figure 8: Pilot line March 2025

2.2. Production of circular Laminate

The MDF/HDF boards that were produced had typically 3 to 5 wt% of recycled fibers. At these %, no distinction can be made visually between the boards with and without recycled fibres, even though those recycled fibers are darker than virgin ones.

Different external customers have used the MDF boards and no complaints have been made on the quality. This showed the synergy of this project with other industries such as the furniture industry.

The HDF core boards containing recycled fibers have been tested in depth when producing circular laminate flooring. The HDF core boards containing recycled fibers are processed as standard HDF core boards containing 100% virgin fibers. The melamine impregnated papers (balancing, printed decor, overlay, etc.) are placed on the HDF core board prior to pressing at high pressure and high temperature. Then these pressed boards are cut and the tongue and groove are milled.

HDF boards (6-10 mm thick) have shown to be sensitive to small lumps passing through the cleaning step during the recycling phase. This is the reason why at the end of 2024, the third version of the cleaning step has been implemented. A state-of-the-art machine has been installed and this machine allows a good separation of the small contaminants that still passed and ended up into the boards in the past.

These contaminants are the cause of small bumps on the surface of the laminate flooring. This increased the reject rate of the production line, although the board complies with the mechanical quality requirements (internal bond, bending strength, etc.).
This issue is solved by the newly installed cleaning machine: the reject rate is very low and in the range of the standard reject rate of the laminate flooring production line.

Figure 9: Circular laminate flooring production (left) and a small defect (bump) on a laminate flooring plank (right)

2.3. Tagging of circular Laminate

In order to be able to couple the individual laminate boards with a digital product passport, like ePRODIS developed within CISUFLO, the boards need to be tagged. The frequency of the tag repetition will depend on the technology used. This can have a cost and process impact. With a high frequency of the tagging repetition, the readability is increased even when the flooring is cut or shred into smaller pieces.

The tag readability is also depending on the technology and may vary depending on the life stage of the circular laminate (installation, use, EoL, etc.).

2.3.1. Different tagging technologies

Tagging tests have been executed on cLaminate with printed and embossed QR codes on the backing of the flooring but also embedded in the decor.

Embossed QR codes are cost-neutral when the tagging is engraved on the press plate for the cLaminate backing. This is however limiting tagging flexibility as changing the press plate requires a production stop. The embossing can be smooth (no structure depth) and only play with gloss variations then having a limited contrast and needing good light conditions to be read.

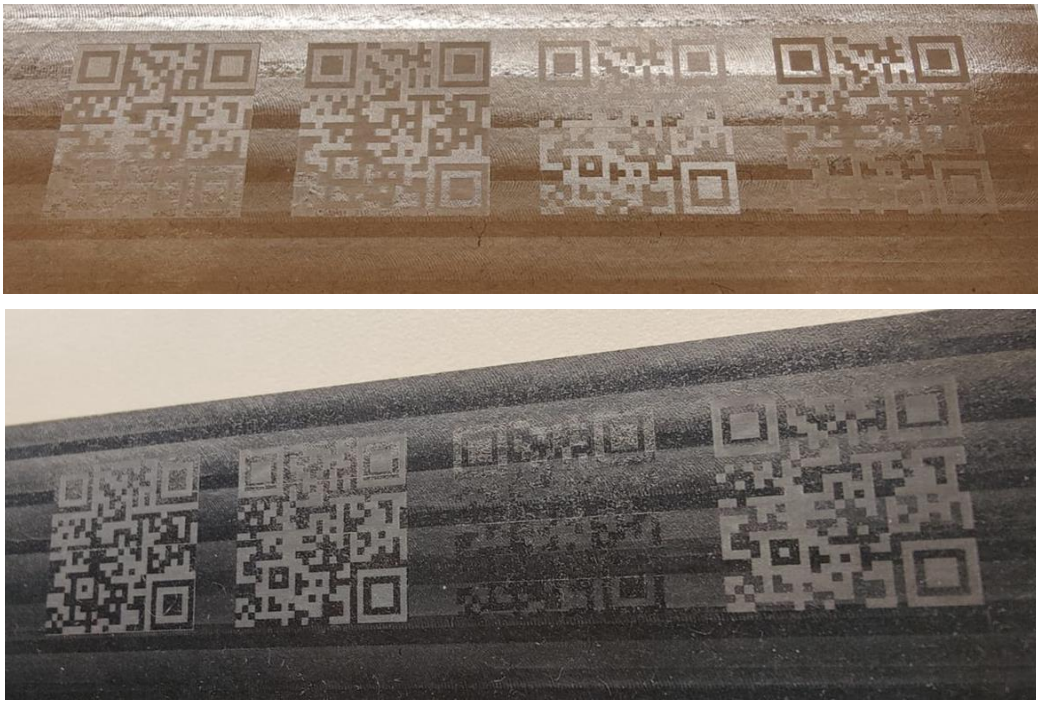


Figure 10: Embossed QR codes with a black and with a brown backing paper

Printed QR codes are almost cost-neutral and the printing can be done online or offline. Offline printing is more reliable in terms of printing quality and can be achieved even before paper impregnation to ensure permanent tagging. When the printing is done online after pressing, the ink is more exposed to chemicals, friction and fading stress but it is the most flexible solution as each plank can even be marked with a unique code.

Figure 11: Printed QR codes of different sizes

A special coding (watermarking) can be embedded in the decorative layer whilst not be visible by the user. This is quite easily doable when the decor is digitally printed but can also be achieved with analogue printing. This technology is commonly used in the food industry for the packaging.

RFID chips can be fixed on the backing of the circular Laminate after milling, just before packing. RFID chips are not cost-neutral and their repetition frequency should be limited to 1/25 m² for instance. Tests on pressing the RFID chips into the HDF boards have not been executed because the process is very sensitive to local thickness variations.

2.3.2. Reading the tags

When the tag is only visible on the backing of the cLaminate, it can be accessed during the installation phase and during the sorting/recycling phase. Customers need to keep at least a piece of a plank or a picture of the QR code if they want to access the tagging during the use phase to have some maintenance and/or repair guidance.

When the tag can be read with a smartphone after cLaminate installation (embedded in the design and/or with radio identification), it seems more user-friendly.

Reading tests of printed tagging have been performed to determine the minimum size and contrast level which could ensure a secured reading during sorting tests. Higher contrast (black on white) is providing better readability performances but the focus was put on black QR code on brown backer as this is the most commonly used backer situation (non-bleached paper) for laminate flooring.

The minimal size for printed QR code is depending on the reader capacity. The conveyor belt speed (18 m/min on the pilot line built in CISUFLO, an overview of the line is depicted in Figure 12), the distance between the reader and conveyor belt, and camera resolution parameters are very important. Optimal dimension was found between 15x15 to 30x30 mm with the pilot reader. The QR code with 6x6 mm was even NOT readable using a smartphone camera.
Additional tests were performed with engraved QR codes (size of 23x23 mm). On top of the above listed parameters, the readability was too much depending on the light conditions and on the type of QR code. This engraved tagging is considered as too difficult to read with actual devices.

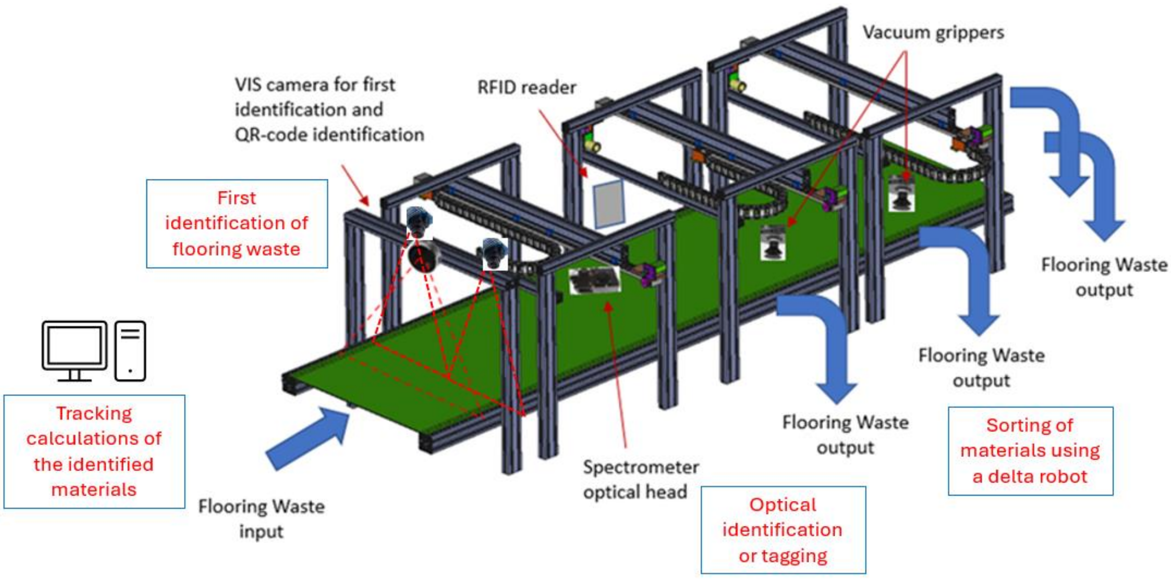


Figure 12: Schematic of the identification and sorting line developed in CISUFLO

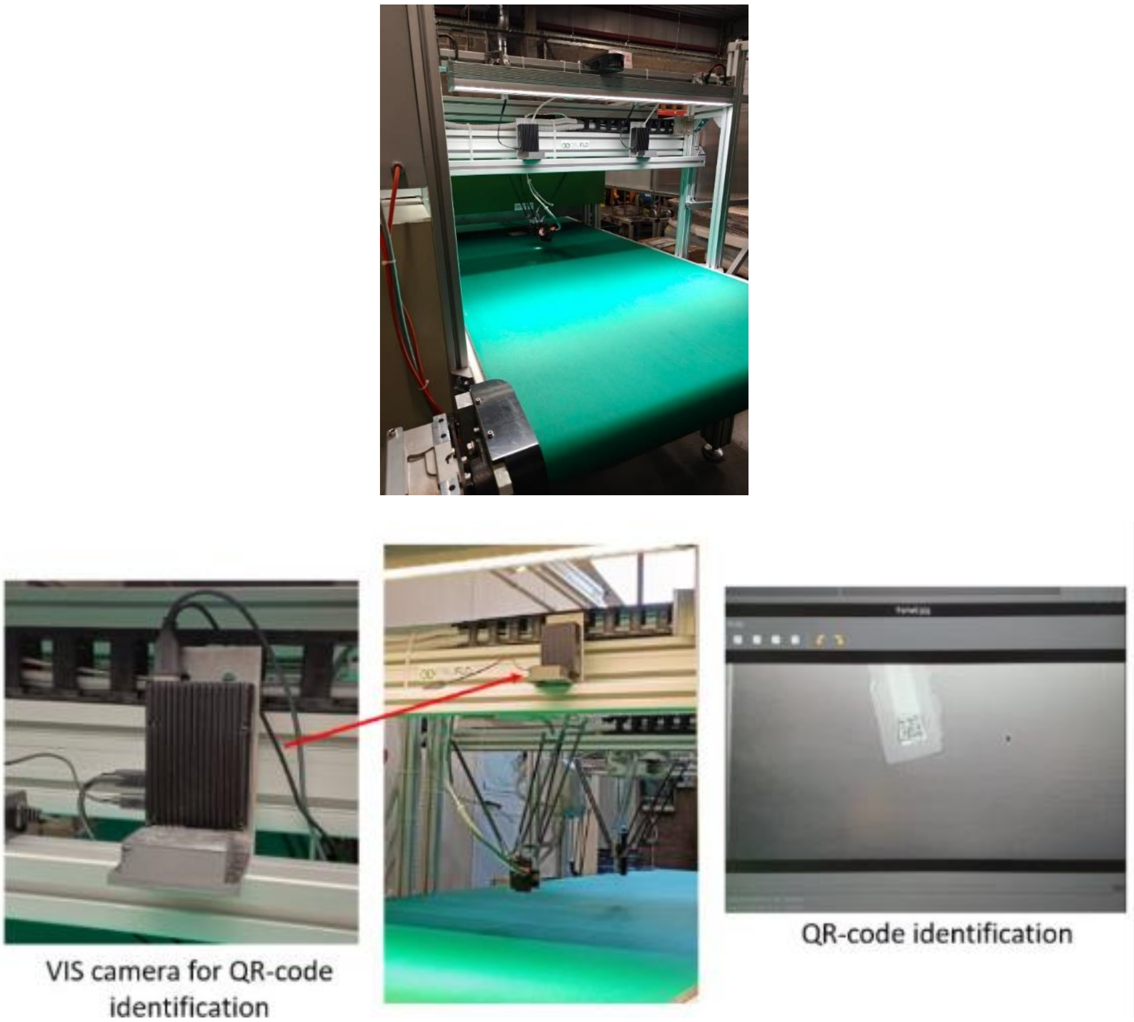


Figure 13: Pilot line for sorting with QR code reader

Embedded QR code in the design is invisible for the user, but can be read out using a special app on a standard smartphone. It is then possible for the end user to easily access information about the floor maintenance and/or repair during the use phase.

3. Textile floor coverings

For textile floor coverings, two design for recycling strategies have been implemented: the monomaterial approach and the separation layer approach. In the **monomaterial approach** (see Figure 14 left) , the carpet is predominantly manufactured out of one material (in this case polyamide 6 (PA6)). Producing from 100% PA6 is not feasible, as the obtained textile floor covering will not meet the technical requirements. The non-PA6 constituents need to be compatible with the chemical recycling process of PA6 (depolymerisation up to caprolactam). The amount of PA6 should be 85 wt% at least, to have a economically viable recycling process.

In the **separation layer concept** (see Figure 14 right) the conventional backing is maintained, but a separation layer is introduced, which can be triggered at end-of-life, leading to separation of the primary and secondary backing. So the textile floor covering is split up into different waste streams, one waste stream containing the secondary backing, and one waste stream containing the primary backing and piles.

Depending on the type of textile floor covering, one strategy can be favoured over the other: broadloom carpet can be made using the monomaterial approach, while e.g. carpet tiles need to be produced via the separation layer concept as the conventional secondary backing is needed for dimensional stability.

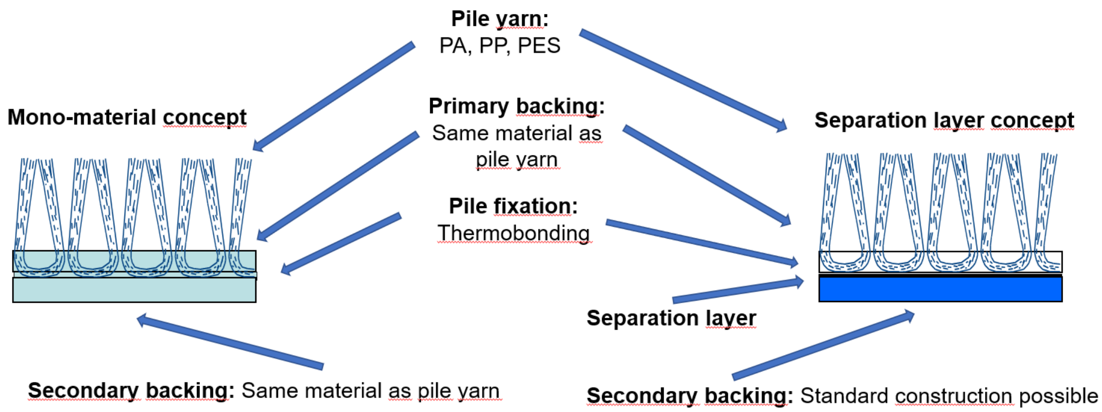


Figure 14: Scheme monomaterial approach (left) and separation layer concept (right) for carpets

3.1. Monomaterial approach

3.1.1. Production of monomaterial carpets

In the project the focus is put on the production of a broadloom monomaterial carpet made of PA6. Due to technical reasons, it was not possible to use 100 wt% of PA6. For the chemical recycling process to be economically viable, at least 85 wt% of PA6 should be present. The fraction of the carpet, not being PA6, should preferable be a polyolefin, as this is compatible with the recycling process (depolymerisation up to caprolactam, the building block of PA6).

The following design-for-recycling was made (see Figure 15):

- Piles from recycled PA6 yarn (ECONYL®)
- Primary backing made from polypropylene (PP)
- Precoat made via polyolefin (PO) powder scattering
- PA6 nonwoven as secondary backing

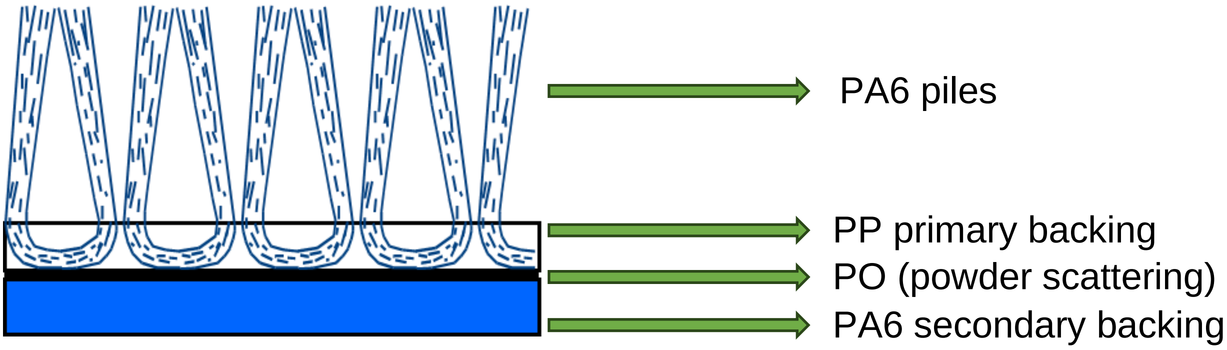


Figure 15: Schematic carpet build-up

The carpet (Figure 16) has been produced at industrial scale at EDEL carpets and meets the technical requirements, as set out for a conventional carpet. The amount of PA6 is 85 wt% in the final carpet, allowing to be recycled as a monomaterial, not needing prior separation of the different layers of the carpet.

Figure 16: Monomaterial carpet: Left) Pile-side, Middle) Backside, Right) Cross-section

The tufting of the primary backing can be done using conventional machinery. To introduce the precoat, a power scattering device is needed. A powder scattering unit is not present in all carpet factories, but is a common device often used in the textile sector.

To meet the requirement of 85 wt% PA6, it is needed to design a carpet with higher piles (in this case of approx. 1,2 cm), making it less suited for areas with higher traffic.

3.1.2. Installation and removal of monomaterial carpets

The Installation trials of this eco-designed broadloom carpet were completed by Contract Flooring Association (CFA) in controlled environments provided by Flooring Industry Training Association (FITA). Trials took place between May 2024 and February 2025, completed by time-served and correctly qualified flooring installers. The trials were planned to be spilt into 3 separate stages beginning with small scale trials and ending with a live installation to a public area.

These trials will be conducted in 4.5 m² training bays at FITA with the intention of establishing robust installation methods whilst also ensuring non-contamination of the product in respect of fully recycling the cTextile at end of life. This included product handling, preferred fitting techniques and initial feedback on uses in both residential and commercial settings.

These trials included;

- Installation using carpet tape direct to a cementitious subfloor
- Installation using tackifier adhesive direct to a cementitious subfloor
- Installation using carpet tape direct to a timber subfloor (plywood)
- Installation using tackifier adhesive direct to a timber subfloor (plywood)
- Installation using stretch fit method with carpet gripper and underlay
- Installation using double stick system with carpet gripper and underlay
- Installation of cTextile joins using various seaming methods
- Installation to stairs using stretch fit method

The preferred installation method was taken forward from the Stage 1 testing and to be applied to a large area trial was adhesion using tackifier adhesive (see Figure 17). This method was deemed the most effective of the tested installation methods and allowed for further testing of cTextile joins to be completed.

Figure 17: Stage 1 cTextile installation trials

Stage 2 of the installation trial was a large area test installed in the conference room of the FITA training centre in Loughborough, England (see Figure 18), where high traffic and wear would be anticipated. The installation remained in situ for 5 months (July 2024-January 2025) to monitor installation integrity, durability against traffic, maintenance and cleaning with regular checks completed and logged. RFID tags were also introduced to the back of the cTextile during the installation process and were periodically checked using a RFID antenna, to identify if the tags would be a suitable method of providing information on the product, its maintenance plan and recycling information come end of life.

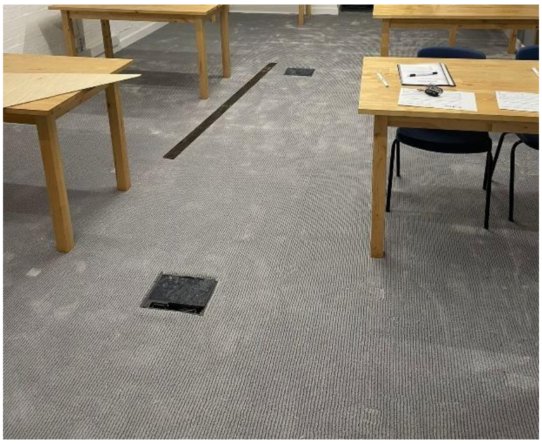


Figure 18: cTextile stage 2 test area

Within a short period of time, it was evident that the installation was failing at any areas where the cTextile was joined or cut to a nett finish (see Figure 19). Initial feedback suggested that the installation method used in conjunction with the weight of the cTextile and the secondary backing applied was the cause of the failure. The hairiness of the secondary backing contaminated the adhesive during installation (caused by the repeatedly uplifting of the carpet around the joints). Additional small scale-controlled tests were completed to prove that a smoother, non-hairy backing is needed and to identify any potential solutions.

Figure 19: Stage 2 cTextile installation issues

As a result of these finding TFI were able to supply small samples of cTextile carpet in which the backing surface was carefully ironed, creating a potentially better surface for bonding (see Figure 20). This surface was achieved by carefully ironing the backing surface with a simple iron at this stage with no systematic trial process in regard to temperature or treatment time.

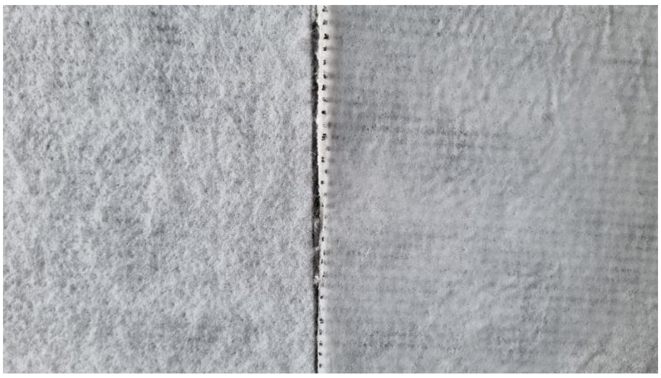


Figure 20: cTextile backing pre-ironed (left) and post-ironing (right)

The samples were then trialled with the tackifier adhesive and the results against previous versions of the cTextile were exemplarily. It could be confirmed that the bond between the backing and the tackifier adhesive was not only stronger but also allowed for the reapplication of the new sample to be placed back into the adhesive multiple times. The transfer to industrial scale has to be checked.

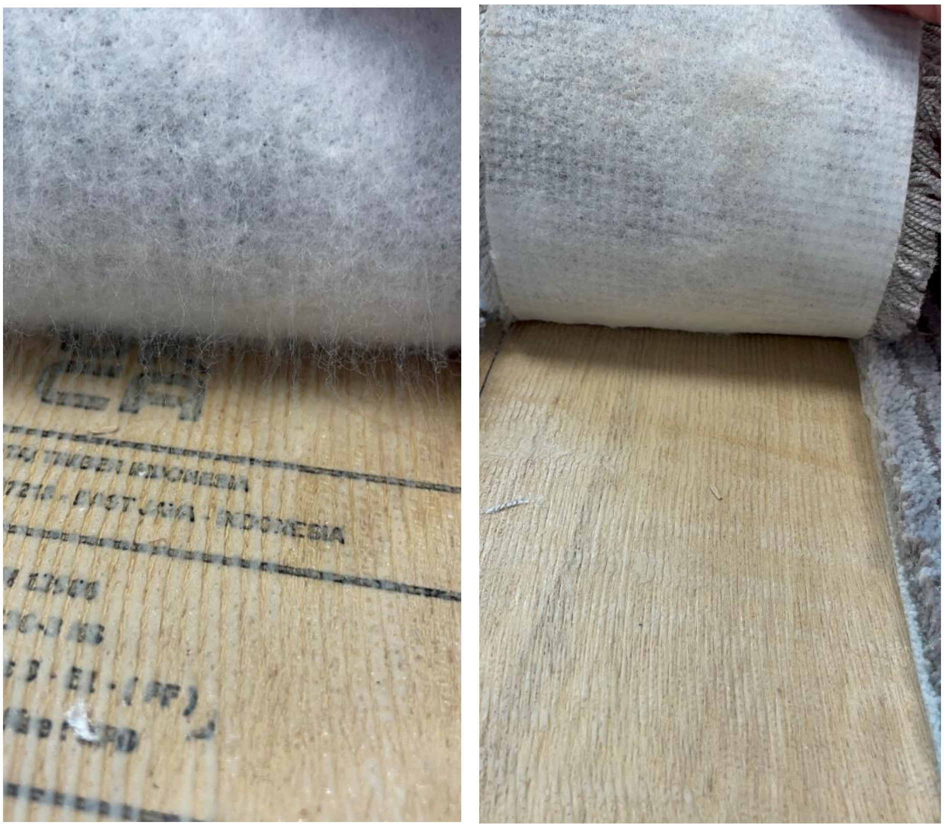


Figure 21: Original cTextile backing sample (left) and modified cTextile backing (right)

The final installation stage was planned to see a public space installed with the cTextile for a longer period with regular maintenance, integrity and durability checks. RFID tags were to be used again and monitored along with footfall too. Planning for the identification of a suitable space began in April 2024, with multiple locations researched but due to timeframe, product design and concerns over installation methods none of the locations researched ended in a live installation trial.

Through all installation stages, clean, non-contaminated uplift of the cTextile has been achieved with ease when using a system designed for clean uplift (caret tape, tackifier adhesive, stretch fit). The cTextile has then been progressed to sorting with samples from Stage 1 and Stage 2 testing being sent for sorting and recycling.

3.1.3. Recycling of monomaterial carpets

The recycling advantage of PA6 monomaterial carpets becomes clear during the actual recycling process. When the carpet composition already meets Aquafil's ECONYL® regeneration requirements, these products can be directly processed without the need of additional separation steps.

Specifically, the target of this last final step was to demonstrate the complete carpet circularity by proving full recyclability of the monomaterial carpet, by converting it into ECONYL® yarn. In this first phase, the recycling test by depolymerization was carried out on off-cuts coming from the installation.

The purpose was to have a first idea about the feasibility of the process, some preliminary results, and to have a term of comparison for the tests done on post-consumer waste.

It's important to underline that this design allows direct recycling firstly because of its high percentage of polyamide 6, but also because a proper selection of the best materials was carried out, so that the process can better tolerate the impurities. An example of this was the substitution of the more common primary backing in PET with the less common PP backing.

3.1.3.1. Recycling process test

The regeneration process was carried out on a pilot plant that can fully simulate industrial hydrolysis. The last step, the purification phase, was not executed because for the purpose of the demonstration it was not necessary, since the purity of the raw caprolactam obtained was sufficient to demonstrate the regenerability of the monomaterial carpet.

Following a brief explanation of the whole ECONYL® chemical regeneration process:

a. <u>Chemical analysis</u>

The first step is always a chemical analysis of the selected material, which in this case were the cuts and trims discarded by the installation process on the monomaterial carpet carried out by CFA. For this reason, the following results are valid only for the pre-consumer waste. After the de-installation of the carpet, the whole test process will be repeated to prove the circularity of the post-consumer carpet.

The chemical analysis of the mono-material carpet reported the following composition: PA6 ~ 84%, PP ~ 16% and inorganics < 1%.

These results are in line with the composition requirements of the ECONYL® regeneration process.

b. <u>Mechanical grinding</u>

The second step is the mechanical grinding of the carpet, to reduce it into smaller pieces that can be easily manipulated and introduced in the reactor of the pilot plant.

c. <u>Depolymerization</u>

During the third step, the obtained material is loaded into the reactor where the depolymerization takes place. The reactor is a pilot plant that simulates the standard conditions used in the ECONYL® regeneration process. Here depolymerization takes place and therefore raw caprolactam is obtained as a water solution. The reaction waste, containing mainly polypropylene, is also extracted from the reactor.

d. <u>Purification</u>

The fourth and last step, a process referred to as "purification", includes the distillation of the different components of the raw caprolactam, resulting in a mixture of high-purity caprolactam: water, light and heavy impurities are removed. For the monomaterial carpet the last step (purification) was skipped because gas chromatography analysis on the raw caprolactam obtained from depolymerization is sufficient to assess its quality.

In Figure 22 is a schematic diagram of the process, as explained above, depicted.

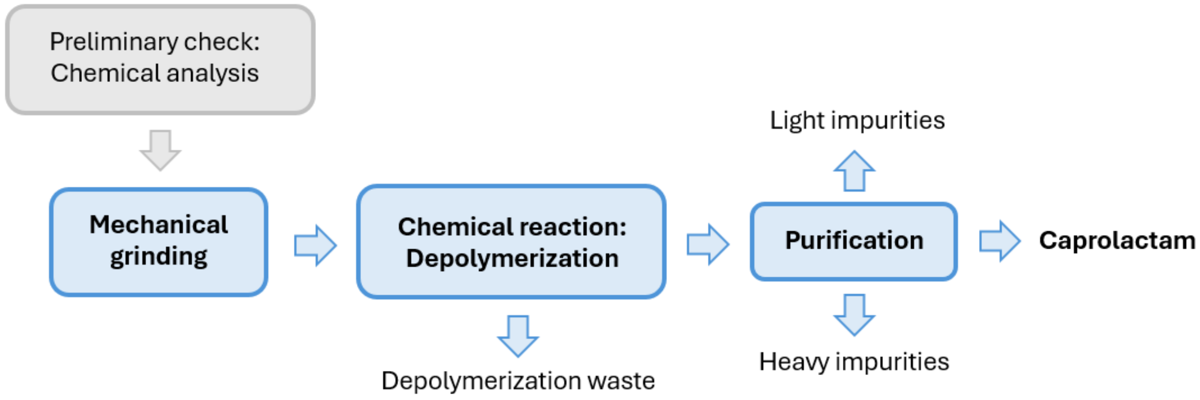


Figure 22: Schematic diagram of ECONYL® regeneration process.

3.1.3.2. Parameters tested

The impact of several variables has also been analysed during the process:

1. Depolymerization time
2. Depolymerization temperature (at too low temperatures reaction kinetics is too slow, at too high temperatures side reactions are producing too many byproducts).
3. Pressure range
4. Catalyst quantity

3.1.3.3. Results depolymerization offcuts

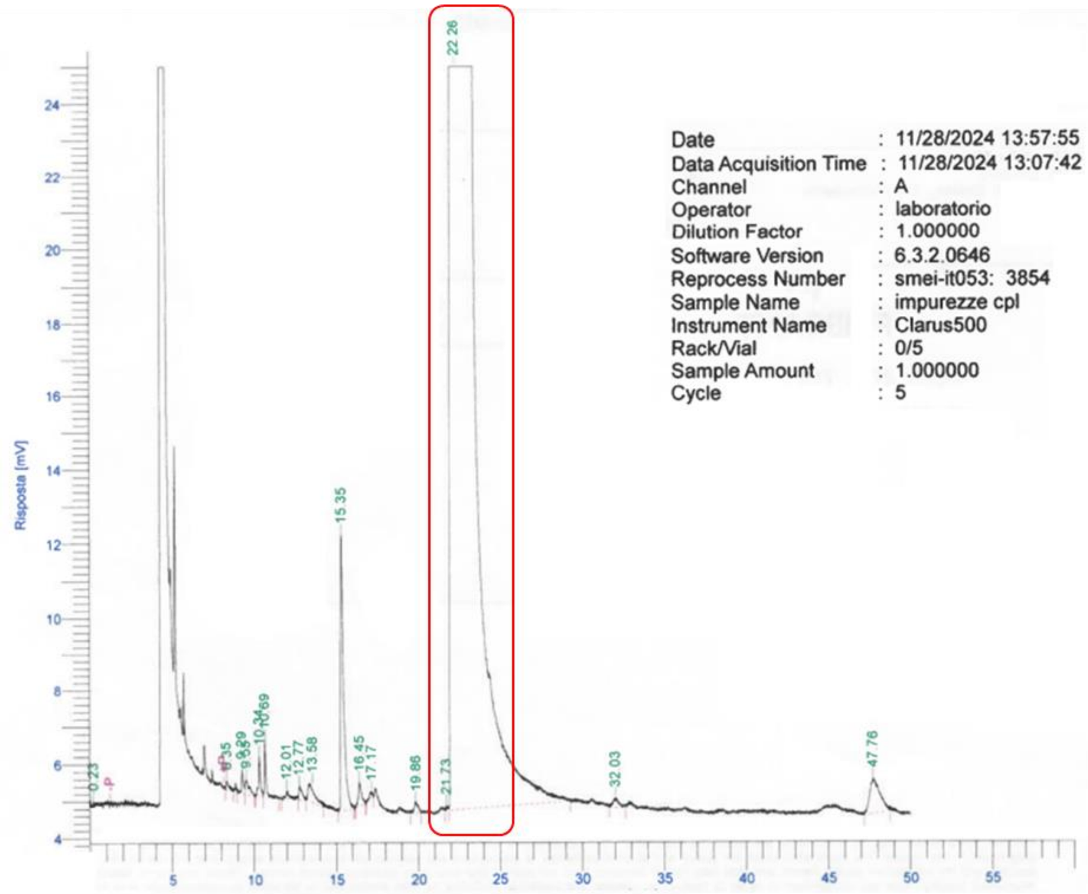
The depolymerization process was carried out without any difficulties and it was comparable to the equivalent tests carried out using pure polyamide 6. Necessarily the process yield was lower, compared to 100% PA6, since the carpet contains around 85% polyamide 6.

All parameters tested have shown values in line with ECONYL® industrial depolymerization process.

Following are the results of the raw caprolactam solution obtained (62% caprolactam in water):

- pH: 5.1
- Acidity: 42 meq/kg
- Gas chromatography area test, caprolactam peak: 99.7%
  This percentage, however, does not correspond to caprolactam purity because the area is a consequence of the amount of caprolactam combined with the sensitivity of the instruments to the substance analysed.
- Number of lighter impurities (gas chromatography test): 14
- Number of heavier impurities (gas chromatography test): 2

The gas chromatography results in Figure 23 shows that the quality of the raw caprolactam is good, and is in line with the industrial values usually found for this substance. The first peak on the left (which is also the second highest peak) represents the solvent used for the test. After it, there are 14 minor peaks corresponding to impurities lighter than caprolactam, which is indeed the main peak (highlighted in red). After that, two more peaks related with heavier impurities can be recognized. So impurities are still present, but the ease of separation for the purification step is acceptable. It's important to underline that, as expected, process waste consisted mainly of polypropylene.



Peak #	Time [min]	Area [µV·s]	Height [µV]	Area [%]	Norm. Area [%]	BL	Area/Height [s]	Rel. RT
1	0.235	901.03	140.29	0.00	0.00	BB	6.4228	1.000
2	8.351	3257.18	240.45	0.00	0.00	BB	13.5462	35.610
3	9.287	5631.09	632.19	0.01	0.01	BV	8.9073	39.602
4	9.549	6817.81	398.58	0.01	0.01	VB	17.1051	40.720
5	10.341	9033.30	1067.23	0.01	0.01	BV	8.4643	44.099
6	10.691	11351.90	1493.93	0.01	0.01	VB	7.5987	45.592
7	12.014	5249.65	231.35	0.01	0.01	BV	22.6910	51.231
8	12.773	4978.44	350.93	0.01	0.01	VB	14.1863	54.470
9	13.584	13390.24	300.42	0.02	0.02	BB	44.5717	57.929
10	15.349	96851.65	7517.54	0.13	0.13	BB	12.8834	65.452
11	16.447	9067.94	645.07	0.01	0.01	BB	14.0572	70.136
12	17.173	2389.66	168.34	0.00	0.00	BB	14.1956	73.233
13	19.857	5477.57	315.39	0.01	0.01	BB	17.3675	84.680
14	21.731	1202.91	124.69	0.00	0.00	BV	9.6472	92.668
15	22.261	76948589.12	989118.11	99.71	99.71	VB	77.7951	94.931
16	32.034	6181.70	252.73	0.01	0.01	BB	24.4598	136.604
17	47.758	40680.86	944.62	0.05	0.05	BB	43.0656	203.660
		77171052.03	1.00e+06	100.00	100.00			

Figure 23: Gas chromatography results

3.1.3.4. Circular recycling

After Aquafil received the post-consumer waste coming from the PA6 monomaterial broadloom carpet use phase simulation performed by CFA, this material was tested in the exact same way as the off-cuts from installation, explained in the previous chapter. Following are the results of the raw caprolactam solution obtained (56% caprolactam in water). Figure 24 shows gas chromatography results, where the caprolactam peak is underlined in red.

- pH: 5.4
- Acidity: 45 meq/kg
- Gas chromatography area test, caprolactam peak: 99.2% (see Figure 24)
  This percentage, however, does not correspond to caprolactam purity because the area is a consequence of the amount of caprolactam combined with the sensitivity of the instruments to the substance analysed.
- Number of lighter impurities (gas chromatography test): 8
- Number of heavier impurities (gas chromatography test): 4

In Table 1 the comparison between the caprolactam analysis of pre-consumer and post-consumer carpet waste is listed.

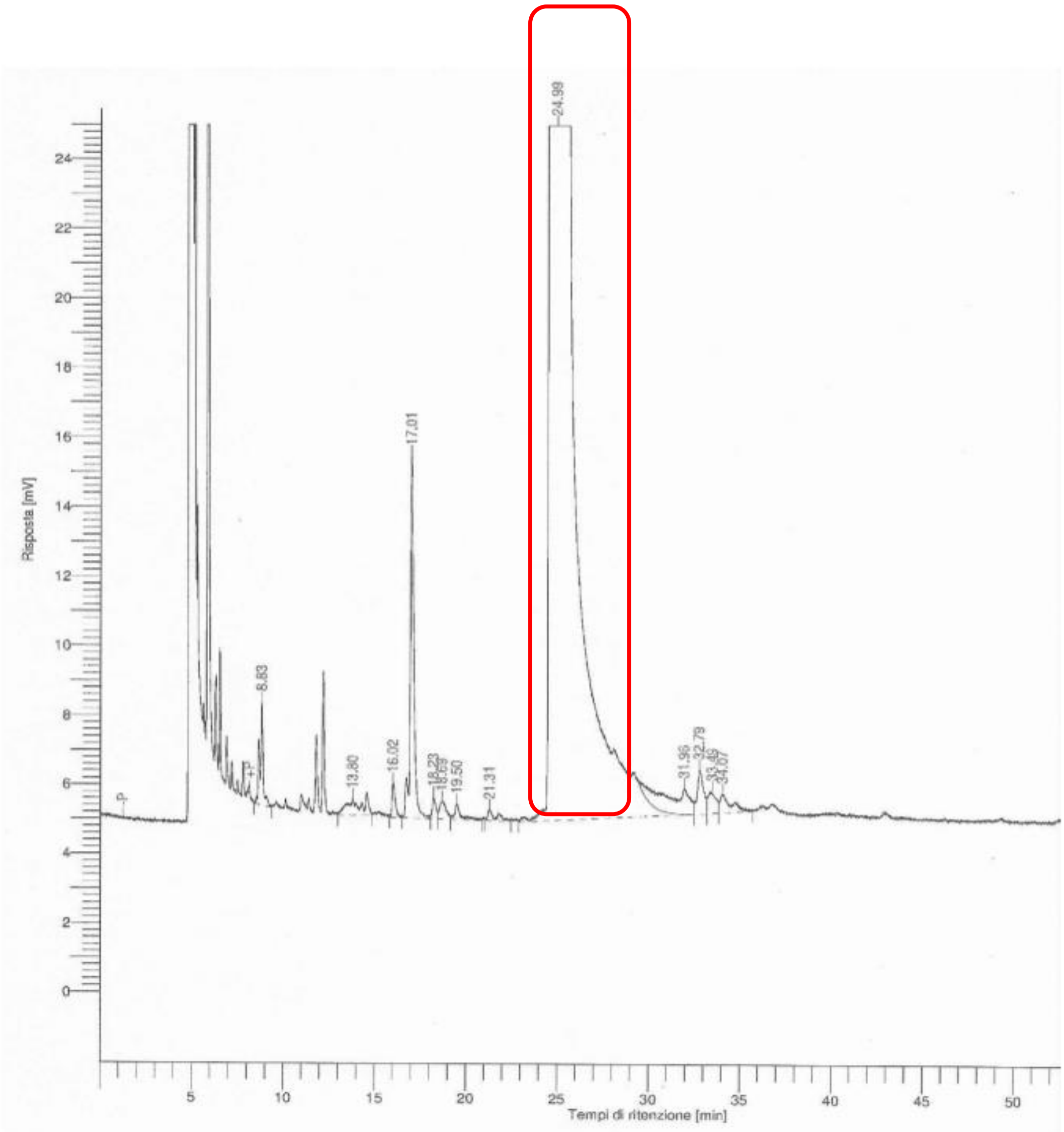
Table 1: Comparison between caprolactam analysis of pre-consumer and post-consumer waste

	Pre-consumer waste	**Post-consumer waste**
Concentration of CPL [%]	62	56
pH	5.1	5.4
Acidity [meq/kg]	42	45
GC area test, caprolactam peak [%]	99.7	99.2
Number of lighter impurities	14	8
Number of heavier impurities	2	4

From these data it can be seen that also the post-consumer waste complies with the requirements of ECONYL® regeneration system, and the quality of the caprolactam is in line with the industrial values usually found for this substance. Impurities are present, but the ease of separation for the purification step is still acceptable.

The pH of the raw-caprolactam of the post-consumer waste is more basic compared to the pre-consumer one, as the presence of impurities such as dust and dirt shift the acidity in such direction.

The GC area shows a slightly smaller peak, as expected from a more contaminated sample. The fact that the number of lighter impurities is smaller is caused buy some peaks not being recognized from the instrument, probably because they are too narrow, as it can be checked in Figure 24.



Peak #	Time [min]	Area [µV·s]	Height [µV]	Area [%]	Norm. Area [%]	BL	Area/Height [s]	Rel. RT
1	8.826	36372.40	2992.14	0.07	0.07	BB	12.1560	1.000
2	13.803	29437.68	469.65	0.05	0.05	BB	62.6805	1.564
3	16.020	12461.43	995.67	0.02	0.02	BV	12.5156	1.815
4	17.014	147088.62	10453.60	0.27	0.27	VV	14.0706	1.928
5	18.228	8597.76	639.56	0.02	0.02	VV	13.4433	2.065
6	18.694	12839.87	513.39	0.02	0.02	VV	25.0099	2.118
7	19.497	11174.29	457.30	0.02	0.02	VV	24.4356	2.209
8	21.308	10220.13	308.93	0.02	0.02	VB	33.0826	2.414
9	24.992	53953292.88	988880.15	99.23	99.23	BE	54.5600	2.831
10	31.965	77964.53	756.57	0.14	0.14	EV	103.0502	3.621
11	32.792	30905.06	1285.19	0.06	0.06	VV	24.0470	3.715
12	33.492	19109.68	589.47	0.04	0.04	VV	32.4185	3.794
13	34.066	24437.83	556.09	0.04	0.04	VB	43.9455	3.860
		54373902.15	1.01e+06	100.00	100.00			

Figure 24: Gas chromatography results on post-consumer waste

Figure 25 summarizes the concept of the circularity of the monomaterial carpet: the end-of-life carpet is fed as a whole into the chemical recycling process, regenerating caprolactam. This caprolactam is the building block for the production of novel PA6 pellets, and subsequently PA6 yarn (called Econyl®). The yarn can be used again in the production of novel carpet.

***Figure 25**: Schematic summarization of the circularity of monomaterial carpet*

3.1.4. Monomaterial carpet: additional initiatives increasing recycling efficiency

As the name suggests, the idea behind a "monomaterial carpet" would be to have a product realized just by one material. As in the case of commercial carpets this is hardly achievable, such product was defined as a textile flooring containing a minimum amount of 85% polyamide 6. For this reason, every material introduced in the final product must be finely selected, to reach the composition goal.

As explained in the chapter 3.1, a monomaterial broadloom carpet was produced with around 85% PA6, using PA6 piles, a PP primary backing and precoat, and a PA6 secondary backing. However, an even higher the percentage of nylon 6 would make the depolymerization of the carpet even more appealing, since caprolactam can be recovered not only from the pile yarn, but also from other constituents.

For this reason, Aquafil studied alternative technologies to introduce even higher amount of PA6 in the composing materials. Since PA6 is not suitable for the realization of the primary backing of the carpet, due to its low dimensional stability, the efforts mainly concentrated on an alternative hotmelt technology.

The purpose was to study, produce and test a hotmelt powder that was consistently made of PA6, or at least in part caprolactam-based. Hotmelt powders are generally a copolymer composed by at least two, but more commonly three or more components. The reason is that, by mixing molecules with similar chemical structures, a decrease in the melting temperature of such blend can be observed.

Commercially, hotmelt copolymers containing nylon are available, but generally those are mainly PP-based, or contain other kinds of nylon, leaving just a fraction of the composition to PA6.

An interesting step forward in this investigation was achieved during studies conducted on PA6.9, a less common kind of polyamide, interesting because one of its composing monomers, azelaic acid, can be biobased. When PA6.9 is mixed with PA6, the blend shows a different melting point that varies according to the ratio of PA6.9 and PA6: the minimum is reached for the copolymer 50-50, whose melting point is 135°C. This relatively low melting point makes this polymer suitable for the use as hotmelt in the carpet industry.

For use as hot melt, it was necessary to convert the obtained "PA6.9-6" chips into powder via an external company specialized in cryogenic grinding. Once the powder was ready, it was sent to an external company specialized in calendering technology (process is illustrated in Figure 26). The tufted half cloth (the primary backing with the tufted PA6 yarn) and the secondary backing, after the application of the hotmelt powder, are forced to pass through a first couple of rolls, kept a sufficient temperature to melt the powder. Once the two layers are glued together, they pass through a second couple of rolls, where they are cooled down to let the hotmelt solidify, obtaining the final carpet.

The test of the hotmelt gave really good results: this copolymer provided a good pile bonding, even in small amount, allowing to use less material compared to the traditional solution available on the market; it is worth to mention that this is a result of commercial interest since the hotmelt is a part of the carpet with a high cost per weight.

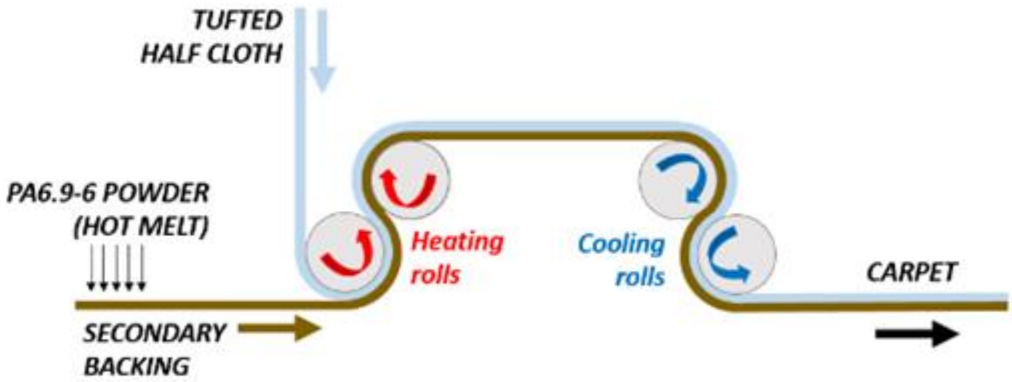


Figure 26: Hotmelt application through calendering technology

3.1.5. Conclusions about the monomaterial carpet approach

Production: A monomaterial broadloom carpet consisting out of recycled PA6 piles, a PP primary backing, a PP based precoat (applied via powder scattering) and a PA6 secondary backing has been produced without issues, allowing to produce a carpet with approx. 84% PA6. This carpet has been used to demonstrate the full life cycle. The feasibility of using a PA6.9-6 hotmelt was also demonstrated, increasing the PA6 content even more.

Installation: Initial small-scale trials were on the whole successful with a clear installation option preferred, installation direct to the subfloor using a release based tackifier adhesive. But when moving to large scale area testing and with the introduction of joining the cTextile together it created the need to revisit smaller scale testing of various versions to combat questions raised over cTextile and adhesive system working harmony to safe and quality driven end result.

The monomaterial approach requires a PA6 value of 85% or higher, dictating both the backing weight and pile height, creating a product that would not currently been seen as suitable for the commercial sector in areas with high use/high traffic. This is due to footfall pile crushing, object pile crushing and general maintenance of the product when compared against current commercial broadloom textile comparison products. The method of installation is also currently not suitable for commercial settings due to the demands of a commercial textile floor and this is compounded by the difficulties experienced in adhering the cTextile to the subfloor with a release-based system like the tackifier adhesive or alternative.

The most notable revision of small-scale testing was achieved by ironing the cTextile backing to provide a more acceptable surface area for the tackifier adhesive to bond too. This development was very encouraging within the small scale test. With identification of industrial process to match and further development of cTextile backing and/or release adhesive technology this could alleviate issues with the initial bond created between product and subfloor. If there is also scope within that development to allow for correct installation of joins and cut edges without compromising the tackifier bond that would also benefit towards a positive outcome.

Clear areas of success for the installation of a cTextile product include rugs, wall to wall rugs and domestic stretch fit installations. With rugs of any variety and size the product would not need to be joined in position at installation and could be free floating or held to the subfloor with carpet tape. The domestic opportunity for the cTextile is significant, the product look and feels like most high-end textile broadloom carpets by comparison, offering the option to serve the high-end domestic market. There would however still have to be innovation into the design of the backing and installation methods to allow for a domestic stretch fit installation to be successful based on the outcomes of some stage 1 testing completed. This innovation would mainly be centred around the standard methods of installation methods used in the UK and countries aligned to similar methods.

Recycling: Off-cuts of the installation trials could be recycled to caprolactam of high purity, the building block of PA6, showing that the monomaterial carpet can be recycled without prior separation steps. Similar results were obtained recycling the post-consumer carpet.

Tagging: Four different RFID tags were placed under the carpet during the use phase simulation of 5 months. After that period, one signal could not be received anymore.

3.2. Separation layer approach

The separation layer approach could be used in case it is not possible to produce a monomaterial textile floor covering for technical reasons. An example of this are carpet tiles, where the conventional backing is important to reach the dimensional stability, and cannot be produced from PA6.

A separation layer is introduced which can be triggered at end-of-life, allowing to separate the primary and secondary backing, so they can be diverted to the corresponding recycling streams.

In CISUFLO two separation layer concepts where assessed:

- A separation layer based on a thermoplastic adhesive, which can be triggered by heat
- A separation layer based on recycled polymer, which can be triggered by solvent treatment

3.2.1. Production of separable textile floor covering

In order to test the separation layer approach different variants of greige fabric were tested. They consisted of the same PA6 pile, but having different primary backings. For all variants the thermobonding principle for the pile fixation was adapted, allowing to melt the backside of the piles. Different settings in regard to temperature and dwell times were used in order to meet the specific material requirements of each sample. The resulting samples were tested regarding pile fixation and change of appearance after Lisson Tretrad and achieved reasonable results.

Subsequently, the separation layer was added to the primary backings with thermobonded piles:

- Heat triggering: different PO hotmelt types were applied at TFI on the backside of the fabric via powder scattering, having full coverage of the surface.
- Solvent triggering: a water based dispersion of a recycled polymer was applied at CTB via knife coating onto the substrate, and dried at in oven. The surface was completely covered after drying.

The obtained materials were transferred to an external company to finish the tiles with both a bitumen and PO secondary backing (see Figure). These backings consist of a black PET spunbonded nonwoven laminated with a bitumen based coating highly filled with CaO_3 (bitumen backed) or a grey PET spunbonded nonwoven laminated with a polyolefin based coating highly filled with CaO_3. Some further finetuning is still needed to improve the adhesion of secondary backing in case of solvent triggered separation layer.

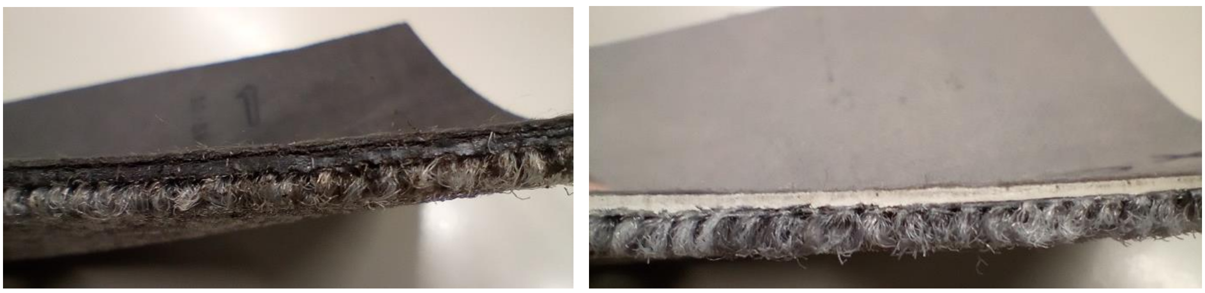


Figure 27: Carpet tiles having a recycled polymer separation layer

Left) bitumen backed; Right) polyolefin backed

3.2.2. Separation of textile floor covering

The separation capability has been demonstrated at lab scale as, for the moment, there is no serial industrial solution existing to carry out this process step. The development of such solutions is not subject of CISUFLO. A prototype of a machine separating the carpet tile after a debonding step has been developed for the Niaga® technology, and a similar device might be suited for the CISUFLO concepts as well.

3.2.2.1. Carpet tile

Heat triggered debonding: The layer separation of carpet tiles was exemplary tested on small samples from the manufactured carpet tile using a heat press. The idea is to trigger the hotmelt layer between primary backing and secondary backing. These hotmelts have melting temperatures of > 150 °C, so a temperature range from 160-170 °C was selected for the trial in order to provide a safe heat transfer through the secondary backing. It is visible that this concept is working, but in some cases the coatings also melt and thus cause a more or less pronounced contamination of the backside of the primary backing. This unwanted effect is very pronounced for the bitumen backing (Figure 29), but could also observed for the polyolefin backing (Figure 28).

Figure 28: Layer separation of polyolefin backed carpet tile samples

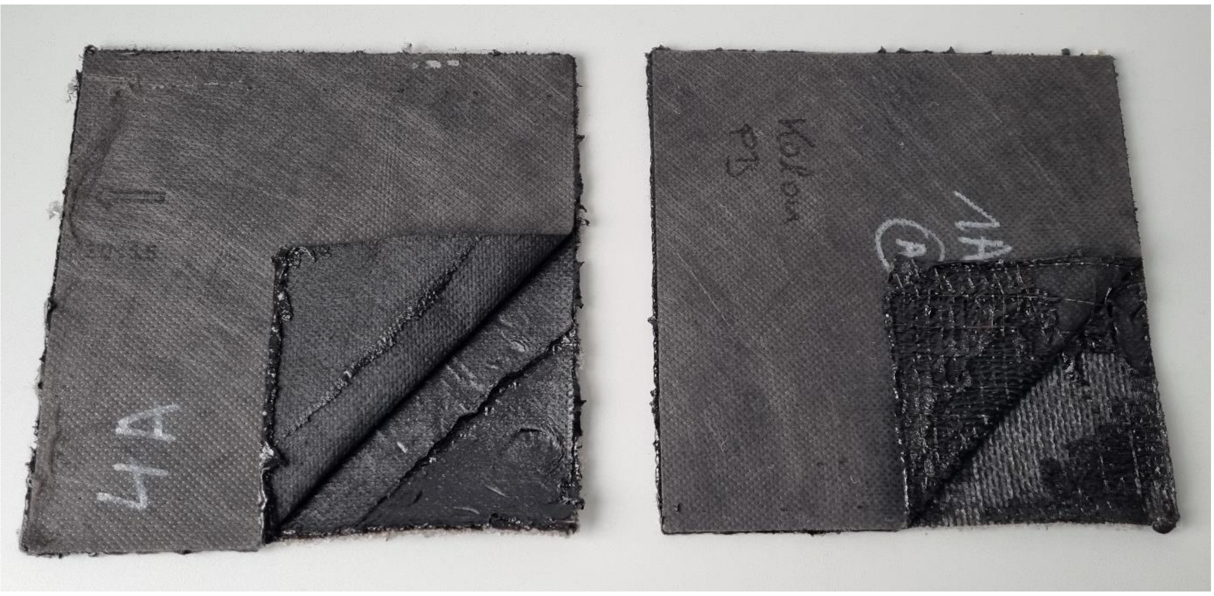


Figure 29: Layer separation of bitumen backed carpet tile samples

Obviously the different melting temperatures of the components are too close to each other to provide a safe separation by the separation layer. Maybe there is also an influence of the selected primary backing. Possibly these effects could be improved by thermal treatment from the pile side, but this solution would be limited to PA6 pile tiles (as they have a high melting temperature). It has to be checked how to transfer these findings to a safe and robust solution for the scale of a typical recycling factory. To transfer these findings to a robust concept, the composition of the layers needs to be tuned to have significantly differing melting points of hotmelts and coatings.

Solvent triggered debonding: The carpet tiles have been cut in small pieces and are both placed in an acidic environment and an alcohol. As can be seen in Figure 30, the bitumen backed carpet tile could be spontaneously delaminated using alcohol. The treatment in acidic environment led to a sticky non-delaminated residue. The polyolefin backed carpet tile on the other hand could not de delaminated using alcohol, but the delamination occurred using acidic conditions.

Figure 30: Outcome reactions on carpet tiles: Left top) bitumen backed in alcohol, Left bottom) bitumen backed in acidic conditions, Right top) polyolefin backed in alcohol, Right bottom) polyolefin backed in acidic conditions

These lab results show that there is potential to separate the different layers of the carpet tiles using a recycled polymer separation layer. Nevertheless, no uniform treatment can be used, depending on the backing material alcohol or acidic conditions should be used.

3.2.2.2. Broadloom carpet

The broadloom carpet described in section 3.1.1 could also be used to assess the separation feasibility via heat as it contains a thermoplastic PO as precoat. For the proof of concept a small sample was treated in a heat press with 180 °C and 30 second treatment duration. In Figure 31 the result is shown. The backing is solved from the use layer in wide areas without any mechanical demand of separation. This effect could be shown for small samples from new goods as well as for bigger parts from deinstalled samples from CFA. It can be assumed that in further investigations a simple setting regarding temperature and time can be found in order to ensure a safe and complete detachment of both layers.

Figure 31: Proof of concept of the separation layer

3.3. Tagging of textile floor coverings

In WP1 it was shown that it was possible to integrate RFID tags during the production process of a broadloom carpet (manual placement). Temperature resistant RFIDs were integrated between the primary and secondary backing, without any aesthetical hinderance. Testing showed that after the production process and use phase simulations (foot steps and castor chair) they could still be read out.

During the production of the monomaterial carpet it was not possible to automatically place the RFIDs, as no industrial equipment was available to pick and place the RFIDs. So the RFIDs were manually placed on the backside of the carpet during the stage 2 testing (see section 3.1.2). Hence, it could be assessed if they could still be read out after the use phase of the carpet. During the use phase testing, signals of 4 different RFID tags were assessed periodically using an RFID antenna and one signal was not received anymore after 5 months of usage.

3.4. Solvent-based separation of textile floor coverings using PolySep

Initially, it was the idea that the PolySep process could be used to treat conventional carpets, not designed-for-recycling. The aim of using the PolySep process on multilayered flooring is to split the material layers and subsequently separate these delaminated materials by commercial techniques (triboelectrification; froth flotation, zigzag system, etc.), so the obtained streams can be further recycled (see Figure 32).

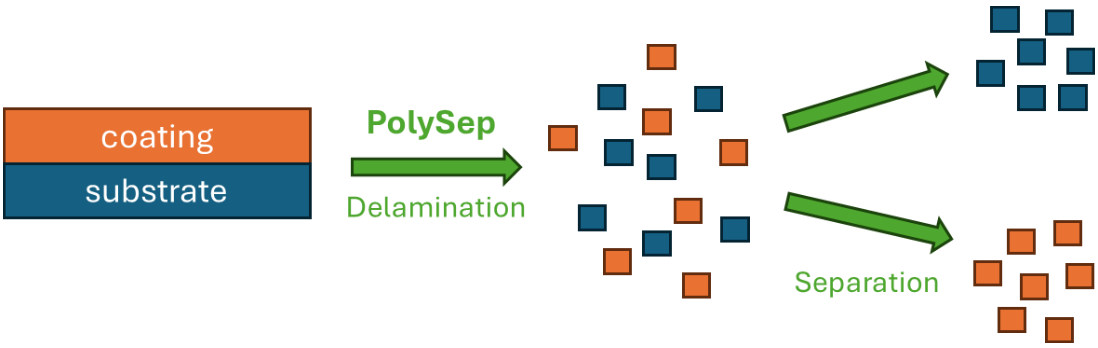


Figure 32: Schematic delamination-separation

The working principle of the PolySep process, installed at Centexbel, is depicted below. Before entering the process, the material is shredded. A pre-separation of light material is performed via a cyclone. The heavier weight particles are soaked with a solvent, after which the material is brought into contact with steam, inducing a flash evaporation of the solvent (referred to as popcorn effect). This evokes the delamination of the layers. The mixed stream of delaminated materials still needs to be separated afterwards using the most suited separation technique (a zig-zag air system is added to the pilot line, other separation technique need to be externally).

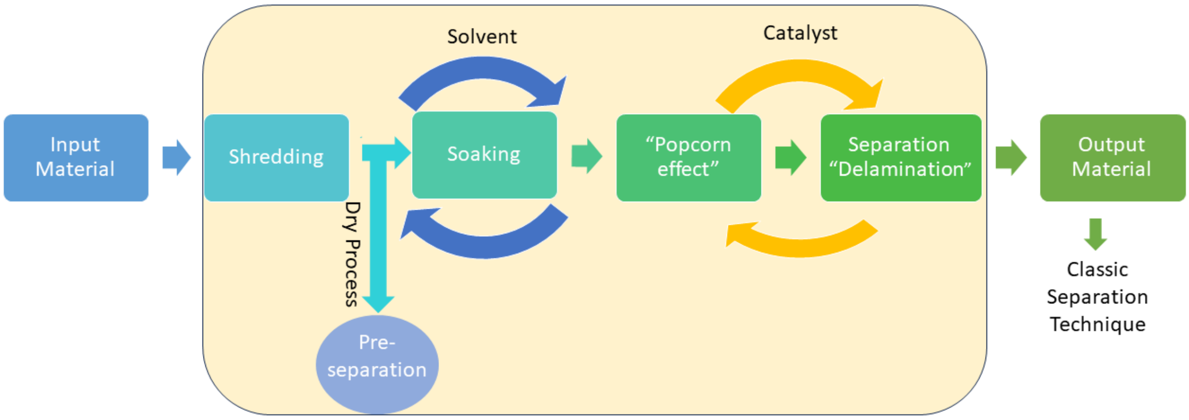


Figure 33: working principle PolySep

The delamination of a broadloom carpet, consisting of PA6 piles, an EVA precoat and a PP primary and secondary backing has been assessed. The pilot line turned out not be suited to process textile floor coverings. After shredding the carpet, a fluffy fibrous infeed material is created, which blocks the line on several spots. Further, the EVA does not swell upon solvent contact, but it dissolves, leading to soiling of the piping.

So to conclude, the pilot line in its current design is not suited to process fluffy materials. So this research line, to treat conventional carpets with the PolySep process to facilitate recycling, was discarded.

3.5. Mechanical recycling of textile floor coverings

The monomaterial approach and separation layer approach are the two paths selected by the CISUFLO project to eco-design textile floor coverings. These two concepts are fundamental to implement circularity in the world of carpets and rugs, enabling the saving of natural resources and reducing emissions.

However, it's important to remember that the average lifetime of carpet tiles, wall-to-wall carpets, rubber mats, and textile flooring in general ranges between 5 and 20 years: this means that all recyclable carpets introduced to the market today, will not affect recyclability in the immediate future. Also, any circular approach will take time to be introduced in the market.

Therefore, there is a need to find new technologies for dismantling and recycling carpet waste that is currently being disposed (according to the European Union, approximately 1.6 million tons of carpets and rugs are disposed of every year through landfills or incineration every year).

Recycling is strictly related to the ability to separate constituting materials, and this is the real challenge: finding technologies that enable carpet dismantling and materials separation, that are both efficient and cost-effective.

3.5.1. Recycling routes

The most common carpet dismantling approaches can be divided into two main categories: chemical and mechanical/physical. Aquafil decided to concentrate its efforts on a technology that had to be cost-saving, easy to operate, versatile, relatively small, energy efficient, reliable and that does not need the use of either solvents or water for material separation. The results, which indeed exploits mechanical dismantling and airflow behaviour separation, were baptized as ACS: Aquafil Carpet Separation machine. This technology can be used an alternative to the initially envisaged delamination by the PolySep technology, which was not working for carpets.

3.5.1.1. ACS: Aquafil Carpet Separation machine

The technology, under Aquafil's patent WO2024061510, is the next generation of the current machine used for broadloom cut pile carpet shredding called ACR (Aquafil Carpet Recycling). ACS is a pilot machine under research and development activities and is currently situated at TRL level 3 to 4. For this reason, Aquafil is trying this recycling approach on different carpet types and constructions: from carpet tiles to wall-to-wall carpets, and even rubber mats.

Machine parameters, such as speed, energy, temperature, processing time and amount of material loaded can be tuned, with the purpose of studying the process and understanding how to achieve the best outcome.

Because of the reasons mentioned above, and because of the promising results that are listed in the next chapters, having a versatile machine as ACS allows a potential customer to process both pre-consumer waste (such as faulty products and trims) and post-consumer waste, obtaining even more interesting results: design-for-recycling hints and recommendations that can be exploited to further improve the recycling rates of textile flooring products.

3.5.1.2. ACS design-for-recycling insights

Having a small and versatile machine enables to test dismantling and separation on different kind of carpets. Eventually, this allows comparing obtained results expanding knowledge about which constructions are more promising or suitable for mechanical recycling: an information that can be extremely valuable for both carpet producers and carpet recyclers.

Here below a summary of ACS design-for-recycling hints:

a. The first consideration is that each product, or even each collection, has a different behaviour in the ACS machine. The results are strongly influenced by carpet construction and materials used, and the behaviour can change even with carpet lifetime: results on carpet trims and production waste are not necessarily valid for end-of-life carpets, and vice versa.

b. A second insight is that in general, textile flooring that contains hard or brittle layer behaves better, especially if this layer is the precoating: this means that it can be exploited as a separation layer, allowing a good separation of the textile part of the flooring from the rest (see Figure 34 for reference). This is a direct consequence of the mechanical dismantling approach used.
   This same aspect is reflected in carpet tiles' secondary backing: when it is heavily filled with inorganic material (commonly $CaCO_3$) or when it has a higher melting point, the mechanical dismantling works much better. This could also explain why, in some cases, tests on post-consumer carpet waste led to better results compared with post-industrial waste: during the long lifetime of some textile floorings, for example, embrittlement of some latex, glues, or secondary backing can be observed. This could be a consequence of ageing, humidity, environmental conditions, or other unknown factors: further studies would be required to dive deeper into these topics.

A direct consequence of this consideration is that more flexible carpets, such as those that have nonwoven needle punch secondary backing, can't be effectively processed with ACS.

c. Like point b, an alternative approach is to have a "weak layer" instead of a brittle one. This means to have a part of the carpet that is strong enough to guarantee carpet lifetime, but weak enough to break down without requiring much energy. It is interesting to have the primary backing as weak layer (Figure 34), since it allows to separate the textile part of the carpet from the other components.

d. About materials used, one important insight is about primary backing. The most common materials are firstly polyester (PET) and secondly polypropylene (PP). However, the second is leading to better results when mechanical dismantling is used. The explanation, probably, has at least two reasons:
On one side, this is likely connected with the polarity of the materials involved: PP is non-polar, PET is partially polar and PA6 is highly polar. This means that if the precoating is exploiting the polarity to fix the pile yarn on the primary backing when this material is made from PP, the bond will be surely weaker than compared with PET. This evidence might not be relevant during carpet's lifetime but could influence the ease of separation heavily.
On the other hand, PP has lower mechanical properties compared to PET; therefore, the primary backing can be destroyed easier allowing separation of the most valuable material, polyamide, from other elements.
A study on the fracture mechanics of these products would be required to have a better understanding of the process behind them.

e. As a last insight, carpet construction technology strongly influences the ease of dismantling. In general, woven carpets are stronger than tufted ones: a first implication is that on these last classes of products, mechanical dismantling is easier and requires less energy, leading, in general, to better results. Much more complicated instead is mechanical dismantling of woven carpets, that can give results just in some kind of constructions.
Also, cut pile and loop pile carpets behave much differently, but it's difficult to make general conclusions. If the tufted polyamide "V"s from the cut pile carpet can be easily separated (for example when the primary backing is made of PP), it is usually easy to isolate them from the rest of the textile mixture of materials: they are generally more compact and heavier compared to longer filaments, and can be either separated exploiting their behaviour in air flow or using sieves with proper holes dimension. Of course, this could imply the need for further separation steps that have to be carried out after the ACS mechanical dismantling process. On the other hand, the yarn from the loop-pile carpets is in general more difficult to be extracted and results mixed and tangles together with other textile components. In the figure the components are illustrated that can be exploited as separation layer: the primary backing and the precoating. The "heavy layer fraction" is commonly referred as bitumen or TPO compound, or simply bitumen/TPO, and it is bitumen/TPO additivated with some inorganic filler, commonly calcium carbonate ($CaCO_3$).

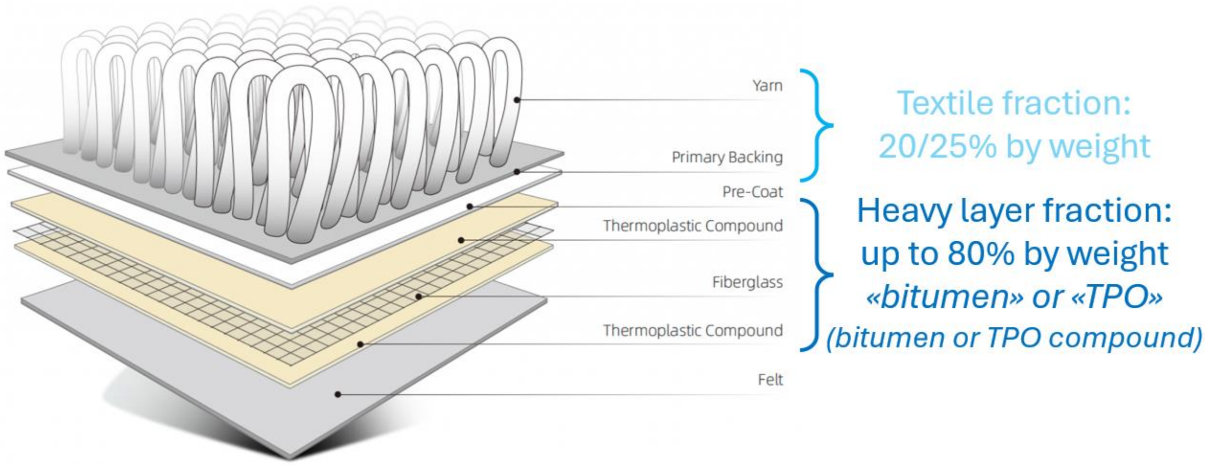


Figure 34: A schematic example of a designed-for-recycling carpet tile

3.5.2. Carpet tiles

Carpet tiles, for our purpose, can be divided based on the material constituting the heavy layer fraction Figure 34. The most common materials used are *bitumen compound*, often chosen for its affordable price and dimensional stability, *polyolefin compound (*also known as *TPO compound)*, which can be in general more ecologic (it can be produced from renewable sources), *PVC compound*, which is strong, stable and has higher humidity resistance and *felt*, which is softer, more sound absorbent, easier to apply but less resistant.

For the moment tiles with bitumen compound and polyolefin heavy layer were tested in ACS.

3.5.2.1. ACS on bitumen-backed carpet tiles

For these products, the ACS machine is usually able to isolate three separate streams, that is commonly referred to exploiting their composition: a waste stream, a backing stream, and the polyamide 6 stream, as visible in Figure 35. It's important to underline that the major one by weight is the backing stream, since it is constituted by the heavier components of the carpet.

Figure 35: Bitumen backed carpet tile processed with ACS machine

The PA6 stream, since nylon is one of the most expensive carpet ingredients, is potentially the most interesting output material. However, for the moment, the machine is still not able to separate this ingredient with a purity sufficient for the ECONYL® regeneration process: further purification steps are needed. An alternative approach would be to tune the process must be accordingly to increase the purity of nylon, which unfortunately comes at the expense of the purity of other streams or the efficiency of the process, without still leading to the desired PA6 purity.

The backing stream is more interesting, also because it is the biggest stream by weight, as it contains most of the heavy layer/secondary backing, which is commonly referred simply as "bitumen" or "bitumen compound", but also "TPO" or "TPO compound" (because it is usually composed of bitumen/TPO charged with $CaCO_3$).
This stream however is still heavily contaminated with textile residuals coming both from the pile yarn, the primary backing, the finishing layer and, in some cases, it also contains fiberglass residues. As the heavy layer consists of up to 80% of carpet tile weight, it is highly important to find value in this stream of material. For the moment, Aquafil is still trying to understand under which conditions this product can be reintroduced in the secondary backing of carpet tiles, but this strongly depends on different factors, mainly on the type of machine used to process the bitumen and the presence of textile contaminations. For this last reason it is sometimes necessary to introduce a further purification step, such as sieving, to further remove unwanted fibres. This topic will be further discussed in the next chapters.
A second observation on this stream is that, when it consists of low-temperature melting bitumen or when the material extracted is quite sticky, several troubles can be faced during processing, stocking and transport, requiring additional steps to avoid material sticking in the machine and sintering in huge and hard blocks during subsequent phases: this challenge can be quite difficult.

Finally, the waste stream, as it can be intended by its name, is the less valuable for the moment. Its composition is quite variable, and this is a consequence of both ACS setting parameters, and the type of carpet tiles processed. Usually, it's a mixture of PET or PP primary backing, polyamide 6 and bitumen compound, together with other elements, very hard to separate. Since this stream is of low value, complex separation and of small volume, Aquafil's efforts are concentrated mainly on the other two.

A general rule is that, for the moment, purity and quality of one stream can be improved at the expenses of the others. Therefore, it is probably more important to exploit the ACS machine to do a good dismantling and a preliminary separation step: a better purification of each stream can be achieved exploiting other technologies. An example of chemical analysis carried out is reported in Figure 36. For the data interpretation, the following considerations are necessary: taking Sample 1 as an example, if all the ashes left from the pyrolysis are caused by CaO coming from $CaCO_3$, the % of $CaCO_3$ in the carpet can be obtained with the formula: %ashes/5,6*10 = 37,6/5,6*10 = 67,1%.

- Sample 1: Bitumen extracted from EoL tiles ($CaCO_3$ 67,1%, bitumen 27,7%, textile 5,2%)
- Sample 2: Bitumen extracted from cutting waste of tiles ($CaCO_3$ 68,9%, bitumen 29,%, textile 2%)
- Sample 3: Textile fluff from EoL tiles (PA6 76,6%, $CaCO_3$ 13%, bitumen 9,2%, PET 1,2%)
- Sample 4: Textile fluff from cutting waste of tiles (PA6 53%, $CaCO_3$ 25%, bitumen 16,6%, PET 5,3%)
- Sample 5: Textile fluff from newly-produces tiles (PA6 49,8%, $CaCO_3$ 23,5%, bitumen 13,5%, PET 13,2%)
- Sample 6: Bitumen stream sieved with 1mm holes ($CaCO_3$ 43,4%, bitumen 54,6%, textile 2%)

As it can be noticed, at the moment no stream has sufficient purity to be categorized as EoW (which for example regarding PA6 is usually above 95%)

AQUASPACE

Comunicazione dati n°: **24AE00327-328-329-330-331-332** del **26/11/2024**

Spett.
AQUAFIL S.p.A.
Via Linfano, 9
38062 Arco (TN)

Dati relativi al campione

Produttore:	AQUAFIL S.p.A
Data accettazione:	18/11/2024
Data inizio analisi:	18/11/2024
Data fine analisi:	22/11/2024
Scopo dell'analisi:	Determinazione quantitativa di umidità, Nylon, PET, ceneri, residuo post idrolisi

Dati relativi al campionamento

Data:	18/11/2024
Campionamento a cura di:	Personale Aquafil S.p.A.

Risultati Analitici

	% H_2O	% Nylon (al **netto** delle ceneri espresse come CaCO3)	% PET	% Ceneri (espresse come ossidi)	% Residuo post Idrolisi Acida/Basica (Bitumi/Gomme/Olefine/Altro)	SAMPLE REFERENCE
24AE00327 *(Vs ID: F_1378_2024_11 - Bitume - B2B EoL Tiles)*	< 0,5	< 2.0	4,2	37,6	27,7	**1**
24AE00328 *(Vs ID: F_1380_2024_11 - Bitume - B2B Cutting waste Tiles)*	< 0,5	< 2.0	< 2.0	38,6	29,1	**2**
24AE00329 *(Vs ID: F_1377_2024_11 - Fluff - B2B EoL Tiles)*	< 0,5	76,6	< 2.0	7,6	9,2	**3**
24AE00330 *(Vs ID: F_1379_2024_11 - Fluff - B2B Cutting waste Tiles)*	< 0,5	53,1	5,3	14,0	16,6	**4**
24AE00331 *(Vs ID: F_1381_2024_11 - Fluff - B2B new Tiles)*	< 0,5	49,8	13,2	13,2	13,5	**5**
24AE00333 *(Vs ID: F_1383_2024_11 - Bitume - Setacciato < 1 mm)*	< 0,5	< 2.0	< 2.0	24,3	54,6	**6**

AQUASPACE S.p.A.
Sede Legale e Uffici Amministrativi: Italy – 38062 Arco (TN) – Via Linfano 9 – tel. +39 0464 581 111r.a. – fax +39 0464 532 267
e-mail: info @ aquaspace.it
Stabilimento: Italy – 38068 Rovereto (TN) – Via del Garda 40 – tel. +39 0464 482 500
Cap.Soc. € 2.600.000,00 i.v. – C.F. 00632300224 – V.A.T. IT 00632300224 – C.C.I.A.A. TN 118591 – Nr. Mecc. TN 005678
www.aquaspace.it

Il Responsabile di Laboratorio
Dott. Chim. Alessio Colomasi

Figure 36: Chemical analysis carried out on ACS different streams coming from bitumen-backed carpet tiles.

3.5.2.2. Results of sieving on the backing stream

Since one of the major problems for the circular reintroduction of the recycled bitumen is the presence of impurities, Aquafil is also performing tests involving different sieving technologies and changing its parameters with the aim of decreasing the textile fraction of this stream. This process can be quite effective from a composition point of view, as it can be observed from **Error! Reference source not found.**. As it can be seen, the percentage of textile contamination (PA6 + PET) is quite low, around 4%

Table 2: Chemical analysis performed on three samples of sieved bitumen coming from carpet tiles from different producers

to 6%.

		Valori			
Sample Type	Origin	Ashes @800°C [%]	PA6 content %	PET content %	PP, rubber, glues [%]
Bitume	Customer 1	41%	2%	2%	35%
	Customer 2	41%	4%	2%	30%
	Customer 3	47%	2%	2%	34%

However, even when the holes of the sieve are very small, there is still a part of contamination that can't be eliminated, see Figure 38. This is probably caused by shorter fibres passing vertically through the sieve's holes. This fibres conglomeration was achieved by vibrating the material in a small container, accumulating lighter impurities on top of the heavier bitumen.

At the same time, introducing sieving in the post-processing of the backing stream separated by ACS adds more variables to the process: for example since sieving can be easily controlled by changing the dimension of the holes used to separate the material, the step can be exploited to control also grain size distribution, as it can be seen in Figure 37.

All these processed materials were also to external partners for testing, since Aquafil does not have the necessary know-how and equipment to understand which sample has better performance. The purpose was primarily to understand under which conditions it's possible to reintroduce a higher amount of recycled content, and other unconsidered variables that might affect the process.

Figure 37: Two images of small samples of sieved backing stream. On the left, the fraction with lower particles size distribution, on the right the coarse fraction.

Figure 38: A picture of the sieved bitumen compound clearly showing fibres accumulation.

3.5.2.3. Bitumen compound recycling tests

Even if the purity of the bitumen compound extracted as backing stream was not enough to reach the end of waste status, an external partner was able to test reintroducing the sieved material back into the heavy layer. The possibility of this kind of recycling strongly depends on two factors: the technology used to add the bitumen compound layer to carpet tiles, and the ability to homogenize this material.

Considering the first factor, the application machine used, it cannot be changed easily. The homogenization of the bitumen compound can be achieved by guaranteeing a regular and fine-grained recycled material and by increasing the mixing time.

This is exactly what it was done, and in Figure 39 the first results can be observed. On the left, a first attempt of introducing higher percentage of ACS heavy stream into the bitumen compound is seen: the result is a non-homogeneous material with a rough surface, non-suitable for industrial application. In the middle and right, results about increasing the mixing time are depicted: samples 117 and 122 have the same amount of recycled material. Sample 122 was mixed for longer, allowing the recycled material to disperse more homogeneously, leading to better results; this is a promising output that could allow to increase the percentage of circular recycled content even further.

The combination of a more "impurity tolerant" technology and longer mixing time, seems to be the promising key to improve the percentage of circular recycled content in the bitumen backing of carpet tiles.

Figure 39: Preliminary results on bitumen recycling.

A second external partner tried to introduce sieved bitumen in its carpet tiles production process using the recipe in Table 3. The recycled bitumen is on average composed by 30% bitumen and 70% inorganic filler ($CaCO_3$).

Table 3: Recipe of the bitumen compound for carpet tiles production.

Component	% (weight)
Recycled Bitumen	9,8%
Bitumen 1	9,8%
Bitumen 2	9,8%
Calcium Carbonate	70%
Additive	0.6%

Unfortunately, the results showed very high viscosity level. It must be kept in mind that viscosity is highly dependent on temperature, and the trend is that viscosity decreases when the temperature of the considered material is increased.

However, some application trials were performed anyway, to produce a few tiles, and fortunately no problem was met. It's fundamental to underline that this trial was performed at higher bitumen temperature for just a short amount of time, it's not clear if the industrial process could handle such modifications.

An assessment of tiles was conducted, and results were in-line with our partner's requirements: the flatness of the tiles after production, dimensional stability and resistance to creeping were all fine.

From the tests performed with sieved bitumen samples shown in Figure 37, the external partner confirmed indeed that a sieved backing stream can increase the amount of recycled material, from the previous 10% to a maximum of 15%, being the increase of viscosity still the major source of problems.

As a conclusion, the main issue remains the textile and fiber glass impurities that are probably the root-cause for the increase of bitumen compound viscosity observed. The main concerns about adding recycled bitumen in production tanks derive from the likelihood of these impurities to clog bitumen filters and the increase of bitumen viscosity is still difficult to manage.

3.5.2.4. ACS on polyolefin-backed carpet tiles

Also, for these products the output streams are three, and all the considerations from bitumen-backed carpet tiles are still valid, except that the heavy stream doesn't have bitumen inside, therefore preventing all sticking issued previously mentioned. Of the three streams, none is still pure enough to reach end-of-waste status, which often requires purity above 90%.

Aquafil efforts now are both in the direction of further improving the purity of each stream (Figure 40), but also to investigate possible applications of these materials.

Tests on the reuse of the TPO backing steam are being carried out with external partners, to check the percentage of recycled material that we can reintroduce and under which conditions sieving is preferred, similarly to the work done for the bitumen compound.

Figure 40: Like bitumen-backed carpet tiles, also PO-backed ones when processed divide into three streams.

3.5.3. Rubber mats

Rubber mats, also known as “dust control mats” or “entrance mats”, play a crucial role in maintaining cleanliness, safety and comfort in both residential and commercial environments. Designed to trap dirt, moisture, and debris at entry points, these mats help reduce cleaning efforts, enhance indoor air quality, and prolong the lifespan of interior flooring. These products, known for their durability, slip resistance, and versatility, are particularly popular in high-traffic areas or environments requiring robust performance (Figure 41).

When considered alone, rubber mats contribute only to a fraction of the textile flooring installed in a building. However, there are several companies that offer a range of services related with these products, from the supply and installation to maintenance services. Because of their application, rubber mats require periodic cleaning, and some companies are specialized in this: they organize a regular service, replacing dirty rubber mats with cleaned ones. The cleaning process is usually done with an industrial washing machine, which is quite aggressive, and the consequence is a lifetime that on average ranges between 100 and 300 cleaning cycles.

As a result, when these products reach the limit of cleaning cycles they can withstand, the companies that provide this kind of services often face the issue of having quite large amounts of these products, that are often difficult to recycle.

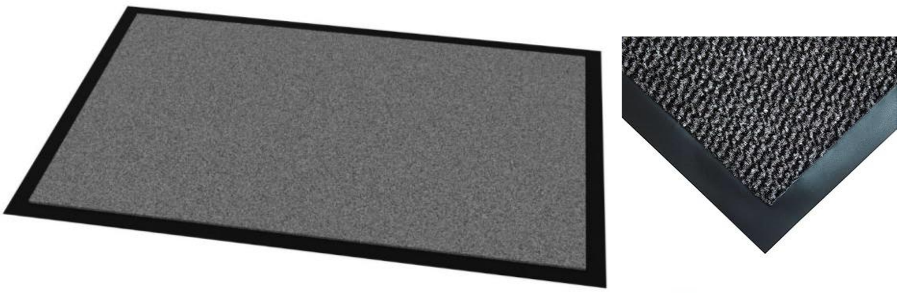


Figure 41: On the left, an example of a common rubber mat. On the right, an enlarged detail.

3.5.3.1. Rubber mats composition

Rubber mats differ from other textile floorings for their composition, which often involves less materials, as it can be understood from Figure 42. Indeed, the most common design includes a pile yarn, that usually has thicker filaments since it is required to have better abrasion properties, which is tufted on a primary backing. Then, the rubber backing is applied taking the place of both precoating layer and secondary heavy layer of carpet tiles.

Traditionally the rubber mats are tufted on a 100% PET based primary of 125 g/m^2. This would make it impossible, even if the textile part would be separated from the rubber, to send it to recycling as the quantity of PET vs PA6 is far too high.

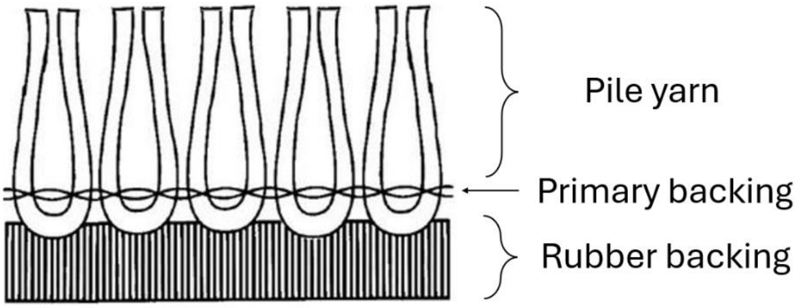


Figure 42: Schematic explanation of rubber mats design

The immediate consequence is that, in principle, only three different materials can be used to realize these products: for example, a polyamide pile yarn, a PET primary backing and a NBR rubber backing.

3.5.3.2. ACS Rubber Mats separation using a separation layer

Aquafil tested a modified rubber mat construction produced by Emco Bautechnik GmbH (external partner), evaluating the use of an SBR precoating acting as a separation layer. The purpose is to simplify the removal of the nylon 6 pile from the rubber and the primary backing, which in this case was composed by 75 g/m^2 of PET and 25 g/m^2 of PA6.

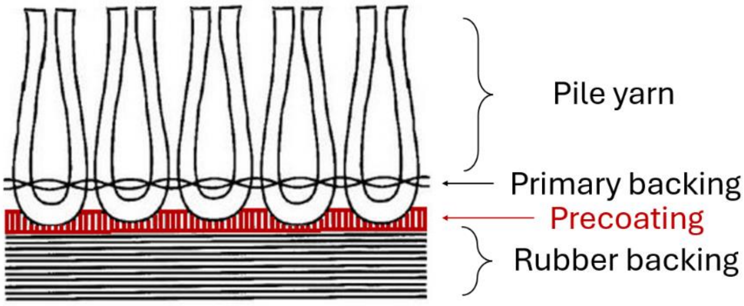


Figure 43: A schematic image of Emco's rubber mat.

The concept behind this test is quite simple, it can be resumed in the presence of a precoating that has the purpose of acting as a separation layer. This additional coating must be designed to be strong enough to withstand the usage of the rubber mat and all its cleaning cycles, but at the same time being weak enough to allow an easy separation of the rubber backing from the textile fraction. The other interesting advantage is that the precoating layer can be tuned so that the contaminations remaining in the textile fraction are not critical for its recycling.

The study had a positive result, as it can be seen in Figure 44, since the dismantling of such products with the separation layer allowed a much easier separation of the components in the ACS machine.

The study demonstrated the recyclability of the pile yarn at a pilot plant scale. However, the recyclability of this product came at the expense that it is from one side more expensive (as an additional step is required), and on the other side that it has worse durability.

Following conclusions can be drawn for the separation layer concept for rubber mats using ACS technology:

- The introduction of a thin but hard precoating acting as separation layer for the rubber from the textile showed interesting results, even if this further step increases the production cost and decreases the durability
- The use of a primary containing less than 75 g/m^2 of polyester (like the Colback 100) could allow the direct regeneration of the nylon6 in ECONYL® technology after a proper separation of the textile fraction.

In Figure 44 an example of the entrance mat is shown that was tested in the ACS. Two streams were obtained, the lighter one was composed mainly of PA6 with some textile contaminations coming from the primary backing, the heavier stream is instead composed mainly of SBR rubber in big pieces: this means that the SBR stream can be easily cleaned from these textile contaminants exploiting the different air flow behaviour of constituting materials.

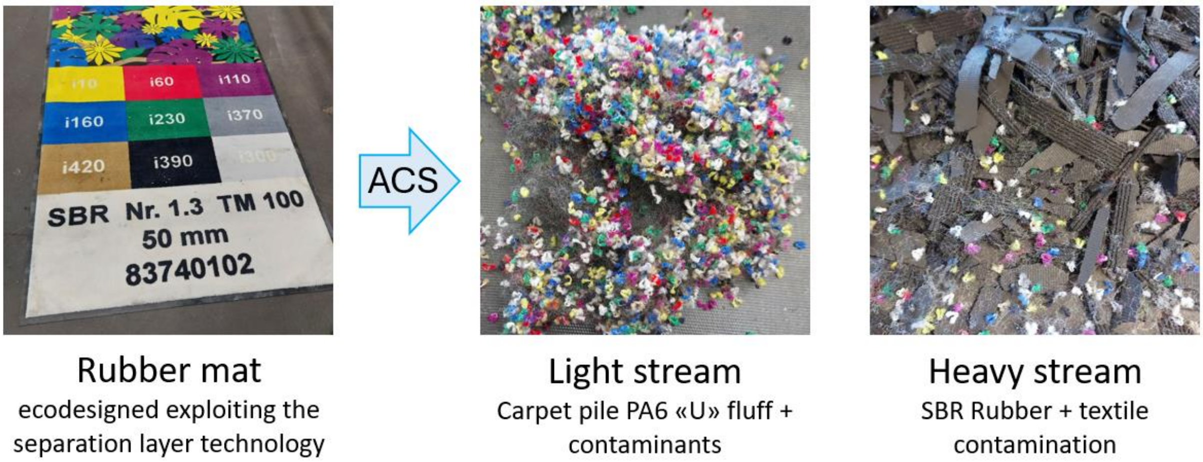


Figure 44: ACS results on rubber mats

4. Vinyl flooring

The vinyl flooring pilot consists out of two types of flooring: cushion vinyl, which is flexible PVC flooring, and Luxury Vinyl Tiles (LVT) which is a rigid PVC flooring product.

The non-circular cushion vinyl flooring, as manufactured today with plastisol coating technology, consists out of at least four layers which can be seen in Figure 45:

- Wear layer on top
- Printed design layer (PVC)
- Impregnated reinforcement (usually glass fibre)
- Back layer (PVC)

Two optional layers can also be added to the CV:

- PU lacquer can be placed on the wear layer
- Needle felt can be added on the back layer (e.g. PET)

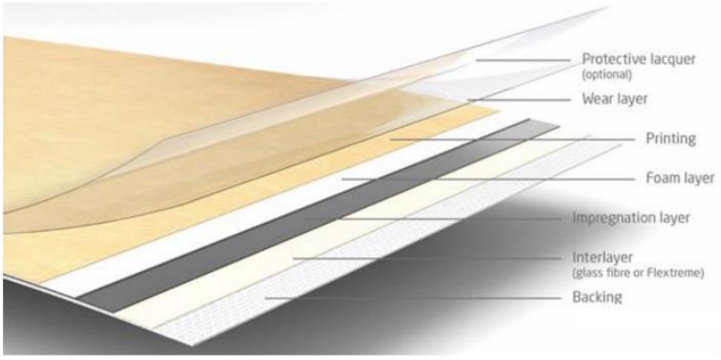


Figure 45: Layering of cushion vinyl

The LVT manufactured today consists of several layers (see Figure 46):

- PU lacquer
- Wear layer
- Printed design layer (PVC)
- Foamed solid extruded PVC board

Or

- CV top
- Foamed solid extruded PVC board

Figure 46: Layering of LVT

4.1. Resilient vinyl flooring

For cushion vinyl flooring, two different options have been researched for the introduction of recycled content into the products.

The first path that was researched, was on how to adapt our formulation of the current plastisol coating process to accommodate recycled content into our plastisols. The main concerns for this research were the quality of the plastisol regarding viscosity and gelation and the quality of the final product concerning the foaming thickness, the quality of the foam (residual indentation and tear resistance). Besides introducing recycled content, research was also conducted into using biocircular materials to produce a cushion vinyl floor with a significantly reduced carbon footprint without the need for new technologies to produce the floor.

As expected and known from lab trials, there is a limit on the amount of recycled content we are able to add in the plastisols as there is a small processing window. Therefore alternative manufacturing methods have been researched, which are extrusion and calendering. With extrusion the material is molten and produced with a flat die into thin sheets of <1 mm and subsequently laminated onto a glass fiber fleece that provides dimensional stability. Calendering is the other technology that has been researched, here the material is processed by an extruder to melt the raw material. The extrudate is then transported to calendar rolls that reprocess the extrudate into a thin film. The recyclate film is then laminated onto a glass fiber fleece. The resulting sheet from both technologies will be finished in our current production line in order to produce a qualitative product with a high amount of recycled content.

4.1.1. Recycling of EoL resilient flooring

4.1.1.1. Mechanical recycling

The two approaches for introducing recycled content in cushion vinyl products require two different approaches.

In order to introduce recycled content in the current plastisol coating process, a particle size of smaller than 300 µm is necessary. A smaller particle would be more ideal but this economically not viable.

Post-industrial cushion vinyl waste is shredded into rough particles between 5 and 20 mm in a first step. The second step is micronisation (in Figure 47, the inside of the micronisator can be seen), the shredded material is pulverised to particles smaller than 300 µm. The micronisation process is performed at ambient temperatures, this process can also be performed at cryogenic temperatures to produce finer material but the cost increases significantly.

Figure 47: Pulverisation disk inside a microniser

The starting material for the alternative technologies can be either shredded material, micronised particles or granules. After performing lab trials to compare the recycled materials with each other, it was decided to work with granules (Figure 48) as the granules gave a more stable process compared to the other materials. Another advantage is that material from different waste sources can be used by compounding and ensuring a constant quality of the material. Another important reason for choosing granules is when looking towards the future. When more post-consumer waste material will be collected and recycled, it will be necessary to have clean material. With granulation combined with melt filtration, it ensures that most contaminants are removed from recyclate.

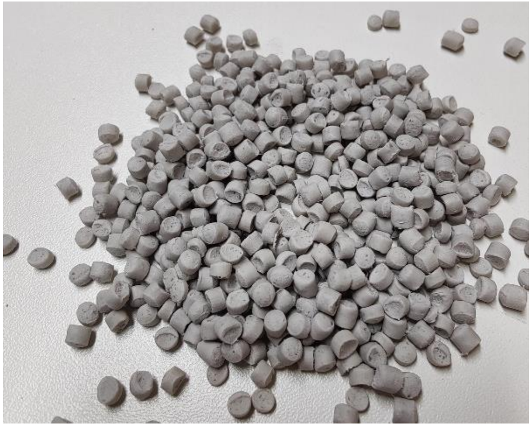


Figure 48: Recycled PVC granules

4.1.1.2. Solvent-based recycling

Cushion vinyl having a PET backing (and a PET reinforcement layer) is known to be non-recyclable, so the idea was to use the PolySep process to remove the PET fraction (description of the PolySep pilot line can be found in section 3.4), allowing for further recycling of the PVC fraction. Via the dry process quite clear PET fibres could be separated from the bulk, which a originating from the backing layer. Subsequently, the bulk is treated with the solvent (wet process), obtaining the popcorn. This popcorn is a mix of PET and PVC flakes (see Figure 49).

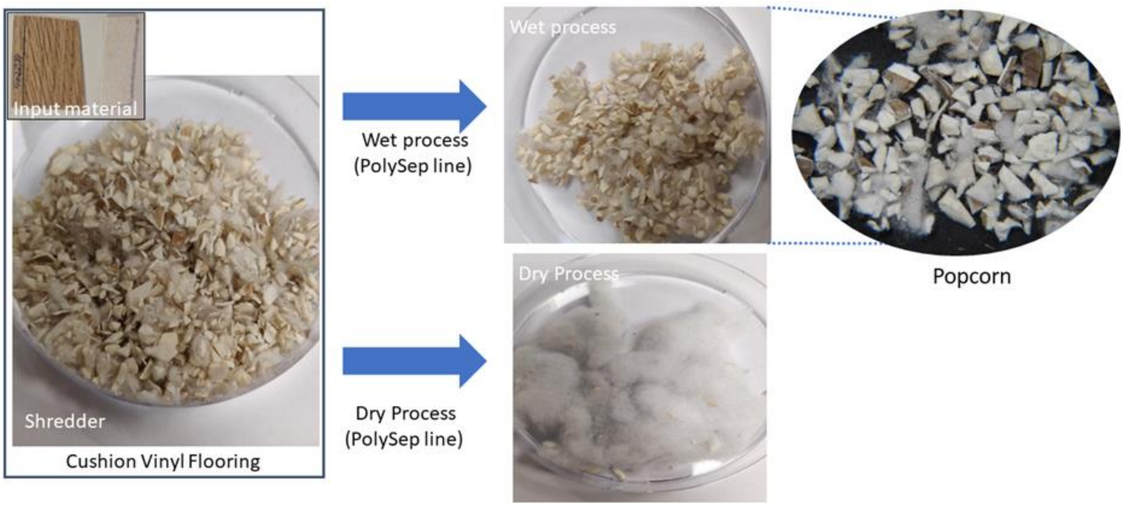


Figure 49: output of the PolySep process

Several attempts have been made to separate the PVC and PET in the popcorn, using an elutriation separator and a sieve shaker. Unfortunately, it was not possible to purify the streams due to agglomeration of the PET with PVC flakes. Further analysis of the flakes showed that the PET interlayer is also still present in the flakes.

So to conclude, a treatment in the PolySep pilot plant does not lead to the wanted separation of the PET from the PVC fraction, and is no viable step in a recycling route.

4.1.2. Production of circular resilient flooring

During the lab research, a formulation with 5 w% of recycled CV was optimised to achieve a similar quality (regarding viscosity, gelation and foaming behaviour) to the reference formulation that is currently being used in production. In order to prepare for the edge trials and future industrial trials, two formulations with 5 w% of recycled content were made for different technical ranges within the CV products that are currently produced. These three technical ranges cover around 80% of the total produced volume.

As 5 w% of recycled content in the backing layer of CV only represents 2-3 w% in the total product, trials were carried out to increase the amount of recycled content to 10 and 15 w%. The lab tests showed that it was not possible to increase the recycled content while maintaining the same quality. Further edge trials and future industrial trials were carried out with formulations with 5 w% of recycled content.

With the developed formulations, edge trials were carried out. Edge trials are tests were a small batch of 1 kg of plastisol formulation is made in the lab. This batch is then poured onto the side of the production line, as indicated in Figure 50. This gives the opportunity to see how the newly developed formulation acts under industrial circumstances. It also enables to compare the formulation with the reference product that is being made at the same moment.

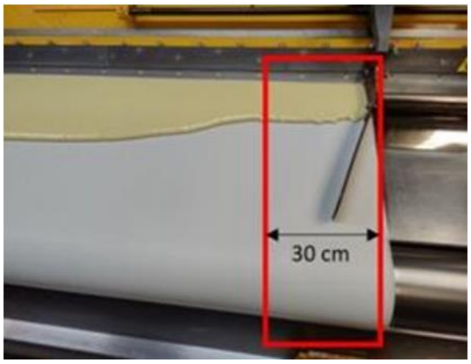


Figure 50: Place of the edge trial on the production line

A first edge trial that was performed with the developed formulations with 5 w% of recycled content. Although the properties after the lab trials were similar, in the edge trial sample a clear difference can be seen with the reference sample. As shown in Figure 51, holes can be seen in the product with recycled content.

Figure 51: Reference vinyl product (left), holes appeared in the back foam with recycled content during the edge trial (right)

Together with our additive manufacturers a solution was found to better disperse the recycled CV powder in the plastisol formulations. Through this cooperation, the formulation was improved. Edge trials were carried out with the adapted formulations. The quality of the formulations with recycled content were comparable to the reference formulations in Figure 52.

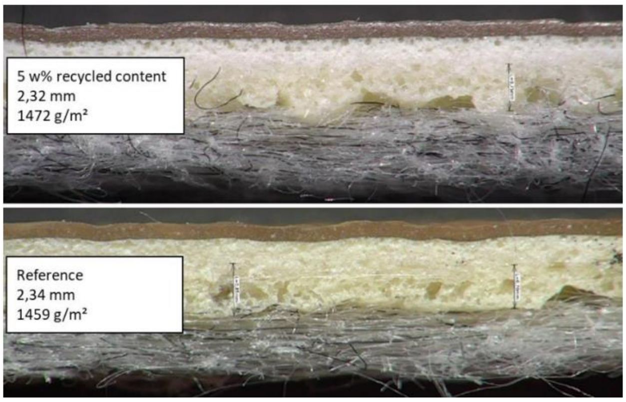


Figure 52: Edge trial sample comparison of 5 w% recycled content (top) and the reference (bottom)

The validated formulations were then used in three semi-industrial trials. These trials were performed on the three technical ranges making up 80% of our total volume. For each trial one batch of plastisol was made, this translates to 45 min to 1h of production or the production of +- 5000 m² of product.

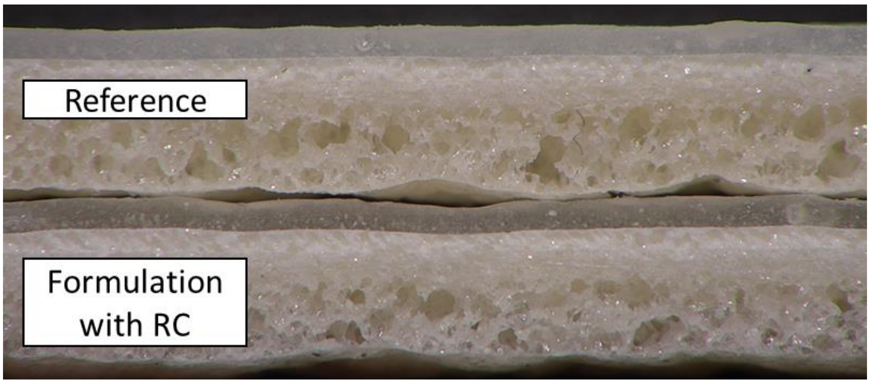


Figure 53: Foam quality comparison between reference sample (top) and the product with recycled content (bottom)

No differences in quality were seen between the reference production samples and the samples from products with recycled content (Figure 53).

An alternative option besides recycled content to improve the sustainability of our cushion vinyl floors produced with the current technology is to use raw material from biobased or bio-circular origins. The choice landed on using bio-circular PVC to replace the virgin PVC in our formulation. The origins of the bio-circular PVC is coming from waste cooking oil and tall oil. Using alternative raw materials has an impact on the production price as these materials are not produced on large scale.

By replacing the virgin PVC with the biocircular PVC, a carbon footprint reduction 40% was reached. This reduction is ISCC+-certified. Together with the solution for easy installation and removal discussed in the next paragraph, the floor is able to be a loose lay installation using double sided tapes at the seams and the edges of the room.

Looking further to the future, alternative technologies will be necessary to further increase the amount of recycled content in cushion vinyl floors: extrusion and calendering were assessed.

Only lab trials have been performed for both technologies focusing on the development of an interlayer with 100% recycled content. The lab trials have not been successful as can be seen in Figure 54 for extrusion.

Figure 54: PVC extrusion lab trials

For calendering technology, a lab trial was more successful. Calendering can be simulated on lab scale via a two-roll mill, a comparison can be seen in Figure 55.

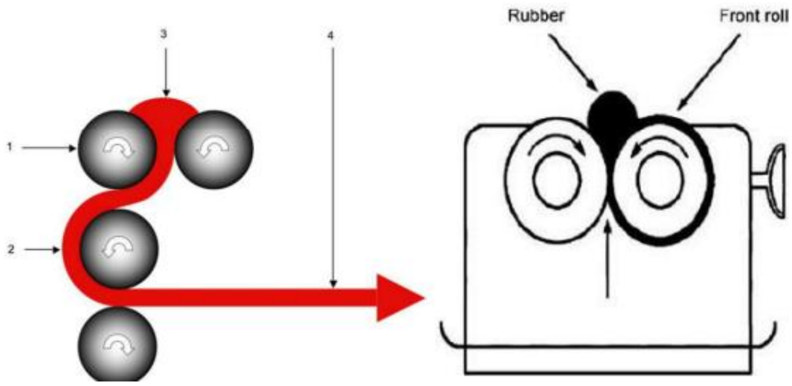


Figure 55: Schematic version of the calendering process (left) and the two-roll mill (right)

The obtained sheet from post-industrial recycled cushion vinyl waste can be seen in Figure 56.

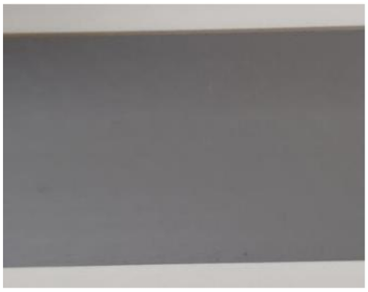


Figure 56: 100% recycled CV sheet obtained by the two-mill roll

The focus has been on improving the formulation by adding additives to increase the quality of the final product. Therefore no further research was performed on both extrusion or calendering. In the coming months further tests and larger trials are scheduled.

4.1.3. Installation and removal of circular resilient flooring

Most CV products need to be glued to the underfloor during their lifetime. During de-installation, the product is ripped out and residues of glue and the underfloor remain on the post-consumer CV product. Some CV products can be loose laid because of a dimensionally stable PET needle felt on the back layer, if the floor space is below a certain surface area (usually <35-45 m²). However, the felt makes the CV more difficult to recycle as this cannot be separated from the PVC.

The following concepts were considered for better de-installation:

1) Develop an alternative method to loose-lay CV without the need of a needle felt backing
2) Develop glues or tapes which are reversible and/or allow for clean de-installation.

In the project, the route of glue and tape development has been focussed on.

The first tests were performed using water based pressure sensitive adhesives (PSAs). These PSAs have been applied onto the backside of vinyl flooring using a manual lab coater and are dried in the oven at 110 °C for 2 minutes. To be able to test the peel resistance, the vinyl flooring is later on adhered to a piece of concrete fibre board. These PSAs were compared to two commercially available tackifiers.

As can be seen in Figure 57, the material adhered with a PSA is more easily removed with minimal damage to the product. While the commercial tackifier adheres the floor very well but is more difficult to remove and some pieces of flooring remain adhered to the base floor.

Figure 57: Results from the experiments – Top) PSA sample, Bottom) commercial tackifier sample

This concludes that a PSA can help the floor to be more easily removed than with the tackifiers.

Besides PSAs, double sided tapes were also investigated. When comparing PSAs and double sided tapes with each other, the double sided tapes have an advantage. With the tapes, it is easier to install as you don't need to cover the whole floor. Only the edges of the room and the seams between two pieces of cushion vinyl flooring need to be glued to the floor as can be seen in Figure 58. The samples were subjected to different quality tests and the results were positive.

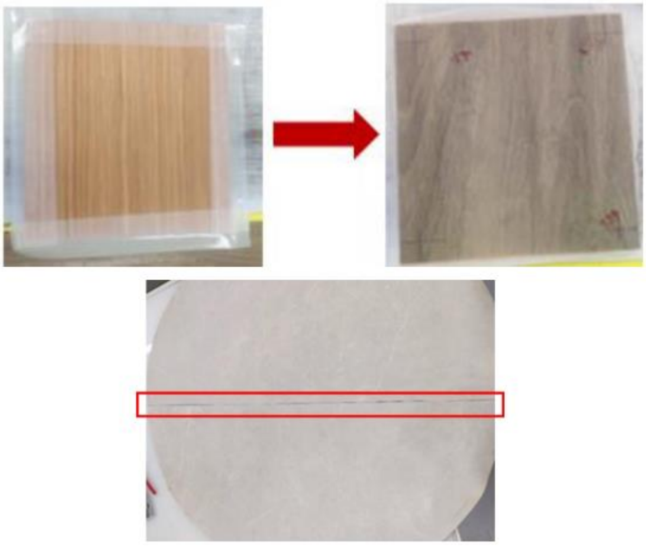


Figure 58: Placement of the double-sided tapes for CV installation

As adhering CV flooring to an underfloor with a double sided tape is easier to manage than applying tackifier glue on the whole underfloor for DIY, the double sided tapes were chosen over the PSAs to adhere our floors for easy removal.

4.1.4. Tagging of circular resilient flooring

Digital watermarking for physical products is an innovative technology that embeds invisible, machine-readable information directly into the physical design of products, packaging, or labels. Unlike traditional methods of marking or tagging, digital watermarks are seamlessly integrated into the product's aesthetic design, remaining imperceptible to the human eye while providing a secure and reliable method of identification.

This technology involves embedding patterns or codes into elements like printed graphics, textures, or product surfaces. These hidden marks can be scanned and decoded using specialized devices, such as smartphones or industrial readers, to reveal detailed information about the product. The embedded data might include information about the product's origin, authenticity, supply chain details, or instructions for recycling and disposal.

This seamless integration of digital watermarking into physical products represents a powerful tool for supporting circular economy initiatives like the DPP but it can also be used to combat counterfeiting and improving supply chain traceability.

A key application of digital watermarking lies in sustainability efforts, particularly in waste management and recycling. Embedded codes on packaging allow advanced sorting systems to identify materials during recycling, ensuring materials are correctly identified and sorted for reuse, significantly improving recycling efficiency.

At BIG, a part of the cushion vinyl flooring is produced with digital printing which could implement digital watermarks easily. In the future, BIG wants to increase the volume of digitally printed floors. Digital watermarking could therefore be a compatible technology.

A couple of companies providing the digital watermarking technology were contacted. After the initial inspection of our designs, they performed a feasibility test to enhance our design with a digital watermark.

In Figure 59, both the original and the enhanced design are depicted as it would be if they were installed and a person was looking down at the floor. No visual differences can be seen between both designs.

Figure 59: Comparison of the original (left) and enhanced (right) designs

But there will be a difference when a person would look closely to the floor. Red and green dot patters can be found all across the design as seen in Figure 60. These patterns will enable anyone to scan them with a simple app and camera of their smartphone to connect to the database where the digital product passport of the product can be found.

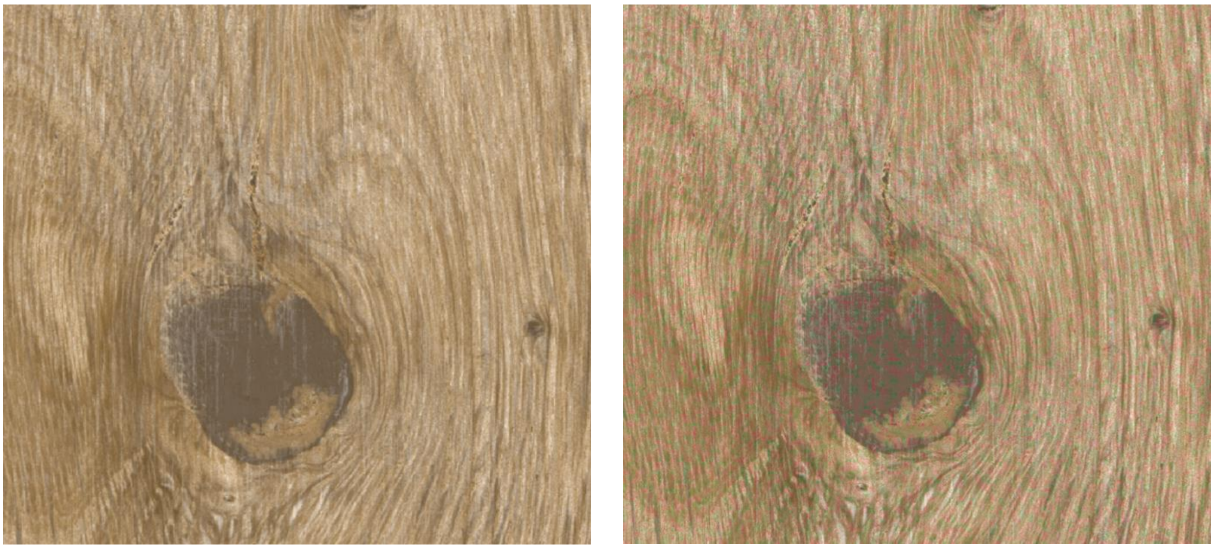


Figure 60: Comparison of a zoomed-in part of the original (left) and enhanced design (right) with green and red dot patterns

4.2. Luxury Vinyl tiles (LVT)

4.2.1. Recycling of EoL LVT

Post-industrial waste coming from our own production is being recycled internally. Three different sources of recycled materials exist in our production.

1) Milling dust coming from the manufacturing the locking system
2) Waste LVT boards without top layer
3) Waste LVT tiles and planks with top layer

The first waste stream can be used directly in production without needing another processing step. The other material waste streams are being shredded into particles smaller than 5 mm. This material is than ready to be used again to produce new products.

4.2.2. Production of circular LVT

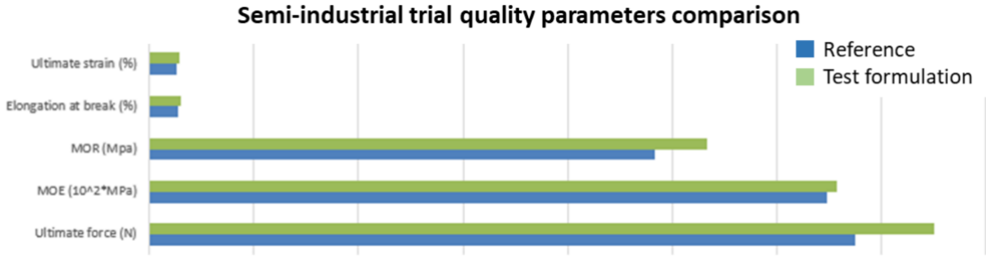
LVT currently already uses quite a lot of recycled content (30-50%). First exploratory lab trials showed that full circularity for LVT was possible. 100% post-industrial waste was used to extrude a base board on the lab-extruder with a quality that proved similar to the reference with virgin PVC.

With the results of these exploratory tests, further tests were performed to finetune a formulation containing 100% recycled PVC on the lab-extruder. The finetuning of the formulation is necessary for the next step of semi-industrial trials. The source of the recycled PVC is post-industrial waste coming from our own LVT production and a mixture of post-industrial and post-consumer PVC from the window frames industry such as from Deceuninck. In the formulation of the base board, this will account for 37 w% and 35 w% respectively.

After finetuning of the new formulation, a semi-industrial trial (1 hour of production) was performed on the production line (Figure 61) to assess the differences in quality between the reference product and a product produced with 100% recycled PVC.

Figure 61: Impression of the LVT production line

The samples of the semi-industrial trial were sent to the lab to undergo quality testing. The ultimate strain and force, the elongation at break and the modulus of elasticity (MOE) and modulus of rupture (MOR) were determined. The results of the quality tests (Graph 1) showed that the formulation containing 100% recycled PVC performed better than the reference.



Graph 1: Quality parameter comparison between the reference and the formulation containing 100% recycled PVC

4.2.3. Tagging of circular LVT

Printing of a QR code on the backside of the board is already industrially feasible.

Another solution similar to the one researched for cushion vinyl, digital watermarking, can possibly also be used for LVT. The print layer can be either digitally printed or analogue via gravure printing. When using digital printing, a digital watermarked could be integrated in the designs.

5. Conclusions

CLaminate

All the goals set for the pilot line are met :

- It is possible to extract good quality fibers from EOL laminate with a good yield
- The cleaning step of the fibers after defibring is sufficient to reuse these fibers in the production of new HDF for laminate flooring and MDF for furniture.
- The goal of 1 ton per hour capacity has been largely surpassed.
- The quality of the circular laminate flooring is good

A good basis is established to go to the next level: the full industrialization of the process.

CTextile

- Monomaterial concept

A monomaterial broadloom carpet consisting out of recycled PA6 piles, a PP primary backing, a PO based precoat (applied via powder scattering) and a PA6 secondary backing has been produced without issues. Installation trials have been performed, showing that the tackifier adhesive has most potential for easy uplift. A room has been fitted with the carpet using the tackifier, and was in use for 5 months. The use of a 'hairy' PA6 felt as backing has created issue around the joints as the loose fibres contaminated the adhesive at those spots (due to repeated uplifting during installation). It was shown that the installation goes smoother when the secondary backing is smooth, and does not contain loose fibres. The offcuts have been chemically recycled, and could be converted to caprolactam without problems. RFID tags have been assessed during the lifetime of the carpet, and some signals were lost after a while.

- Separation layer concept

In order to show the complete potential of the novel approach a complete integrated process consisting of pile fixation, glue coating and backing lamination is required.

The separation layer concept was tested with the main focus on carpet tiles which is to be expected to be an important application for this principle. It could be shown that a reasonable pile fixation was achieved using a thermobonding process and the coating of the separation layer on the backside is possible. Applied separation layers are: I) a thermoplastic PO triggerable by heat and II) a recycled polymer triggerable via solvent. The conventional secondary backings (bitumen and PO) can easily be applied. Separation tests were performed on lab scale to assess the potential of this concept. When using the recycled polymer separation layer, the bitumen backing can be delaminated using an alcohol, the polyolefin backing can be delaminated in acidic environment. The concept of the heat separation could also be demonstrated, but the material choice needs more finetuning (larger difference in melting temperature) to avoid contamination of bitumen or polyolefin on the primary backing.

For the industrial separation of carpet layers after lifetime a technology is completely missing. Here some novel approaches in order to provide a robust technology for the practise of recycling companies is urgently needed. It has to contain the steps trigger effect, mechanical separation and safe guidance to defined material waste streams in a highly automated degree.

- Mechanical recycling

ACS technology was developed to exploit an evolution of the shredding process, to mechanically dismantle textile floorings. The idea is to have a multi-functional machine that can efficiently process different kind of carpet constructions separating them into their constituent materials. Rather than concentrating on a perfect separation, that seems too challenging, the aim is to study a robust and versatile dismantling process, leaving further materials purification to subsequent steps. To obtain such results, several machine's parameters can be tuned to allow the processing of several different kinds of products.

For the moment the machine is still on a pilot level, and the main goal now is to test and study its dismantling ability on different textile products with the aim of understanding how to improve its results. Secondary goals are also testing of the obtained streams (PA6 steam, bitumen stream, latex stream etc) for circular reintroduction in the carpet production system.

The final objective of the project is to realize a commercial machine for carpets recycling that is small, energy efficient, versatile, reliable and that does not require either solvents or water: a quite challenging task that can be achieved by continuing this research with the support of carpet producers and carpet recyclers.

One interesting outcome of having such a device is that a carpet producers could install this machine for processing its production waste, such as trims and defective carpets, obtaining not just valuable streams of material, but also design-for-recycling insights to further improve the efficiency of recyclability of its products.

The preliminary results from ACS mechanical dismantling can be summarized as follows:

- Results are strongly influenced by carpet construction and materials used, and the behaviour can change even with carpet lifetime.
- A textile flooring that contains hard or brittle layer behaves better: this means that it can be exploited as a separation layer.
- An alternative approach is to have a "weak layer" instead of a brittle one, meaning a part of the carpet that is strong enough to guarantee carpet lifetime, but weak enough to break down without requiring much energy.
- The most common material for primary backing is PET, but PP is leading to better results when mechanical dismantling is used.
- Woven carpets are stronger than tufted ones, making their dismantling more difficult.

These hints can be used for carpet designing to improve even further the efficiency of ACS recycling process.

CVinyl

Cushion vinyl

- Current process

Industrial trials showed that it is possible to introduce micronized cushion vinyl as recycled content in the current plastisol coating process. But due to a lack of technical feasibility it was not possible to reach a recycled content of higher than 2-3 w%.

By using bio-circular PVC instead of virgin PVC in one product range, a carbon footprint reduction of 40% could be achieved. With loose lay installation by the use of double sided tapes, this material could be 100% recycled after use.

- Alternative technologies

Research was conducted into two alternative technologies with which a higher amount of recycled content can be achieved than using the current technology. Both technologies have shown promise but the focus has mainly been on developing a qualitative formulation of the recycled PVC granules. Further research needs to be conducted to validate the feasibility of the technologies on an industrial scale.

- Luxury Vinyl Tiles (LVT)

The full replacement of virgin PVC by recycled PVC showed good results and demonstrates that it is possible to manufacture LVT without the use of virgin PVC.