TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Material and Environmental Technology

THE USE OF NONWOVEN MATERIAL MADE FROM MECHANICALLY RECYCLED TEXTILE FIBRES IN PACKAGING INDUSTRY

MEHHAANILISELT ÜMBERTÖÖDELDUD TEKSTIILKIUDUDEST VALMISTATUD LAUSMATERJALI KASUTAMINE PAKENDITÖÖSTUSES

MASTER THESIS

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Tallinn 2022

(*On the reverse side of title page*)

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THESIS TASK

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Thesis topic:

(In English) The use of nonwoven material made from mechanically recycled textile fibres in packaging industry

(In Estonian) Mehhaaniliselt ümbertöödeldud tekstiilkiududest valmistatud lausmaterjali kasutamine pakenditööstuses

Thesis main objectives:

1. To analyse the characteristics and properties of the nonwoven textile material made of recycled cotton and poly(lactic)acid that is developed during the thesis research.
2. To develop two designs for the packaging applications.
3. To evaluate the suitability of the developed applications as an alternative for the cardboard packaging.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Overview of circular textile awareness and waste categories	08.04.21
2.	Researching recycling methods of textile waste	07.11.21
3.	Preparing materials for practical part	29.10.21
4.	Overview of recycled nonwoven textile applications	17.12.21
5.	Conducting various laboratory tests with the specimens	10.01.22
6.	Analysing the test results and material properties	11.02.22
7.	Prototyping and discussing the test results	12.03.22
8.	Reviewing the work with supervisor and making corrections	13.05.22
9.	Uploading the Thesis in Moodle	24.05.22
10.	Defending the thesis	03.06.22

Language: English **Deadline for submission of thesis:** 24th May 2022

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CONTENTS

PREFACE

The topic of the thesis is derived from author's keen interest in circular economy and cradle-to-cradle design philosophy. With rising consumption levels and billions of consumers across the world being involved in so-called linear value chain, the focus is on reusing the natural resources and waste more efficiently.

One of those valuable sources is the textile waste that is highly globalised. With various waste classifications and recycled routes existent, the prospects of reusing discarded textiles are positive. Thus, the study presents a current situation within the textile waste sector from an EU perspective and briefly discusses the strategies on how the waste sources are handled. With similar approach, the author proposes a solution of using mechanically recycled post-consumer textile waste in a scalable nonwoven application for the packaging industry.

The material development along with specific technological parameters, suitable technologies and testing methods in present research were suggested by the supervisors Senior Lecturer Tiia Plamus and Researcher Illia Krasnou. All the material preparations and laboratory tests were conducted by the author of the thesis, Liis Tiisvelt. The concept and the design, along with cutting out the prototypes with conventional technologies and folding them into boxes was also performed by the student. Processing the materials with laser cutter was performed by supervisor Tiia Plamus.

Therefore, the author would like to thank the supervisor Tiia Plamus for her guidance in material selection and for providing welcoming working environment. Author would also like to show gratitude to Illia Krasnou, whose advise helped to achieve the best result in material testing and who inspired to see the larger picture beyond the scope of this research.

Keywords: Circular economy, Textile waste, Textile recycling, Nonwoven, Packaging application, Product development.

List of abbreviations and symbols

C2C - Cradle-to-Cradle

CE – Circular economy

CEAP - Circular Economy Action Plan

EC – European Commission

EEA - European Environmental Agency

EGD – European Green Deal

EPR – Extended Producer's Responsibility

EU - European Union

GPP - Green Public Procurement

HP - Hot-pressing

ISO – International Organization for Standardization

PLA - Poly(lactic) acid

RCF - Recycled cotton fibre

1. INTRODUCTION

In the last decade, the waste has become extremely present across the whole planet, driving the demand for raw materials. It is estimated that approximately 80% of all materials and consumer goods are disposed because of the linear economy practices and the lack of managing the waste streams economically. Furthermore, if the global population increases at same pace, the demand for raw materials in the next 20 years will grow more than 200% for farmland, 137% for water and 32% for energy. [1] Those three aspects are interchangeably related to the textile industry, where the most widely used fibre, cotton alone, uses 3% of the world's agricultural water consumption [2].

Textile waste accounts for a large part of the global waste streams and today less than 1% of it is being recycled into value-added products [3]. Consequently, it is no surprise that the EC (European Commission) has identified textiles, namely apparel and fabrics, as a priority product category for the CE (circular economy). Endeavouring towards C2C (Gradle-to-Gradle) philosophy not only helps to preserve natural resources and encourage social prosperity but also enables holistic economic growth. It is estimated that the transition to CE would gain the EU (European Union) manufacturing sector an additional 600 billion EUR in a year [4].

Hence, different classifications of the textile waste and recycling routes are discussed in the present work. Even though textiles are almost 100% recyclable, it requires diverse approach in waste management [5]. Along with the specific methods for recovery, the properties of the new application made of recycled textile fibre must be considered and assessed.

Last decade has introduced various new materials and applications made of recycled textile waste with the majority destined to construction market. However, the materials' recovery rate in the construction sector is low due to the complexity of dissembling and thus reusing them for higher value [6]. Packaging industry, in contrary, is known for its high circulation rate as being under constant pressure of reusing, recycling, and designing more eco-friendlier products. Nonetheless, packaging remains to be a major consumer of virgin materials, using up to 40% of plastics and 50% of paper in EU [7].

In view of the urgent need to finding solutions for high volumes of various textile waste, present thesis demonstrates the possibility of using discarded textiles as a secondary raw material for the production of e-commerce packaging. The focus is on developing an alternative for the corrugated paperboard packaging in the form of a box. The use of textile fibres, along with the reinforcing biopolymer as a binder in such composite application enables to circulate the discarded low-quality clothing or pre-consumer textiles. Moreover, by reusing various textile waste streams as a raw material, we lower the landfilling rates and incineration levels, while maintaining both economic and social benefits within the circular business model [8]. Regarding CE aspect, the developed application, constituting mainly textile fibres, can be recovered via different recycled routes, which are briefly described in the work.

The study describes the materials and methods for developing a solid-structured nonwoven material from mechanically recycled textile fibres. The methods include preparing and mixing fibres by carding and pressing them into a composite matrix with the combination of heat and pressure. The mechanical characteristics of such material are determined via water absorption and flexural tests. Upon the derived test results, improved materials are prepared for the prototyping. The suitability as a packaging application is determined via flexural tests. The obtained results are discussed and compared with the requirements set for the traditional cardboard packaging.

Therefore, the main aim of the thesis is to develop a nonwoven material made from mechanically recycled textile fibres for a packaging application.

To achieve the aims on the thesis the following objectives were set:

- work through the literature regarding various textile recycling methods and requirements set for the packaging application;
- analyse the properties of the developed nonwoven textile material made of mechanically recycled cotton and poly(lactic)acid fibres;
- develop two packaging prototypes in the shape of a box and determine their properties via flexural tests;
- evaluate final product’s suitability as an alternative for the cardboard packaging.

The theoretical part of the research is based on the scientific articles and papers about the textile recycling practices, available technologies, and methods for developing recycled applications. Various regulation and strategies of CE are explained via corresponding EU directives. The practical part of the study is based on laboratory experiments conducted at Taltech according to the specific ISO standards.

2. CIRCULAR TEXTILE AWARENESS

Before Ursula von der Leyen was elected as President of the EC, she envisioned in her agenda that EU shall be the world leader in CE and become the world's first climate-neutral continent [9]. The statement referred to production and consumption, which over generating environmental, social, and economic costs and benefits, also accounts for extensive environmental burden. The environmental and climate pressures and impacts related to the textile system include the use of water, land, chemicals, energy, emission of the greenhouse gases and release of pollutants [8]. All these aspects contribute to global warming, which reached its highest level ever in 2021 [10].

Considering supply chain pressures from an EU consumption perspective, textiles sector that includes clothing, footwear, and household fabrics, had the third highest impact on water and land use, and was the fifth highest in terms of raw material use and greenhouse gas emissions. Even though majority of textile production takes place outside of Europe, in 2020 EU consumed nearly 15 kg of textiles per person more than it exported [11]. Out of which 11 kg per person was discarded [8].

European textile sector employs 1.5 million people across 160 000 companies with the turnover of 162 billion EUR, making it among the largest and important industries in EU [8, 11]. However, most business models within textiles value chain are still designed and optimized to fit the linear system, despite the EU Ecolabel and Eco-design Directive established already in 1992 and 2009 respectively [11]. The former promotes circular economy by encouraging producers to generate less waste and CO2 during manufacturing, while the latter entails a preventive approach to optimizing the environmental performance of products [12, 13]

Nonetheless, global textile production doubled between 2000 and 2015, compared to the world population that grew only 20% during the same period [3, 14]. Despite the efforts of shifting the textile industry into CE, the consumerism thrives due to the dopamine that helps control the brain's reward related to the pleasure of shopping. For instance, between 1996 and 2018 the clothing prices in the EU have dropped by over 30% relative to inflation, triggering low product quality and thus leading consumers and the industry to treat clothes as *disposable* goods. As a result, textiles are often discarded before the end of their technical lifespan, despite having high potential for reuse. [8, 15]

It is estimated that in EU only about 30% of discarded textiles are collected separately, suggesting that two thirds end up in residual waste, and is either incinerated for energy recovery, or landfilled. A large part of separately collected textiles are meant for reuse within EU or exported to foreign markets. [15] However, when exported, there is a lack of proof whether these textiles are reused, recycled, or stocked.

When EC identified textiles, namely apparel and fabrics as a priority product category for the circular economy, the EEA (European Environmental Agency) envisaged a circular textile system with targeted keywords to ensure the circularity of product's lifecycle. The system, introduced in 2019, included product related phases such as materials, eco-design, production, distribution, consumption, stock, and waste. Broader circular aspects were emphasized via education and behavioural change, policy options and general circular business models. (Figure 1) [8]

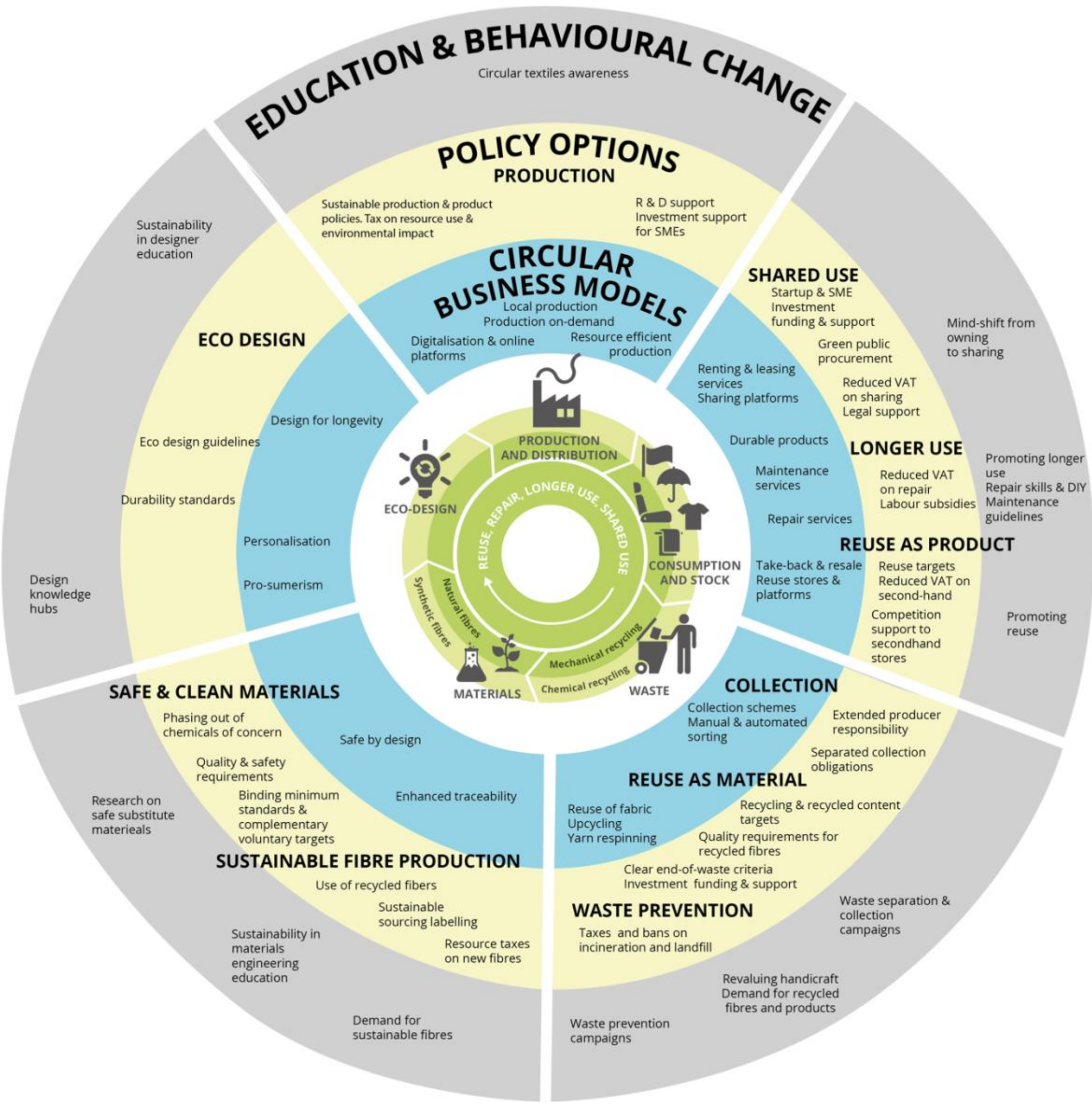


Figure 1. The role of circular business models, policy options, educational and behavioural change in circular textiles system [8]

Figure 1 illustrates a textile system divided into five sectors which are all interchangeably connected and highly dependent of each other. Considered as basis in textile industry, these sectors are further divided into three different social levels - circular business models, policy options, and educational and behavioural change. Maintaining both economic and social benefits within such circular business model is vital. Doing so requires wide-scale implementation of circular models supported by effective policies that address all the phases throughout the product lifecycle. Some of these policies include GPP (Green Public Procurement), waste framework directives, eco-design, EPR (Extended Producer's Responsibility), labelling and other standards. [8]

The clear schematic construction of the textile system makes it a useful and comprehensive tool, indicating the relationship between different sources. For instance, the choice of raw materials and the design aspect may influence heavily the environmental and climate impacts of a textile product and thus, decreasing its likelihood for circularity. For clothes to be recycled, they should be designed to have multiple lifecycles, be made of recyclable materials, and must be suitable for disassembly. Therefore, the research and development for recovering materials into higher value products or into new textiles is mutually important. [16]

More comprehensive data would enable to create a solid evidence base and accelerate the implementation of indicators and targets. Though, the complex and highly globalized value chain and the lack of data on textile waste remains one of the key challenges. [15]

2.1 EU strategies for textile waste prevention

The recent statistics about climate change and environmental degradation have urged EU to introduced various new strategies, regulations, agendas, and action plans to tackle the growing textile waste problem (Table 1) [17]. Considering the complexity of the textile value chain, EU has proposed a comprehensive strategy for textile-based industries and stakeholder inputs to tackle these challenges.

One of the most recent strategies designated for textile industry is the EU Strategy for Sustainable and Circular Textiles, also known as Textile Strategy. It addresses the production and consumption of textiles by looking at the entire lifecycle of a product. Implementing the commitments of the EGD (European Green Deal), the new Circular Economy Action Plan (CEAP) and the Industrial Strategy, the Textile Strategy ensures that by 2030 textile products placed on the EU market are long-lived and recyclable. Similarly, it harmonises with the EPR's policy approach, only with economic incentives. [18, 19]

Table 1. EU green strategies related to textile industry by the date of implementation

Green strategies in EU	Date	Main goal
Ecolabel [12]	23rd March 1992	Label of environmental excellence that promotes the circular economy.
Extended Producer Responsibility (EPR) [19]	20th March, 2001	Policy approach preventing wastes at the source.
Green Public Procurement (GPP) [20]	2008	Voluntary instrument whereby public authorities procure goods to reduce their environmental impact.
European Green Deal (EGD) [17]	December, 2019	Become the first climate-neutral continent by 2050.
European industrial strategy [21]	10th March, 2020	Twin transition to a green and digital economy.
A new Circular Economy Action Plan (CEAP) [22]	11th March, 2020	A plan focusing on the design and production for a circular economy.
European Climate Pact [23]	December, 2020	Part of Green Deal to make its operations climate neutral by 2030.
Textile Strategy [18]	30th March, 2022	Greener and more competitive textile sector, resistant to global shocks.
Ecodesign for Sustainable Products Regulation [24]	30th March, 2022	Making sustainable product the norm.

Furthermore, the newest CEAP extends its future-oriented agenda even further and is encouraged by the fact that up to 80% of product's environmental impacts are determined at the design phase, and that the system simply lacks incentives for producers to make their products more circular. Even though instruments such as EU Ecolabel and the GPP are broader in scope, they have reduced impact due to the limitations of voluntary approaches. [22]

By their nature, the EGD, European Climate Pact and GPP are growth strategies that aim to boost the sustainability by turning the environmental challenges into opportunities [17, 25, 26]. As 93% of Europeans see climate change as a serious problem, the EGD aims to make EU climate neutral by 2050 via means of turning political commitment into a legal obligation [17].

Part of the strategy is a proposal for a regulation on Ecodesign for Sustainable Products that sets new requirements to make products more durable, reliable, reusable, upgradable, reparable, easy to maintain and to recycle. In addition, the product-specific information requirements will be regulated via Digital Product Passport. [24]

Another goal is to achieve high levels of separate textile waste collection by 2025, under the EU waste directive and EPR's policy. The framework obliges all EU members, especially fast fashion brands, to collect discarded post-consumer textiles separately from other municipal waste so to further promote recycling and avoid landfilling. [18] Currently, less than 1% of clothing are recycled globally, and mostly into lower grade products. Due to many technical and commercial challenges, high-quality fibre-to-fibre recycling is virtually non-existent at commercial scale. [3]

That is the reason why EU waste strategy includes measures to support circular material and production processes, tackles the presence of hazardous chemicals and helps consumers to choose sustainable textiles [27].

2.2 Textile waste

Textile waste is considered as discarded or unwanted material from the production, and use of fibre, textiles, and clothing [28]. As textiles are almost 100% recyclable, nothing in the textile and apparel industry should be wasted [5]. By its origin, textile waste can be categorized into two broad categories requiring diverse approach in waste management. Pre-consumer or post-industrial textile wastes generated during the manufacturing process, while the post-consumer or household wastes are described as goods that have reached the end of their lifecycle. [29]

Due to high resource consumption and environmental impacts generated via fibre and textile production, better handling of discarded textile materials is highly recommended. Not only for ecological, but also for economic reasons. As fibre reprocessing is difficult and complex, a large portion of fibrous waste ends up in landfills or, largely based on legislative forces, in waste incinerators. [29]

It is estimated that in the past 20 years, the global fibre production has doubled, reaching around 111 million tonnes in 2019 [30]. Most of the fibres are composed of natural or synthetic polymeric materials with cotton and polyester dominating the market. The majority of textile materials contain a blend of cotton and polyester to enhance material's durability at lower cost [28]. Other fibres are used in great variety of products and when discarded, they end up in diverse waste streams [29]. It is estimated that the amount of waste generated is thought to be equal to one full truckload of textiles going to landfill or incineration every second [3].

Consequently, the discarded textiles are recognized as the fastest-growing waste stream in municipal waste across the globe [28]. Today, waste is increasingly seen as (secondary) raw material, while zero waste concept is representing the current ideal in waste management [29].

Generally, apparel, home furnishing, and industrial textiles are the three broad end-use categories consisting of textile fibres. The life expectancy of textile products ranges from short, medium, to long term. (Table 2) [30]

Table 2. End-use for fibres including their respective share and typical examples [29]

End-use	Life expectancy	Share, %	Example
Apparel	Short	44	Outerwear (e.g. trousers, coats) Underwear (e.g. briefs, stockings, undershirts)
Interior and home	Medium	33	Carpets Home textiles (e.g. curtains, blankets) Automotive
Industrial and technical	Long	24	Transport Building and construction Medical, pharma, and health Filters and membranes

The EU Waste Framework Directive has established a five-step waste hierarchy for managing and disposing waste, consisting of prevention, preparing for reuse, recycling, recovery, and disposal (Figure 2). While preventing waste is the utmost preferred option, sending waste to landfill is to be avoided as last resort. Reuse is currently the most common option for utilization of apparel and textiles, which occur after the primary customers have sold or given away the product. In most industrial countries, end-of-life apparel, and home textiles, are collected separately from other types of waste and hand-sorted by different fibre fractions. [31]

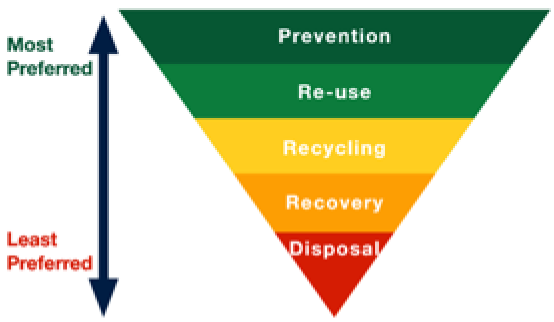


Figure 2. The 5-step waste hierarchy established under EU Waste Framework Directive [31]

However, the textile recycling's potential is still not fully realised due to a lack of proper technology, particularly when it comes to sorting the collected clothing, separating blended fibres, separating fibres from chemicals, and establishing which chemicals were used in the production in the first place. The technological challenges mean full recycling of clothing into new fibres is still far from commercially viable. [16]

2.2.1 Pre-consumer textile waste

Pre-consumer waste, often referred as post-industrial waste, is generated by the original manufacturer or during the production process of upstream products and thus, never reaches the consumers [32]. Such waste is viewed as *clean waste,* because the by-product during the manufacturing process is already a fibrous material or other textile scrap [33, 28]. On average, about 15% of the fabric used in garment production is cut, discarded, and washed in the process, which contributes to post-industrial waste [32].

The pre-consumer waste is classified largely as yarn spinning wastes, weaving, or knitting wastes and confection wastes. The sub-categories include ginning, opening, carding and roving waste, ring spinning waste fibres, ring spun waste yarns, open-end spinning waste fibres, knitting and weaving waste yarns, clothing production wastes and fabric cutting scraps. These types of materials are usually re-manufactured for the automotive, aeronautic, home building, furniture, mattress, coarse yarn, home furnishing, paper, apparel, and other industries. (Figure 3) [33]

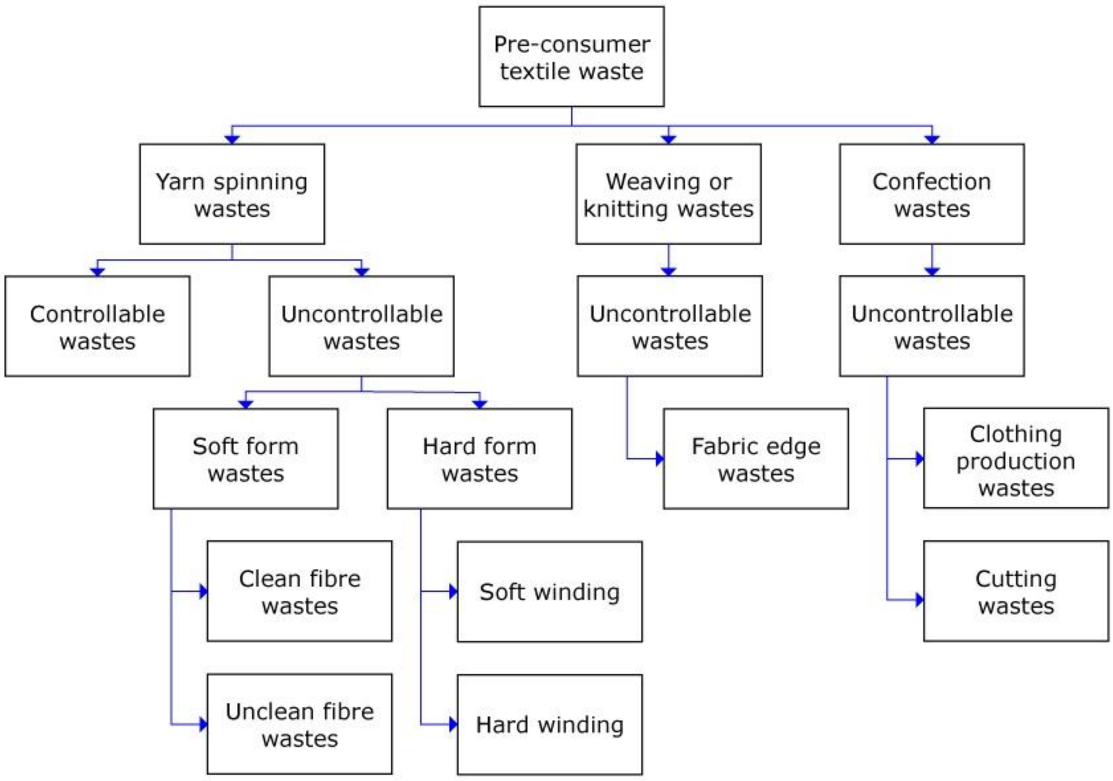


Figure 3. Classification of pre-consumer textile waste [34]

2.2.2 Post-consumer textile waste

Post-consumer textile waste is generated after the product reaches its end-of-life phase and is discarded. Such textiles include garments and home textiles that are donated to charity shops, textile sorting centres or recycling companies, where they are often sorted manually by the fibre fraction, colour, and other features. [35]

The drawbacks for hand-sorted method are high labour cost, low speed operation and the impossibility of full automation, which is required to process huge volumes of materials. However, conventional methods and systems for sorting are usually incapable to classify different textile materials and require inputs from well-trained operations. Though, some of the advanced automatic sorting technologies such as NIR (Near infrared) spectroscopy or ATR-FTIR (Attenuated total reflection and Fourier transform infrared) methodology are available in the market and can distinguish between different fibre fractions. [35]

As shown in Table 3, majority of the collected textiles are reused and mainly exported as second-hand clothing to emerging countries such as Africa and Eastern Europe. However, many doubt in the environmental benefits the second-hand market brings, before eventually reaching its end-of-life, and will be discarded. Instead, the preferred alternative to end-of-life textile management is integrating the waste material into the production process to reduce the raw material consumption. [36]

Today, almost third of the collected textiles, not suitable for wearing, are reused as low-quality components, e.g., cleaning and wiping rags. Only small proportion is being recycled for fibre or energy recovery and being landfilled as a last option. [36]

Table 3. Mass flow of end-of-life apparel during the sorting process [31]

<table>
<tr><th>Fraction category</th><th>Use</th><th>Portion, %</th></tr>
<tr><td>Reuse first quality</td><td>Second-hand clothes for second-hand shops in industrial countries</td><td>1-3</td></tr>
<tr><td>Reuse second quality</td><td>Second-hand clothes for export to emerging countries</td><td>40-48</td></tr>
<tr><td>Component reuse</td><td>Cleaning and wiping rags</td><td>29-38</td></tr>
<tr><td>Recycling</td><td>Fibre recovery</td><td rowspan="3">7-12</td></tr>
<tr><td>Incineration</td><td>Energy recovery</td></tr>
<tr><td>Landfill</td><td>None</td></tr>
</table>

3. RECYCLING OF TEXTILE WASTE

Textile recycling industry is one of the oldest and most established recycling industries in the world [37]. In simple terms, recycling is the breakdown of a product into its raw material, which enables to use the reprocessed textiles as the raw material for value-added products [32]. Recycling processes are especially important because of the high energy and resource demands of fibre manufacturing. Though, it is argued whether the reuse is the best option as the energy required for collection and sorting is negligible in comparison to the energy intensity of apparel production. [38]

EU directive 2008/98EC gives more precise definition for recycling. Recycling means any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. [39, 40, 40]

Similarly, upcycling and downcycling can be also considered as examples of recycling. The term *upcycling* was developed in 1994 and described as a concept of adding value to the old or used products. The process of upcycling requires a blend of factors like environmental awareness, creativity, innovation, and results in a unique, sustainable and often handmade product. While upcycling means reusing waste without destroying it, recycling refers to breakdown of a product into its raw state so that it could be reclaimed and used in new products. [32]

Downcycling, on the other hand, recycles waste into products of lower value than the original products. Also, it is argued whether downcycling saves much less energy than reuse of the waste derived fibres. Today, most existing textile recycling routes are downcycling, where clothing or home textile are recovered into industrial rags, low-grade blankets, insulation materials or upholstery. However, the term *downcycling* can be considered subjective as the quality consists of immeasurable components such as aesthetics, fit-for-purpose or material qualities defined by fabric construction rather than fibre quality. As a result, certain end products made from recycled fibres or fabrics may still be described rather as upcycled. [41]

The necessary steps in the textile recycling process involve the donation, collection, sorting, and processing of textiles, followed by the subsequent transportation to end users of used garments, rags or other materials. The process of recycling natural textiles includes the sorting of materials by type and colour, which reduces the need for re-dying the fabric, thus saving energy, water and avoids pollution. [16]

The recycling processes can be further categorised by the degree of processing that takes place in the operation. For instance, if the fabric of a product is recovered and reused in new products, it is called *fabric recycling* or material reuse. When the fabric is dissembled, but the original fibres are preserved, it is referred to as *fibre recycling*. If the fibres are dissembled, but the polymers or oligomers are preserved, it is *polymer or oligomer recycling*. However, if the latter is dissembled, but the monomers are preserved, it is called *monomer recycling*. These types of recycling routes can be achieved by various means, often by combining various mechanical, chemical, and thermal processes. (Figure 4) [41]

Another classification for recycling routes is *closed-* or *open-loop recycling*. Closed-loop recycling sees products retain their value indefinitely by which the material from a product is recycled and used in an identical product. Open-loop recycling, also known as cascade recycling, occurs when the material from a product is recycled and used in another product. The former can be illustrated with the occasion when the T-shirt is being recycled into a T-shirt rather than the recycled fibres from PET bottles being used for manufacturing a T-shirt. In the material category, the closed-loop recycling would mean that a material category, such as packaging, is recycled back into the same type of packaging. [41]

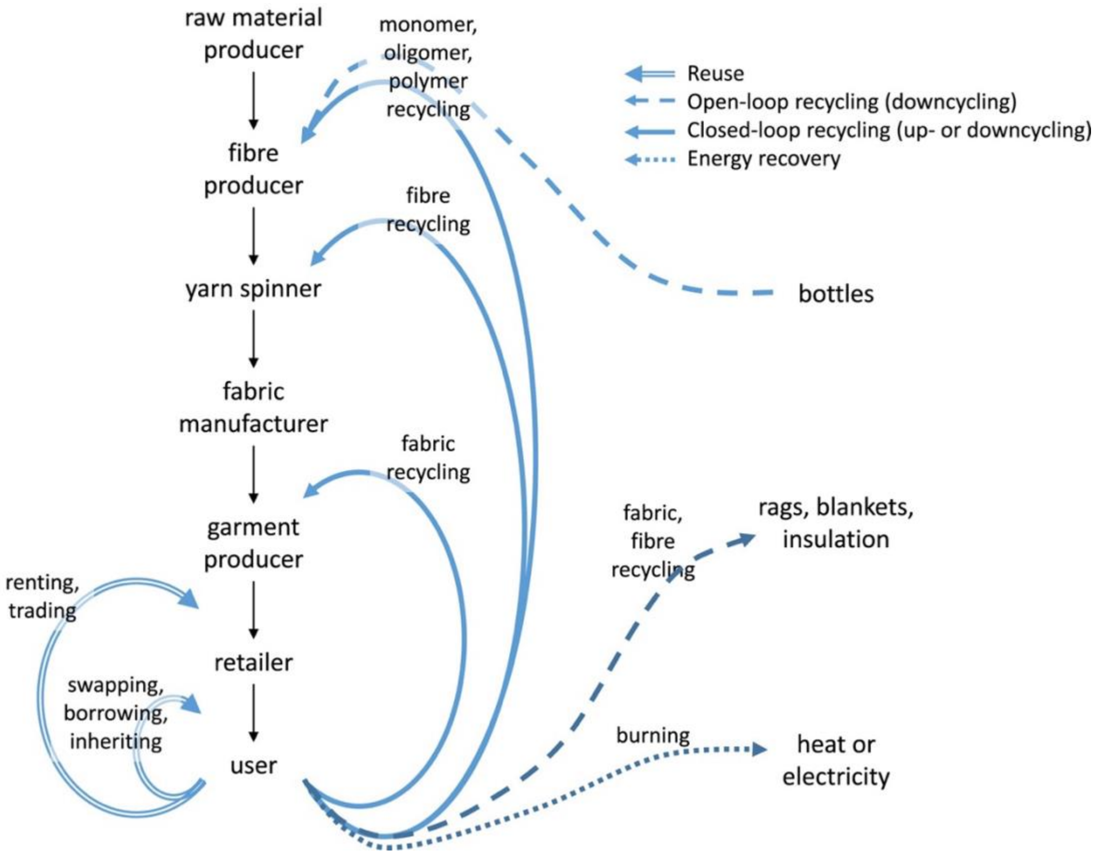


Figure 4. A classification of textile reuse and recycling routes [41]

3.1 Mechanical recycling

Mechanical recycling is the process of recycling the textile fabric back into fibres without the use of any chemicals. This process includes collecting, separating, cutting, shredding, and carding. [42] Although the method is simple and cheap, mechanical recycling shortens and damages the fibres and therefore influences the quality of the end product [43]. That is the reason why recycled cotton fibres are often blended with virgin fibres to obtain the needed quality and strength [42].

A typical mechanical recycling starts with the process called *cleaning*, where the metal and non-textile materials are removed. The fabrics are then baled and cut with a rotary blade into small pieces. Next, the pieces are feed into the textile-shredder that separates fibres via *picking, pulling, or tearing* as the fabrics are rolled on progressively smaller spiked surfaces. [44] The textile-shredder is usually composed of 2 to 8 rolls, depending on the fibre quality required. The more rollers, the greater the quality of recycled fibre. The rollers have different diameter with numerous needles on its surface that rip and shred the rags. The design of the textile-shredder machine works in accordance with the textile waste composition used and is capable to shredding from 50 to 3000 kg per hour. (Figure 5) [43]

In fully automatic recycling production lines, the fibres are also sent to Garnett machine for fibre extraction. These machines perform heavy and rough carding actions by tearing the fabric with opposite sets of strong sharp teeth transforming it to its component fibres. Since the teeth are mounted on the surface of cylinders rotating on a parallel axis, the teeth of several opposing cylinders travel all in parallel planes and the yarns which happen to extend in the direction of the travel of the teeth in radial planes can and do pass through the machine in end-on relation and thus escape being opened into individual fibres. [38]

(a) (b) (c)

Figure 5. (a) Scraps prepared for shredding; (b) A textile-shredding machine; (c) Recycled fibres [43]

3.2 Chemical recycling

In chemical recycling, also known as physical method, the fibres in sorted textiles are broken down to a molecular level or to their original monomeric building blocks. After melting or dissolving the fibres, the building blocks can be repolymerised into a new polymer. The derived feedstock is then passed through a spinneret, generating new filament or fibres that are either ready to be spun into yarn, sent to weaving or can be knitted into new fabric. [44]

Similarly, to mechanical method, chemical recycling starts by shredding the sorted textiles to remove all the non-textile components via conventional separation technology. Followed by the de-dyeing, where the large fraction of textile dyes is solubilized in a reductive alkaline and removed at washing step. During the subsequent steps, the remaining colour components are bleached, and their viscosity adjusted by treating the material in a specific environment. Fibre separation step removes the non-cellulosic fibres by purifying the cellulosic pulp from contaminants. Before dried and packed, the fibres are washed once more to remove process chemicals. (Figure 6) [44]

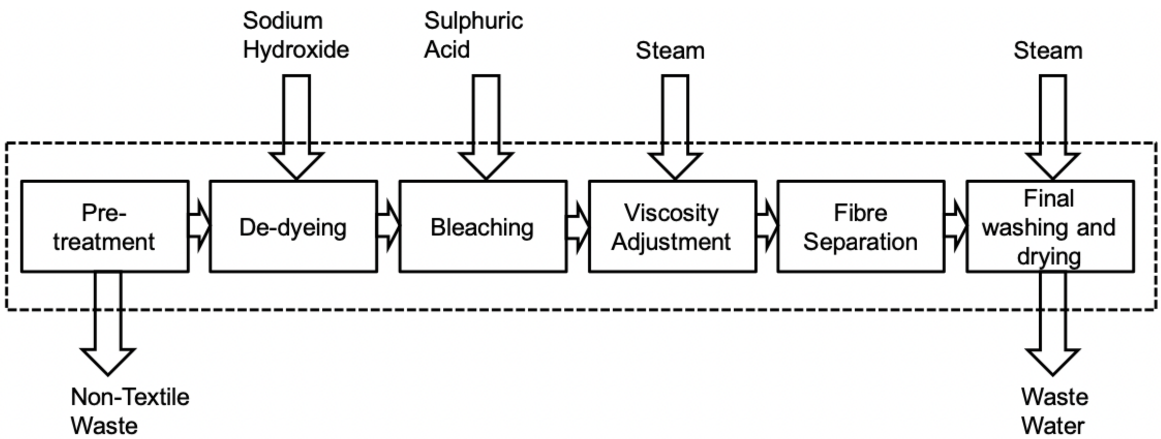


Figure 6. The process flowchart for chemical recycling [44]

Compared to mechanical methods, chemical recycling is a promising technology that increases the recycled content of garments and enables recycling of the same materials for multiple times. Thus, chemical recycling is considered as high value recycling system, which is mostly used for cellulose-based mono-fibrous textiles such as cotton and viscose. [44]

Some of the well-known companies offering chemical processing plants are Worn Again in UK, Teijin in Japan, by EVRNU in US and Re:newcell in Sweden [44].

3.3 Thermal recycling

Thermal recycling is defined by the melt extrusion, where the PET flakes, pellets or other synthetic chips are converted into textile fibres. The method is often used interchangeably with mechanical recycling as the flakes, pellets and chips are initially produced from PET waste by mechanical means. Also, the term thermal recycling can be easily confused with thermal recovery, which occurs when the textile waste is incinerated to generate heat or electricity. However, the literature states that incineration with energy recovery is occasionally labelled as recycling, although the term recycling most often refers solely to material recycling. [41]

Thermally recycled fibres can be produced either directly extruding flakes into fibres, or firstly converting flakes into pellets or chips and then melt-extruding them into fibres. The latter is used more commonly, where the PET flakes are dried prior to the melt-extrusion step, following further purifying through a filtration step. After a cooling process, the polymer is pelletized and dried, and transported to the fibre spinning plant, where they are melt-spun into filament fibre. (Figure 7) [45]

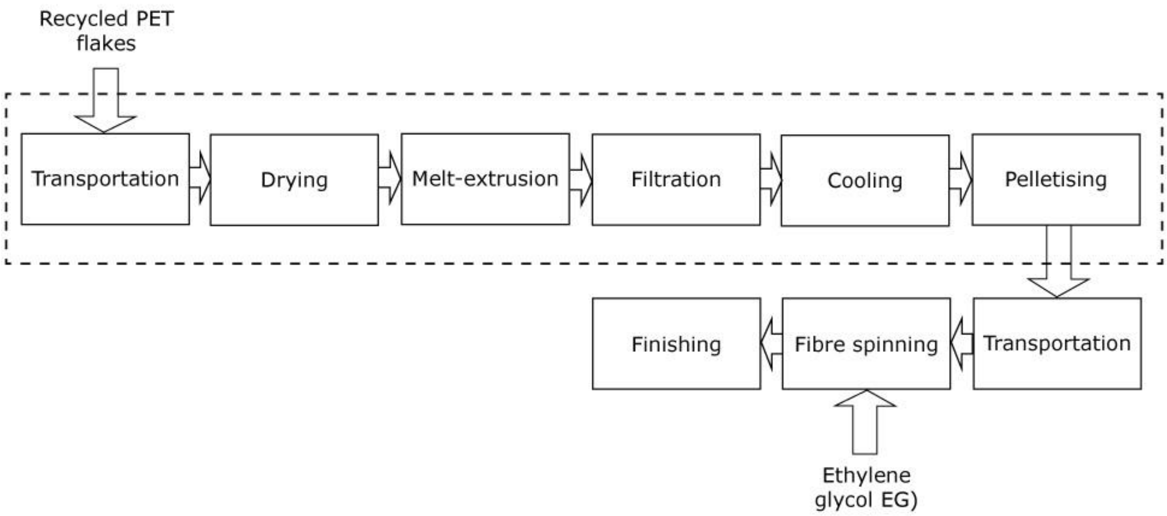


Figure 7. The process flowchart of thermal recycling when producing PET fibres from mechanically recycled PET flakes [45]

4. MATERIALS AND PRODUCTS DEVELOPED FROM RECYCLED TEXTILE FIBERS

A potential outcome for the recycled textile fibres is to incorporate them into a composite material to enhance the characteristics of the final product. Composites are considered as engineered materials that offer high strength to weight ratio and have extremely attractive combination of toughness, stiffness, durability, and flexural strength [46]. By its nature, a composite material is defined as the formation of at least two immiscible materials with remarkably different chemical or physical properties. One of the constituents in the composite is known as *binder* or *matrix* that shapes and creates a bond, while the other component is called *reinforcement*, that gives good mechanical properties to the material. Possible configurations with different types of reinforcements are shown in Figure 8. [47]

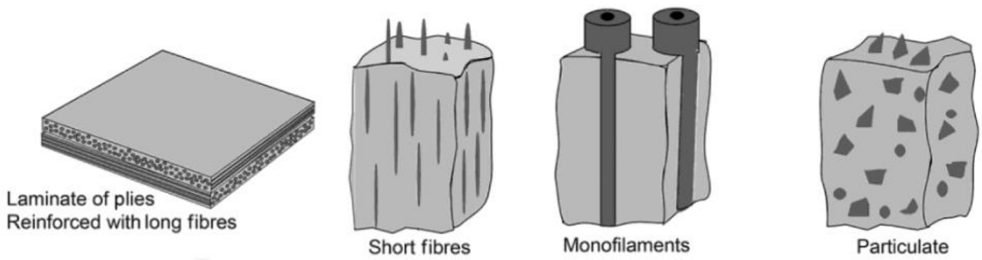


Figure 8. Different types of reinforcement configurations [47]

Composite materials can be categorized by the nature of the matrix material and involve ceramic, metallic, and polymeric matrix composites. Polymeric matrices include either thermoplastics, or predominantly thermosets (resins). Extensive ongoing research is constantly looking into novel types of composites with enhanced properties. [47]

The most widely used manufacturing methods for fibre reinforced composite materials is the injection moulding, film stacking and HO (hot-pressing) with heat. The latter method is suitable for moulding large, intricated parts, is cost effective and easily handled. [48] HP temperature depends on the thermal properties of fibres and matrix. The processing temperature for composite manufacturing is usually equal to or higher than the melting point of the matrix, however below that of the fibre [49].

Cotton and polyester fibres constitute the majority within the textile materials and thus, are most commonly recycled [32]. Textile nonwovens often use PLA (poly(lactide) acid) as a binder due to its relatively low melting point [50]. PLA is a biodegradable polymer that is widely used from apparel and agricultural products to packaging applications. It is derived from abundantly available, natural, and sustainable sources such as the starch of corn, wheat, sugar beet and sweat potato. PLA is produced commercially mainly by fermentation of glucose present in starch, though before 1990 another common route was via petrochemical feedstock. The polymerization of lactic acid to high molecular weight can be achieved either via direct condensation or solvent free formation of the lactide. The catalytic polymerization enables to control the molecular weight of PLA, which then can be tailored to fit different requirements. [51] PLA melting temperature varies from 130 °C and 180 °C. (Figure 9) [50]

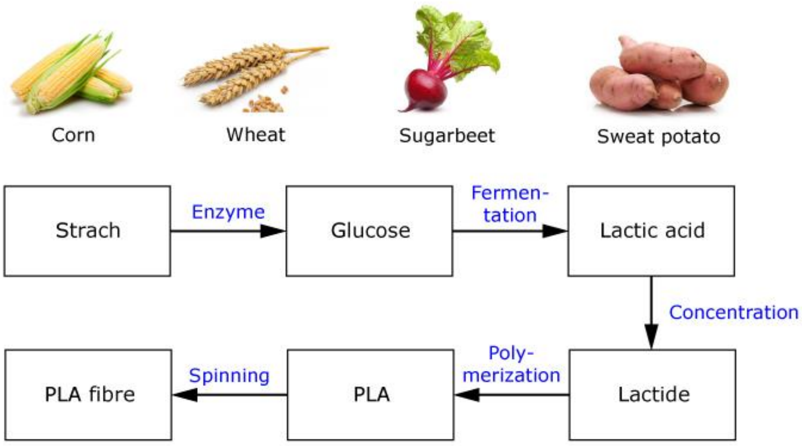


Figure 9. Synthesis of PLA via fermentation from various natural sources [51].

Composites made of recycled textile fibres have wide range of features and can be found in mechanical, construction, automobile, marine, aerospace, biomedical, and many other manufacturing industries [46]. Some of the applications are found in Table 4. [52]

Table 4. Examples of incorporating recycled fibres into polymer composite matrices for wide range of applications [52]

Thermosetting matrix	**Fibres**	**Applications**
Epoxy resin	Glass fibres	Military and ballistic protection
	Flax fibres	Eco-friendly materials with high tensile wear
Thermoplastic matrix	**Fibres**	**Applications**
Poly(lactic acid)	Aramid fibres	Fused deposition models
	Cellulose fibres	Polymer recycling for additive manufacturing
Polypropylene	Hemp fibres	Semi-structural automotive components
Poly(lactic acid) / Thermoplastic starch	Cotton fibres	Structural reinforced components, green packaging
Nylon	Carbon fibres	3D printings
Hybrid matrix	**Fibres**	**Applications**
Epoxy resin	Hemp fibres	Rotorcraft interiors
Thermoplastic PU	Sugar palm fibres	Building, automotive part, construction

4.1 Acoustic insulation

One of the materials made of recycled textile fibres is an acoustic insulation. It is an application that helps control the noise via sound absorption. The quality aspects of sound absorption depend upon on the fibre type, fibre fineness, density, airflow resistance, the bonding and thickness of insulation, and pore structures inside the nonwoven. [53] Porous materials allow sound waves to enter in their matrix and to dissipate [54]. Thus, acoustic insulation panels are widely used in sound recording rooms, offices and in other spaces, where the acoustic performance must be improved.

An alternative for conventional acoustic insulation is a nonwoven material made of recycled textile fibres, mainly polycotton blend, due to its low carbon footprint and hazardous effect on health. Though, the actual sustainability of natural fibres is questionable due to the toxic chemicals used during their production. [54]

Acoustic insulation from recycled textile fibres can be produced in various methods. Present work covers only main bonding techniques such as chemical, thermal, and thermochemical hybrid bonding, which are all preceded by mechanical fabric waste opening into fibres. [53]

In chemical or adhesive bonding, the fibres are firstly fed into the web forming machine for opening and cleaning action. The opened fibres are then deposited to the condenser unit of the web former. The resulting thin fibrous layer is sent to nozzled chemical adhesive unit and sprayed with either PVOH, PVA, PVC or other acrylic binders at constant pressure. The bond is a result of combination of physical and chemical forces, which act on the boundary layer between the two polymers. Lastly, the web is passed between calendar rolls and is dried. (Figure 10) [53, 55]

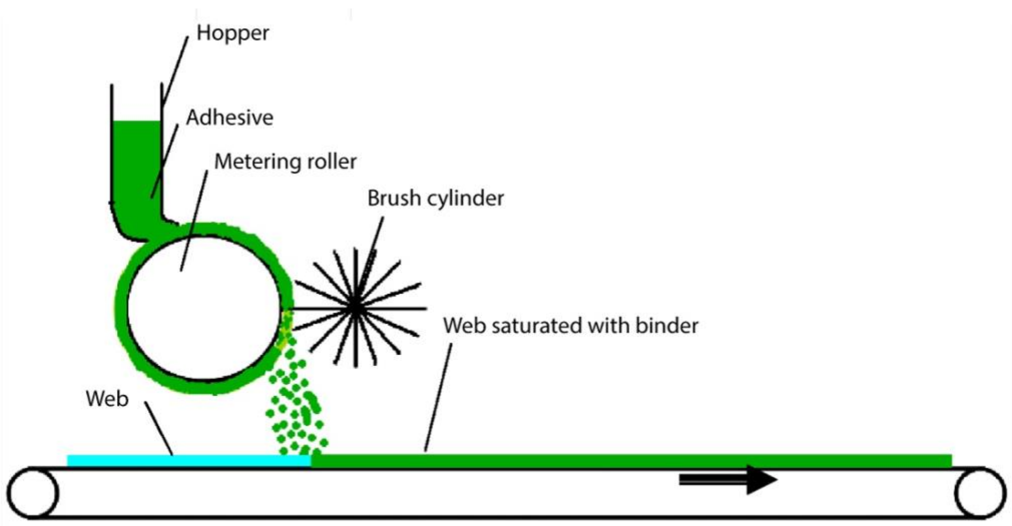


Figure 10. The process flowchart of adhesive spraying [55]

In thermal bonding method, the fibrous nonwoven layer is treated with heat in variety of ways, often in addition to other processes (Figure 11). The different methods of thermal bonding include hot, belt or point-bond hot calendaring, ultrasonic bonding, radiant-heat bonding, and through-air thermal bonding. [55]

For the latter method, the unit is installed just above the web development section and the negative air pressure release from the underside of the web. The nonwoven passes over the perforated drum, where the hot air is passed through the drum to heat and melt the nonwoven structure. [53] Fabrics made of bicomponent fibres or a blend of bi-component and regular fibres are often bonded thermally by through-air bonding [56].

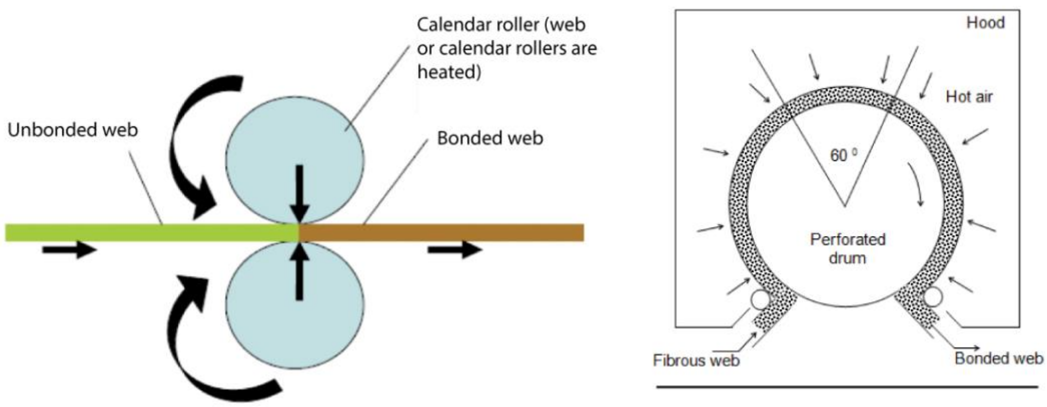


Figure 11. The principle of thermal bonding (left) and through-air bonding (right) [55]

In hybrid thermochemical bonding method, 50% of layers are prepared with the thermal bonding method and 50% with the chemical bonded technology. Mild quantity of epoxy resin treatment is applied between the layers by hand layup technique, then cured for 6 h and pressed with compression moulding unit at 60 °C to maintain the thickness of 6-7 mm. Higher thickness nonwoven materials possess higher sound absorption coefficient due to higher frictional losses caused by the higher thicker material. [53]

An alternative method, using post-consumer recycled cotton denim fibres and PLA fibres is also used to successfully produce insulation materials. Insulation panels with uniform thickness were produced by dry-laid process where firstly both fibres are blended and then fed into a carding machine where it is passed through different fine wire mounted rollers. Carding is generally known as a pre-spinning treatment to mix and align the fibres within the prepared composite material. Carding and stripping actions open and clean the fibres and produce uniform fibre web. 12 layers are then consolidated and hot pressed at 180 °C with pressure set to 380 kPa (55psi). The result is a formed composite panel. [57]

4.2 Thermal insulation

Thermal insulation is a building insulation material, which is commonly produced from synthetic materials including glass fibre, mineral wool, and plastics. Thermal insulation is defined by the property of a material to reduce heat flow or transfer. [54] Transfer of heat through fibrous materials depend on the number of fibre layers, packing geometry, contact between fibres, porosity of the material and temperature differences [58].

Most of the conventional thermal insulation materials are derived from non-renewable sources and have non-disposable properties. Thus, the demand for eco-friendly insulation materials is increasing. [59] One of the alternatives for such insulation is recycled post-industrial nylon/Spandex (NS) mixed with thermoset polyurethane (PU) foam offcuts. While PU is known as an excellent thermal insulator, NS provides binding upon melting to form a rigid composite material. [60]

Thermal insulation panels can be formed via various manufacturing processes, one of those being a lamination method. Once the PU and NS fabric offcuts are shredded down to 2 mm x 2 mm pieces, the particles are processed further with commercial shredding machine. Then the shredded PU and NS fibres are compress moulded into separate panels at 215 °C, with pressure set to 2T. Heating and cooling times are 40 min and 10 min for PU and NS respectively. Lastly, the panels are sandwiched with PU layer in the middle (Figure 12). [60]

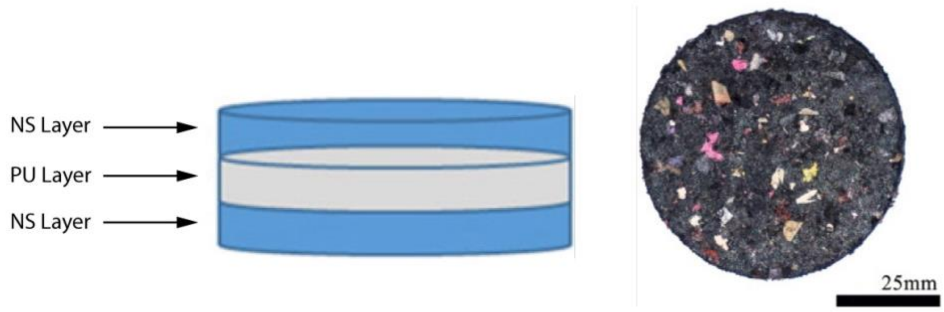


Figure 12. Configuration of the sandwich and hot-pressed panel [60].

The benefits of the laminated configuration rather than a mixture of shredded particles are to avoid additional cost of extensive mixing as well as better insulation properties. The method can be tested with different combinations of PU and NS, however, when the PU percentage is increased over 70%, the physical integrity is not favourable. This is because of the insufficiency of Nylon polymer as the binding material to keep the increasing PU parts in place. Also, thermal conductivity decreases proportionally with material thickness. Thus, the studies show the least thermal conductivity at ratio of 60% NS and 40% PU. [60]

4.3 Geotextiles

Construction of earth structures and exploitation of open mines can form slopes prone to land sliding and erosive damage. The protection of the slopes to ensure their stability is highly important. Recycled fibres and textiles are good alternative over geosynthetics or geotextiles for meandrically arranged thick ropes to protect and stabilize the steep slopes. A meandrical rope made of mechanically recycled textile waste can be produced by means of the stitch bonding Maliwatt technique.

The nonwoven material made from mixture of recycled natural and synthetic fibres is obtained by shredding and carding the post-consumer textile waste. The fibres are turned into a strip of web and stitched with polyester multifilament thread. Then the nonwoven is bounded into a thick rope sheated by the polypropylene twine by means of Kemafil technology. The ropes with diameter of 100 mm were arranged in the meandrical pattern. (Figure 13) [61]

Figure 13. The Kemafil rope manufactured from the nonwoven made from blended recycled fibres (left) [61] and the ropes arranged meandrically on the surface of the steep slope in a gravel pit [62]

The content of the fibres is not fixed and varies depending on the amount and kind of waste. The raw material can be a mixture of 60% polyester, 30% cotton and 10% wool. Recycled textiles have better performance than conventional material as geosynthetics do not retain water, which can be provided to vegetation on the slope during a drought. Therefore, part of the ropes made from recycled fibres are manufactured with the addition of perennial ryegrass (Loliumperenne) seeds (40 g per 1 m^2 of nonwoven). Research have shown that the slope is covered with vegetation after approximately 20 months of period. [61]

4.4 Interior design

Recycled textile waste potential for interior design applications is huge, especially for the decorative purpose. French design agency FabBRICK transforms discarded textile waste into decorative panels suitable for furniture or partition walls, and insulative bricks of different shape and colour (Figure 14). Each brick uses about two or three t-shirts worth of shredded material that is binded with proprietary glue consisting of 100% ecological ingredients. Even though the particularies of the manufacturing method is classified, a general description of the process is available. FabBrick only uses the discarded clothing already sorted by colours. When the textile waste is crushed into fibres and scraps with in-house shredded, they are mixed with the glue at the patented machine and compressed mechanically in a special brick mould for 30 minutes. The wet bricks are left to dry in ambient air between 10 to 15 days. No dye is used, and the colour of bricks is obtained by the original colour of the textile. [63]

FabBRICK bricks have supposedly good thermal and acoustic insulating quality, and a good resistance to fire. The material has also enhanced resistance to water, however the company recommends using their applications only indoors. [63]

Figure 14. Decorative bricks from discarded textiles by French company FabBRICK [63]

4.5 Packaging made of recycled textiles fibres

Packaging is a product made of any material of any nature which is used for the containment, protection, handling, delivery, and presentation of goods. The conventional materials used for packaging include paper and cardboard, plastic, wood, glass, and metal [40] Packaging made of recycled textile waste or fibres is relatively new phenomena in the packaging industry due to high requirements for packaging materials according to their end-use [64].

Plastic packaging is one of the most widely used packaging materials, especially for polyester mailer bags for e-commerce and for food and beverage sector. Textile materials, on the other hand, are not widely used for packing goods, and certainly not in food sector. The nature of their fibrous property can contaminate the food, except for the woven muslin bags from natural fibres that are used for conserving fruits, vegetables, tea, bakery, or other grain products [65].

Estonian company Woola, founded in 2020, produces biodegradable e-commerce packaging made of leftover sheep wool that is otherwise buried or burnt. Their product, a protective wool packaging for fragile items, is an alternative to a synthetic polyethylene bubble wrap, reducing plastic waste of online shopping (Figure 15). There is no specific info available about the manufacturing method of Woola's packaging, however it is known that the wool is mixed with a bio-based binder. Regarding a bubble wrap imitation on the surface, the material is most likely calendared, and the side of the envelope could be heat pressed. The wool envelope is wrapped into a recycled paper where a waybill can be added. Woola's production is in Paldiski, Estonia. [66]

Figure 15. The compostable bubble wrap from leftover sheep wool by Estonian *startup* Woola [66]

4.5.1 Product design

Developing a concept for product design is a creative and dynamic process where customer needs and product requirements shall be met. In terms of packaging, an ideal product design must perform various roles such as protection, maintenance, and identification of the good, including marketing, and transportation [67]. On top, packaging of consumer goods is an area where these conditions are continuously changing because of internationalization and influencing factors in the supply and demand side of the packaging industry [68].

In general, packaging system is classified via three main categories known as primary, secondary, and tertiary packaging. Each of the category holds a particular role in the supply chain, determining the product design, material, end-use and the way of disposal. [69]

Primary packaging is not only regarded as the first envelope directly protecting the product, but all of the packaging which surrounds it when the consumer takes it home. Such packaging includes medicine bottles, beer cans, chocolate wraps, wrapping papers, etc. The lifecycle of primary packaging is short, and it eventually finds its way into domestic waste stream once the product is discarded. (Figure 16) [69]

Figure 16. Some of the widely used packaging types [Author]

Secondary packaging contains and protects the primary packaging, and involve, for instance, an outer box containing a tube of toothpaste, or an outer carton holding several primary packaging [69].

Tertiary packaging is used for bulk handling in warehouse, or in transportation and is not commonly displayed on the retail shelf. Such packaging reduces damages, while holding goods tightly together. Examples include pallets, plastic films, polystyrene foam, ropes, carton boxes, etc. [69, 70]

Product design, especially for packaging, depends highly on the materials used. The material often sets the limits for the shape of the packaging and the suitable goods it can withhold. The convenience and safety are another important feature when handling the package. These compromise intuitive and ergonomically sound user experience when the pack should be picked up, accessed, opened, reclosed, or repacked. [69]

Furthermore, there are significant differences on product requirements during the transportation of goods online or via e-commerce sector. Earlier, most of the items were sold in physical stores and shipped in large quantities to distribution centres while packed in secondary and tertiary packaging. This has changed with the growth of e-commerce and today single packages are transported directly to the end consumer with approximately 30 handling stops along the way. Meaning that e-packages pass through far more touch points to their way from the manufacturer to the consumer than the packages for sold in brick-and-mortar stores. The number of extra handlings increases, considering customer returns in case the physical item is dissatisfying. Therefore, it must be easy for the consumer to open, re-seal and return or recycle the package. [71]

In some cases, packaging may be considered as a part of the product which contributes greatly to the usage. Apart from the material, shape, size, and colour being important parts of the packaging, also the graphics, logotype and texture can add extra value. Therefore, packaging and packaging design has become an important factor in marketing diverse *consumer goods* and have a key role in communicating product benefits to the customer. This is especially the case, when the consumer finds the packaging so attractive and wants to keep it for other purposes. Also, many end-users desire products that have considered the social, economic, and ecological impacts for the world, and prefer the designs with zero or positive impact. [68]

Ideally, every packaging should be designed for a specific order and use, manufactured cost-effectively and be easily recyclable. In reality, it would be economically too costly and resourceful to produce infinite number of packaging shapes and sizes, which also leads to unnecessary environmental burden. According to EU packaging waste directive, waste should be prevented or minimized along with the amount of recycled packaging material produced. The directive also emphasizes the fundamental importance of energy recovery and reuse of packaging that enables faster transition towards a circular economy. [40]

5. RECYCLING PRACTICES IN PACKAGING INDUSTRY

It is though that recycling of packaging waste can directly reduce the consumption of raw materials, while minimizing the demand on landfill and land pollutions. Thus, packaging sector is under constant pressure of reusing, recycling, and designing biodegradable applications.

In 2019, packaging waste generated in EU was estimated at 178.1 kg per inhabitant and approximately 160 kg per person in Estonia. Packaging waste covers wasted material that was used for the containment, protection, handling, delivery, and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer, excluding production residues. Packaging waste constitutes 35% of the total municipal waste with the majority being paper and cardboard, followed by plastic, glass, and wooden packaging waste respectively (Figure 17). The average recycling rate for all the packaging in EU was 64.4%, led by paper and cardboard segment at 82%, metal at 77.4%, plastic at 40.6% and wooden waste at 31.1%. [72]

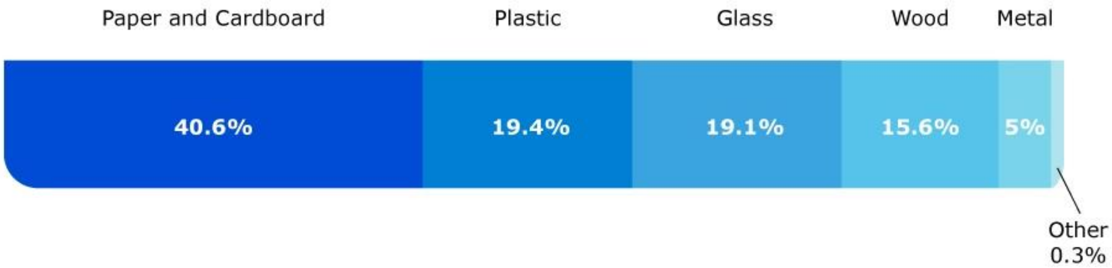


Figure 17. Packaging waste generated by packaging material in EU in 2019 [73]

Despite the high recycling rates in some categories, packaging remains to be a major consumer of virgin material, using up to 40% of plastics and 50% of paper in Europe. The amount of packaging material has been growing in past years due to e-commerce developments, including increased convenience, thus the supply chains have moved to increasingly to single-use packaging. [7]

With strict governmental regulations such as "New EU Directive for Single-Use Plastics" and "Extended Producer Responsibility (EPR)", EU aims to reduce leakage of single-used plastic, set higher recycling targets or only using recyclable packaging [74]. For instance, fast-moving-consumer-goods industry which is characterized by increased demand for e-commerce has set goals to incorporate high degree of recycled content in packaging and to increase recyclability even up to 100%.

5.1 Plastic recycling

Packaging recycling is often more economically feasible than other sectors of the plastic market due to high turnover rates of the collected post-consumer waste in Europe. In 2018, 29.1 million tons of post-consumer plastic waste was collected in Europe, though less than a third of it was recycled. [75] Divided into different applications, the main polymers in the packaging sector are PET, HDPE / LDPE, PP, PVC, and PS (Table 5) [76].

Table 5. The five main packaging polymers and their main uses [75]

Polymer	**Application in packaging**
PET	Beverage bottles, trays, jam, jars
HDPE and LDPE	Bottles, bags, bin liners, food wrapping material, squeeze bottles
PP	Bottles, straws, bottle caps
PVC	Films, trays
PS	Fast-food packaging, food packaging, disposable cutlery, consumer goods

There are four types of polymer recycling – primary, secondary, tertiary, and quaternary recycling. The primary and secondary recycling involves mechanical reprocessing, e.g., bottle-to-bottle closed-loop recycling (primary) and recycling into a lower value plastic (secondary). Tertiary recycling is chemical recycling and used on polymers no longer suitable for mechanical recycling methods. Tertiary recycling turns the polymer to its monomeric feedstock and is based on variety of chemical steps such as hydrolysis, methanolysis, glycolysis or a combination of different processes. Quaternary recycling is applied to plastics that are not suitable for any other type of recycling and are used for energy recovery via pyrolysis. [75, 76]

The recycling of polyethylene terephthalate (PET) packaging is one of the oldest recycling practices in Europe, dating back to 1998 when the first bottle-to-bottle recycling plant was installed in France. Most of the re-collected PET bottles exist in either clear, blue, green, or brown colour, which allows effective sorting in separate recycling streams by the colour. Moreover, as PET bottles are manufactured only from one material with low level, if any, polymer additives, huge amounts of re-collected and well-sorted post-consumer waste is available. [76].

Another important factor is the polyester-type chemical nature of PET, where the chemical ester bonding is a reversible process and therefore, after being recycled, can have even better material properties as virgin polyester [76]. This is because the broken polymer chains during first use, or within the recycling steps, can be easily rebuilt by heating the polymer up in high vacuum or dry inert gas streams in so-called solid-state polycondensation processes (Figure 18) [77].

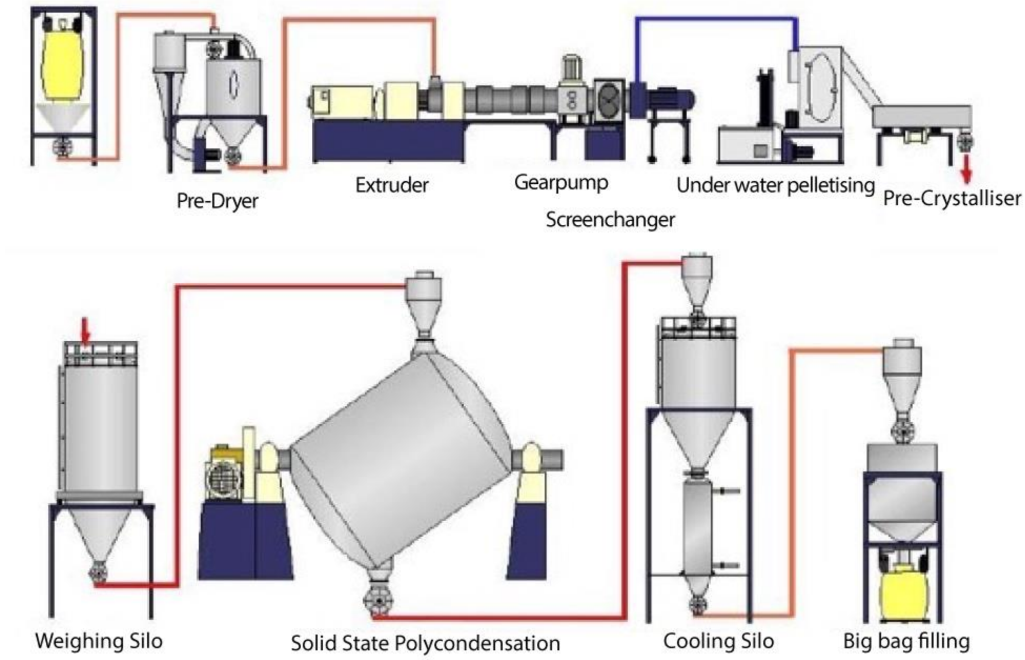


Figure 18. The process of decontamination and solid state polycondensation of post-consumer PET plastic packaging [78]

In addition, PET has a very low intrinsic diffusivity for organic molecules, which means very low interaction between packaging material and food [76]. This means that in super-clean PCR PET, universally used flavour substances cannot be detected anymore, hence it can be converted back into a virgin PET quality, containing only monomers or additives, which are listed in the positive list of European Regulation 10/2011 [79].

5.2 Paper and cardboard recycling

It is mentioned in literature that paper and cardboard has been recycled for over 600 years with a significant rise in the 1990s. Most of the recovered paper is derived from industrial and commercial sources. Even though paper has high recycling percentage, virgin fibres are simultaneously introduced in the recycling process. [80]

Paper and its waste are easily degradable in nature and recyclable within a paper mill. Paper is made of cellulose fibres and combined with several chemicals that determine the properties and quality of the paper. It is thought that fibres of cellulose can be recycled up to seven times. [81] In Europe, a large amount of used paper is supplied by waste management companies. Paper for recycling must be collected separately from other materials as contaminated papers are not acceptable for recycling. [76]

In principle, the paper and cardboard recycling process is the similar as the one for paper from virgin fibres. Discarded paper is soaked in large container, which breaks the paper into pulp. However, prior to recycling, paper waste undergoes number of sorting steps to remove various paper qualities such as hygienic products, and cleaning steps to eliminate non-fibrous materials such as plastics, staples, and inks [76]. The latter is called de-inking – a method, where the ink is removed in a flotation process, while air is blown into the solution. The ink adheres to bubbles of air and rises to the surface from where it is separated. When the ink is removed, fibres may be bleached, usually with hydrogen peroxide [82]. The process, where fibres are gradually cleaned, deinked, sieved and filtered, is repeated several times until they are suitable for production of recycled paper (Figure 17) [81].

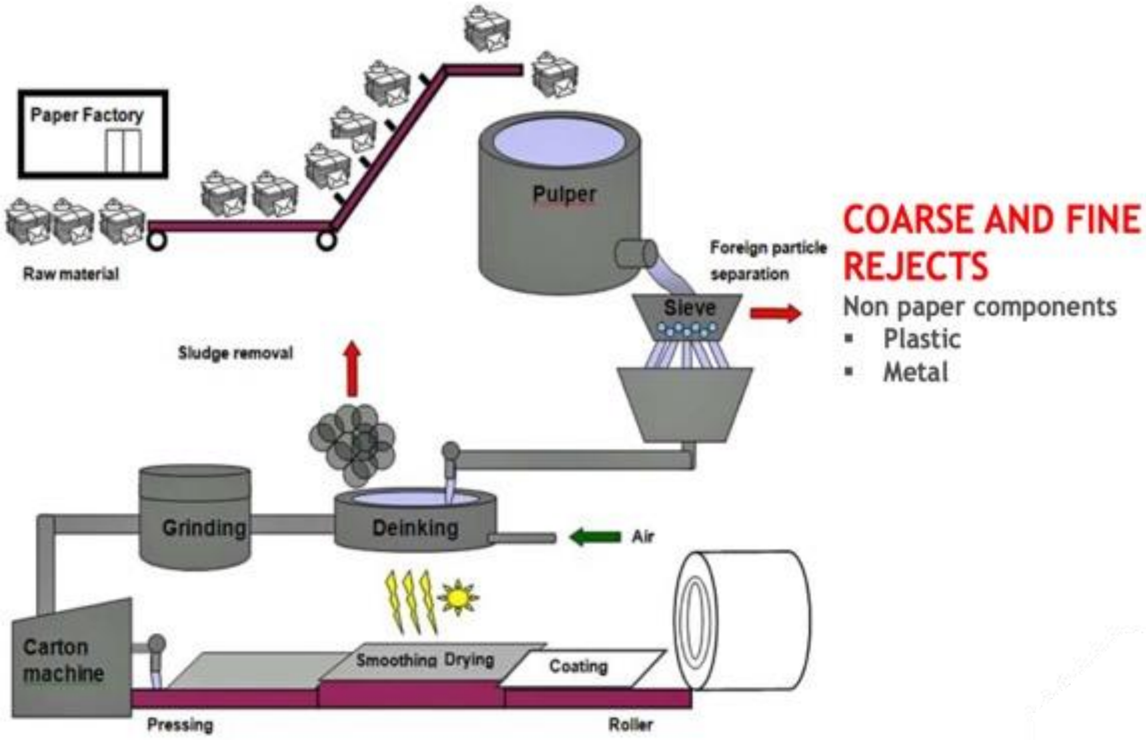


Figure 17. The process of paper and cardboard recycling [83]

Depending on the quality and the required properties of finished paper good, quantities of fresh wood fibre cellulose may be added. This is due to limited number of recycling cycles as the mechanical and printing properties of the material deteriorate and the length of the wood fibre decreases every time it is recycled [81]. Many packaging producers thus use mixed types of paper for recycling, that may ultimately lead to unwanted contaminants in the ready-to-use paper products [76]. Some papers such as a newsprint and corrugated materials, can be made of 100% recycled paper [82].

6. PRODUCT DEVELOPMENT

Current study presents a production method for a composite matrix made of RCF (recycled cotton fibres) and PLA ((poly(lactide)acid)) for packaging industry. PLA is a thermoplastic polymer derived from natural starch via fermentation. PLA's versatility is owed to its mechanical property profile, thermoplastic processability and biological properties such as biocompatibility and biodegradability. [51]

The idea of reusing textile fibres in the packaging application is inspired by the C2C design concept, whereby the integration of design and science are vitally beneficial for the entire society. C2C design framework emphasizes the biological lifecycle in the nature, where the term *waste* does not only exist, but is rather empathized as a resource for something else. [84] Similarly, the textile packaging developed in current study, closes the loop within the textile industry by reusing the discarded clothing or pre-industrial scraps.

Textile matrices, either from natural or synthetic fibrous materials, are known for their outstanding mechanical and physical properties. The research shows that structural textile composites have become more and more dominant as alternatives to replace conventional load bearing materials, especially due to their high performance to weight ratio, light weight, resistance to corrosion, wear, and to degradation at high temperatures. The strength and multifunctionality of fibre reinforced materials make them suitable to use in structural applications [85].

The focus regarding present product development is to achieve a matrix that is stiff and though, however with relatively thin structure. As the aim is to form a box for e-commerce packaging, the composite structure and surface should resemble the one to the corrugated paperboard. Such material is mainly supported by its corrugated structure and is often used for shipping various e-commerce consumer goods or other fragile items, where the shape-holding feature is relevant. Furthermore, corrugated carton box is mainly used for shipping premium goods that require an aesthetically neat packaging for marketing purposes. [71].

Plant-based fibrous composites are also receiving greater attention for their low contribution to greenhouse effect, biodegradability, and the fact that they are obtained from natural and renewable sources [85]. When reaching its end-of-life period, RCF and PLA composites can be mechanically recycled back into their fibrous state and reused for producing new packaging. Studies related to lifecycle analysis of various reprocessing methods show that mechanical recycling has less impact on climate change in comparison with chemical recycling and energy recovery [41].

However, the downside of mechanical recycling is the quality of the recyclates. Shredding process shortens the fibres and can thus influence the quality of the final product [44]. With such method, short and already blended PLA and RCF fibres can be obtained and thus the outcome mixed fibres may by directed again to carding and HP phase in the production process. Though, it is not certain whether the shortened fibres will form a thoroughly interlocked matrix for the second time around. It is also unknown the mechanical properties and the durability for such composite.

Owing to the biocompatible and thermoplastic nature of PLA, one solution is to separate the polymer from the matrix via chemical recycling by hydrolysis. PLA degrades naturally in *in situ* mechanism in which the water molecules break the ester bonds that constitute polymer backbone. [51] The degradation rate depends on several factors such as molecular weight, crystallinity, polymer composition, pH, sterilization, and fabrication processing to name a few [86]. Once degraded, PLA physical properties can be modified by material modifications. However, transforming the PLA back into textile structure is complicated. Extrusion of the polymer into monofilament and multifilament is achieve by melt spinning, wet spinning, dry spinning, and dry-jet-wet spinning. [51]

Apart from the origin of materials, production methods and recycling routes, the entire life cycle of the textile product must be considered to achieve for being compliant with circular economy concept. Waste and environmental should be considered in design phase, fibre, and fabric production, dyeing and finishing, confection, distribution, use and recovery [22]. (Figure 18)

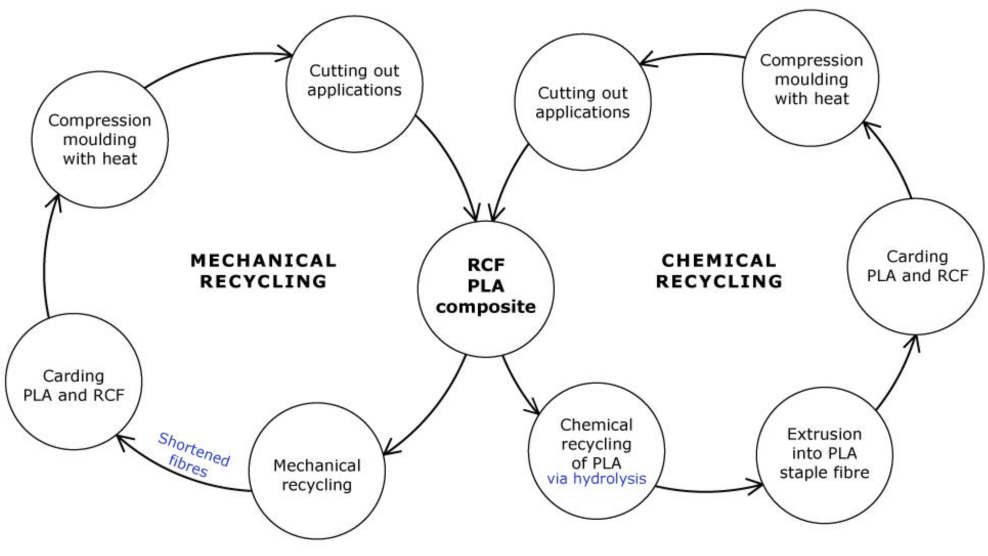


Figure 18. Simplified scheme of different recycling routes for the application

6.1 Design

Product design, especially for packaging, depends highly on the functionality of the end-use and various customer requirements. Present design is developed in the form of a stiff and structured box that is convenient to handle. The concept of the designed box is simple – it can be easily folded or unfolded and sealed without the need of extra auxiliary components such as adhesion, sealants, staples, or tapes. It can be transported flat in bulk and easily stacked up in the storage when folded.

Two box designs are presented to test and analyse whether and how the different shapes influence the properties of the application. A bigger box compromises a form of conventional cardboard box that is widely used for e-commerce packaging (Figure 19). Its rectangular layout is economic and therefore, reduces the cutting waste during manufacturing. The double folded walls in front of the box are crucial for holding a rigid form when in usage. As seen on Figure 19 the outer cutting edges are highlighted with black and inner folding lines with red. Both designs and layouts were made with Adobe Illustrator

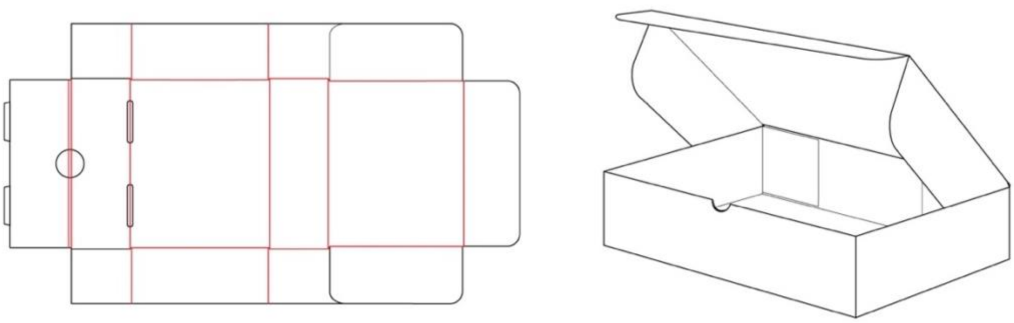


Figure 19. The flat layout and the 3D image of the bigger box

Smaller box differs from the opening method and compromises fewer folding lines. Thus, can be folded in faster time. The downside is the ineffective layout plan. (Figure 20)

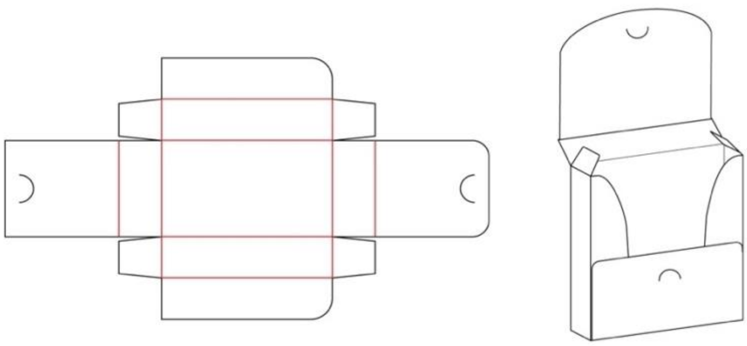


Figure 20. The flat layout and the 3D image of the smaller box

7. MATERIALS AND METHODS

The practical part of the thesis, in terms of laboratory processes, is divided into two phases. Phase 1 describes the characteristics of the chosen raw materials and methods for developing a nonwoven composite. The specimens were measured and prepared for various mechanical tests according to ISO standard procedures. At the end of the phase 1, the test results were analysed and discussed. (Figure 21)
Phase 2 involved prototyping according to the test results drawn in phase 1. When the new specimens were prepared and tested, the designs were cut out with the laser cutter and folded into boxes. Compression properties of the final product were tested.

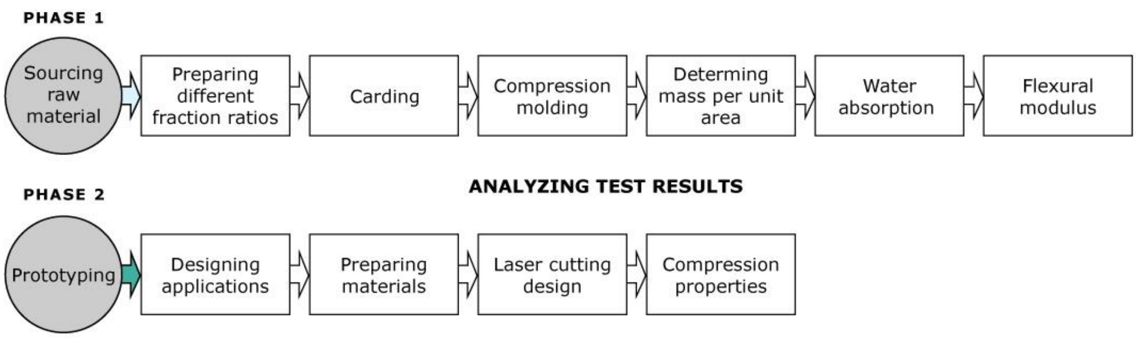


Figure 21. The process of practical part.

Table 6 presents various instruments and machinery that were used in different material development phases. As the prototyping phase required wider specimens, the carding and HP procedures were conducted in larger machinery.

Table 6. Instruments and machinery used in the thesis

Instrument	**Description**	**Phase**
KERN KB, 6500 g	Precision balance for weighting fibres	1; 2
Louët Junior 46 tpi	Manual drum carder for textile fibres	1
Louët Standard 46 tpi	Manual drum carder for textile fibres	2
STATOP-2MG	HP, small	1
INFOR PM84	HP, large	2
Insize 2871-10	Digital thickness gauge	1; 2
Instron 2525-816, 500N	Flexural tests	1; 2
Laser cutter	Cutting out designed layouts	2

The selection of fibre fraction ratios of the specimens in current study was determined by the experimental reasons, aiming to find the most suitable composition ratio for the developed packaging application. Though, higher percentage of RCF in the composite was preferred to reuse as much recycled textile waste as possible (Table 7).

In total of 10 specimens were prepared and divided by two weight groups. Heavier specimens, 35 g were chosen according to the specifications of the drum carder, while the lighter specimens, 25 g, were prepared to define whether and how the material properties differ by the weight. The lighter specimens are beneficial for the fact that lightweight packaging can potentially save from the logistical costs.

Table 7. RCF and PLA fibre fraction ratios by the weight of the carded specimen

Fibre ratio, %	**35 g, heavy**				
RCF/PLA	90/10	80/20	70/30	60/40	50/50
Fibre ratio, %	**25 g, light**				
RCF/PLA	90/10	80/20	70/30	60/40	50/50

7.1 Materials

7.1.1 Recycled cotton fibres

The positive environmental effect on reusing RCF is widely researched and approved as an eco-friendly alternative in lieu of virgin textile fibres. Several studies highlight successfully incorporated RCF into a polymeric matrix to produce composites with significant mechanical level.

In this study, hand-sorted and mechanically recycled post-consumer cotton fibres of mixed colour were used and sourced from Finland. Sorting textiles merely by the hand-feel may not always give the most accurate fibre composition, therefore, it was noted by the supplier that both cotton and other cellulosic fibres could be present. (Figure 22)

Figure 22. PLA staple fibres (left) and RCF (right) used in the study

7.1.2 Poly(lactic) acid

The PLA staple fibres in this study were sourced from Paragon Sleep AS. The exact specification of PLA can be found in Appendix 1, where the melting temperature is specified 130 °C to 170 °C. For achieving a solid and tough structure, 155 °C was chosen for the hot-pressing of RCF / PLA composite.

7.2 Methods

7.2.1 Carding

Manual drum carding machine Louët Junior 46 tpi was used to interlock RCF and PLA fibres into a nonwoven matrix (Figure 23). It is a compact drum carder with long and strong flexible intermeshing teeth that enables to produce a thick fleece of coarser fibres of about 78 x 10 cm. The carder consists of a large drum and a small roller for feeding in the fibres. By moving the handle, the rollers accelerate with 9:1 ratio, which refers to the difference in surface speed between the large and the small roller. The term *tpi* stands for teeth per square inch. [87]

After weighting the corresponding fibre fraction ratios, the RCF and PLA fibres were fed into a carder via smaller roller. At least three carding cycled was done with each specimen.

Figure 23. Mixing RCF and PLA fibres with manual carded Louet Junior 46 tpi [87].

7.2.2 Hot-pressing

HP temperature was chosen by the melting point of PLA, at 155 °C for all the specimens despite the weight, thickness, or composition ratio.

Before placing the specimen in HP instrument, the upper and lower heat plates were heated up to 155 °C. The specimen, covered with baking paper to avoid sticking, was inserted between the hot plates and was pre-pressed for 2 min with the pressure of 10 bars. Then, the specimen was HP-d for another 5 min with increased pressure. As a result, a thin, solid, and rigid composite was formed. (Figure 24)

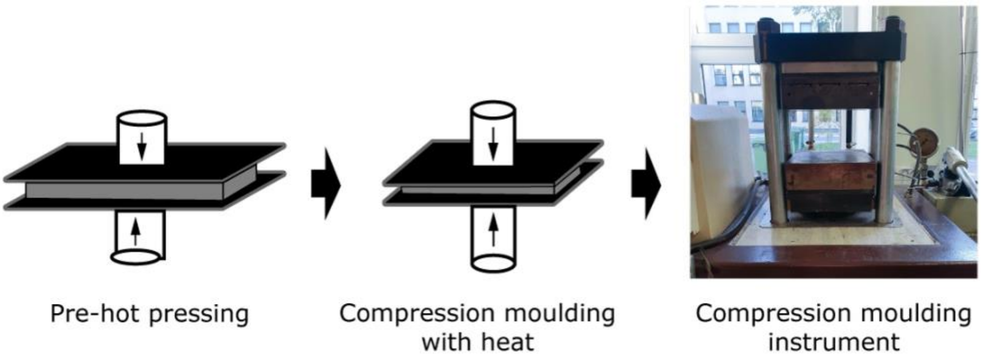


Figure 24. Schematic diagram of composite HP steps

Since the size of the HP heat plates were limited to 20 x 20 cm, the carded fleece with the initial length of 78 cm was cut into four pieces in order to test different HP pressures from 40 to 70 bars. Consequently, the number of specimens increased to 40 (Table 8).

Table 8. HP parameters for all the 40 specimens

Initial fleece weight, g	**Composition RCF/PLA, %**	**Specimen before cutting in 4**	**Compression pressure, bar**			
			40	**50**	**60**	**70**
35	90/10	1	1	2	3	4
	80/20	2	5	6	7	8
	70/30	3	9	10	11	12
	60/40	4	13	14	15	16
	50/50	5	17	18	19	20
25	50/50	6	21	22	23	24
	90/10	7	25	26	27	28
	80/20	8	29	30	31	32
	70/30	9	33	34	35	36
	60/40	10	37	38	39	40

7.2.3 Mass per unit area

Mass per unit area was specified in the standard EVS-EN 29073-1:2000 Textiles – Test methods for nonwoven – Part 1: Determination of mass per unit area. The standard specifies a method for measuring the area and mass of a test piece and calculating its mass per unit area in grams per square meter with following equation [88]:

$$M = \frac{m\,x\,1000}{A} \tag{7.1}$$

Where m is the mass of the specimen in grams and A is an area in square centimetres.

The standard atmosphere for the specimens was employed according to ISO 291:2008, which is a standard atmosphere for plastics. Although the developed composite material contained mostly textile fibres, its structure was solid and tough, thus the choice of conditioning. [89] For measuring the mass per unit area, the same specimens were used as in water absorption test. Two test pieces per specimen, instead of three as described in the standard, were cut out using a fabric sampler cutter with the diameter of 37 mm and an area of 10.75 cm^2. (Figure 25)

Figure 25. Fabric sampler cutter and the measurement of the specimen [90].

7.2.4 Water absorption test

Water absorption test in this study was performed according to ISO 22836:2020 Fibre-reinforced composites – Method for accelerated moisture absorption and supersaturated conditioning by moisture using sealed pressure vessel. The standard specifies a method for obtaining practical saturated moisture absorption for effective and short research and development process for thermoplastic materials. [91].

The standard atmosphere for testing was set according to ISO 291:2008 [89]. The test was conducted with two test pieces per specimen that were priorly cut out for measuring the mass per unit area. The diagram of the specimen was 37 mm.

Before immersing into water, the test pieces were oven dried at 105°C for 4 hours and placed into an air-sealed container immediately after. A container filled with 250 ml of distilled water at room temperature was prepared, where the specimens were soaked for 1 hour. When removed from water, the specimens were placed on the cotton tissue to remove any excess liquid. The measurements such as thickness and weight of the specimens were recorded throughout the process.

The water uptake W_c is expressed in percentage and determined using the following equation [91]:

$$W_c\,(\%) = \frac{Wt - W0}{W0} \times 100 \tag{7.2}$$

Where W_t is the weight of the specimen at time t and W_c is the initial weight or thickness of the specimen before placing into water.

7.2.5 Flexural modulus test

Flexural modulus test in this study was performed according to EVS-EN ISO 178:2019 Plastics – Determination of flexural properties. The standard specifies a method for investigating the flexural behaviour of rigid and semi-rigid plastics and the determine the flexural strength, flexural modulus, and other aspects of the flexural stress/strain relationship under the conditions defined. For instance, the maximum compressive load and extension at maximum compressive load. [92]

The standard atmosphere for testing was set according to ISO 291:2008 [89]. However, the actual air temperature in the room was 17.8 °C and relative humidity 19.3%, which is 61% lower than was specified in the standard. The test was conducted with three test pieces per specimen, although the standard specified five. The size limit of the initial specimens did not permit to cut out more test pieces. The required dimension for the specimens were 25 x 80 mm (±2), whereas the width was determined by the average thickness of 1.2 mm among all the specimens. [92]

The test was conducted on *Instron 2525-816* apparatus with following parameters [92]:

Span length L – 25 mm;
Pre-load crosshead speed – 1 mm/min;
Pre-load crosshead load – 0.3 N;
Crosshead load – 500N;
Crosshead speed – 20 mm/min;
Endpoint – 10 mm of specimen bending depth.

The span length L was adjusted according to the standard and by the thickness of the specimen. The equation gave the span length of 19.9 mm, however, since the loading head did not fit between the support plates, the span length was increased to 25 mm. [92]

According to test procedure, the rectangular specimen, resting symmetrically on two support plates, is deflected by the means of a loading edge acting on the specimen midway between the supports. The specimen is deflected at constant rate until the rupture occurs at the outer surface of the specimen is reached. (Figure 26) [92]

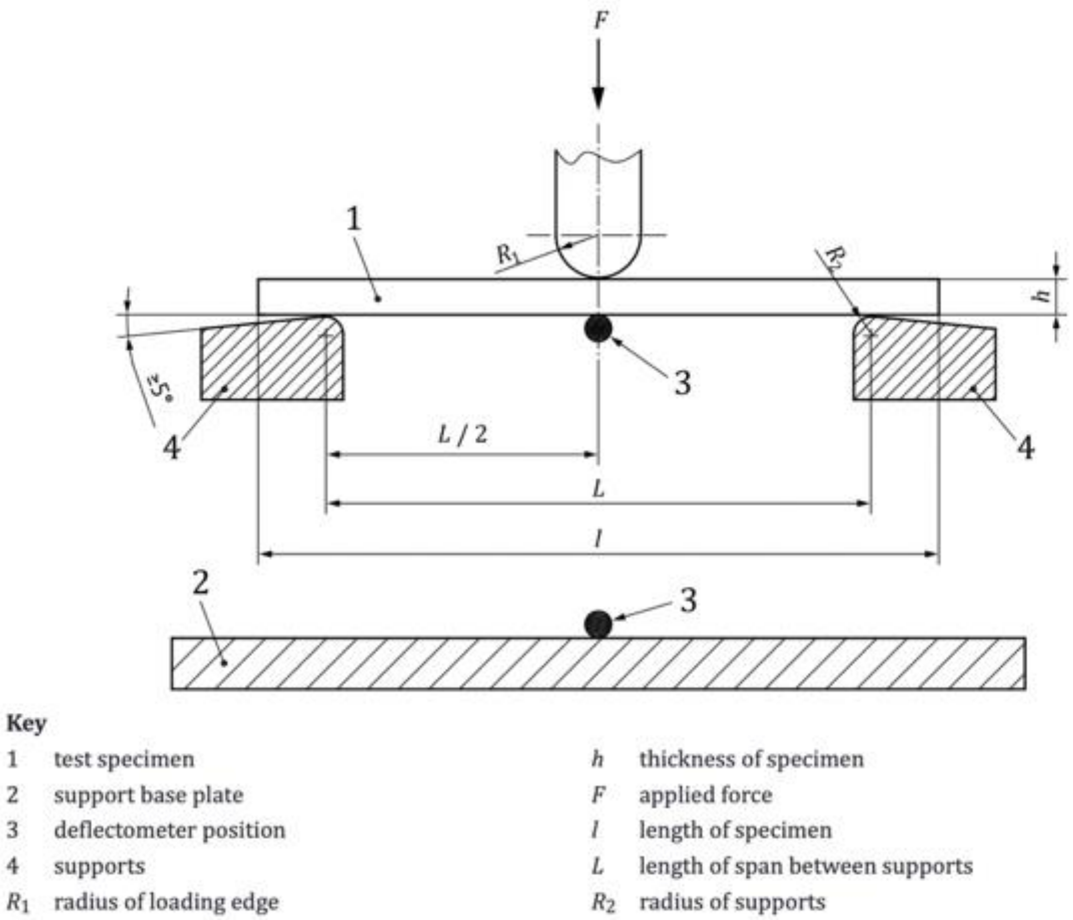


Figure 26. Position of the test specimen and deflectometer at start of test [92]

7.3 RESULTS AND DISCUSSIONS

Current paragraph analysis and discusses the test results of the procedures mentioned in the previous section.

A series of sheet-like materials with different content of PLA as binder were prepared by manual carding of textile waste fibres and PLA fibres. The thickness of the sheets was about 10 mm. Carded materials were hot-pressed at 155 °C according to the procedure described in paragraph 7.2.2.

For comparing instead of PLA fibres, the granulated PLA was used as a binder. After the HP the specimen's surface contained dark stains of melted PLA, was not uniform and fragmented, and thus, not applicable for any further tests (Figure 27).

Figure 27. Experimentation for binding the RCF with granulated PLA

Before measurements of thickness, weight and size, materials were oven dried and cut into specimens needed for specific tests. For example, for water absorption test sheets were cut into discs (Figure 28).

Figure 28. Measuring and conditioning the test specimen for water uptake test

7.3.1 Mass per unit area

Figure 29 shows mass per unit area specified by the composition and of all the 40 specimens. Each column per fibre fraction volume group represents different compression pressure of 40, 50 and 70 bars written inside the column. The value above columns indicates the average mass per unit area per composition group.

As expected, the value of mass per unit area varied greatly between the heavier and lighter specimen. The mass of heavier specimen fell between 501 and 576 g/m^2 and for lighter specimens 359 and 437 g/m^2. There was no correlation noticed in the fibre fraction ratio. From the heavier group, the specimens with 60% of RCF / 40% of PLA had the highest average value of 576 g/m^2, while among the lighter specimen, it was 50% of RCF / 50% of PLA with 437 g/m^2.

However, the variance of weight within the same composition group was substantial. The reason for this could have been the lack of quality assurance in manual carding. As a result, the fibres are distributed unevenly on the drum roller and the RCF may not blend thoroughly with PLA fibres. Leading to a poor surface bonding during the HP.

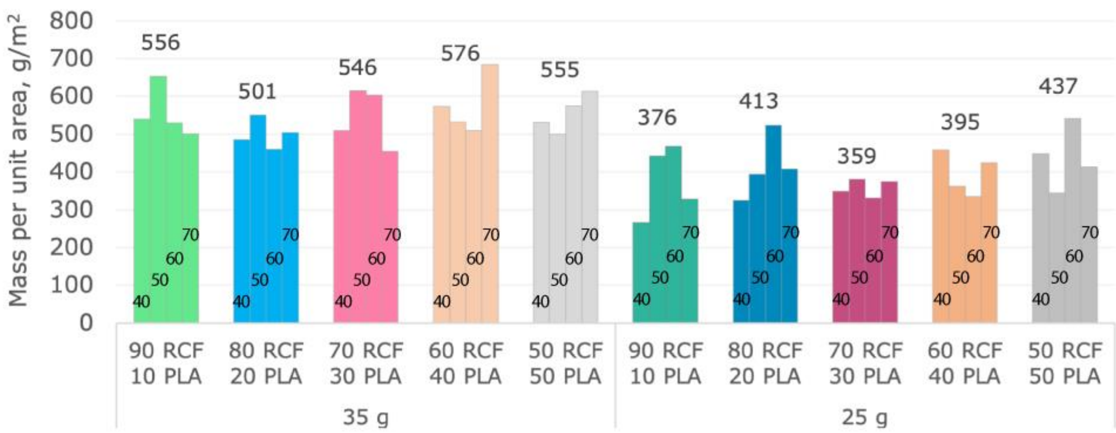


Figure 29. Mass per unit area per weight and composition

7.3.2 Water absorption of the material

Water absorption and water uptake are important factors that influence physical and mechanical properties of high-performance applications such as packaging. Water absorption rate depends on the origin and the volume of fibre, viscosity of matrix, temperature, and humidity. The composites containing natural fibres have naturally higher moisture absorption, leading to premature moisture-related failures such as swelling of the fibre, forming of voids and micro-cracks at the fibre-matrix interface region that results in dimensional instability. [93]

Figure 30 shows the moisture gain in millimetres, that is highlighted in red on top of each column. The results compare water gain with oven dry state. Below the red area is the initial thickness of the specimen. The results are divided between different weight and composition groups, including compression pressures from 40 to 70 bars, written below each column.

The specimens that had higher RCF fraction absorbed more water compared to the specimens with higher PLA content. This is due to the hydrophilic nature of cotton that causes the fibre to absorb water and swell. The water molecules attack actively the interface, leading to the degradation of fibre-matrix interface region and causing them to de-bond from the matrix. [93]

The increase in thickness was gradual starting from the 50% to 90% of RCF. Though, both weight groups, 35g and 25g, absorbed the same amount of water, with an average of 12%, compared to their initial oven dry thickness.

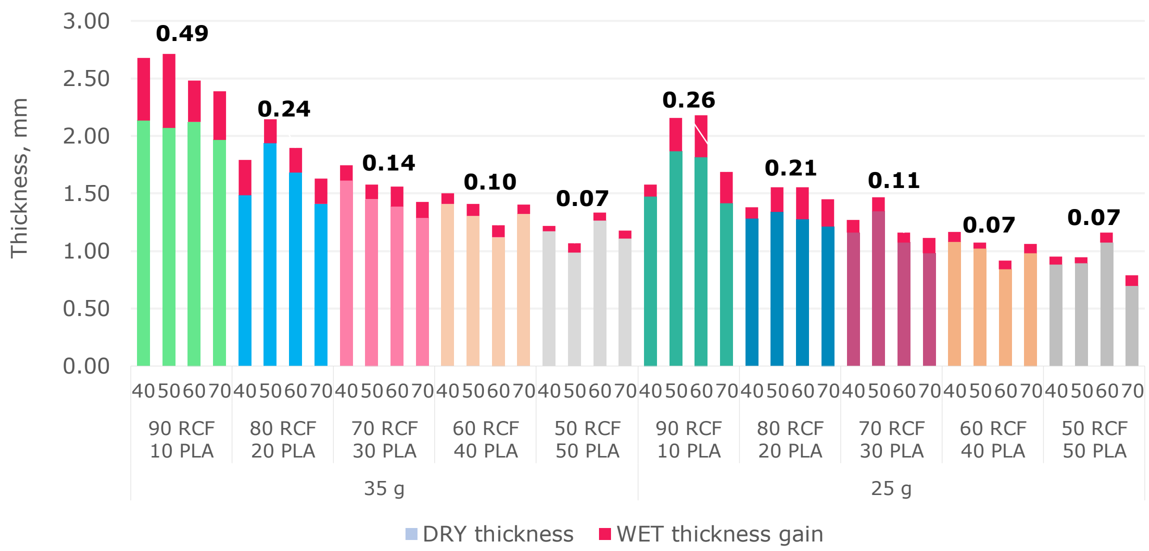


Figure 30. Moisture gain in thickness. Each column indicates compression pressures from 40 – 70 bars.

Figure 31 presents the weight gain percentage compared to the oven dry weight of the specimen. Compositions and compression pressures from 40 to 70 bars are highlighted below each column that represent each specimen. An average weight gain percentage per composition group is written on top.

Similarly, to previous results, the specimen with higher RCF showed poorer moister resistance and thus, became multiple times heavier compared to their oven dry weight. Among the lighter specimen, there was a dramatic weight decrease between the specimens containing 90% of RCF and 80% of RCF, which can be explained by the low PLA and weight ratio. When the composite is lightweight with low percentage of binder, the fibres may not be spread evenly throughout the carded fleece. The substantially higher value on the lighter specimen with 90% of RCF that was hot-pressed with 40 bars, indicated the unevenness of the entire fleece. Since all four specimens in this composition group were carded as one fleece

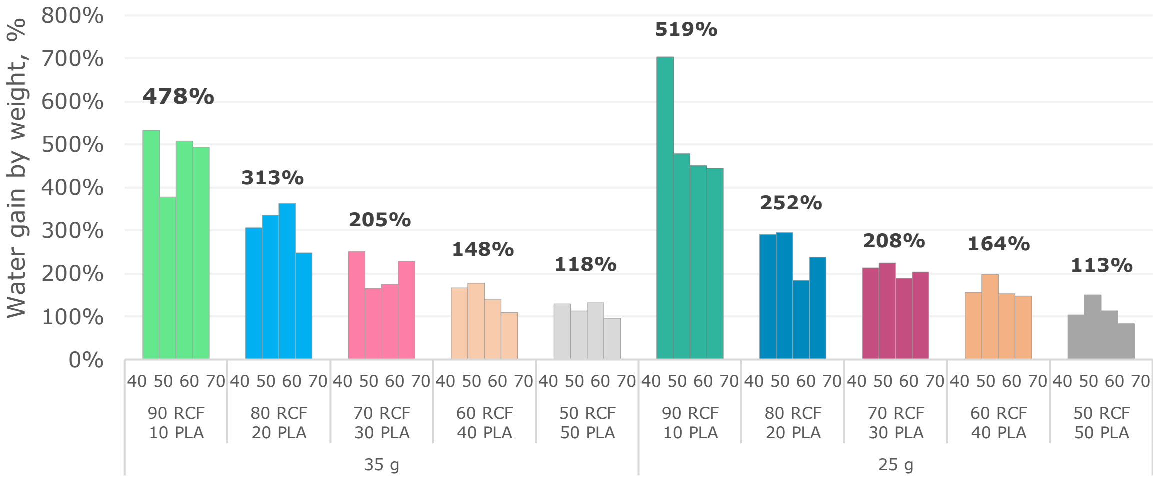


Figure 31. Moisture gain in weight specified by different compression pressures.

There was a slight correlation between the different compression pressures and moisture absorbency, which is gradually decreasing with the decrease of pressure. When considering the highest pressure value of 70 bars used in total of 10 specimens, 6 test pieces showed lower water uptake. However, 5 out of 10 test pieces had the highest absorbency at 50 bars.

Water gain per weight indicated that the heavier and thicker the material was, the more resistant to humidity it had. The specimen containing 50% of PLA had an average of three times lower result compared to the test pieces containing only 10% of PLA. Researches show that water uptake effect could be reduced by using coupling agents or fibre surface treatments for fibre-reinforced polymeric composites. [94]

7.3.3 Flexural properties of the material

Flexural modulus measures the reaction to stiffness of any material under mechanical force applied perpendicular to its longitudinal axis. Flexural modulus is often considered equal to tensile modulus, though, it has several advantages of being more accurate in terms of strain values or when testing for service failure. The behaviour of stress and strain are considered as important loading parameters for calculating the flexural modulus. Therefore, the basic understanding of stress-strain behaviour of materials is fundamental for designing an application. [95]

The physical properties of the fibre, its orientation in the matrix and fibre fraction ratio in the material are parameters influencing the flexural strength. In general, the higher interfacial adhesion smoothens the stress transfer between the fibre and the matrix, being especially beneficial for the packaging made of corrugated paperboard. Though, the hydrophilic aspect of natural fibre decreases the adhesion between fibre's interface and matrix resulting to poor stress transfer from the fibre to matrix and vice-versa. [96]

The stress-strain curve is related to various material properties and is classified in terms of softness, brittleness, hardness, and toughness. The area under the stress-strain curve indicates the toughness of material, while the low yield stress is a characteristic of the soft and weak material. Such properties are especially useful when analysing the stress-strain curves of the polymeric materials. As the composite matrix in the study involves a natural biopolymer PLA, the beforementioned properties can be applied. (Figure 32) [96]

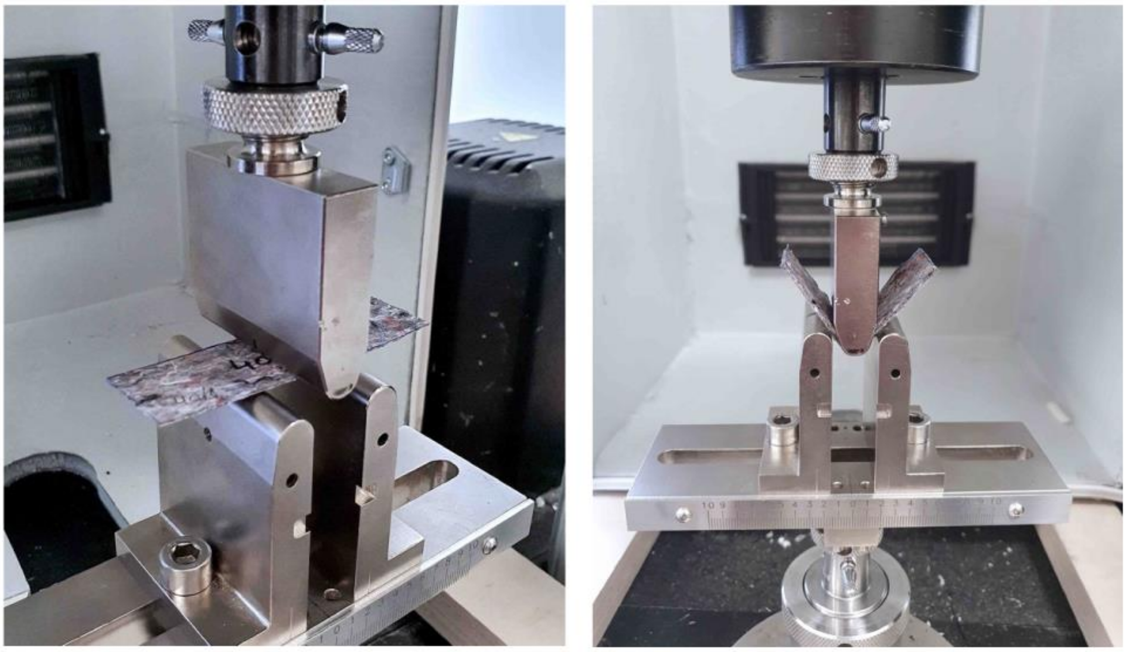


Figure 32. Flexural tests conducted with Instron apparatus

7.3.4 Maximum compressive load of the material

Maximum compressive load N is defined as the maximum stress the material can withstand. Figure 33 highlights the maximum compressive load N by compression pressure value and composition. Each colour represents different compression pressure. The correlation between PLA fibre volume fraction and the maximum compressive load could be seen, especially for the heavier specimens, in the group of 35 g, that contained at least 70% of PLA. Lighter specimen, in the weight group of 25 g, beared almost three times less load, making those materials rather weak.

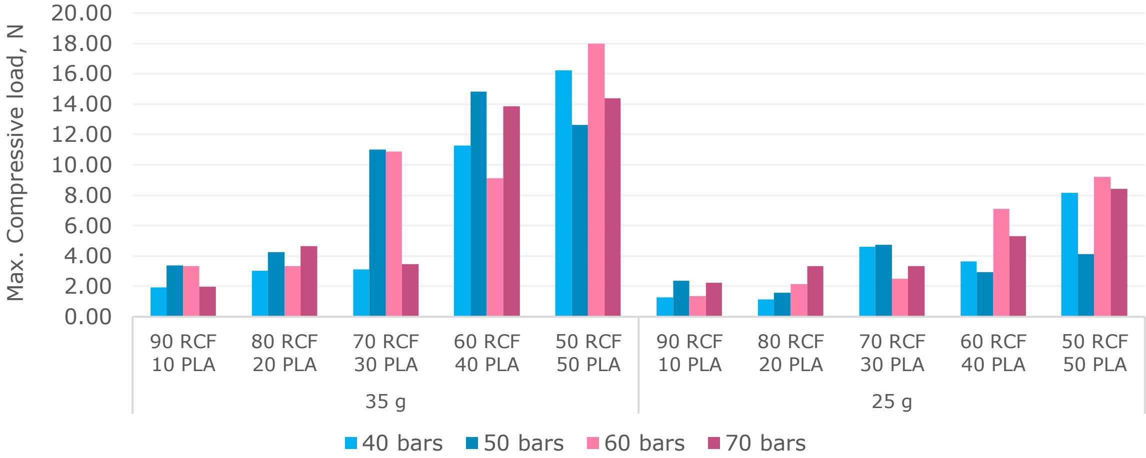


Figure 33. Maximum compressive load by the material composition.

The values of maximum compressive load by different compression pressures are specified in Figure 34. Among the heavier weight group, 35 g, the specimens hot-pressed with 50 bars showed the highest flexural strength, followed by the test pieces compressed with 60 and 70 bars. However, the lighter weight group, 25 g, achieved the highest result when compressed with 70 bars. Higher compression pressure with applied heat enabled the PLA fibres to bond better in the composite matrix, resulting firm and embedded material structure.

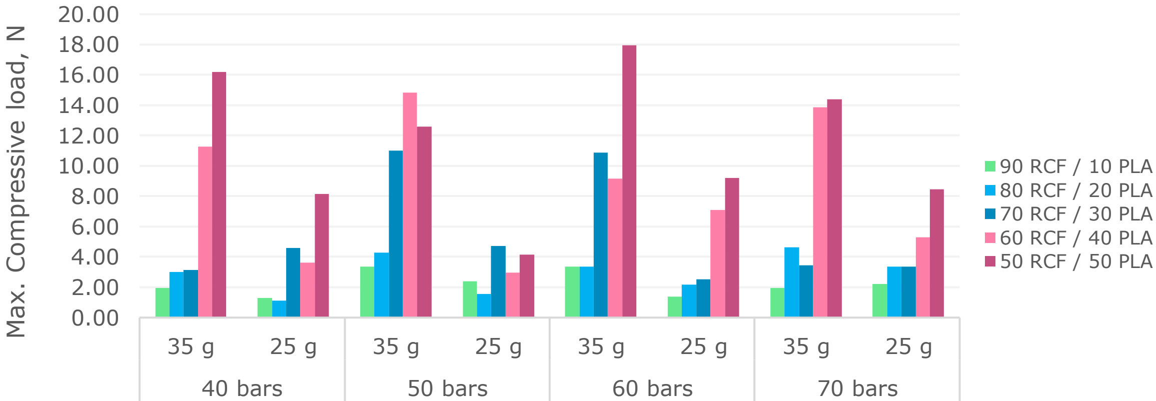


Figure 34. Maximum compressive load specified by different compression pressures.

The results represented above indicate that material thickness and composition, in this case higher PLA content, attributes to increased compression strength. Therefore, new and heavier specimens with increased fibre volume were produced to compare whether such hypothesis can be confirmed. Additional specimens were prepared on a drum carder approximately twice as large as the initial carder. When the first carder held maximum of 35 g of fibre volume per fleece, then the large carder held 73 g. In this study, the latter is subsequently named as 100% of fibre volume to distinguish materials with different weights and thicknesses. Thus, new materials consisted of 100%, 150% and 200% of fibre volume.

Figure 35 shows a comparison of maximum compressive load for materials with different compositions, while carded with different size drum carders. The chosen fibre fraction volume was 70 RCF / 30 PLA and 60 RCF / 40 PLA. However, increasing the fibre volume in the material did not yield in higher compressive strength, except for materials containing 200% if fibre volume.

The highest value, 10.34 N, was achieved with small carding machine and with 60 RCF / 40 PLA. Though, it shall me mentioned that the result is affected by the fact that the test failed and was re-done with already deformed specimens. Consequently, the standard deviation was the highest at 3.06 N.

The reason why the new specimens did not yield higher compressive strength may be due to the quality of carding so that the fibres were not spread throughout the carding drum equally.

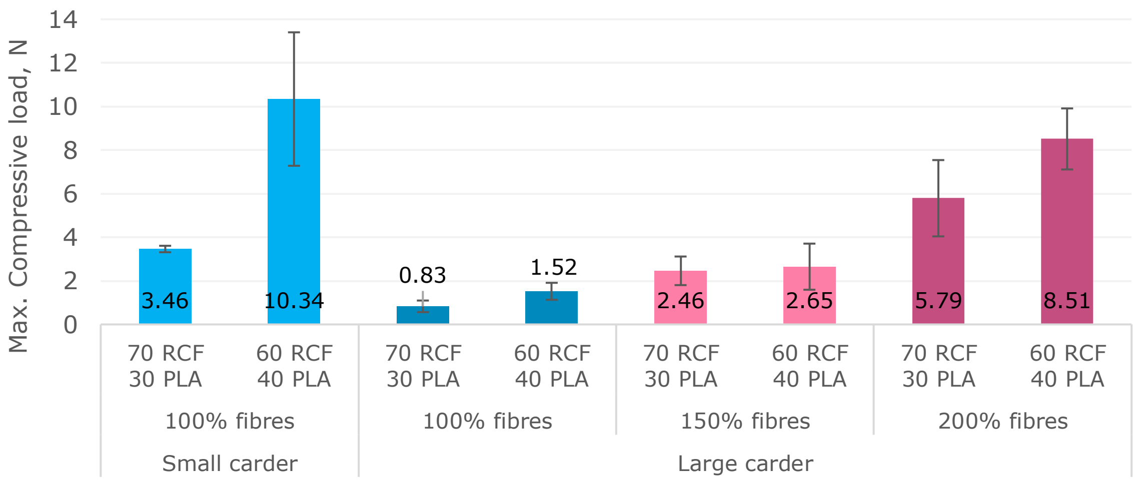


Figure 35. Maximum compressive load by small and large drum carder and by material thickness

When comparing how the thicker material affected the mass per unit area, the only substantial difference occurred with the specimens that contained 200% of fibre volume. The specimens with 100% of fibre volume and 60% of RCF / 40% of PLA showed unexpectedly lower value than the specimens from the same fibre volume group but containing more cotton fibres. The reason why many specimens had similar mass per unit area, though having higher volume of fibres, may be affected due to the greater surface area of the larger carding drum. Adding 50% more fibres with current carding methods may not be simply enough to increase the overall thickness of the material. (Figure 36)

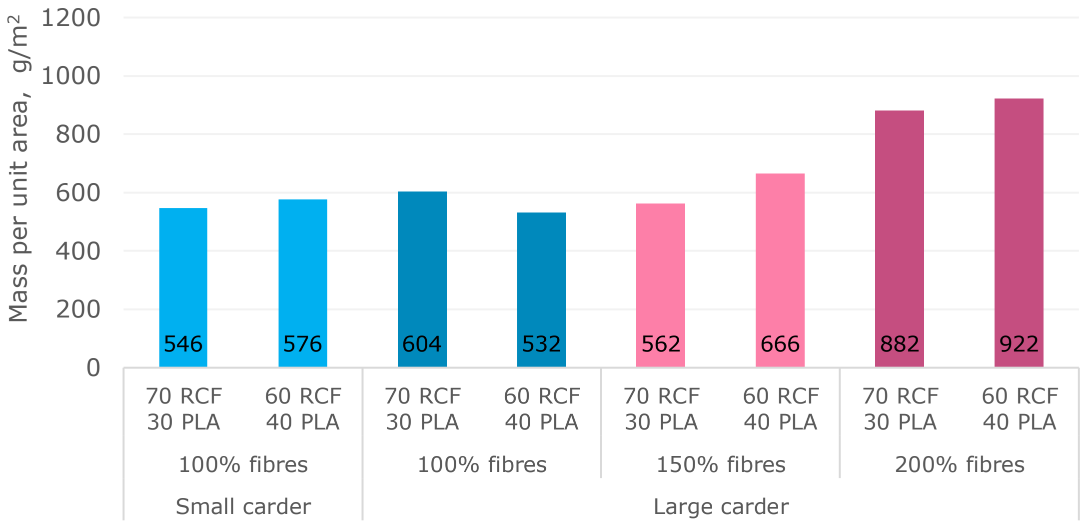


Figure 36. Mass per unit area by small and large drum carder and by material thickness

7.3.5 Extension at compressive load of the material

Extension at maximum compressive load, expressed in mm, is used to measure the maximum bended displacement of the specimen before it breaks [92].

Figure 37 shows that there was no correlation between the maximum compressive load and the maximum extension value. The average elongation was slightly higher for the specimen that contained at least 80% to 90% of RCF. However, the average deviation per weight group was similar, falling between 0.5 and 1.7 mm for the heavier specimens and 0.5 – 1.8 for the lighter test pieces.

As expected, the more the PLA the more tough was the specimen, with lower value in bending. In current case, the increase of the PLA fibre volume fraction does not change the material’s properties significantly.

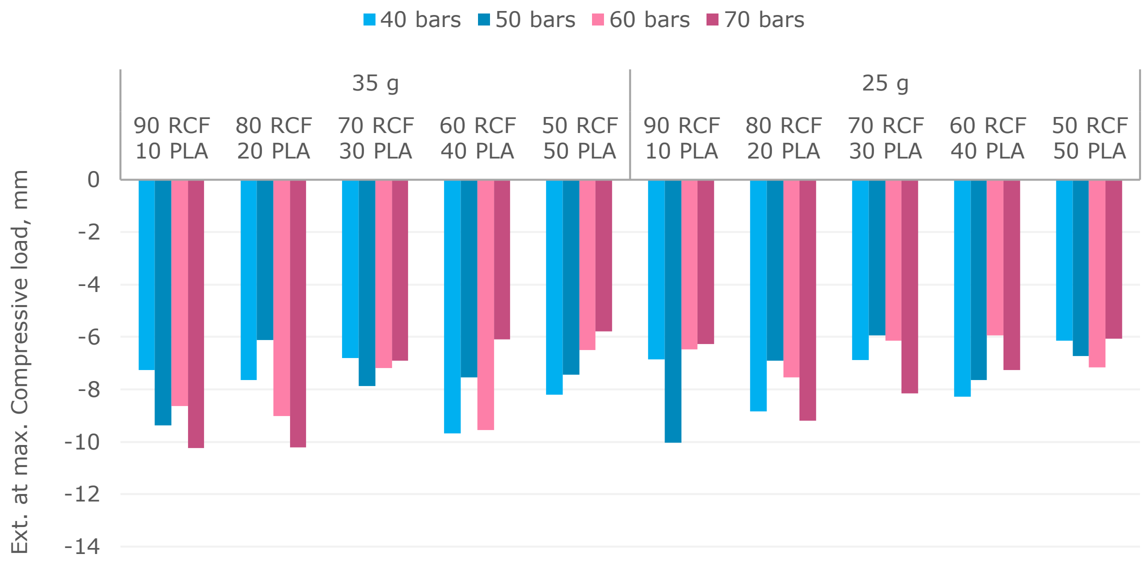


Figure 37. Extension of maximum compressive load

Heavier specimens showed more flexibility and toughness as regard to their relatively low compression strength value. Especially considering that the materials were thicker and contained more fibres. Thus, the high deformation at elongation may have occurred be due to higher fibre volume, which prevented the material from breaking. (Figure 38)

There was no correlation on the standard deviations, except for the specimen that was carded with larger carder and contained 70% of RCF. The same specimen had also relatively high mass per unit area compared to its initial preparation parameters.

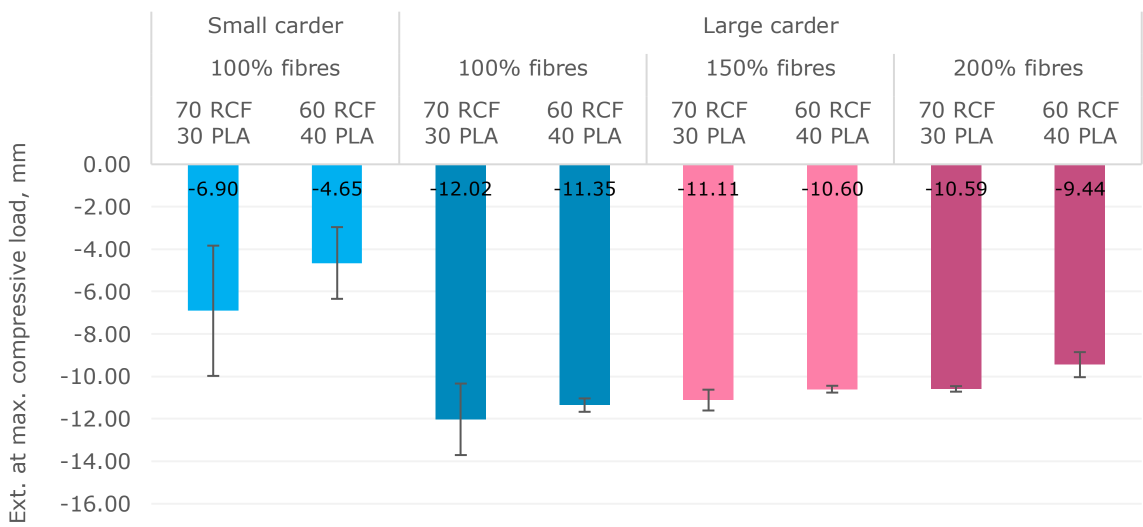


Figure 38. Extension of maximum compressive load by small and large drum carder and by material thickness

7.3.6 Flexural modulus of the material

Flexural modulus measures the toughness of a material, which is influenced by the ratio of stress to corresponding strain below the proportional limit of a material. It is calculated from the slope of the stress versus strain linear part of deflection curve and is expressed with MPa. For elastic materials, the stress is proportional to the strain, whereas the plastic materials are characterized by high yield stress and low elongation. [95]

The average flexural modulus values by the composition and weight groups are presented in Figure 39. As seen from the graph, the flexural strength decreased with increased RCF content. This can be explained by the fact that there is insufficient amount of PLA fibres in relation to RCF to form a firm and strong bond. It is also noted that stress concentration points increase simultaneously along with the increase of RCF content, resulting in decreased flexural strength. [95]

Most of the specimen had the modulus below 0.9 MPa, except for the specimen with 50% of RCF / 50% of PLA from the heavier weight group. The lighter weight group had substantially lower modulus values with majority falling between 0.02 and 0.35 MPa. The specimens with higher PLA content, weighting 35 g, had substantially higher modulus with an average of 0.87 MPa.

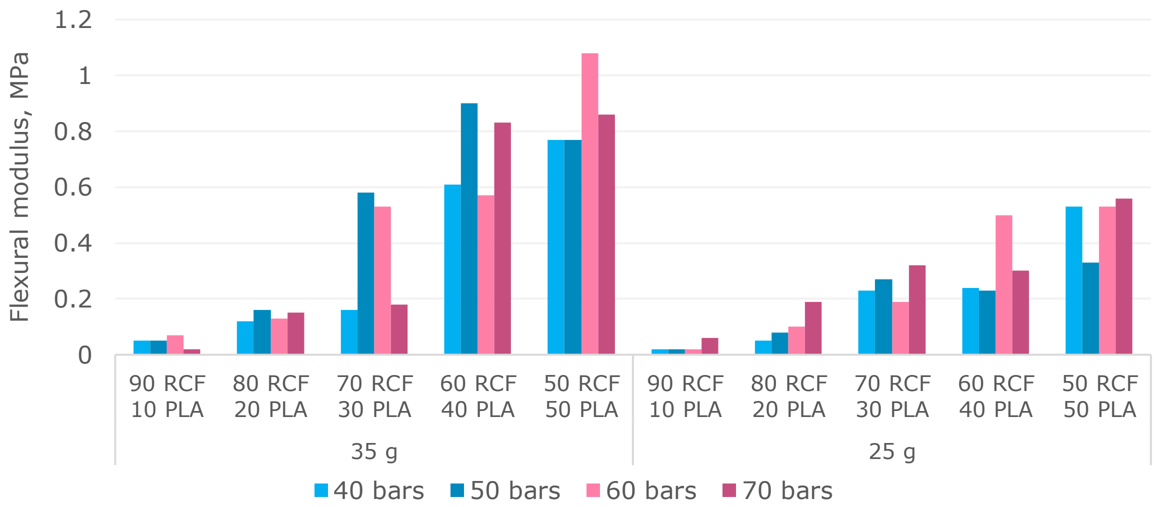


Figure 39. Flexural modulus of the specimens

The flexural modulus for new specimens was relatively low compared to the specimens that were carded with smaller carder. However, the modulus grew exponentially as the material became thicker. New specimens are on the other hand showed more flexibility. (Figure 40)

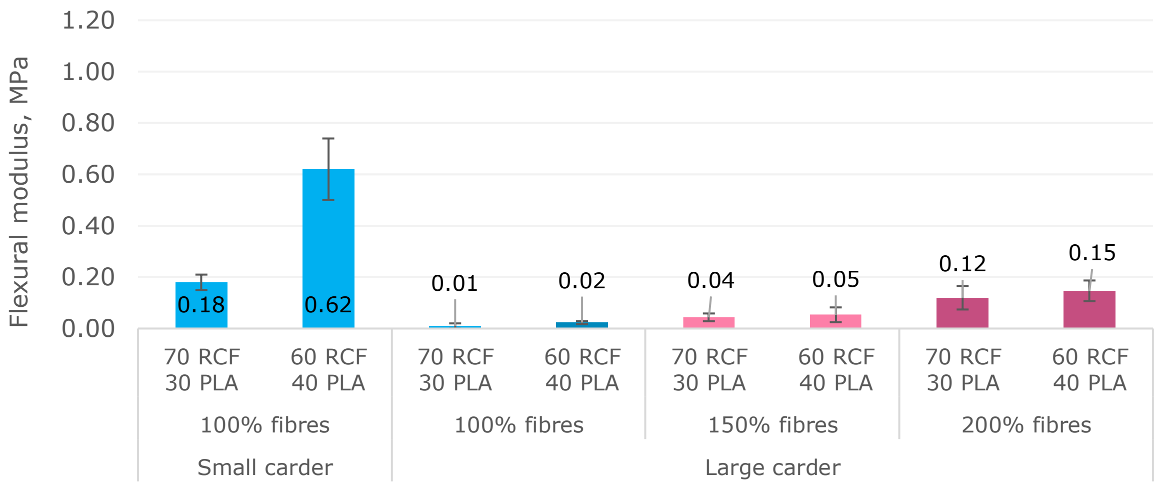


Figure 40. Flexural modulus by small and large drum carder and by material thickness

To summarize the mechanical testing of materials addition of at least 30% of PLA fibers as binder material is needed to achieve good mechanical properties. Addition of bigger amount of PLA make material stiffer, lower amount of PLA results in softer material. Compression pressure has no significant effect on the materials properties. The amount of fibers in fleece has no significant effect on properties, but on thickness of the material.

7.4 Prototyping

The laboratory test results with the specimens indicated that the higher the PLA content, the better mechanical properties the material had. PLA acts as binder that interlocks fibres into a firm and though structure. Thus, having more suitable properties for a packaging application in the form of a box, which is able to carry a load placed inside.

The mechanical properties were especially highlighted in the flexural modulus values, where PLA fibre volume fraction of 30% and above showed substantial increase. However, there was no specific correlation regarding the stress-strain curve, composition and the compression pressure values. Contrary, it was shown that specimen compressed with 70 bars had at times even the highest deflection value. For polymers, this is an indication for soft and though material. [96]. Higher pressure value enables fibres to bond better in the matrix and creates a smoother surface, which is an important feature to prevent loose fibres getting mixed with the product inside the box.

Also, the weight and mass per unit area played significant role in flexural properties. The specimen with PLA content of 30% and above were more rigid and had therefore lower values in extension at maximum compressive load. The group with heavier materials had an average of 47% higher results in maximum compressive load test. The same occurred in flexural modulus, which showed strong correlation between lighter and heavier specimens. The heavier the specimen with higher mass per unit area, the greater the flexural modulus value. This is a good indication for an application that must carry loads and protect goods during the transportation.

From the circular economy perspective, it is preferred to circulate as much textile waste as possible. However, the assessment of aforementioned material tests clearly shows that high RCF volume fraction in the matrix does not yield the required properties for the developed application. On the other hand, even though the specimens that contained 50% of PLA appeared to be the most rigid and tough, such composition ratio would not serve the aim of current thesis. That is incorporating more of the post-consumer textile waste into the packaging application material.

Material compositions and other parameters for developing the prototypes are specified in Table 9. In total of 12 prototypes were produced, 6 bigger boxes and 6 smaller boxes. Each prototype per size composed of 60% of RCF / 40% of PLA and 70% of RCF / 30% of PLA and was produced containing three different fibre volumes to achieve higher thickness and therefore increase the compressive strength. Hence, the construction of the prototype consisted of either one or two layers of fibres. The latter was limited due to the carding machine parameters, which did not allow to construct thicker fleeces in one layer. Also, the fleece containing 80% of RCF / 20% of PLA was experimented, however the structure of the material was too soft to form a box. Moreover, the cotton fibres became loose from the matrix during the handling.

Table 9. The material parameters for both boxes

Design	**RCF / PLA, %**	**Material construction**	**Mass per unit area, g/m2**	**HP temp., °C**	**HP pressure, bar**
Big box 140x100x40 cm	70 / 30	1 layer (100% fib.)	604	155	70
		2 layers (150% fib.)	562		
		2 layers (200% fib.)	882		
	60 / 40	1 layer (100% fib.)	532		
		2 layers (150% fib.)	666		
		2 layers (200% fib.)	922		
Small box 70x120x30 cm	70 / 30	1 layer (100% fib.)	604	155	70
		2 layers (150% fib.)	562		
		2 layers (200% fib.)	882		
	60 / 40	1 layer (100% fib.)	532		
		2 layers (150% fib.)	666		
		2 layers (200% fib.)	922		

All materials were prepared on a large manual drum carder, producing a rectangular fleece of around 20 x 78 cm. The fibre volume per carding drum was 73 g. Three different thicknesses were prepared, where the thicker materials consisted of two layers of fleece compressed together, consisting of 100%, 150% and 200% of fibre volume Both boxes had the same HP parameters, including temperature and pressure. Also, the layouts of both boxes were fitted on the same carded fleece, therefore the mass per unit areas were considered the same.

Firstly, the layout plan of the first prototypes were drawn on the material manually and cut out with fabric scissors. However, this method was not precise and left unsharp edges around the design. Instead, the laser engraving cutting machine Bodor BLC – 1309XU was used and layout pattern for both boxes was designed in Adobe illustrator with .dxf file format.

Regarding the layout plan, it was important to separate the cutting lines from folding lines, therefore two separate files per layout were created. The laser cutting machine parameters were chosen according to similar materials that have been previously cut by the same machine. Firstly, the cut settings were tested on a sample, following by the actual cutting.

Bodor BLC – 1309XU laser cutting machine parameters are specified below:

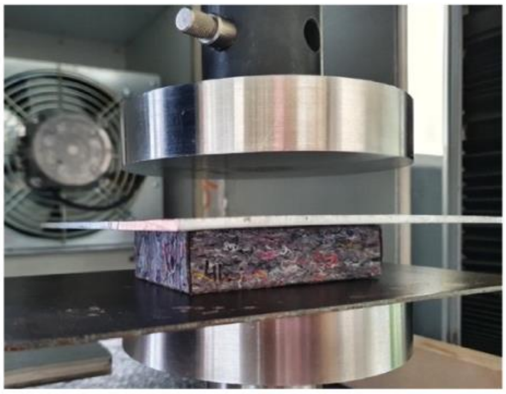
- Maximum power of the laser cutter – 100 W;
- Test cutting power – 23 W;
- Test speed – 53 mm/s;
- Actual cutting power – 23 W;
- Actual folding line – 17 W;
- Speed when cutting – 50 mm/s.

Once the designs were cut out, the boxes were folded along the folding lines. The final products are shown in Figure 41.

Figure 41. Bigger box (left) and smaller box (right) developed part of the study

7.5 Compression properties of the final product

Compressive properties of the final products were performed according to the procedure described in paragraph 7.2.5. (Figure 42)



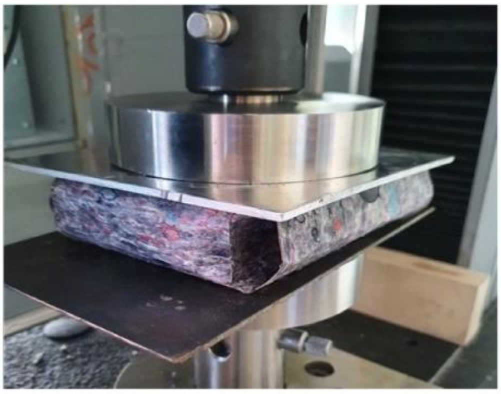


Figure 42. Compression test with the final product

Figure 43 summarizes the test results of the maximum compressive load for the bigger and smaller box. The graph specifies different fibre compositions and material constructions – 100%, 150% and 200% of fibre volume – written below the columns. 7 boxes out of 12 reached the maximum compressive load which was set to 500 N for the test. Even though the value is 449 N, it is considered as maximum as this was the point, where the test terminated, and the crosshead was lifted to the initial position. Bigger boxes showed higher values with 4 out of 6 reaching the maximum, while the same occurred with 3 of the smaller boxes. All the prototypes that consisted of 100% of fibres, showed lower values, nonetheless the composition or the size of the box. Comparing with same test results performed only with the material specimens, the folded boxes show substantially higher compressive strength.

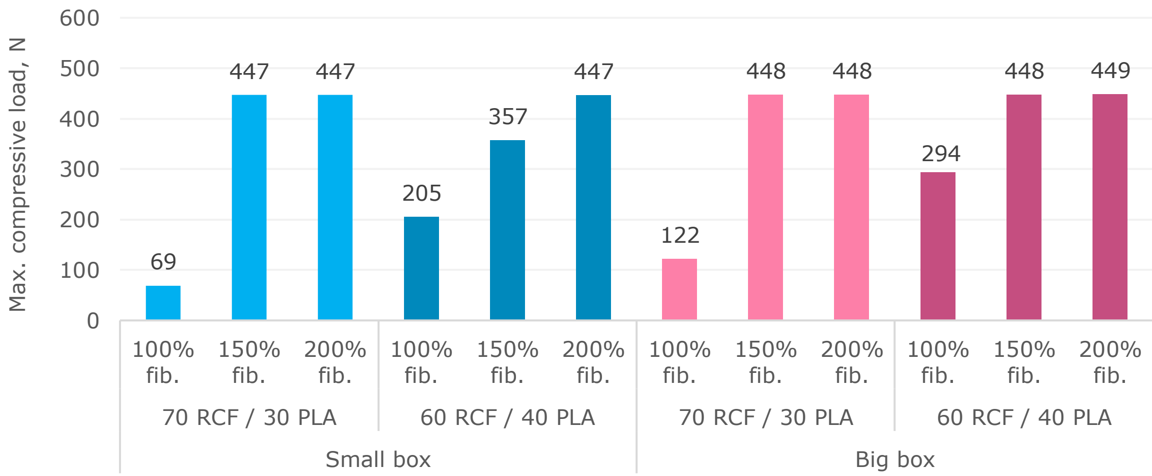


Figure 43. Maximum compressive load of the final products

Figure 44 shows mass per unit area, written on top, per material construction and composition, written below each column. The products with the mass per unit area of 822 g/m^2 and 922 g/m^2 had twice the number of fibres incorporated, than the materials consisting only of 100% of fibre volume. Hence, the products that weighted more, also had the higher compressive strength as show in Figure 43.

The other products that consisted only of 100% of fibre volume showed also relatively high mass per unit values, despite having less fibres incorporated in the matrix than the products with 150% of fibre volume. Such result can be explained by the uneven quality caused by manual carding.

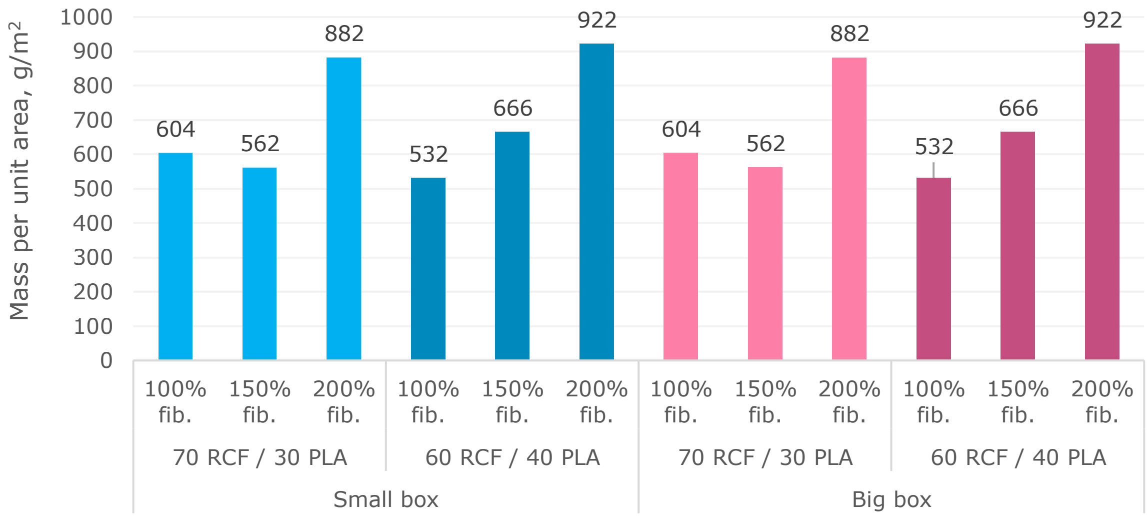


Figure 44. Mass per unit area of the final products

Figure 45 summarizes the results for the extension at maximum compressive load for the bigger and smaller box. The graph groups together different compositions and material constructions that are written below the columns. The only product that failed the test was a bigger box with 60 % of RCF and consisted of one layer or fibres. The test failed as the elongation reached above 29 mm, though the endpoint was set to 10 mm of specimen’s bending depth.

A slight correlation in higher extension value was noticed for the products having higher cotton fibre fraction. Bigger boxes, on the other, showed overall higher elongation than the smaller boxes. The reason being the larger surface area that favour higher flexibility.

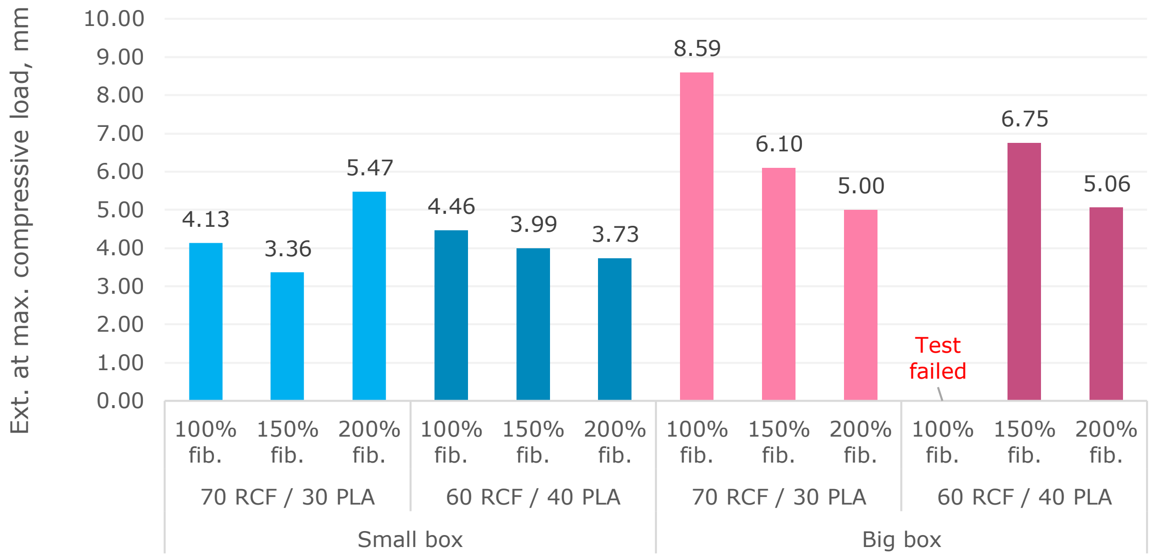


Figure 45. Extension at maximum compressive load of the final products

The result of the flexural modulus indicates higher values for the smaller boxes, even though the deviation between the compositions is also high. Bigger boxes achieved more equal results with clear correlation between the different material construction and mass per unit area. Emphasizing the fact that increasing the fibre volume of the material yields in higher modulus. (Figure 46)

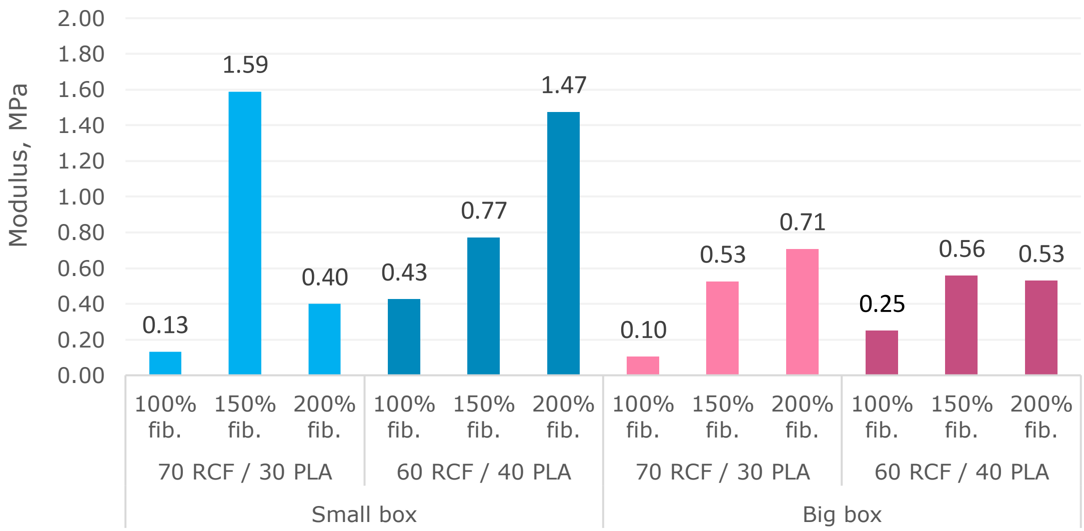


Figure 46. Flexural modulus of the final products

8. CONCLUSIONS

One of the most important measurements to determine the strength of the packaging is its load-bearing capacity before buckling. Explained more often as compressive strength. To understand whether the mechanical properties, as well as the visual appearance of the final product are suitable for the packaging industry, the laboratory test results were compared with the most alike application - a box made of corrugated paperboard. Corrugated cardboard is a layered structure, whose strength is determined by the individual ply selection and combination. [97]

Based on the set objectives and laboratory test results with the final product, following conclusions can be drawn:

- **The flexural tests proved that the final product was able to bear a load equal to at least 50 kg.** Although, the load was placed on the upper part of the box, showing more of the stacking load rather than bearing load, it is nevertheless a good indication for understanding the overall strength capacity of the application [97]. The stacking load is especially important for the retail-ready packaging, which are usually stacked upon each other during the storage. For instance, a box bearing at least 50 kg could be stacked in 50 on top of each other and having an item inside weighting 1 kg [98]. Stacking durability, especially for fibre reinforced applications may be also influenced by stacking time, room conditions and humidity [97].

- **The material containing 70% of RCF / 30% of PLA became twice as heavy in the water moisture test.** Known for their relatively poor resistance to moisture, textile fibres often undergo several treatments and modifications to improve fibres/matrix compatibility [99]. The fibres used in current study had not been modified, except for the treatments done to clothing before they were recycled. However, moisture absorbency is especially important for the packaging that is used under various atmospheric conditions. The most sever (around 90% relative humidity) correspond to storage in cold room with forced moisture. Hence, the water uptake test results in the study showed that by increasing RCF fibre fraction volume, the water content of the material increases appreciably and breaks the bonds in the matrix. For instance, the material containing 70% of RCF / 30% of PLA become twice as heavier when immersed into water for one hour. The moisture content tests with corrugated cardboard found from literature show that in the environment where relative humidity is 90%, the Young’s modulus falls more than 30%. Current study did not involve the compressive tests with wet specimens. [100]

- **Flexural modulus of the final products was influenced by the design and composition.** In this study, the flexural modulus values of the final products can be directly interpreted with overall fibre volume in the material and the way the application is designed. Having at least two layers compressed together, the bigger boxes yielded lower modulus, whereas for smaller boxes, it was overall higher. The design of the smaller boxes enabled higher flexibility, compared with the bigger boxes, that were compromised with thicker double-walls.

  The aspect of the design is equally essential in other conventional mechanical tests for carboard. Such as edge crushing, burst strength, shear stiffness, and buckling strength. The latter behaviour depends strictly on the dimensions of the box as well as on the geometry of the box and its composition [97]. Both boxes in the study showed enhanced plasticity as the deformation that occurred during the compression test was recovered immediately after removing boxes from the grips. Textile nonwovens, depending on the type and degree of used binder, are generally known for their softness and porousness, offering at the same time resistance to mechanical deformation [101]. Hence, the boxes containing more cotton had higher elongation and consequently, recovered their initial shape more easily.

- **Final products containing above 80 RCF had loose fibre on the surface and had too soft structure for holding the shape.** As for the visual aspect, one of the goals was to achieve a smooth material surface with relatively stiff and robust structure. High stiffness is thought to resist buckling of the box panel and hence increase the compression strength [102]. Stiffness also enables the box to hold its shape when folded and thud, protect the goods inside. The ratio of weight, thickness and stiffness is an advantage for cutting out the boxes as the cut and fold edges need to be relatively sharp, so to not *"unravel"* during the use. For textile boxes, the sharpness is related to the composition and production method. The materials containing at least 80% of RCF did not have all the fibres fixed firmly in the matrix and therefore, the cut edges were not sharp. Furthermore, the structure of the box was softer, hence more flexible, with some cotton fibres loose on the surface.

- **Manual carding of the specimens resulted in high deviation in thickness and thus in mass per unit area.** One of the major downsides in manual carding was the uneven material structure, which expressed in the high thickness deviation, despite having the same fibre volume and composition. In comparison, cardboards tend to be recognized precisely by their thickness rather than their weight [102]. An average e-commerce cardboard package is an E-Flute type corrugated cardboard with the thickness of 1.2 mm [103]. The material thicknesses in current study deviated substantially, depending on whether measured from the side or middle area of the material. The value was in correlation with the fibre volume and the compression pressure level. However, the standard deviation increased noticeably with the increase of the fibre volume in the material.

- **Increasing the PLA fibre fraction has a risk of turning the material surface plastic-like during the compression moulding**. It is noted that high compressive strength has advantage of reducing the thickness of the package walls. Contrary to current boxes, the thicker material yielded higher compressive strength. Thus, it is not possible to achieve higher compression strength with present machinery parameters. Also, the increase of PLA fibre volume fraction, could possibly result in more stiff and thinner matrix, however it would also render the material surface too plastic-like. This was the case with some of the boxes, where the compression moulding was done with larger heat press machinery. As a result, dark spots of melted PLA appeared on the surface of the material, making the material appear shiny and plastic-like.

Although present test results proved that mechanically recycled textile fibres could be successfully incorporated into a composite matrix, which is suitable for forming a rigid box-shape application, more experiments shall be carried out regarding different the most suitable design and size. The developed packaging application performed well in compression tests, however, had relatively low flexural modulus and moisture resistance. With current carding method, the uneven thickness of the material set limits for obtaining more accurate results in compressive strength. It was also noted that the uneven thickness was directly related to the carding quality, hence the lack of spreading out RCF and PLA fibres equally throughout the entire surface of the fleece.

In general, packaging testing can be a qualitative or quantitative procedure requiring various measurements such as subjective evaluations by people and field testing. Furthermore, in current economy trends, packaging testing must be extended for the full life cycle to determine their recyclability or ability to degrade in the landfill or under composting conditions. Therefore, current laboratory test methods only suggest the first validation for the purpose and more extensive research shall be done regarding the production methods and recovery of fibres.

SUMMARY

The global consumption levels have rapidly increased on behalf of virgin materials. Alone in EU textile sector, the amount of clothes bought per person has increased by 40% in just few decades, driven by a fall in prices and so-called linear value chain. With extremely low recycling rates, the focus has shifted to reusing the natural resources and textile waste more efficiently. Today, various textile waste classifications and corresponding recycling methods exist along with products made of recycled materials. Though, to catch up with elevated consumption levels, more scalable applications incorporating recycled textile fibres are needed.

Based on the above reason, present study proposes a method of developing a scalable nonwoven application made of mechanically recycled textile waste for the packaging industry. The goal was to incorporate the textile fibres into a solid-structured composite matrix that holds its shape when folded into a box. Hence the focus was equally addressed on the design, enhancing properties like simplicity, convenient usage, and the fact that no extra components would be needed for sealing. Such application is widely used and preferred in the e-commerce sector, where the most important requirement for the packaging is to protect the goods from damage during the shipping.

Therefore, the widely used corrugated paperboard was set as a blueprint for analysing the mechanical performance of the developed application. Various material thicknesses and fibre compositions ratios of post-consumer recycled cotton with biodegradable binder were experimented. The goal during the material development was to achieve sufficient compressive strength as it is one of the most important measurements for determining the load-bearing capacity of packaging before the buckling occurs. Also was studied the water absorption that helped understand the suitable environmental conditions for the application. At the end of the research, two of the final products were designed and their compressive strengths measured.

Laboratory results showed that higher material thickness and fibre fraction volume of binding fibres yielded higher compressive strength compared to the specimens containing more cotton fibres. Likewise, the latter had also higher water absorbance level. Modulus, on the other hand, was dependant on the design and the size of the surface area with smaller area yielding higher modulus. In contrary, the elongation was higher for the design with higher surface area.

The experiments proved that mechanically recycled textile fibres could be successfully incorporated into a composite matrix with a relatively rigid structure that is suitable for

packaging application. Despite good compressive properties, the author notes that the surface of the application was not satisfactory for being commercially acceptable. The increase in the fibre fraction volume of the binding fibres resulted in darker plastic-like stains across the surface of the material. However, the experimental part showed that the quality of fibre carding along with the compression moulding temperature has the utmost importance on the final product. Changing those parameters can therefore improve the overall appearance of the material.

As the study attempted to analyse whether the developed composite material is suitable as a packaging application, more extensive research may be carried out for assessing additional properties that the industry requires from the cardboard packaging.

The author is also suggesting that the method and application mentioned above could be potentially produced from other types of fibres or post-consumer fibre blends. Even though the recycling of such application is viable in theory, more extensive research along with practical tests shall be carried out to finding viable method for creating truly circular application.

KOKKUVÕTE

Maailm on jõudnud punkti, kus tarbimine kasvab suuresti piiratud ressursside arvelt. Ainuüksi EL-i tekstiilisektoris on ostetavate rõivaste hulk inimese kohta kasvanud vaid mõne aastakümnega 40%, mis on tingitud kaupade odavnemisega ja niinimetatud lineaarse väärtusahela ekspluateerimisest. Seoses tekstiilmaterjalide madala ümbertöötluse määraga, on loodusvarade ja tekstiilsete jäätmete tõhusam taaskasutamine tõusnud fookusesse. Kuigi erinevad tekstiilijäätmete klassifikatsioonid ja nendele vastavad ümbertöötlusmeetodid eksisteerivad, on suurenenud tarbimisele järele jõudmiseks vaja arendada enam skaleeritavaid rakendusi, mis sisaldavad ringlusse võetud tekstiilkiude.

Sellest tulenevalt käsitleb käesolev magistritöö ühte võimalikku lahendust, töötades välja mehaaniliselt ümbertöödeldud tekstiilijäätmetest koosneva lausmaterjali, mis sobiks kasutamiseks pakenditööstuse rakendusena. Selleks integreeriti tekstiilkiud jäiga struktuuriga komposiitmaatriksisse, mis karbiks kokkuvolditina hoiaks oma kuju. Peale materjali arenduse, keskenduti uurimustöös ka loodava pakendi disainile, kus peamiselt lähtuti lihtsast disainijoonest, kasutajamugavusest ning sellest, et paki sulgemiseks või kasutamiseks poleks vaja kasutada lisakomponente. Üks selliseid olemasolevaid rakendusi on lainepapp karp, mis on täna laialdaselt kasutuses ja eelistatud just e-kaubanduse sektoris. Valdkonna olulisim nõue e-poe pakendile on kaitsta kaupu potentsiaalsete transpordivigastuste eest.

Seetõttu seati lainepapp karp töös arendatava toote omaduste analüüsimisel näidiseks. Uurimustöös katsetati tarbimisjärgse ümbertöödeldud puuvilla ja biolaguneva sideaine erinevaid kiu koostise suhteid ning eksperimenteeriti erinevate materjali paksustega. Materjali väljatöötamisel oli eesmärgiks saavutada piisav survetugevus, kuna see on üks olulisemaid aspekte pakendi kandevõime määramiseks. Samuti uuriti toote veeimavust, mis aitas mõista rakenduse kasutamiseks sobivad keskkonnatingimused. Magistritöö tulemusena valmis kaks lõpptoodet, mille survetugevused mõõdeti.

Materjali testide tulemused näitasid, kõrgem survetugevus avaldus nii sideaine kiuvahekorra suurendamisel materjalis kui ka üleüldises materjali paksuses. Rohkem puuvillakiude sisaldavad materjalid imasid aga rohkem niiskust. Paindejäikus seevastu sõltus pakendi lõikest, konstruktsioonist ja pindalast, kusjuures väiksema pindalaga toode andis kõrgema paindemooduli. Toote elastsus oli vastupidiselt kõrgem jälle suurema pindalaga disaini puhul.

Uurimustöös läbiviidud katsed ning tootele püstitatud eeldused tõestasid, et mehaaniliselt ümbertöödeldud tekstiilkiude saab edukalt integreerida jäiga struktuuriga komposiitmaatriksisse, mis oma mehaaniliste omaduste poolest sobib e-kaubanduse toodete pakendamiseks. Vaatamata lõpptoote küllaltki heale surveomadusele, jääb autor rahulolematuks toote välise struktuuriga, mis ei saavutanud eeldatavat kaubanduslikku välimust. Nimelt tekitas sideaine kiumahu suurenemine kuumtöötluses materjali pinnale tumedamad termoplastsete kiudude sulamisest tingitud plekid. Analüüsides hiljem tooraine ettevalmistamise protseduure sai autorile selgeks, et lõpptoote kvaliteet, nii visuaalne kui füüsiline, on otseses seoses tekstiilkiudude kraasimise kvaliteedi ning pressimise temperatuuriga. Seega võib vastavate parameetrite muutmisel parandada oluliselt materjali ja toote üldisi omadusi.

Autor usub, et ülalmainitud rakendust võib tulevikus proovida valmistada ka teist tüüpi kiududest või tarbimisjärgsetest kiusegudest. Samuti on täna sellisel meetodil valminud pakkelahenduse ümbertöötlemine küll teoreetiliselt võimalik, kuid põhjalikumaid uuringuid koos praktiliste testidega on rangelt soovituslikud, leidmaks parim tehnoloogia ringmajandusliku tekstiilpakendi loomiseks.

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APPENDICES

Appendix 1. PLA specification A7.1.2

NONWOVENS FIBER

ingeo™

Commercial Product Description

Ingeo Bicomponent bonding Fiber SLN2450CM

Ingeo fiber type SLN2450CM is a medium denier polylactic Acid (PLA) staple fiber. The Ingeo fiber starts with an abundant, natural, and sustainable raw material like corn, The Ingeo means ingredient from the earth keeping humanity, nature, and technology in balance.

The Ingeo bonding fiber is a bicomponent fibers with low-melt PLA sheath and PLA core. This fiber has low melting point (130°C/ 170°C), thermoplastics and self-adhesive properties. Ingeo bonding fibers have a range of melting temperatures and can bind with PLA Ingeo fibers as well as other natural fibers. The performance will not diminish or fade after washings or over time. It provides a bridge between Ingeo fiber or other natural fibers to make nonwoven 100% natural ingredient.

Applications：

Padding，Wadding，Cushion，Duvet，Comfort，Filter， etc.

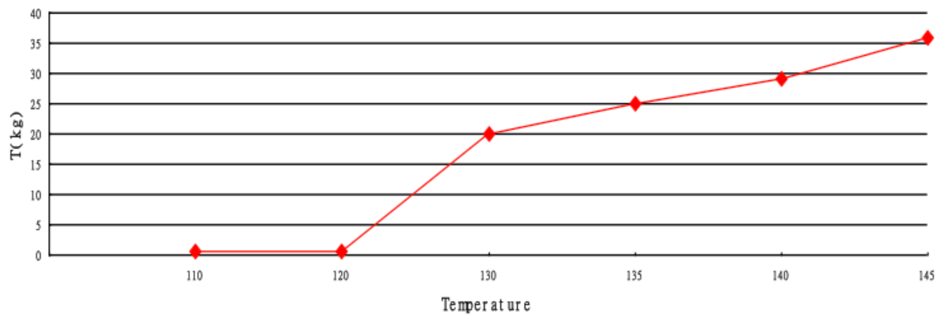
Packing Information：

Ingeo fiber type SLN2450CM is supplied in bales weighing average 250Kgs per bale.

Typical Physical Properties

FIBER SPECIFICATION	
Denier:	4
Length(mm):	51

PHYSICAL PROPERTIES	
Tenacity(g/d):	3.6±0.5
Elongation at Break (%):	45±10
Hot-Air Shrinkage(85°Cx15min) (%):	≦6.5



TEL: 886-2-27378806; 27378825 FAX: 886-2-27358270 ; 23772947

Appendix 2. Specimen's parameters A7.2

Fleece weight, g	Spec. nr.	RCF, %	RCF, g	PLA, %	PLA, g	HP pressure, bar	HP temp. °C	Mass per unit area, g/m²	Thick., mm	STD thick., mm	Weight, g	STD weight, g
35 g	1	90	31,5	10	3,5	40	155	541	1,60	0,21	0,58	0,02
	2	90	31,5	10	3,5	50	155	653	1,83	0,12	0,70	0,04
	3	90	31,5	10	3,5	60	155	530	1,66	0,16	0,57	0,08
	4	90	31,5	10	3,5	70	155	501	1,55	0,20	0,54	0,06
	5	80	28	20	7,0	40	155	487	1,29	0,09	0,52	0,10
	6	80	28	20	7,0	50	155	551	1,55	0,20	0,59	0,20
	7	80	28	20	7,0	60	155	460	1,35	0,09	0,49	0,02
	8	80	28	20	7,0	70	155	505	1,27	0,10	0,54	0,09
	9	70	24,5	30	10,5	40	155	510	1,30	0,13	0,55	0,03
	10	70	24,5	30	10,5	50	155	616	1,30	0,11	0,66	0,01
	11	70	24,5	30	10,5	60	155	604	1,26	0,09	0,65	0,06
	12	70	24,5	30	10,5	70	155	455	1,07	0,13	0,49	0,03
	13	60	21	40	14,0	40	155	574	1,31	0,10	0,62	0,11
	14	60	21	40	14,0	50	155	532	1,14	0,10	0,57	0,01
	15	60	21	40	14,0	60	155	510	1,16	0,20	0,55	0,08
	16	60	12	40	14,0	70	155	685	1,24	0,14	0,74	0,04
	17	50	17,5	50	17,5	40	155	532	1,21	0,15	0,57	0,01
	18	50	17,5	50	17,5	50	155	500	1,01	0,12	0,54	0,07
	19	50	17,5	50	17,5	60	155	575	1,06	0,16	0,62	0,04
	20	50	17,5	50	17,5	70	155	614	0,99	0,10	0,66	0,00

Fleece weight, g	Spec. nr.	RCF, %	RCF, g	PLA, %	PLA, g	HP pressure, bar	HP temp. °C	Mass per unit area, g/m²	Thick., mm	STD thick., mm	Weight, g	STD weight, g
25 g	21	90	22,5	10	2,5	40	155	266	1,24	0,15	0,29	0,10
	22	90	22,5	10	2,5	50	155	443	1,68	0,25	0,48	0,12
	23	90	22,5	10	2,5	60	155	468	1,45	0,18	0,50	0,02
	24	90	22,5	10	2,5	70	155	328	1,15	0,10	0,35	0,04
	25	80	20	20	5	40	155	326	1,10	0,13	0,35	0,10
	26	80	20	20	5	50	155	395	1,01	0,19	0,42	0,05
	27	80	20	20	5	60	155	524	1,09	0,13	0,56	0,04
	28	80	20	20	5	70	155	408	1,12	0,21	0,44	0,03
	29	70	17,5	30	7,5	40	155	349	1,12	0,15	0,38	0,07
	30	70	17,5	30	7,5	50	155	381	1,10	0,09	0,41	0,07
	31	70	17,5	30	7,5	60	155	332	0,94	0,08	0,36	0,04
	32	70	17,5	30	7,5	70	155	374	0,96	0,13	0,40	0,07
	33	60	15	40	10	40	155	460	1,04	0,14	0,49	0,06
	34	60	15	40	10	50	155	362	0,84	0,09	0,39	0,04
	35	60	15	40	10	60	155	336	0,80	0,08	0,36	0,05
	36	60	15	40	10	70	155	424	0,77	0,09	0,46	0,03
	37	50	12,5	50	12,5	40	155	449	0,86	0,09	0,48	0,05
	38	50	12,5	50	12,5	50	155	344	0,74	0,09	0,37	0,04
	39	50	12,5	50	12,5	60	155	542	0,90	0,10	0,58	0,02
	40	50	12,5	50	12,5	70	155	414	0,71	0,06	0,44	0,03

Appendix 3. Water absorption test results with the material A7.3.2

Specimens' preparation parameters							Oven dried state		Wet state		Moisture gain compared to oven dried state	
Carded fleece weight, g	Spec. nr.	RCF, %	PLA, %	HP pressure, bar	HP temp., °C	Mass per unit area, g/m²	Thick., mm	Weight, g	Thick., mm	Weight, g	Weight gain, %	Thick. gain %
35 g	1	90	10	40	155	541	2,14	0,57	2,68	3,60	533%	26%
	2	90	10	50	155	653	2,07	0,69	2,71	3,30	379%	31%
	3	90	10	60	155	530	2,12	0,56	2,48	3,40	508%	17%
	4	90	10	70	155	501	1,97	0,53	2,39	3,13	494%	21%
	5	80	20	40	155	487	1,48	0,51	1,79	2,09	306%	21%
	6	80	20	50	155	551	1,94	0,58	2,15	2,54	336%	11%
	7	80	20	60	155	460	1,68	0,49	1,90	2,25	363%	13%
	8	80	20	70	155	505	1,41	0,53	1,63	1,85	248%	16%
	9	70	30	40	155	510	1,61	0,54	1,75	1,89	251%	8%
	10	70	30	50	155	616	1,45	0,65	1,58	1,72	165%	9%
	11	70	30	60	155	604	1,39	0,64	1,56	1,75	175%	12%
	12	70	30	70	155	455	1,29	0,48	1,42	1,57	228%	11%
	13	60	40	40	155	574	1,41	0,61	1,50	1,62	167%	6%
	14	60	40	50	155	532	1,30	0,56	1,41	1,56	177%	8%
	15	60	40	60	155	510	1,12	0,54	1,22	1,29	139%	10%
	16	60	40	70	155	685	1,32	0,73	1,41	1,52	109%	6%
	17	50	50	40	155	532	1,17	0,56	1,22	1,29	129%	4%
	18	50	50	50	155	500	0,99	0,53	1,07	1,13	113%	8%
	19	50	50	60	155	575	1,27	0,61	1,33	1,42	132%	5%
	20	50	50	70	155	614	1,11	0,65	1,18	1,28	96%	6%

Specimens' preparation parameters							Oven dried state		Wet state		Moisture gain compared to oven dried state	
Carded fleece weight, g	Spec. nr.	RCF, %	PLA, %	HP pressure, bar	HP temp. °C	Mass per unit area, g/m^2	Thick., mm	Weight, g	Thick., mm	Weight, g	Weight gain, %	Thick. gain %
25 g	21	90	10	40	155	266	1,47	0,28	1,58	2,22	704%	7%
	22	90	10	50	155	443	1,87	0,46	2,15	2,67	478%	15%
	23	90	10	60	155	468	1,82	0,49	2,18	2,68	451%	20%
	24	90	10	70	155	328	1,42	0,34	1,69	1,86	444%	19%
	25	80	20	40	155	326	1,28	0,34	1,38	1,33	291%	8%
	26	80	20	50	155	395	1,34	0,41	1,55	1,63	296%	16%
	27	80	20	60	155	524	1,28	0,55	1,55	1,56	184%	22%
	28	80	20	70	155	408	1,21	0,43	1,45	1,44	238%	20%
	29	70	30	40	155	349	1,16	0,37	1,27	1,14	213%	9%
	30	70	30	50	155	381	1,35	0,40	1,47	1,29	225%	9%
	31	70	30	60	155	332	1,08	0,35	1,16	1,01	189%	8%
	32	70	30	70	155	374	0,98	0,39	1,11	1,19	204%	14%
	33	60	40	40	155	460	1,08	0,48	1,17	1,24	156%	8%
	34	60	40	50	155	362	1,02	0,38	1,08	1,13	198%	6%
	35	60	40	60	155	336	0,84	0,35	0,92	0,89	153%	9%
	36	60	40	70	155	424	0,98	0,45	1,06	1,10	148%	8%
	37	50	50	40	155	449	0,88	0,47	0,95	0,96	104%	8%
	38	50	50	50	155	344	0,89	0,36	0,95	0,91	150%	6%
	39	50	50	60	155	542	1,07	0,57	1,16	1,22	113%	8%
	40	50	50	70	155	414	0,70	0,44	0,79	0,80	83%	13%

Appendix 4. Flexural test results with the material A7.3.3

Specimen nr.	RCF / PLA, %	Compr. pressure, bar	Test piece nr.	Modulus, MPa	Max. compr. load, N	Ext. at max. compr. load, mm
1	90 / 10	40	1	0.03	1.26	-4.69
			2	0.07	2.64	-9.81
			3	0.04	1.94	-7.26
			AVG	**0.05**	**1.95**	**-7.25**
2	90 / 10	50	1	0.08	5.43	-9.18
			2	0.03	2.56	-9.27
			3	0.01	2.14	-9.66
			AVG	**0.04**	**3.38**	**-9.37**
3	90 / 10	60	1	0.04	2.25	-6.84
			2	0.11	4.5	-9.57
			3	0.05	3.28	-9.51
			AVG	**0.07**	**3.34**	**-8.64**
4	90 / 10	70	1	0.01	1.39	-10.65
			2	0.03	2.05	-9.95
			3	0.03	2.48	-10.09
			AVG	**0.02**	**1.97**	**-10.23**
5	80 / 20	40	1	0.08	2.54	-10.02
			2	0.13	3.1	-5.09
			3	0.16	3.46	-7.8
			AVG	**0.12**	**3.03**	**-7.64**
6	80 / 20	50	1	0.14	2.8	-5.96
			2	0.18	4.51	-4.49
			3	0.16	5.5	-7.91
			AVG	**0.16**	**4.27**	**-6.12**
7	80 / 20	60	1	0.07	2.69	-7.35
			2	0.18	4.74	-10.07
			3	0.15	2.61	-9.63
			AVG	**0.13**	**3.35**	**-9.02**
8	80 / 20	70	1	0.14	3.81	-10.15
			2	0.16	5.81	-10.29
			3	0.16	4.29	-10.17
			AVG	**0.15**	**4.64**	**-10.20**
9	70 / 30	40	1	0.13	3.1	-10.13
			2	0.16	2.94	-6.59
			3	0.19	3.36	-3.67
			AVG	**0.16**	**3.13**	**-6.80**
10	70 / 30	50	1	0.6	11.81	-9.68
			2	0.71	13.05	-4.41
			3	0.44	8.2	-9.53
			AVG	**0.58**	**11.02**	**-7.87**

Specimen nr.	RCF / PLA, %	Compr. pressure, bar	Test piece nr.	Modulus, MPa	Max. compr. load, N	Ext. at max. compr. load, mm
11	70 / 30	60	1	0.59	11.13	-4.53
			2	0.65	13.96	-6.63
			3	0.36	7.49	-10.4
			AVG	**0.53**	**10.86**	**-7.19**
12	70 / 30	70	1	0.21	3.63	-10.41
			2	0.17	3.36	-5.61
			3	0.16	3.39	-4.69
			AVG	**0.18**	**3.46**	**-6.90**
13	60 / 40	40	1	0.91	14.37	-8.9
			2	0.58	10.39	-10.13
			3	0.33	9.03	-10.04
			AVG	**0.61**	**11.26**	**-9.69**
14	60 / 40	50	1	0.82	14.83	-6.97
			2	0.87	14.54	-8.58
			3	1	15.12	-7.09
			AVG	**0.90**	**14.83**	**-7.55**
15	60 / 40	60	1	0.66	9.12	-8.03
			2	0.58	10.25	-10.21
			3	0.47	8.06	-10.39
			AVG	**0.57**	**9.14**	**-9.54**
16	60 / 40	70	1	0.66	13.07	-2.69
			2	0.72	10.92	-5.65
			3	0.49	7.03	-5.6
			AVG	**0.62**	**10.34**	**-4.65**
17	50 / 50	40	1	0.65	13.47	-9.47
			2	1	20.8	-9.71
			3	0.66	14.37	-5.39
			AVG	**0.77**	**16.21**	**-8.19**
18	50 / 50	50	1	0.64	9.89	-8.78
			2	0.95	16.2	-7.42
			3	0.72	11.75	-6.12
			AVG	**0.77**	**12.61**	**-7.44**
19	50 / 50	60	1	0.96	14.24	-5.2
			2	1.34	23.79	-5.26
			3	0.93	15.85	-9.06
			AVG	**1.08**	**17.96**	**-6.51**
20	50 / 50	70	1	0.83	13.9	-5.63
			2	0.81	13.71	-5.68
			3	0.93	15.57	-6.02
			AVG	**0.86**	**14.39**	**-5.78**
21	90 / 10	40	1	0	0	0
			2	0	0	0
			3	0.02	1.28	-6.85
			AVG	**0.02**	**1.28**	**-6.85**

Specimen nr.	RCF / PLA, %	Compr. pressure, bar	Test piece nr.	Modulus, MPa	Max. compr. load, N	Ext. at max. compr. load, mm
22	90 / 10	50	1	0.01	2.39	-10.2
			2	0.03	2.72	-9.9
			3	0.03	2.05	-10
			AVG	**0.02**	**2.39**	**-10.03**
23	90 / 10	60	1	0	0	0
			2	0.03	1.82	-9.3
			3	0.03	2.29	-10.15
			AVG	**0.02**	**1.37**	**-6.48**
24	90 / 10	70	1	0.06	2.1	-6.63
			2	0.1	3.07	-6.4
			3	0.03	1.51	-5.78
			AVG	**0.06**	**2.23**	**-6.27**
25	80 / 20	40	1	0.05	1.26	-11.26
			2	0.08	1.43	-9.35
			3	0.03	0.68	-5.9
			AVG	**0.05**	**1.12**	**-8.84**
26	80 / 20	50	1	0.08	2.24	-6.57
			2	0.07	1.11	-6
			3	0.09	1.38	-5.99
			AVG	**0.08**	**1.58**	**-6.19**
27	80 / 20	60	1	0.05	1.27	-6.3
			2	0.14	3.15	-8.71
			3	0.1	2.05	-7.65
			AVG	**0.10**	**2.16**	**-7.55**
28	80 / 20	70	1	0.15	3.49	-9.16
			2	0.26	3.52	-10.84
			3	0.16	3.05	-7.57
			AVG	**0.19**	**3.35**	**-9.19**
29	70 / 30	40	1	0.25	5.62	-8.59
			2	0.25	4.35	-5.67
			3	0.19	3.87	-6.41
			AVG	**0.23**	**4.61**	**-6.89**
30	70 / 30	50	1	0.25	4.26	-4.77
			2	0.21	3.87	-7.18
			3	0.35	5.23	-5.32
			AVG	0.38	6.3	-8.31
31	70 / 30	60	1	0.17	3.71	-3.5
			2	0.23	5.01	-6.56
			3	**0.27**	**4.73**	**-5.94**
			AVG	0.22	2.81	-6.34
32	70 / 30	70	1	0.29	3.37	-10.09
			2	0.34	3.19	-5.02
			3	0.34	3.49	-9.38
			AVG	**0.32**	**3.35**	**-8.16**

Specimen nr.	RCF / PLA, %	Compr. pressure, bar	Test piece nr.	Modulus, MPa	Max. compr. load, N	Ext. at max. compr. load, mm
33	60 / 40	40	1	0.22	3.42	-8.18
			2	0.25	2.98	-10.16
			3	0.25	4.53	-6.46
			AVG	**0.24**	**3.64**	**-8.27**
34	60 / 40	50	1	0.17	2.05	-10.35
			2	0.30	3.36	-6.47
			3	0.22	3.48	-6.1
			AVG	**0.23**	**2.96**	**-7.64**
35	60 / 40	60	1	0.3	4.02	-6.11
			2	0.46	6.95	-6.1
			3	0.73	10.32	-5.65
			AVG	**0.50**	**7.10**	**-5.95**
36	60 / 40	70	1	0.28	5.14	-7.67
			2	0.34	6.34	-7.98
			3	0.28	4.42	-6.17
			AVG	**0.30**	**5.30**	**-7.27**
37	50 / 50	40	1	0.58	7.53	-4.43
			2	0.64	10.18	-6.97
			3	0.36	6.72	-7.03
			AVG	**0.53**	**8.14**	**-6.14**
38	50 / 50	50	1	0.37	4.16	-6.91
			2	0.32	4.4	-5.5
			3	0.29	3.84	-7.75
			AVG	**0.33**	**4.13**	**-6.72**
39	50 / 50	60	1	0.5	8.27	-7.28
			2	0.56	10.21	-7.02
			3	0.52	9.13	-7.15
			AVG	**0.53**	**9.20**	**-7.15**
40	50 / 50	70	1	0.32	5.22	-6.53
			2	0.65	9.9	-5.99
			3	0.71	10.2	-5.65
			AVG	**0.56**	**8.44**	**-6.06**
New specimen prepared with larger drum carder and with more fibre volume						
41	60 / 40 100% fibers	70	1	0,02	1,36	-11,58
			2	0,03	1,96	-10,99
			3	0,02	1,23	-11,48
			AVG	**0,02**	**1,52**	**-11,35**
42	70 / 30 100% fibers	70	1	0,01	0,78	-11,99
			2	0	0,56	-13,72
			3	0,02	1,09	-10,35
			AVG	**0,01**	**0,81**	**-12,02**
43	60 / 40 150% fibers	70	1	0,07	3,31	-10,65
			2	0,07	3,21	-10,42
			3	0,02	1,43	-10,73
			AVG	**0,05**	**2,65**	**-10,60**

Specimen nr.	RCF / PLA, %	Compr. pressure, bar	Test piece nr.	Modulus, MPa	Max. compr. load, N	Ext. at max. compr. load, mm
44	70 / 30 150% fibers	40	1	0,06	3,13	-11,45
			2	0,04	2,43	-11,34
			3	0,03	1,82	-10,55
			AVG	**0,04**	**2,46**	**-11,11**
45	60 / 40 200% fibers	50	1	0,11	7,45	-8,81
			2	0,19	10,10	-9,98
			3	0,14	7,99	-9,54
			AVG	**0,15**	**8,51**	**-9,44**
46	70 / 30 200% fibers	60	1	0,13	6,29	-10,71
			2	0,16	7,23	-10,60
			3	0,07	3,84	-10,45
			AVG	**0,12**	**5,79**	**-10,59**

Appendix 5. Flexural test results with the final product A7.5

Final product	Constr.	RCF / PLA, %	Mass per unit area, g/m²	Modulus, MPa	Max. comp. load, N	Ext. at max. compr. load, mm
Small box	100% fibres	70 / 30	604	0.13	69	-4.13
	150% fibres		562	1.59	447	-3.36
	200% fibres		882	0.40	447	-5.47
	100% fibres	60 / 40	532	0.43	205	-4.46
	150% fibres		666	0.77	357	-3.99
	200% fibres		922	1.47	447	-3.73
Big box	100% fibres	70 / 30	604	0.10	122	-8.59
	150% fibres		562	0.53	448	-6.10
	200% fibres		882	0.71	448	-5.00
	100% fibres	60 / 40	532	0.25	294	Failed
	150% fibres		666	0.56	448	6.75
	200% fibres		922	0.53	449	5.06