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

PROPERTIES OF NONWOVEN MATERIALS PRODUCED FROM MECHANICALLY RECYCLED TEXTILE FIBRES

ÜMBERTÖÖDELDUD TEKSTIILKIUDUDEST VALMISTATUD LAUSMATERJALIDE OMADUSED

MASTER THESIS

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Tallinn 2021

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THESIS TASK

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Thesis topic:

(in English) Properties of nonwoven materials produced from mechanically recycled textile fibres

(in Estonian) Ümbertöödeldud tekstiilkiududest valmistatud lausmaterjalide omadused

Thesis main objectives:

1. Producing nonwoven materials from mechanically recycled post-consumer textile waste to establish a potential circular textile economy.
2. To understand the optimum process parameters for producing nonwovens from recycled fibres, comparable with nonwovens made from virgin fibres.
3. To explore the possible applications for nonwoven materials made from recycled textile waste.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Overview of textile waste and current recycling technology.	22.05.2020
2.	Determination of linear density, length and melting point of textile fibres.	13.12.2020
3.	Fibre web preparation through carding process and thermal treatment to manufacture nonwoven materials.	28.02.2021
4.	Determination of mass per unit area, air permeability and tensile properrties of nonwoven materials.	30.04.2021
5.	Test results analysis	20.05.2021
6.	Final master's thesis submission.	24.05.2021

Language: English **Deadline for submission of thesis:** “24.”May.2021a

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PREFACE

This thesis is written as part of the master’s programme of Tallinn University of Technology, Tallinn, Estonia. The materials and equipment used for this work were provided by TalTech. Experimental works were also done in TalTech Laboratory of Polymers and Textile Technology. Some materials were also prepared by the University of Tartu Viljandi Culture Academy. This work has been partially supported by SA Keskkonnainvesteeringute Keskus under the project "Developing of textile waste shredding technology and innovative materials to adding value to textile waste and support the circular economy". In this work, nonwoven materials were prepared from mechanically recycled textile fibres and the properties were compared the properties with nonwovens made from virgin fibres.

It is glee to come to an end of the thesis. I would like to give my heartfelt gratitude to the respectable and beloved supervisor senior lecturer Tiia Plamus of whose consistent advice and suggestions have led me to a successful end to this thesis. My acknowledgment is insignificant without the mention of Tiina Mäe and Dr. Illia Krasnou, who help me with valuable tasks.

Keywords: textile waste, textile recycling, mechanical recycling, recycled fibre, nonwoven materials.

List of abbreviations and symbols

CO - cotton
CO_2 - carbon-di-oxide
CV - coefficient of variation
DSC - differential scanning calorimetry
GSM - gram per square meter
HC - hand-carded
IC - semi-industrially carded
LMP - low melt polyester
NWM - nonwoven material
P - polyester
PEG - polyethylene glycol
PET - polyethylene terephthalate
PES - polyester
PLA - polylactic acid
PP - polypropylene
RCO - recycled cotton
RMF - recycled mixed fibre
SAPs - superabsorbent polymers
S.D - standard deviation
TQI - total quality index
TTT - thermal treatment temperature

List of terms

Chemical recycling - turning waste for suitable raw materials by chemical treatments.
Circular economy - system of utilising maximum value while using and converting waste into new products at the end of life.
Fast fashion - an approach to supply clothes at low cost by mass production, rapid changing of style.
Mechanical recycling - breaking down the materials employing mechanical action.
Thermal treatment - mechanical bonding process of nonwovens by applying heat.
Reuse - using a product as it is without any further treatment.
Recycle - collecting and processing waste materials to turn into new products.

1. INTRODUCTION

Global textile production is increasing sharply due to rapid population growth, lifestyle development, and fast fashion trends [1][2]. Thus, the amount of textile waste also is escalating every year. The growing demands of textile products and use not only contribute to the loss of virgin raw materials and natural resources but also the introduction of large amounts of textile waste creating numerous environmental impacts. The textile industry is considered the second polluting industry after oil industry [3]. Approximately 87% of textile waste is disposed of in the landfill or incinerated, 12% is mechanically recycled, and the rest are chemically recycled [4]. More than 90% of this textile waste is recyclable or reusable [5][6]. Clothes also are used about 70% of their useful life and then will discarded [5][7].

Due to the challenges as mentioned earlier, the EU commission passed a bill on the new circular economy action plan, which calls for additional steps to establish an environmentally friendly, zero carbon emission, toxic-free, and utterly circular economy by 2050, including stricter recycling regulations and binding resource usage and use goals by 2030. In addition, by 2025, EU countries will be expected to collect textiles separately under a waste directive approved by the Parliament in 2018[8].

To minimize the use of virgin fibres and also to minimize environmental impact, reuse and recycling would be the most effective. Compared to incineration and landfilling, reuse and recycling of textile waste have a lower environmental impact [9]. Textile recycling, on the other hand, is the method of modifying pre- or post-consumer textile waste that can be used in new textile or non-textile items. Mechanical, chemical, and, less commonly, thermal recycling routes are the most common forms of textile recycling routes [9]. Nonwoven materials (NWMs) made from recycled fibres would be more economical and advantageous in terms of environmental friendliness.

Producing virgin raw materials is costly in terms of environmental friendliness. Textile waste has been considered a valuable source of raw material. For this reason, it is essential to develop products and processes where it would be flexible to use recycled fibre. Producing nonwoven materials could be a potential option to use recycled fibre due to the simple manufacturing process. The main aim of this thesis is to produce nonwoven materials from recycled fibres to establish a potential circular textile manufacturing system. Additionally, find out the optimum recycled fibre compositions and process parameters comparable with virgin fibre nonwoven materials.

This study consists of theoretical and experimental sections. In the theoretical part general overview of textile waste and problems, the present status of recycling, and possible applications of recycled fibres in different products are discussed. A brief illustration is also given about nonwovens: raw materials for nonwoven, processing methods, general properties, and NWMs applications.

The experimental chapter includes materials and methods, also results and discussion. The materials and methods part describes the fibres used in the current study and their properties, also the carding and thermal treatment steps used for NWMs preparation, and test methods to determine fibres origin and NWMs properties. In the discussion section, comparison of NWMs properties made with different types and content of fibres and thermal treatment temperature (TTT) are revealed, more specifically the properties of NWMs made with recycled fibres from other nonwovens made from virgin fibres are compared. In addition, a comparison between hand-carded (HC) nonwovens and semi-industrially carded (IC) nonwovens is also illustrated. Finally, the possible best composition of NWMs made from recycled fibres and the optimum process parameter are also discussed.

2. TEXTILE INDUSTRY AND TEXTILE WASTE

2.1 Global textile production and consumption

The global textile industry accounts for 2% of total domestic products and is worth 3 trillion USD [10]. In 2019, approximately 111 million tons of textile fibre was produced globally. In the last two decades, fibre production has increased two times, and the projected fibre production in 2030 is 146 million tons by adding more 30% [11].

Figure 2.1 illustrates global fibre production in 2019. Since the mid-1990s, when synthetic fibres surpassed cotton, synthetic fibres have dominated the fibre industry. Synthetic fibres accounted for approximately 63% of global fibre output in 2019, with about 70 million tons. Polyester alone had a market share of around 52% of total global fibre production. Approximately 58 million tons of polyester was produced in 2019. Cotton is considered as the second most valuable fibre in terms of production volume, which has a global market share of approximately 23% and around 26 million tons was produced in 2019 [11].

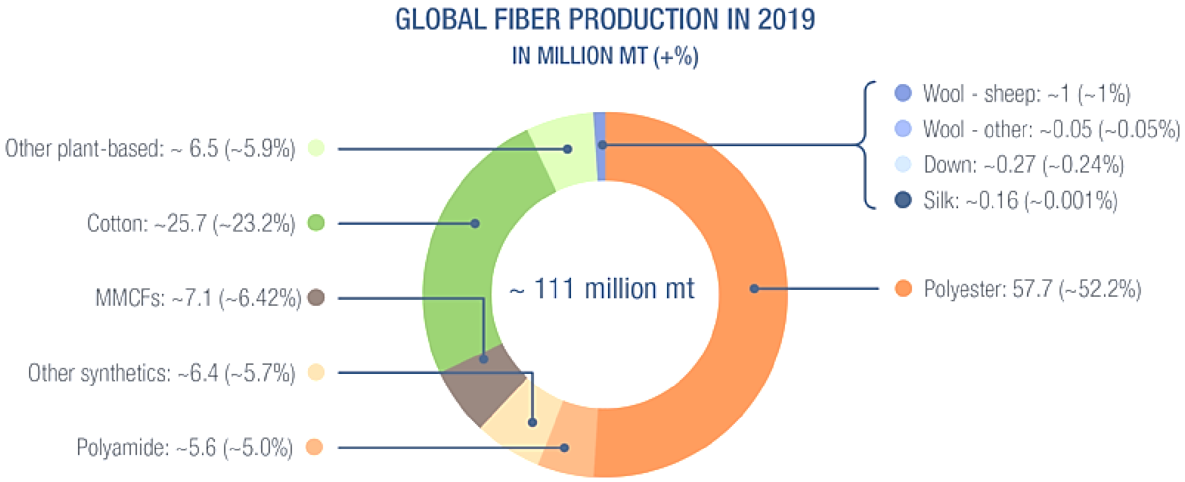

Figure 2.1 Global fibre production (MMCFs - man made cellulosic fibres) [2].

Figure 2.2 shows textiles sales and utilization trends from 2000 to 2015. In the last 15 years, clothes production has doubled, driven by fast fashion, and population growth. Nevertheless, worldwide, consumer loss 460 billion USD by throwing clothes, those are wearable. Globally, clothes utilization, number of wearing in the lifetime of cloth, have declined 36% than from 2000 to 2015 [12]. Even some clothes are predicted to be thrown after 7-10 times wearing.

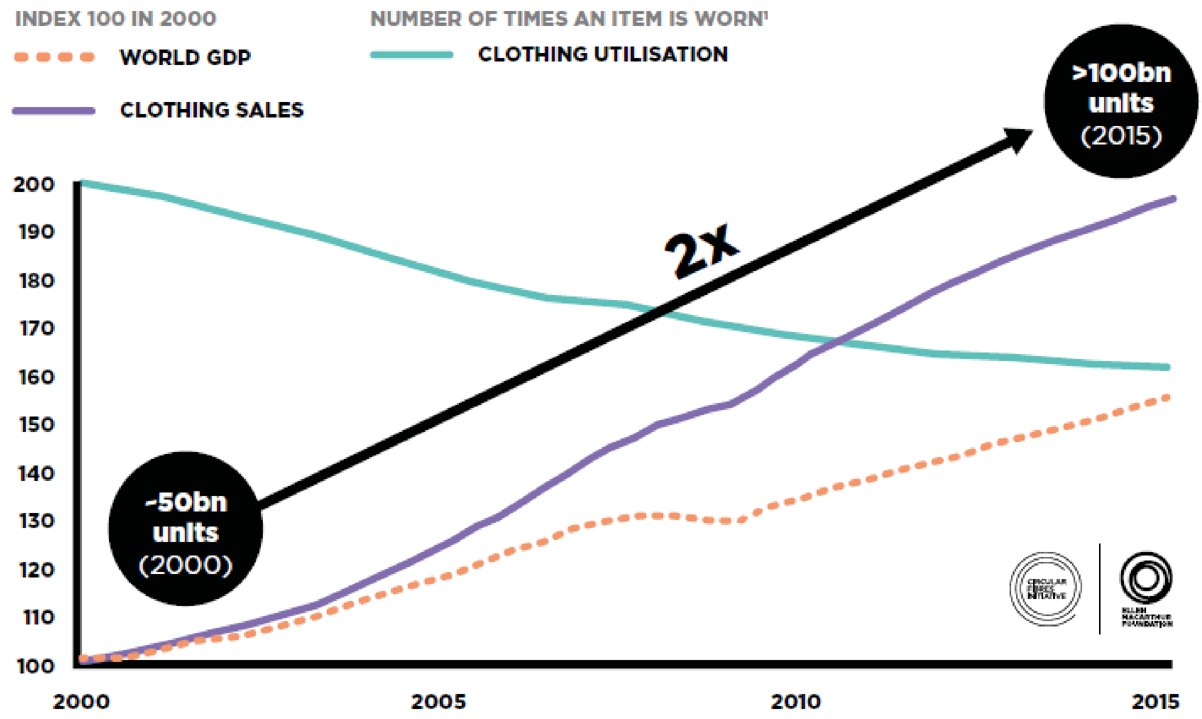

Figure 2.2 Textile sales and utilization trend since 2000 [12].

Figure 2.3 depicts textile products export, import, production, and consumption in EU-28 in 2017.In 2017, the EU countries manufactured 7.4 kg of textiles products per person while using around 26 kg. The EU imported nearly 28 kg of textile products per person (mainly finished products from Asia). The EU countries mainly export intermediate textile products, such as technical textile and high-performance fabrics in which the European industry specializes [13].

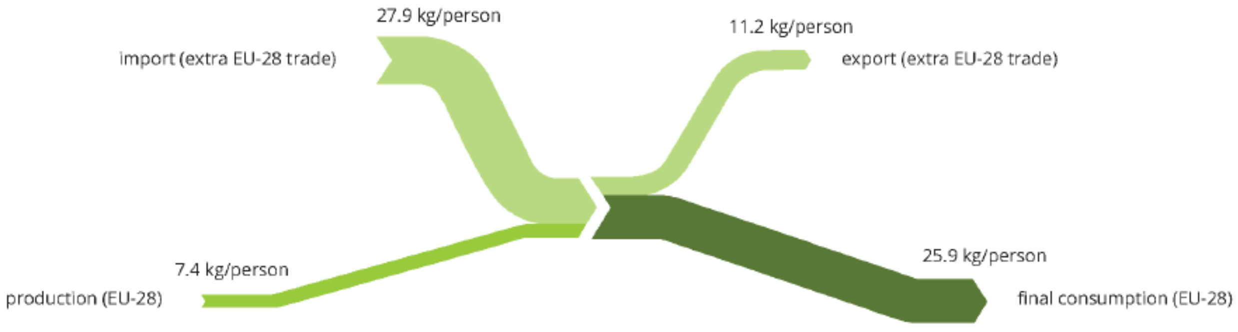

Figure 2.3 Flows of textile products (export, import, production, and consumption) in the EU-28, 2017[13].

2.2 Textile waste generation

The total global surplus in clothing (83.5 million tons in 2015) was reported to be more than 90 percent of the total global fibre supply (94.5 million tons in 2016). Figure 2.4 illustrates global fibre and waste production comparison. It is predicted that by 2030 it will rise by about 60 percent, with an additional new 57 million tons. Tons of waste are produced annually. The textile industry in the EU produces approximately 16 million tons of waste per year.

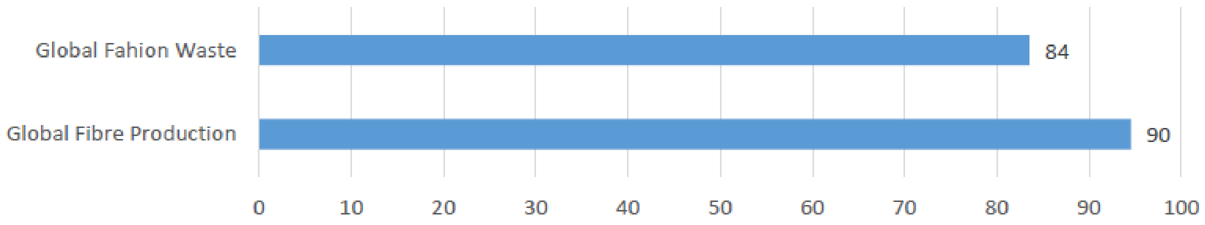

Figure 2.4 Global fibre production compared to global textile waste, 2015 [14].

A greater sustainability alteration is essential within the textile value chain from the raw materials, use, and end-of-use phases. Figure 2.5 illustrates projected textile material waste flows from raw material production to end-of-life. It is recorded that 87 percent of clothing-making products are disposed of in landfills or pulverized or wasted in processing phase, resulting in a 100 billion USD yearly opportunity expense. Apart from this, for recycling and reusing only 13% of textile waste is recorded to be collected, and below 1% of clothing waste used to manufacture apparel undergoing fibre-to-fibre closed-loop recycling [12]. Consequently, in conjunction with all other phases in the production value chain, the end-of-use stage is a critical enabler in moving the industry closer to a circular economy.

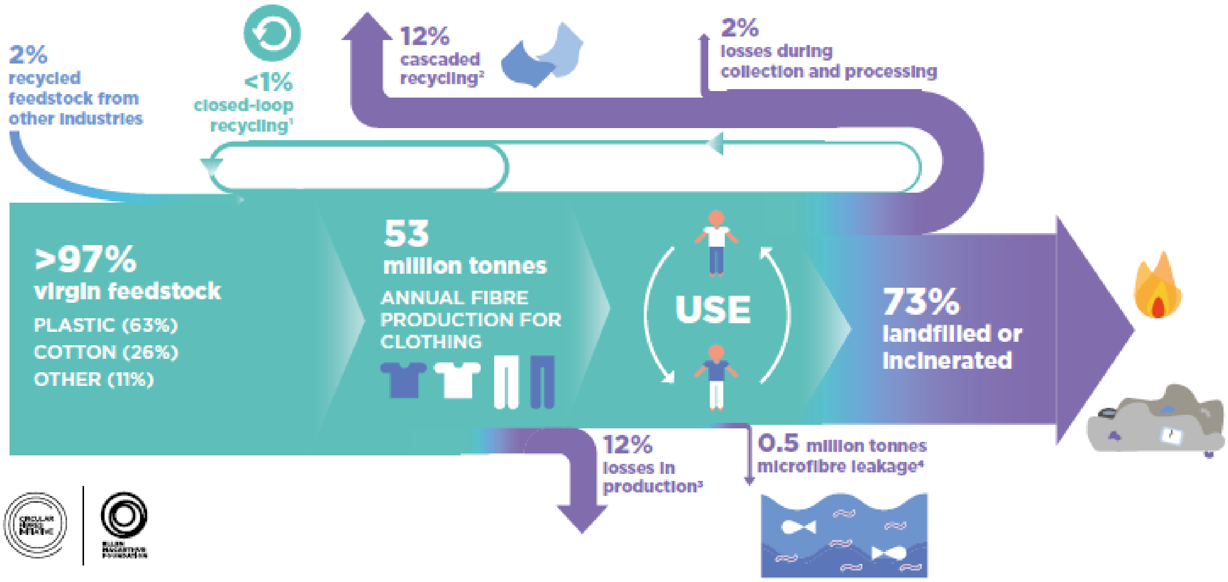

Figure 2.5 Worldwide materials and waste flow for clothing [12].

Each year, EU consumers dispose approximately of 11 kg of textiles per person. Used clothes exports is important and rising, primarily to Asia, Africa, and Eastern European countries. Since the bulk of used clothing that is not exported is incinerated or landfilled, the recycling rate is poor [13].

2.3 Types of textile waste

According to council of textile recycling, textile waste can be divided into two types such as pre-consumer waste and post-consumer waste

2.3.1 Pre-consumer waste

It is also known as processing waste, clean waste, and post-industrial waste. Throughout the first phases of the supply chain, pre-consumer waste is produced. This kind of waste can be produced at any stage in the production line, from spinning to weaving to cut-make-sewing operations. Carding waste, comber nails, yarn waste, textile cutting excess, trimmings, dye lot defects, print experiments, manufacturing surplus, and end of rolls are all included in the pre-consumer waste. On average, about 15% of the fabric used in the manufacture of garments is cut scrapped and wasted in the process that leads to post-industrial waste [15]. For the furniture, automobile, pillow, home decor, coarse yarn, paper, and other sectors, 750,000 tons of this waste are recycled into raw materials each year. About 75% of pre-consumer clothing wastes are recycled [16].

2.3.2 Post-consumer waste

It is also known as household waste and dirty waste. Post-consumer waste is any item made from fabricated textiles, discarded due to aging or damage. This consists of any apparel or household items, consisting of some cloth produced that the person no longer needs and chooses to dispose of [17]. Since post-consumer waste contains various materials, it is challenging to recycle compared to pre-consumer waste [18]. Such items are either scrapped because they have been worn out, destroyed, outgrown, or gone out of fashion. Occasionally, they are donated to charity but are more commonly disposed of in the garbage and end up in local landfills. However, the recycled amount constitutes less than 25% of the total textile waste generated as post-consumer waste. Furthermore, 26% of this post-consumer waste is processed into fibre used in goods similar to those derived from pre-consumer textile waste [16].

2.4 Environmental and economic impact

Since the textile is one of the most valuable sectors of the world, the production and consumption of textiles also have a significant socio-economic impact and environmental. Textile is considered a significant polluting industry in the world [10][3]. The traditional linear structure of manufacturing textiles consumes many resources and has detrimental consequences for the environment and community [12]. It puts a significant and ever-increasing strain on resources while also causing significant pollution. Currently, materials used have massive flaws to make a circular system. For example, harvesting cotton needs a large number of chemicals and pesticides, and producing polyester requires non-renewable resources [10][12]. Moreover, hazardous chemicals endanger the health of textile workers and clothing consumers, and plastic microfibres are released into the atmosphere, often ending up in the ocean [12].

The production of new textiles produces nearly 15 kg of CO_2 per kilogram of fibre [10][19] and requires large amounts of water, electricity and chemicals. When it comes to climate change, the textile industry produces 15-35 tons of CO_2 equivalent for each ton of textiles produced [13]. Approximately 63% of textile fibres are petroleum-based, and the production and use of these types of products is largely responsible for CO_2 emissions. The remaining 37% of the textile fibres is dominating by cotton [2]. The cultivation of cotton requires plenty of natural water and land. Globally, 3% farmland, 25% pesticides and 10% agricultural chemicals are used for cotton cultivation [20][16]. In addition, growing 1 kg of cotton, approximately 1000 litres of water is needed [16].

Textile processing and consumption are responsible for 3% of all global greenhouse gas emissions [6][21].

For the vast majority of environmental effects, later stages in the textile manufacturing process result in even more remarkable consequences [9]. Yarn manufacturing and fabric manufacturing (weaving/knitting) often use fossil fuels, resulting in CO_2 and particles emissions [9][22][23]. Wet treatment processes (dyeing, finishing, printing) are the leading sources of toxic emissions which adversely affect water, soil, and the ecosystem by releasing a massive amount of toxic, for example, chemicals chromium and chlorinated phenols [9][10]. Thus, the textile industry's critical environmental problems are carbon gases, water use, hazardous substances, and waste [9][23].

Textiles in landfill biodegrade to produce methane gas [24][25]. It is a greenhouse gas that produces a warming effect twenty-five times greater than CO_2 and contributes significantly to climate change. Since most of these are non-biodegradable, drainage and waterways are clogged out. Once poured into incinerators, they cause pollution and further disruption to the surrounding air. Around 87% of the total fibre production used in clothing is dumped or combusted, resulting in a loss of more than 100 billion USD per year [12].

3. TEXTILE RECYCLING

Though textiles are almost 100% recyclable, a huge amount of textiles end up in landfills for several reasons. Consumers, regulators, researchers, and industry professionals have paid more attention to value-added items made from recycled textile materials in recent years. They concentrate on environmental sustainability, strategic alliances, and alternative therapies that contribute significantly to the recycling process [26]. However, textile recycling processes have long existed but have been greatly influenced by factors such as volume, cost, and availableness of virgin raw materials, which have restricted the ability to be integrated as established and economically viable operations. Recycling strategies such as re-spinning of post-consumer and post-industrial materials, nonwoven material manufacturing, and pulping of cotton and linen have existed for centuries, with variations of such operations presently practiced [27].

Because of a growing understanding of the impacts of the apparel industry's current linear supply chain, there has been much interest in rising textile reuse and recycling, especially in further improving textile recycling processes [27]. Reuse is the process of using an item in its original state, while recycling is the process of converting waste into a product. Recovery of energy and resources, notably through the development of recycling technologies, has the potential to increase value creation in the textiles economy and would extensively contribute to the Ellen McArthur Foundation's vision of a circular economy model – a restorative, regenerative, and relational system by design, in which value is redistributed among stakeholders, from a source to a destination [28].

3.1 Status of textile recycling

Textile recycling is well established in the form of downcycling. Worldwide 13% of discarded textiles are recycled. In Europe, on average, 15-20% of textile waste is collected for reuse, and recycling [29][30][9], of which 50% is recycled and 50% is exported to developed countries [9]. However, there is a variation in collecting and recycling in different EU countries; for example, around 70% of textile waste is collected in Germany. In France, 210,000 tons of textile waste was collected separately in 2020, of which 60% reused as second-hand cloth selling and the rest was downcycled as insulations, felts, and nonwovens [29], and in 2020 the collection amount was 250,000 tons [31]. Though Belgium has an almost similar collection figure, using recycled fibre is higher (47%) [31]. In 2018, the USA total textile waste generation was 3.2 million tons, of which 14.7% was recycled that accounts for 2.5 million tons. An additional 9.3 percent of textile waste was combusted for energy recovery [32].

3.2 Recycling technologies

There are four recycling process groups, and they include primary, secondary, tertiary, and quaternary methods [33][24]. Figure 3.1 refers the possible textile waste reuse and recycling routes. The primary approach is the recycling of waste in its original form to get equal value. Generally, industrial scraps are used to produce products of the same value and quality. The secondary recycling system is also known as the mechanical processing of post-consumer products to produce products of different chemical and physical properties. The tertiary approach of recycling converts the waste into basic chemical constituents, monomers, or fuels by the chemical process. This is also known as chemical recycling. Quaternary recycling is the conversion of waste to energy systems, such as solid waste incineration or the use of heat produced. Quaternary recycling is considered as recovery.

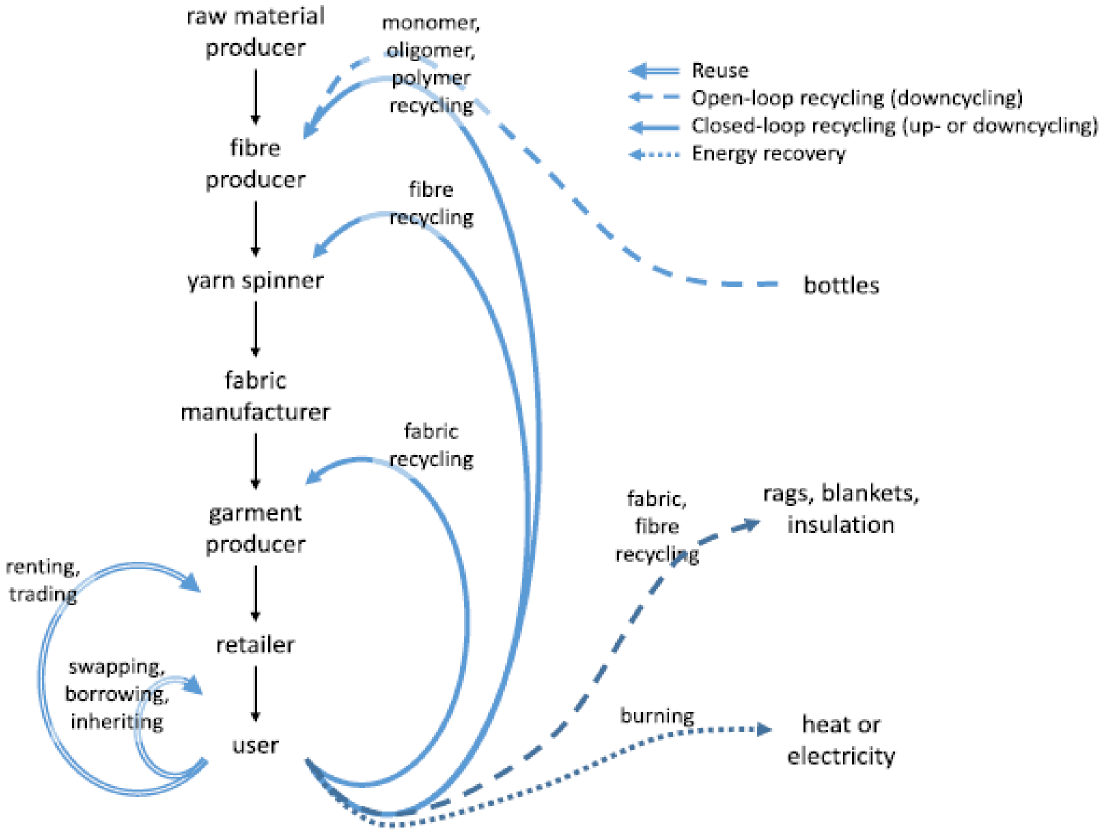

Figure 3.1 Textile recycling and reuse routes [9].

For example, there are two main methods to recycle cotton fabric back into fibre that can be used to produce new product. These two common methods are mechanical recycling and chemical recycling. Any company looking to integrate recycled cotton into their garments would need to determine which of these choices ties into the organization's expense, price, supply, and environmental impact objectives.

3.3 Chemical recycling

Before going through a spinneret to produce new fibre that can be spin to yarn and then woven or knit into cloth [34]. The fibres in textiles are broken down to the molecular level in chemical recycling, and the feedstock is repolymerized [35]. Figure 3.2 shows the common process flow of chemical recycling of textile waste. Unlike mechanical recycling, the final product is a higher-quality fibre that has a high equivalence to virgin fibre.

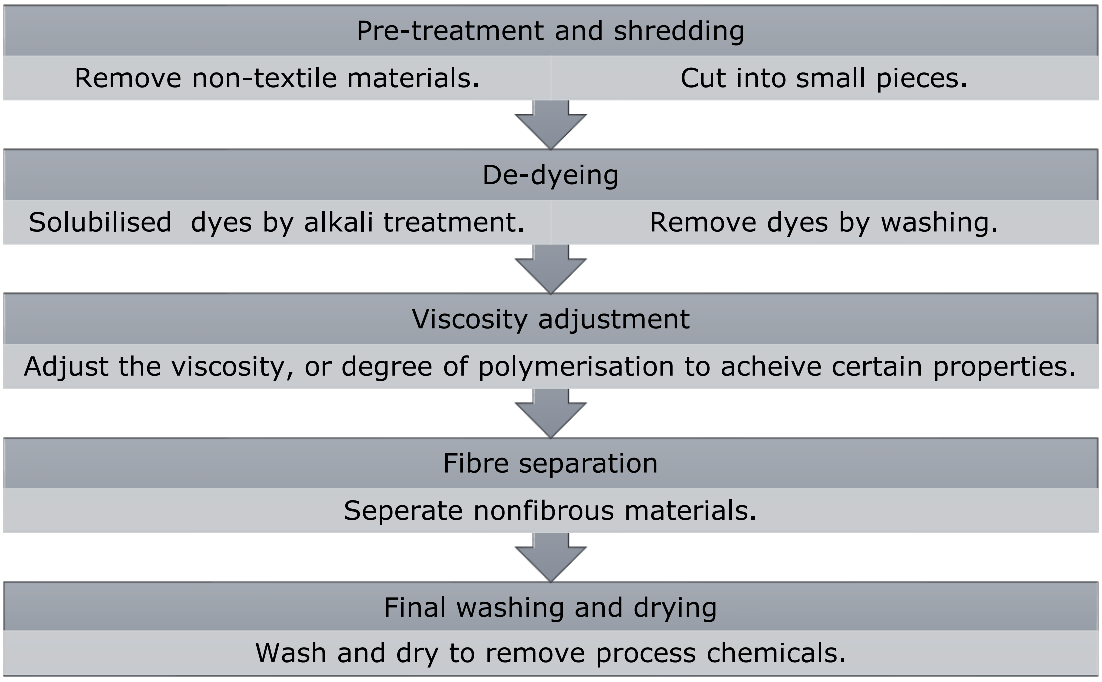

Figure 3.2 Chemical recycling process [36].

Chemical recycling of cotton is mainly based on the dissolution of cellulose. Dissolution of cellulose by using solvent and depolymerization are the two possible methods for cotton. Depolymerization of glucose monomer could be used for another application, where the former method is applicable for cotton recovery as regenerated cellulose fibre such as viscose and, lyocell. A chemical recycling process of cotton is shown in the figure 3.3.

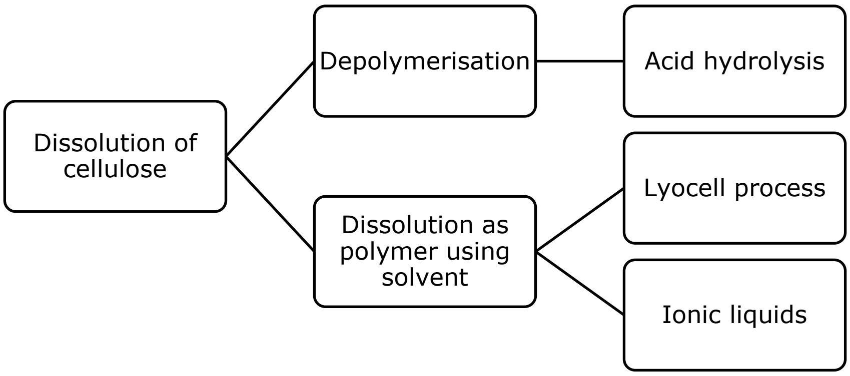

Figure 3.3 Chemical recycling of cotton [33].

3.4 Mechanical recycling

The most common method of mechanical processing is to cut and break the fabric into small pieces that can be used as padding in mattresses or upholstery, as insulation, or as the underlay of a carpet. Since various mechanical actions are applied to deform waste materials into the fibrous stage, the strength, and quality are decreased, therefore it is necessary to mix with virgin fibre or other materials, and to provide colour matching, thereby eliminating the need for re-dyeing. Other applications which use pre-consumer and post-consumer waste as feedstock materials include a variety of nonwovens used for insulation, automotive felting, oil-sorbent sheets. In terms of sustainability, mechanical recycling has less environmental footprint than chemical recycling [27][37]. However, mechanical recycling requires pure feedstock to get quality output [27].

3.4.1 Steps of mechanical recycling

Two main steps of mechanical recycling are sorting waste materials base on fibre types and colour depending on the desired output, and breakdown the materials into fibrous form.

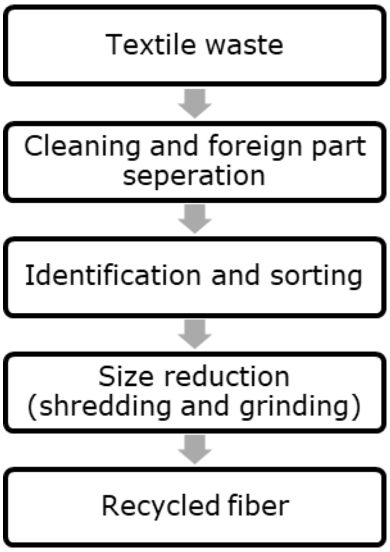

Figure 3.4 Process flow of mechanical recycling. Modified from [27][37].

Identification and sorting are done according to fibre types. In textile recycling a manual sorting is the universal practice. The basic method of sorting in clothing recycling is manual system. This is also used as a preparation for automate sorting processes, as clothing with reuse value is separated before automated sorting processes. Melt point indicator is a cheap device that can classify most types of fibres, but it is relatively slow. Studies are going on to develop and automation the identification and sorting of textile waste by applying Near-infrared (NIR) and Radio Frequency Identification (RFID) [38][39][40], [41]. Some studies have proposed a model of fibre identification and sorting based on NIR. This methods able to sort fibres with 100% accuracy [38][42]. Though, automatic sorting is not yet fully operational, but its purpose is to sort textiles according to fibre composition (pure and blended) and color [43]. These NIR and RFID are not new technologies, have been used for plastic sorting.

Size Reduction or shredding or breaking down the large fabric or garments. In the preparation stage of most recycling operations, size reduction to break large pieces of items into smaller size is often needed. Shredding or grinding is the mechanical process of size reduction that has been reported and many types of machinery are commercially available for textile and waste processing. In a standard operation, a rotary drum fitted with hardened blades against a feeding bed would cut the feedstock, and then transfer the cut material against a screen with a defined opening [44]. A machine like this has several pairs of rollers of different diameters and a lot of needles on the surface. The rollers shred the textile waste thoroughly by rotating at a high speed. Figure 3.5 shows textile waste shredder.

Figure 3.5 Textile waste recycling machine [45].

3.4.2 Mechanical recycling companies

Many companies including private and non-profit organisation are working to recycle post-consumer textile waste for producing new products. Table 3.1 presents name of some companies and their products.

Table 3.1 Mechanical recycling companies.

Company	Input	Output
Gebrüder Otto GmbH &Co.[46] (Germany)	Post-industrial textile waste, 100% cotton	Recot^2® fibre. 75% virgin cotton with 25% recycled cotton or 50% virgin cotton and 50% recycled cotton.
RECOVER TEXTILE SYSTEMS, S.L. [47] (Spain)	post-consumer and Post-industrial textile waste, 100% cotton	Recover® yarn. Blend 50% synthetic (PET, acrylic) with 50% recycled fibres.
GIOTEX[48] (Mexico, USA)	Post-industrial textile waste, 100% cotton.	Giotex™ yarn 75-90% recycled cotton blende yarn.
SOEX, Germany [49].	Post-consumer waste.	Mixer of recycled fibres.
Lounais-Suomen Jätehuolto (LSJH) [50].	Post-consumer waste.	Recycled fibres.

3.5 Challenges in textile recycling

Textile recycling is the potential alternative to minimize the production and consumption of virgin material and the generation of textile waste. However, recycling systems has been facing many challenges [33]. Textiles are made of complex materials. The materials present in the apparel have the possibility to hinder the flexible recycling process. In the current textile manufacturing chain, information about substances and amounts is not delivered to the recycling company [28]. Different types of fibres, both natural and manmade, are blended to achieve desired properties, even the sewing threads are also not identical with base fabrics. Different types of fibres are recycled with recycling techniques, this makes the recycling process complicated. The addition of accessories such as buttons, zippers, etc. makes the recycling process more difficult [33][51]. When textiles are coloured, the dyes and pigments are strongly bonded with fibre. Moreover, high-performance textiles also undergo several intense chemical treatments to impart special properties, for example, fireproof, waterproof treatments, etc. All these colorants and chemicals inhibit the easy recycling process, as to remove these additional kinds of additives requires more steps in terms of chemical recycling.

Use and laundering harm textiles not only at the fibre level but also at the polymer chain level, implying that mechanical recycling is at best a down-cycling operation with items with reduced fibre properties [52]. Although mechanical recycling systems are currently the most common method of textile recycling, it has limited capacity to provide alternatives to the raw materials used by the garment industry[33][51]. The lack of reasonably clean recyclable waste sources is a barrier to the use of these facilities to recycle textile waste, requiring the creation of recycling systems that can up-cycle mixed wastes [51].

4. APPLICATIONS OF RECYCLED FIBRES

Mechanically recycled fibres pose inferior quality compared to virgin fibres because of mechanical action during recycling operation. Furthermore, due to wear and laundering fibres lose their strength. In addition, the quality of recycled fibres might not be consistent due to different types of colour, fibre types and structure. Reprocessing a new product is the purpose of recycling textile waste. Traditionally, recycled textile waste is widely used for carpet cushion, clean-up products, home insulation, fibre stuffing, landscaping, mattress pads/futons, geotextiles, and concrete reinforcement [53]. However, many studies have also been done to make medium to higher count yarn from mechanically recycled fibre to produce garments.

4.1 Yarn manufacturing from recycled fibres

Ring spinning is a widely used yarn manufacturing process for knit and woven fabrics. However, some other yarn manufacturing systems are also available such as open-end spinning, air-jet spinning, friction spinning. The yarn manufacturing process includes fibres opening and cleaning, carding, blending and mixing, and spinning. Figure 4.1 illustrates the step-by-step process of yarn manufacturing.

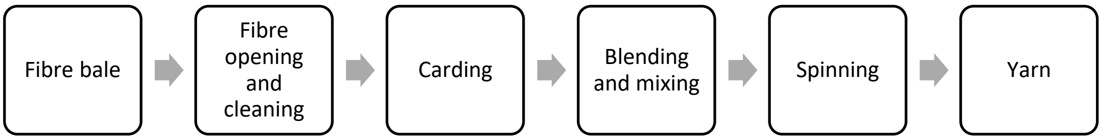

Figure 4.1 Process flow of yarn manufacturing.

Few studies have been done for manufacturing yarn from recycled fibres through different spinning systems. Merati et.al. produced Two-component and three-component core yarn of medium count through friction spinning system from recycled fibres in such a way that the recycled fibres remain in the middle of the yarn. The appearance and strength of the yarn was researched. This study concludes that yarn made from recycled fibres or blended with virgin fibres is compatible with 100% pure cotton yarn [54].

The open-end spinning process is widely used for producing yarn from low grade fibres. As recycled fibres pose inferior properties, the open-end spinning system was also studied for producing yarn from recycled fibres [55][56]. Inhomogeneous fibre type and non-uniform short fibre lengths distribution characterizes recycled fibre collected from post-industrial and post-consumer waste, all of which have a negative impact on the manufacturing process and the quality of recycled yarns generated from it. Blending recycled and virgin fibres is one of the most popular ways to use recycled fibre in yarn production. Demiroz et.al. investigated the quality of open-end yarns made from recycled fabric scrap wastes and virgin polyester fibres in various blend ratios and spinning parameters. Waste form, waste origin, yarn count, blend ratio, twist coefficient, and rotor diameter were chosen as material and spinning parameters, and their effects on the quality of recycled yarns were assessed. The quality of the yarns is greatly influenced by the blend ratio, yarn count, and twist coefficient, according to statistical findings. This study concluded that blending of virgin fibres with recycled cotton tends to enhance the yarn quality [57]. Lindström et.al. proposed an improved method for mechanical recycling of textile waste. The study expressed that producing yarn from 100% recycled fibres was possible, if the waste textiles were treated with polyethylene glycol (PEG) [58].

Yuksekkaya et.al. have done a comparative study on the physical properties of open-end yarn and fabric produced from recycled fibres. The results showed that yarns and fabrics made recycled fibre may be suitable for applications where unevenness, imperfections, and handling properties are necessary, but yarn and fabric strength are less essential. As a result, recycled fabrics appear to be best suited to the production of casual clothing such as sweatshirts, t-shirts, and sleepwear [59]. Ütebay et.al. studied the impact of waste type and recycling parameters on recycled fibres and open-end yarn quality. This study revealed that, in comparison to dyed fabrics, shredding of greige fabrics resulted in a lower short fibre ratio. Furthermore, yarns made from greige fabric-based recycled fibres had higher strength and were less hairy. Moreover, feeding size to shredder and number of shredding also affect the fibre and yarn quality [60].

Wanassi et.al. produced 100% recycled cotton yarns from post-industrial waste and investigated the effect of rotor speed and twist factor on yarn quality. The result showed that the twist factor has no significant impact on recycled yarn. However, rotor speed increased hairiness and CV% but decreased total quality index (TQI) [56]. Another study concluded, that the reclaimed and virgin cotton blended yarn has almost identical physical and mechanical properties compared to 100% cotton yarn and is less expensive thus the overall value of the yarn can be increased by more than 33.5 percent [55]. Yarns developed from a blend of virgin cotton, recycled cotton, and recycled polyester by the open-end spinning system, and the study resulted that yarns of 25% recycled cotton and 75% Recycled polyester blend showed optimum physical and mechanical properties [61].

Some studies have been done to produce yarns from chemically recycled polyester fibres blended with virgin cotton and viscose [62]–[64]. However, very few attempts were taken to develop ring-spun yarn from recycled post-consumer cotton waste. Producing yarn from post-consumer cotton waste through is still expected because ring-spun yarn is stronger and softer compared to open-end yarns [65]. M. Kuppen produced yarn through ring spinning system from 60% recycled cotton blend with medium grade cotton and flax fibre. This report showed that fibre friction and rigidity are the key factors that affect the spinnability of recycled fibres. Moreover, the recycled cotton fibres' spinnability is also affected by the blending with other virgin fibres. The recycled cotton fibres became more spinnable by the incorporation of virgin cotton, and the yarn gained tensile strength by adding flax fibres [66]. The knitted fabric prototype from these yarns was relatively weak with high standard deviation but had good abrasion resistance that would be usable for upholstery application [66].

Reiter, a textile machinery company, has develop Reiter recycling system for producing yarns through rotor and ring spinning system from recycled cotton (figure 4.2). This company claimed that it is possible to make yarn up to Ne[1] 20 from 75% recycled fibres blend with virgin fibre or Ne 30 from 87.5% recycled fibres blend with polyester through rotor spinning system. Additionally, through Reiter ring spinning system, it is also possible to produce recycled yarn up to Ne 20 from 60% recycled fibre blend with 40% virgin cotton or yarn up to Ne 30 from 60% recycled fibre and 40% virgin polyester [67].

4.2 Nonwoven materials from recycled fibres

Producing NWMs from postconsumer textile waste is a possibility to valorise textile waste. Nonwoven products made from textile waste need less processing steps than yarn, resulting in lower costs for the new materials and less environmental impact. Currently, the most common method of processing post-consumer waste is shredding

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[1] English counting system of yarn. This is expressed by numbers of hanks (840 yards) per pound. 10 Ne yarn means, the weight of 10 hanks (10×840 yards) yarns is 1 pound.

it to fibre fluff, then carding it to fibre web following needle punching or thermal bonding to make nonwovens. Recycled post-consumer waste is already used for some applications such as concrete reinforcement, carpet cushion, mattress pad, clean-up products, and home insulation. Recycled post-consumer waste also has the possibility to use in geotextile, landscape application, fibrefill stuffing [53].

NWMs are suitable for insulation materials due to their special structure. Recycled materials are increasingly being used in construction because they not only extract materials from the landfills but also reduce the consumption of natural resources and energy during the manufacturing process. As a result, insulation is a clear example of a recycled material application [68][69]. Nonwoven made from recycled cotton and polyester can be used as functional sound absorption in various applications such as insulation, interior for auditorium, automobile, aircraft [70][71].

The object of using carpet cushion is to prolong the life of the carpet's appearance. Other factors could include improved aesthetics, thermal insulation, energy absorption, and sound absorption. Carpet cushions are usually nonwovens, and needle punching, and thermal bonding processes are traditional manufacturing techniques for carpet cushions. Several companies have successfully used 100% recycled post-industrial garment trimming and recycled post-consumer fabrics in carpet cushioning and backing [53].

Cleaning products can be made from post-consumer waste. The absorption ability of a cleaning product is the most significant output characteristic. Both the form of fibre and the construction method has been found to influence the absorption ability of a nonwoven material. Oil sorption abilities of needle-punched cotton-containing sorbents were significantly higher than those of sorbents made entirely of polypropylene fibres. As a result, cleaning products made from recycled cotton waste are appropriate [53]. Recycled post-consumer waste can also be used in mattress pads. Needle punched or thermally bonded nonwoven made from textile by-product are currently used for mattress pad.

Filtration, separation, drainage, reinforcement, and erosion control are all important functions of geotextiles. Synthetic fibres are commonly used in geotextiles for a variety of reasons, including longevity, resilience, workability, and chemical and soil resistance. Since most geotextiles are intended to last a long time, using cotton or other natural fibres for these purposes will be ineffective owing to the biodegradability of natural fibres. Most geotextiles are used in civil engineering ventures. Nonwovens are suitable for high volume applications in geotextiles due to their lower production costs and a wide variety. So, to meet the requirement for geotextile application blend of synthetic and natural fibre could be a suitable technique [53].

Another possible application of post-consumer waste is in landscaping. Landscape fabric can be woven or nonwoven. Functions of landscape fabric are regulating soil temperature and moisture level. Landscape fabrics can be made from a blend of natural and synthetic recycled fibres. For example, if landscape fabric is made from recycled cotton and polyester, the recycled cotton will gradually degrade but the polyester part will remain in the soil structure [53].

4.3 Other applications of recycled fibres

Producing different types of composite by mixing together recycled textile waste materials and polymers, could be another possibility to use recycled fibres. Echeverria et al. developed composite materials for building application from textile waste by isothermal hot compression. In contrast to traditional wood-based particleboards, the recycled mix fibre reinforced composite displays optimum moisture tolerance, as well as load-bearing and non-load bearing applications [72]. Meng et al. developed composite from denim waste with epoxy resin. These composites show promising results in a variety of applications, including boards, plywood, and floors. Such products effectively substitute wood and help to conserve trees, thus benefiting the ecosystem [73]. Shaktivel et.al. developed recycled fibre reinforced nonwoven hybrid composite and explored the mechanical properties of the composite. It was concluded in the report that this resulted that this hybrid composite has potential as a building construction materials [74].

Fibre stuffing, such as for pet items or packaging envelopes, offers a potential market for recycled pre- and post-consumer fibres. Since neither the strength, the fibre quality, nor the sanitation of the fibrefill is of serious importance for stuffing used in pet products, it may be possible to use recycled postconsumer fibrefill in place of virgin polyester to save money [53].

5. NONWOVEN MATERIALS

According to ISO 9092:2019 Nonwovens-vocabulary, the nonwoven is an engineered fibrous assembly, primarily planar, which has been given a designed level of structural integrity by physical and/or chemical means, excluding weaving, knitting, or papermaking. Nonwoven is a novel engineered material made directly from fibres. Nonwovens have a wide range of applications in the field of healthcare, filtration, apparel, home textile, construction materials, etc. Nonwovens are in almost every step of our life. Depending on the application nonwoven can be absorbent, biodegradable, breathable, conductive, non-conductive, drapeable, permeable, impermeable, dyable, printable, smooth, soft, strong, and so on.

5.1 Fibres for nonwoven production

NWMs can be made from almost any kind of fibre. Fibre selection mostly depends on the required fabric profile and price. For NWMs production natural fibres (cotton, jute, flax, wool), synthetic fibres (polyester, polypropylene, polyamide and, special fibres (bicomponent, carbon, glass, nano-fibres) are commonly used [75][76]. Materials used in nonwovens are classified into types such as base materials or fibres and binders. Here binder can be in a liquid or fibre form. Binder fibres usually has low a melting point. NWMs properties, as well as processing efficiency, are influenced by fibre properties. The main quality parameters are web cohesion, web weight uniformity, and fibre breakage, which are controlled by fibre diameter, fibre thickness, tenacity, fibre finish, and crimp. Fibre properties and nonwoven's structural geometry play a big role in NWMs properties [76].

Figure 5.1 illustrates global fibre consumption for nonwoven in 2018. For NWMs manufacturing the most used fibre is polyester, which accounts 36% and followed by wood pulp and minerals fibres. Global NWMs production was 8.8 million tons in 2018 and 8% of them was from cotton or natural fibres.

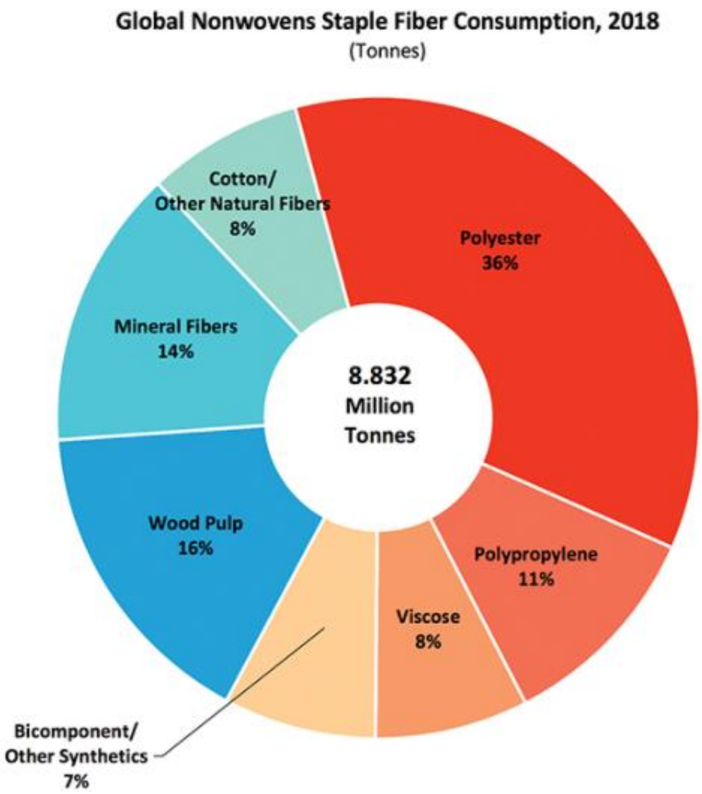


Figure 5.1 Global staple fibre consumption of nonwovens in 2018 [77].

Raw materials commonly used for nonwovens:

- Fibrous materials:
    - natural fibres (cotton, flax, hemp, wool),
    - synthetic fibres (polyester, polyamide, polypropylene),
    - regenerated fibre (viscose),
    - industrial fibre (glass fibre, carbon fibre, boron fibre, metal fibre),
    - reclaimed fibre,
- Other raw materials:
    - cellulose pulp,
    - granules (polyamide, polyester, polyolefin),
    - powder (polymer, additives, stabilizer, pigments),
    - absorbent polymers,
- Binders:
    - binder fibre/ adhesive fibre. (bicomponent PET, PLA),
    - binder liquid.

Since a wide range of NWMs are either being developed or already in manufacture, it is difficult to describe all types of NWMs, and fibres that are used. Details of textile fibres are presenting here.

5.1.1 Cotton

Cotton is a versatile and widely used natural cellulosic fibre. Cotton has hollow structure, ribbon shaped cross-section, spiral twist and hygroscopic in nature. All these properties make cotton perfect materials for nonwovens in terms of mechanical properties and serviceability. Figure 5.2 shows cross-sectional and longitudinal view of cotton fibre.

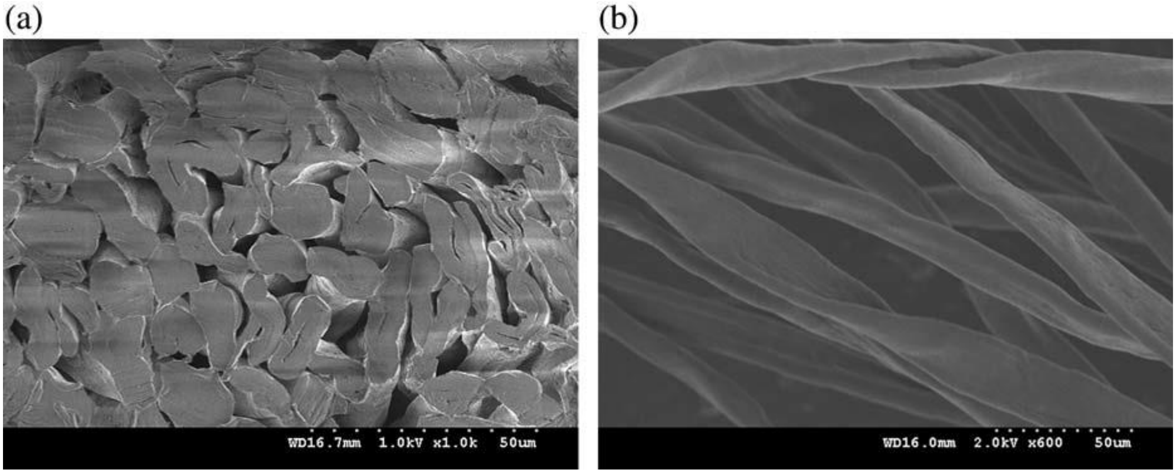


Figure 5.2 Cross-sectional (a) and longitudinal (b) views of cotton [78].

Raw Cotton consists of:

- cellulose (88–96%),
- pectin (0.7%–1.2%),
- waxes and fats (0.4%–1.0%),
- proteins (1.1%–1.9%),
- other organic matter (0.5%–1.0%),
- ash (1% to 1.8%) [78].

For extra ordinary characteristics, cotton use in the early years for the development of nonwoven bonded fabrics was successful. Cotton become popular because of its absorbency and softness along with availability at low cost. Table 5.1 illustrates properties of cotton fibre.

Table 5.1 Properties of cotton fibre [78].

Parameters	value
Fibre length	9-60 mm
Linear density	1.0-2.8 dtex
Elongation	5-10%
Tenacity	25-40 cN/tex
Moisture content	7.5-8%
Elastic recovery	45% recovery from a 5% stretch.
Specific gravity	1.54
Resilience	Low

Cotton is extensively used for apparel such as or underwear, leisurewear, jeans, shirting, work wear, knitwear, sportswear, dresses, and children’s wear. It is also used for home furnishing, such as curtains and bedding. Additionally, cotton is blended with other fibres, such as viscos, nylon, polyester, or modal to improve properties.

5.1.2 Polyester

Polyester is popular synthetic fibre. Polyester monomers are linked together with ester. Polyethylene terephthalate (PET) is by far the most significant polyester in commercial terms. Polyesters could be developed from a variety of acids and alcohols, according to this definition of the structure. Structure of polyester is shown in the figure 5.3.

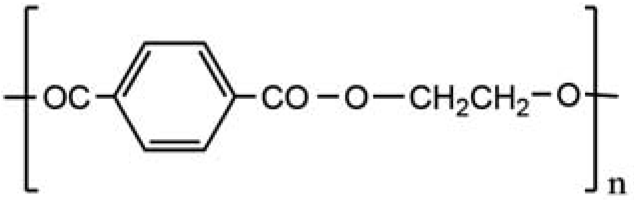


Figure 5.3 Polyethylene terephthalate (PET) structure [78].

Synthetic fibres are produced by extrusion of melted polymer through spinneret. This spinneret could be variety in shape. For successful extrusion, the viscosity of polymer should be adjusted. Polyester is melt extruded. After extrusion stretched the filament to give it suitable shape and properties.

Polyester fibres are extensively used in apparel, medical, industrial, and household application. Polyester is often blend with natural fibre and other synthetic fibres. Properties of polyester are shown in the table 5.2.

Table 5.2 Properties of polyester(PET) [78].

Parameters	**value**
Specific gravity	1.38
Tenacity	35–56 cN/tex
Elongation at break	15–40%
Elastic recovery	80% from an 8% stretch
Resilience	High
Melt temperature	260 °C
Moisture regain	0.4%
Abrasion resistance	High

5.1.3 Recycled fibres

Textile fibrous materials used in the second or subsequent manufacturing cycles are referred to as recycled fibres. They are made from used and discarded textiles. Textile fibrous fabrics are ideally suited for repeated use due to their unique characteristics and inherent functionality.

The traditional source of raw material for the manufacture of recycled fibres is used clothes and waste textile materials. Recycled fibres have different properties than original fibre because of wearing and recycling treatment. Recycled fibres contain high amount of short fibre together with yarn and fabric scraps. Mostly recycled fibres are blended if sorting have not performed according to fibre types before recycling.

To turn them into nonwovens, high proportions of broken-down fibres with long enough lengths for the appropriate web-forming process are needed. Short fibres and dusts, as well as leftover fabric parts, obstruct production. Their share should be held to a minimum, which can be accomplished by the use of optimum material-related tearing technology [75].

Automotive textiles and construction textiles with the key functions of insulation and shielding, and geotextiles are examples of nonwovens made from or with recycled fibres. Nonwovens for the upholstery and mattress industries, as well as cloth secondary backs for floor coverings, are other examples [75].

5.1.4 Bicomponent fibres

Bicomponent fibres are made up of two different polymers that run the entire length of the fibre. The two component polymers do not interact at the molecular level. Sheath-core structures and side-by-side structures are common examples of bicomponent fibres, but other more complex structures have also been developed. An example of sheath core bicomponent fibre is shown in Figure 5.4.

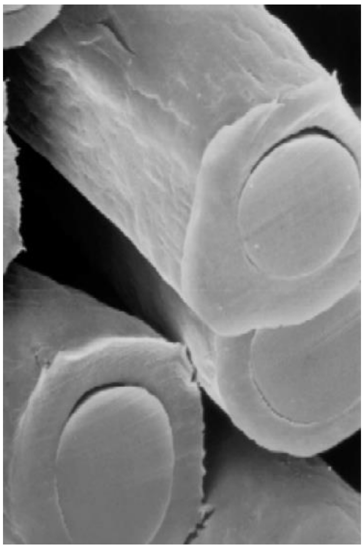


Figure 5.4 Cross-section of bicomponent fibres [78].

There must be two different component streams in the extruder before they converge just before emerging via the holes in the spinneret in order to obtain the structure of the two component polymers in a bicomponent fibre. The design of the spinneret must be tailored according to desired fibre types. Furthermore, for the efficient generation bicomponent fibres, the viscosities of the component polymers must be well balanced under the selected extrusion conditions.

Bicomponent fibres possess several benefits over single component fibres. Mechanical creep and thermal shrinkage may also be minimized. In polyolefin bicomponent, for example, the second polymer can allow effective dyeing. Where the waviness of the fibre is essential, bicomponent fibres can be used. Crimping has a lot of appealing visual qualities. Bicomponent fibres based on two variants of acrylic polymers are a good example. Bicomponent fibre are made in such a way that have a sheath with a lower melt temperature than the core. PE-PP, co-PET/PET, PLA sheath-core fibres are a common example. The sheath melts when the fibres are sufficiently heated, but the core remains intact. In Co-PET/PET, the sheath melts approximately at 100-110 °C while the core melts at 250-265 °C.

Bicomponent fibres have potential application in nonwoven manufacturing. Bicomponent fibres are using as binder fibre in nonwoven manufacturing. Depending on the application bicomponent fibre are blends at 10-50% ratio. An experimental guide of using co-PET/PET bicomponent based on handle properties is shown in the table 5.3.

Additionally, Polylactic acid (PLA) as a thermoplastic and biodegradable material could be produced from natural resources. Among other application PLA can be better choice for nonwoven production due to its physical and chemical properties. PLA could be bicomponent by low melting sheath PLA and core PLA.

Table 5.3 Nonwoven production guide from co-PET/PET bicomponent [76].

Parameters	**Nonwoven fabric handle**		
	Soft	Medium	Harsh
Bicomponent fibre content (%)	10-20	15-30	>30
Bonding temperature (ºC)	140-150	150-160	160-180
Fibre fineness (dtex)	1.7-3.3	3.3-6.7	>6.7

5.2 Nonwoven manufacturing process

One of the major merits of nonwoven is that it is directly produced from raw materials to finished products without any materials handling. Nonwoven processing can be done in two steps, preparation of fibre web appropriate for bonding and the bonding process. there are several ways for fibre web formation, all of which have their own characteristics on final products. Similarly, bonding of fibre web also has different methods. Application of bonding methods depends on the end products.

5.2.1 Fibre web preparation

The aim of web development is to create a finished product with unique features. The preconditions for economic growth are consistent high quality, high production rates, and low costs. The fibre material used, as well as the machines and aids used in the process, influence all three factors. Fibre web preparation can be divided in to two process, dry-lay process, and wet-lay process.

Dry-lay method is method of fibre web preparation by carding. The object is carding is to open the fibre tuft into single fibre and make parallel. Depending on the fibre short-staple flat carding or long-staple roller carding can be used. Normally, prepared web by carding is light weight to make nonwoven, to make it heavy and more uniform several layer of webs can be use over each other. Air laying is alternative method of dry-laid method, which is suitable to form heavy web [79].

Wet-lay method is mainly based on paper making process [75]. Typical stages for wet-lay method are:

- fibre dispersion in water,
- continuous web formation through filtration on wire cloth,
- consolidation, drying and batching the web.

Figure 5.5 shows stages of dry-lay fibre web formation.

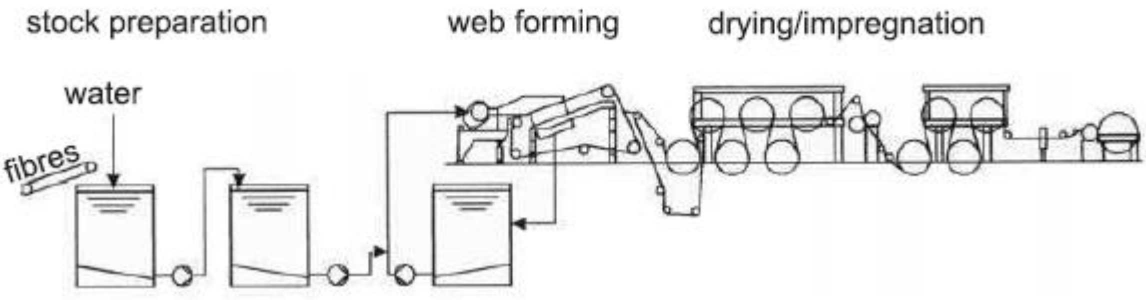


Figure 5.5 Steps of wet-lay process [75].

5.2.2 Web bonding

The fibres are consolidated during the web bonding phase to ensure that the finished felts meet the required requirements for the intended end use. The level of web bonding is determined by fibre characteristics such as geometry, tenacity, and form, as well as fibre position within the felt, felt mass, and the bonding process changes.

A physical, chemical, or thermal method is used to transform a fibre web into a cloth. The bonding occurs all over the layer, or areas of it. The fusion of the web during the bonding phase strengthens the entanglement of fibres or continuous filament. Cohesion, friction, and adhesive surface forces all contribute to physical entanglement between fibres. Only when dissolved fibre surfaces meet or binding agents of the same polymer are added do chemical bonds between fibres form. The chemical composition of the polymer's monomer unit can be used to establish these fibre surface bonds. Figure 5.6 illustrates different bonding process.

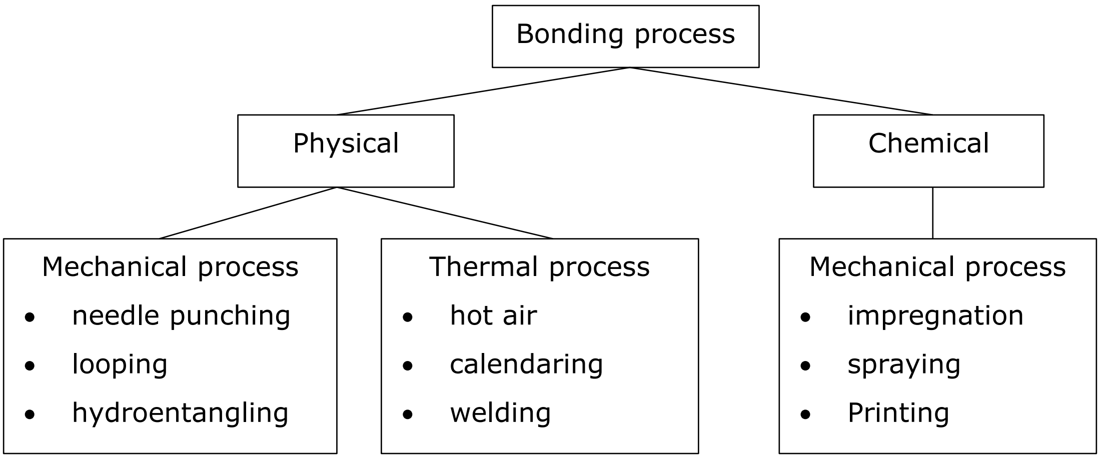


Figure 5.6 Different bonding process [75].

Mechanical bonding are three types, needle punching, stitching and hydroentangling. Mechanical processes rely on frictional force and fibre entangling. Needling is a simple process of penetrating a number of needles through the web. Figure 5.7 shows basic needle punching process. Needled nonwovens have high strength properties but poor modulus and recovery. Needled felt mostly used as filtration media.

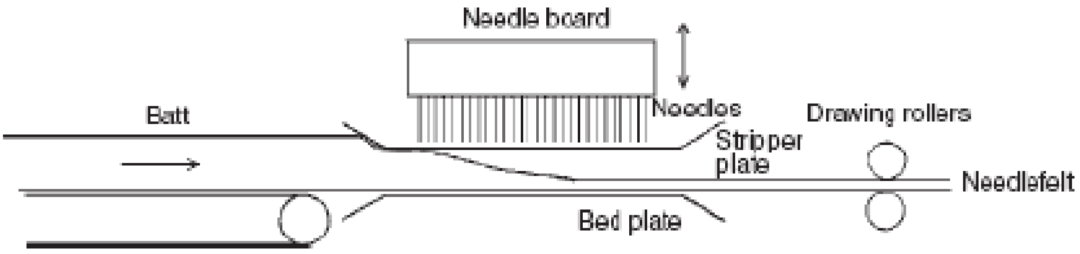


Figure 5.7 Needlepunching process [79].

Looping or stitch bonding is done based on warp-knitting or weft-knitting principle, compound needles are used for loop formation. Stitch bonding can be done with or without threads. Stitch bonded nonwovens are textile like and flexible [79].

Hydroentangling bonding is performed with high pressure by water jet [79][75]. Webs of fibres, filaments, or sheets of various fibre structures are bonded by the action of a mechanism of fluid jets or currents with a required minimum force in which fibres or fibre sections are captured and repositioned by the striking jets or currents and become intertwined, entangled, or even knotted with other fibre components. Hydroentangled nonwovens are soft, drapeable and have good abrasion resistance, can be used for polishing, wiping and cleanings cloths.

Thermal calendar boding is used for the webs made with or blend with thermoplastic fibres. During thermal bonding heat is applied for certain time and pressure, thus the fusible fibres melt and create bond with other fibres. The degree of web bonding depends on:

- the fibre properties such as length, fineness, crimp, elasticoviscous characteristics under thermodynamic situation and their melting and softening temperatures,
- roller diameter, line pressure in the roller gap,
- mass of the web to be bonded,
- speed,
- thermal treatment temperature,
- type and share of engraving on the roller surface [75].

5.3 Properties of nonwoven materials

On an early age nonwoven fabric are substantially utilized only in medical textiles as it is easy to produce, environment friendly, low cost in production and versatility [80]. This kind of fabrics are popular and easy to use because it is cheap, cost effective, superficial, high longevity, impermeable, soft, and disposable easily [81]. According to European disposal and nonwoven association nonwoven is defines as: A manufactured sheet or a form of either directional or irregular fibre which is bonded by any kind of fiction, cohesion or adhesion and also eliminating paper and products which are woven, knitted, tufted, stitched and also incorporating binding of yarn or filaments. It also excluded the form which is bounded by wet-milling whether it can be additionally needled or not. Nonwoven can be naturally produced or can be manufactured artificially. It can also be staple or continuous filament [82][83]. The basic properties of nonwovens are discussed below.

5.3.1 Physical properties

Important physical properties of nonwovens are thickness and mass per unit area. These properties can be altered depending on final application. Functional properties of nonwovens are significantly influenced by physical properties. For example, air permeability mostly depends on thickness when other parameters are constant.

5.3.2 Mechanical properties

When considering the mechanical properties of nonwovens tensile strength, elongation, toughness, breaking length, tear strength, bursting strength have the key interest. Mechanical and geometrical properties of fibres used for nonwoven preparation are important factors that determine the nonwoven properties. The mechanical properties of nonwovens are determined to some degree by its structure. The factors that affect nonwoven mechanical properties[84]:

- fibre length and diameter,
- fibre distribution,
- fibre web preparation mechanism,
- thermal treatment temperature.

5.3.3 Functional properties of nonwovens

Absorbency, while discussing the key properties of nonwoven, is the main attraction of this kind of textiles. Considering the absorbency of nonwoven, it is widely used in hygiene materials. This kind of fibres are naturally very soft and easily disposable, thereby this softness can be adjusted by adjusting spinning speed, polymer type and filament diameter e.g- by reducing the filament diameter fabric of softer touch can be achieved [83]. Taking into account this absorbency, it can create a barrier property to avoid unpleasantness caused by urine degradation and thereby, ensure proper hygiene. It can create a very uniform web so that it can grant a stronger protection. It also eliminates the use of several layers as it possesses a good absorbency property [82][83].

The important properties regarding this absorbency are wicking, water absorption, water retention and minimal linting characteristics. For example, superabsorbent fibres can be made from superabsorbent polymers (SAPs). SAPs are kind of hydrogels that can absorb water at 100 times of their own weight while in comparison to conventional wood pulp with cotton filler absorbents absorb only 6 times their weight [85]. Example of superabsorbent fibres are OASIS SAF®, Aquakeep®, and Norsocryl® which perform effectively in the industry of hygiene because of their low density that allows soft non-bulky products. It also creates almost invisible blending while incorporating with other fibres and thereby allowing products a satisfying, gratifying organic and natural appearance to the end user. By generating high absorbency rates it can decrease blocking large molecules that are present in blood and other body fluids [86].

Nonwoven textiles show effective filtration properties in great extent. In past 30 years nonwoven geo textiles are widely used as drainage and filter materials in the sector of geo technical and geo chemical and environmental project. Moreover, it is very permeable and compressive material thereby, the thickness of it decreases under stress and creates coefficient and of permeability and pore dimensions [87]. Filtration efficiency means the ratio of weight of particles eliminated and weight of particles transferred to the filter. Filtration efficiency is expressed in term of percentage [88]. Both woven and nonwoven textiles act as typical filter fabrics due to fibrous materials. However, as nonwoven fabrics shows higher air permeability controlled pores per unit area thereby, shows higher filtration efficiency rather than woven fabrics [89].

Nonwovens which are thermal bonded and spun bonded ensure better filtration in comparison to other filtration fabrics as it exhibits minimal pore size and its proper even distribution [90].Nonwoven filter samples which are thermal bonded and produced from staple fibres got multiple filtration layers of inter connected and confined pore paths through the fabric thickness [90][91] . This thermal bonded fabric is produced by area bonding or point bonding process in presence of web containing binder fibres [92]. For example, Polypropylene is displayed as a suitable binder fibre to produce staple fibre of thermal bonded nonwoven fabric [93][94]. Polypropylene blended with cellulosic fibres can also produce this kind of nonwoven fabric. For instance, hemp and polypropylene are blended to produce nonwoven fabrics and used in multi purposes [95].

Thermal properties: Thermal insulation materials are widely used in automotive industry and civil engineering in terms of ease and comfort, reducing energy, safety, cost effectiveness and finally saving the world from global warming [96]. The continuous technical and mechanical developments in polymers and fibre technology privileged the improvement of nonwoven textiles. The unique and predominant porous structure gives the nonwoven materials profound and potential thermal and acoustic properties [97]. The complex three-dimensional fibre structure which is created while using needles to manufacture nonwoven textiles materials applied in different industrial sectors for thermal insulation properties. Needle-punched nonwovens create a structure of anisotropic hardy possess an explicable behaviour regarding nonwoven textiles. In the operation of needling process, fibres in the felt are interconnected with their own fibres and after that using needles of special construction that transfer fibres from the surface into the felt depth. This procedure leads a product of special structure which is resistant to mechanical action and therefore finds broad and various applications [98].

Nonwovens are porous materials which contain solid matrix (the fibres) with interconnected pores. The interconnectedness of the pores thereby allows the flow of one or more fluids through the material. In this process the flow constituted by the air, which makes the nonwoven materials ideal media for insulation applications [99]. However, studies of investigating the thermal insulation properties of nonwovens depict that 100% polyester and 100% polypropylene nonwovens appear themselves as thermal insulator. This is because, it is found that Polyester fabric had higher thermal resistance and specific heat resistance than polypropylene as fabric thickness has an outstanding effect on the fabric temperature variations [100].

Higher tensile strength, higher stiffness, lower elongation, lower thermal conductivity, lower air permeability, and good absorption coefficient make nonwovens suitable for automotive interior noise control. For thermal insulation least air permeable NWMs are suitable. For ventilation or comfort, in clothes, high air permeability is preferred.

5.4 Application of nonwovens

Nonwoven textiles are prevalent because it is sustainable, versatile, low cost, unique, innovative, easy to convert into high tech engineered product. The application of this kind of materials starting from medical textiles and now has been widely used in every aspect of life as it also has a good disposable capacity without creating any kind of disturbance to the nature. In contemporary world, customers are much more concerned about sustainability rather than other feature of the products; and these nonwoven textiles prevail over other textiles in terms of green technology. Some of the application features are discussed below:

5.4.1 Hygiene Materials

Nonwoven materials offer standard soaked up capacity, smoothness, durability, comfort, high breathability, uniformity, and easy to discard without contamination to the environment. This nature has made it popular in terms of health and hygiene care [101].

5.4.2 Medical textiles

In medical textiles like surgical gloves, mask, cap and gown are mostly made by this nonwoven. The use of nonwovens in clinical area is going lower back to the time of Second World War while want for brand new and massive volumes of clinical product had arisen. In numerous reviews published, nonwovens have been appeared because the simplest substances for bacterial barriers. They have been additionally determined advanced to linens with inside the discount of air-borne infection.

After enormous improvement of nonwovens, they have been designed in a manner to in shape the clinical desires and deliver an overall performance a great deal higher than their woven opposite numbers in phrases of value, effectiveness, disposability etc. In hospitals, cross-infection is usually certainly considered one among the most important issues which have been attributed in large part to re-the usage of woven gowns, mask and different comparable articles which might get infected and doubtlessly unfold the germs. The creation of nonwovens facilitated the improvement of a greater value powerful opportunity which become disposable and decreased the hassle of cross-infection greatly.

5.4.3 Nonwoven as home textiles

Nonwovens are used largely in various home textiles and interior design and thereby ensure an aesthetic and traditional effect in modern life. For instance, upholstery materials, floorcoverings, wallcoverings, and furnishings are popular among them. The role of nonwoven in interior design starts from supplied as roll raw goods, work in the production process, repair and restoration of upholstered furniture, the laying of textile and flexible floorcovering, the production of wallcoverings, the production and fitting of window furnishings[75].

Upholstery supports and upholstery covers are most of the time made of nonwoven. Approximately 80 to 90% production in upholstery furniture and all types of mattress are made by this nonwoven. Earlier plain-weave cotton fabrics were used for backing of mattress and carpet but due to tremendous development in the industry of nonwoven textiles, now a days various nonwoven filament polymer is utilized in this interior industry. Depending on the type of bonding, a distinction is drawn between:

- bonded polyester wadding or polyester nonwovens for covering upholstery materials in cases parts of the upholstered furniture are not subjected to much stress,
- thermal bonded nonwovens as covers for foam backed upholsters,
- nonwovens laminated or quilted with lock knit on one or both sides as covers for foam backed upholstery with high dimensional stability.

However, the main parts of upholstered furniture and mattresses are produced from foam, as it has good elasticity, compressibility and recovery properties. 'Fibrous webs' were made from bicomponent fibres which produce good bonding points when heat and pressure are applied. Dynamic loads are pressed to ensure that the thick, bulky nonwovens have high compressibility and a good recovery capacity.

Nonwoven floor covering: Needled nonwoven fabrics are usually processed form which used approximately 20–25% of all the floor coverings manufactured in Germany. A mattress is part of bed which is made of a strong cloth cover and filled with a resilient material (such as cotton, hair, feathers, foam rubber, an arrangement of coiled springs and sometimes also with water) used either as a bed or on a bedstead which makes the bed more comfortable to lie on[79].

Needled nonwoven used particularly in the household sector which are two-colour patterns with high-low effects. Needlefelt floorcoverings are mainly produced from polypropylene or polyamide fibres. In the production of textile floorcoverings with a smooth surface, using the two-stage process, the covering layer can be produced from primary fibres and the bottom layer from waste fibres. High dimensional stability is achieved by using reinforcing fabrics or back coating.

Nonwoven fabrics for wallcoverings: Nonwoven fabrics are only used to a limited degree in wallcoverings. Thus, for example, use is made of textile wallpaper, where medium- to heavyweight paper is laminated with, amongst others, fibre webs and then coated with polyethylene to form wallcoverings. Further, nonwoven wall hangings, so-called ‘furnishing felts’, are used as wallcoverings. These wall hangings are needled nonwoven fabrics from synthetic fibres. Walls can be suitably decorated by using the appropriate surface patterning.

Tufting substrate: Tufted carpets consist of 3 elements: pile, tufting substrate (or primary backing), and secondary backing. Of these three, the primary backing is sandwiched in between pile and secondary backing: invisible to the end user, it is nevertheless an important factor in determining carpet properties and influences some aesthetic aspects. The substrate’s role goes beyond end use properties, however, and is also quite significant in the various processing stages: tufting, dyeing, coating, and – where applicable – moulding. Substrate properties depend on the choice of raw material and manufacturing specifics. The principal raw materials in current use are polypropylene (PP) and polyester (PET). Of these two, PP has the lower strength. Its thermal resistance is also lower, and it is harder to stabilize against the effects of climate change, more flammable, and capable of only moderate adhesion to coating materials [75]. From the manufacturing perspective, there are two fundamentally different tufting substrates: woven substrates and nonwovens (such as spunbonded materials).

6. MATERIALS AND METHODS

This chapter gives an overview of types and characteristics of raw materials used for current study. In addition, nonwoven preparation methods, raw materials and nonwovens test methods are also described in method section.

6.1 Materials

In this work, for nonwoven preparation seven different types of textile fibres were used. They are following:

1. Virgin fibres used for nonwovens
    a. cotton,
    b. regular polyester (P).
2. Recycled fibres used for nonwovens
    a. recycled cotton type 1 (RCO),
    b. recycled cotton type 2 (R'CO),
    c. recycled mixed fibre (RMF).
3. Virgin bonding fibres (bicomponent fibre) used for nonwovens
    a. low melting polyester (LMP),
    b. polylactic acid (PLA).

Virgin cotton and regular polyester fibre were used as base fibres of nonwoven processing. Table 6.1 shows specification of virgin cotton and regular polyester. Figure 6.1 shows cotton and regular polyester.

Table 6.1 Specification of virgin cotton and regular polyester (appendix 1).

	Cotton	**Polyester**
Supplier	Paragon Sleep AS	Fiber partner
Fibre length (mm)	-	
Linear density (dtex)	-	1.66-1.76
Tenacity (g/dtex)	-	4.5
Elongation (%)	-	49

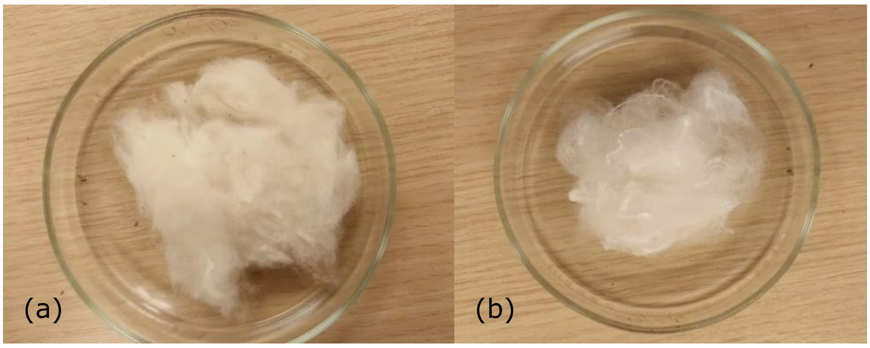


Figure 6.1 Images of (a) virgin cotton and (b) regular polyester.

LMP and PLA were used as bonding fibres. LMP and PLA are bicomponent fibre, which have low melting point. PLA bicomponent fibre made with PLA low-melt sheath and PLA core. Table 6.2 illustrates virgin bonding fibres specification. Figure 6.2 shows LMP and PLA fibres.

Table 6.2 Specification of virgin bonding LMP and PLA fibre.

	LMP	**PLA**
Supplier	Taekwang industrial Co. Ltd	Far eastern textile Ltd.
Fibre length (mm)	51	51
Linear density(dtex)*	4.4	4.4
Tenacity (g/dtex)	-	3.2
Elongation at break (%)	-	45
Melting temperature	110 °C	130 °C-170 °C

*dtex - decitex

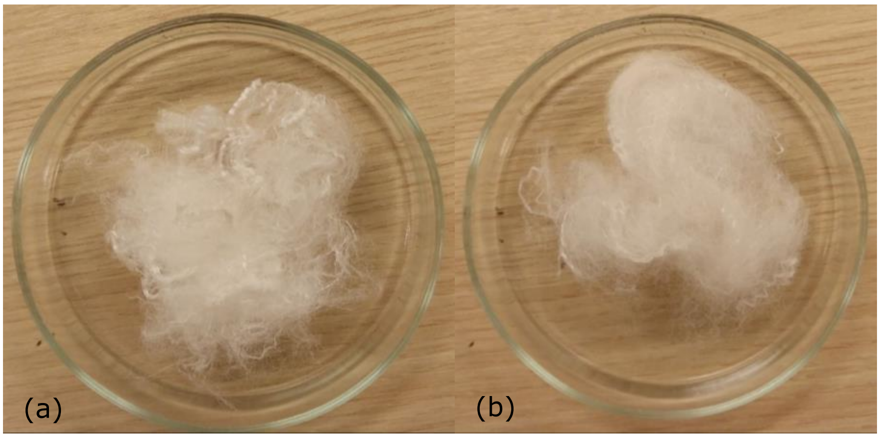


Figure 6.2 Images of (a) PLA and (b) LMP fibres.

In this study three types of recycled fibres were used for nonwoven preparation. All types are mechanically recycled from post-consumer textile waste. Table 6.3 shows specification of recycled fibre.

Table 6.3 Specification of recycled fibres.

	RCO	R'CO	RMF
Supplier	Department of Mechanical and Industrial Engineering	Lounais-Suomen Jätehuolto (LSJH), Finland	Lounais-Suomen Jätehuolto (LSJH), Finland
Recyclling system	Mechanical	Mechanical	Mechanical
Waste type	Post-consumer	Post-consumer	Post-consumer

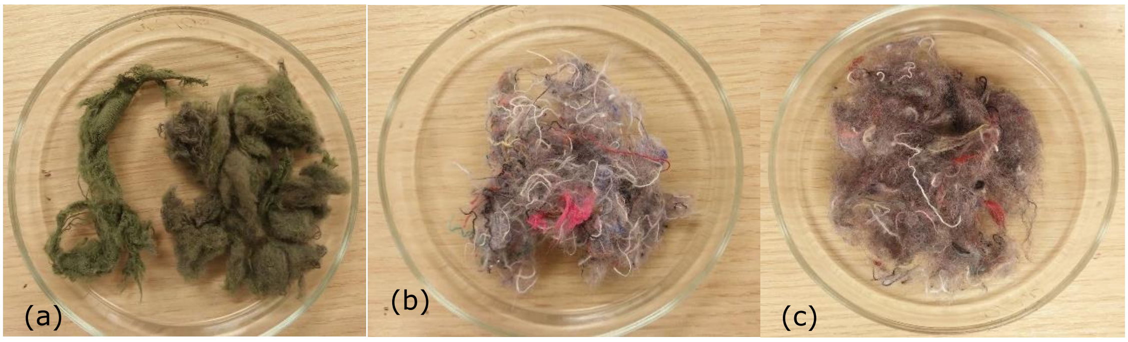


Figure 6.3 Images of (a) Recycled cotton Type 1, (b) Recycled cotton type 2 and (c) Recycled mixes fibre.

6.2 Methods

In this section manufacturing process of nonwoven is discussed. Moreover, test methods for determining fibre length and linear density, and nonwoven mass per unit area, air permeability and tensile properties are also described.

6.2.1 Nonwoven preparation

In this work nonwovens were prepared by two steps fibre web preparation and thermal treatment. Fibre webs were prepared by dry laid method. This method includes fibre web preparation by carding process. In this study two types of carder, hand carder and sei-industrial carder, were used. After fibre web preparation final nonwovens were made by thermal heat treatment by using a fusing machine.

Table 6.4 Fibre mixing ratio for hand-carded nonwovens (all materials were treated with 120 °C, 135 °C, 150 °C).

Fibre content	P: LMP	CO:P: LMP	CO: PLA	CO: LMP*	CO:PLA*	RCO: LMP	RCO: PLA	CO:RCO:LMP	CO:RCO:PLA
Fibre ratio	90:10	90:10	90:10	90:10	90:10	90:10	90:10	90:10	90:10
	80:20	80:20	80:20	80:20	80:20	80:20	80:20	80:20	80:20
	70:30	70:30	70:30	70:30	70:30	70:30	70:30	70:30	70:30

*carded web prepared by Early Stage Researcher Tiina Mäe.

Table 6.5 Fibre mixing ratio for semi-industrially carded nonwovens*(all the materials were treated with 120 °C, 135 °C, 150 °C).

Fibre content	P:LMP	CO:P: LMP	CO:P: PLA	CO:LMP	CO:PLA	RCO:LMP	RCO:PLA	CO:RCO:LMP
Fibre ratio (%)	90:10	90:10	90:10	90:10	90:10		90:10	
	80:20	80:20	80:20	80:20	80:20	80:20	80:20	
	70:30	70:30	70:30	70:30	70:30	70:30	70:30	70:30

*semi-industrially carded nonwovens were prepared by staff of University of Tartu Viljandi Culture Academy.

Carded web preparation is the first steps of nonwoven preparation. The purpose of carding is to parallelise and blend fibres in the web.

Machines used for carded web preparation:

- Louët classical hand carder (Figure 6.4) - classical hand carder mainly designed for long staple fibre carding, wool, hemp, flax etc. Cardings were done in TalTech Laboratory of Polymers and Textile Technology.
- Ramella semi-industrial carder (figure 6.5). Cardings were done in University of Tartu Viljandi Culture Academy by their staff.

Figure 6.4 Louët hand carder. [102].

Figure 6.5 Ramella semi-industrial carder [103].

Experimental procedures for hand-carding:

- At first loosen the fibre tuft with hand and when making web from recycled cotton (type 1) separate fabric scraps, as recycled cotton contains significant amount of fabric scraps.
- Fed fibre on to the liker-in drum and for better carding action fed small amount of fibre at once. Cranked the swift drum clockwise so that licker in drum pull the fibre. Fed all amount of fibre for certain sample.
- By rotation, the fibre will be transferred from licker into swift drum. Figure 6.6 shows hand driven carding process.
- Fed the fibres evenly along entire width of the drum for uniform web thickness. When the swift drum is filled with fibres, remove the web carefully from the drum.
- In this study, when making hand-carded nonwoven, the frequency of carding was six, that means that the same web was card six times to get even and proper blended web [104].

Figure 6.6 Carding process.

- Blend with second fibre (bonding fibre) during second carding. For carding second time spilt the prepared fibre web lengthwise. Elongate and spread the split web into full width. Then fed the loosen fibre web and make sure the fibres are distributed across the whole width of the drum.
- If nonwovens made from three different types of fibres, then blend the third fibre with previously blended web during third carding. Figure 6.7 illustrates carding and blending process flow of two and three different types of fibres.
- After sixth carding take the carded web from carder carefully. Figure 6.8 shows carded webs after six times carding.

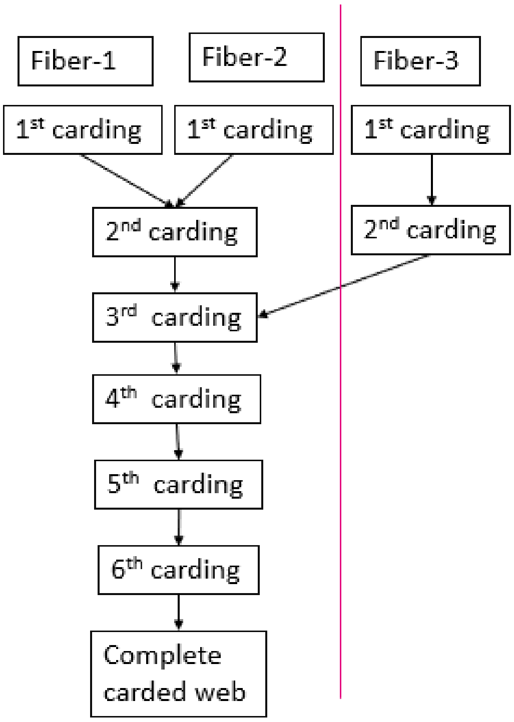


Figure 6.7 Carding and blending process sequence.

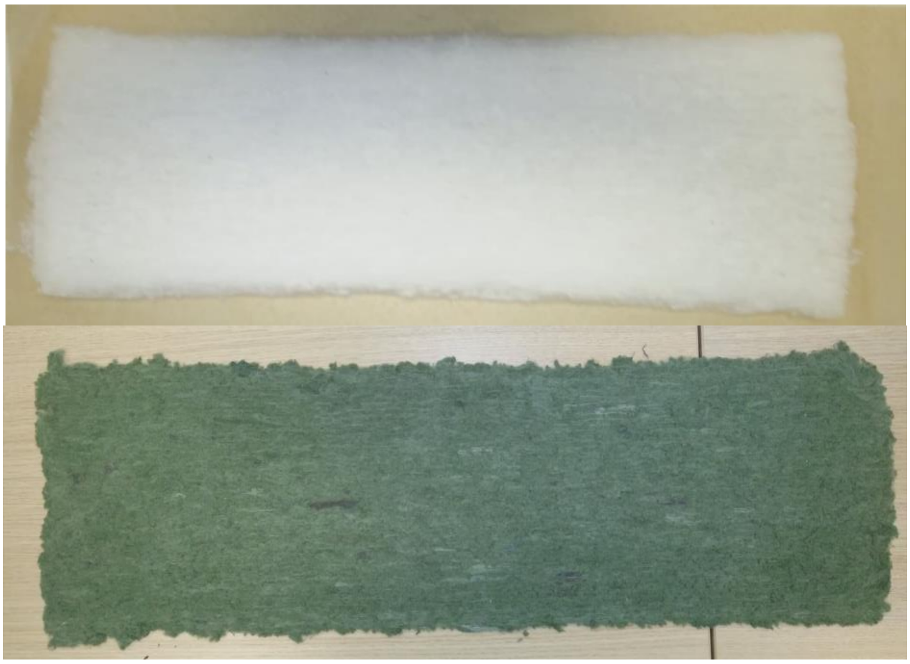


Figure 6.8 Carded webs after six cardings.

In this study, for hand-carded nonwovens, 66.6 gm of fibres were taken with different ratio. For semi-industrially carded nonwovens the ratio also same but processing was different.

Thermal treatment was done by MEYER RPS-L400 fusing machine in TalTech Laboratory of Polymers and Textile Technology. Figure 6.9 shows the fusing machine used for thermal treatment.

Three parameters of the fusing machine used for nonwoven preparation:

- the conveyer belt speed - 2.5 m/min,
- applied pressure - 0 N/cm^2,
- applied thermal treatment temperatures (TTT) – 120 °C, 135 °C and 150 °C. These temperatures were selected based on the melting point of bonding fibres.

Figure 6.9 MEYER RPS-L400 fusing machine.

6.2.2 Characterisation of textile fibres and nonwovens

Fibre length and linear density were tested before nonwoven preparation. Mass per unit area, air permeability and tensile strength tests were done on nonwovens. Table 6.7 shows the overview of different testing methods used to test the textiles fibres and nonwovens.

Table 6.6 Overview of fibre and nonwoven test methods.

Test name	Test method	Apparatus used
Fibre linear density	EVS EN ISO 1973:2000 [105].	Lenzing vibroscope
Fibre length	ISO 6989:1981 [106].	Ruler, digital microscope
Fibre Melting point	DSC analysis, Hot stage microscope	PerkinElmer DSC 7, Zwiss primostar3
Mass per unit area	EVS-EN-ISO ISO 9073-1:1989 [107].	KERN KB 6500-1NM analytical balance
Air permeability	EVS-EN-ISO 9073-15:2007 [108].	TEXTEST FX 3340 MinAir
Tensile strength	EVS-EN 29073-3:2000 [109].	Instron 5886

Fibre linear density was measured according to EVS EN ISO 1973:2000, textile fibres-determination of linear density (vibroscope method). Lenzing vibroscope (figure 6.4) machine was used to conduct this test in TalTech Laboratory of Polymers and Textile Technology. Test was conducted in conditioned room and materials were also conditioned according to standard EVS EN 139. Individual fibre under specific tension were subjected to vibration at resonance frequency. The linear density is determined from the resonance state, i.e., resonance frequency, fibre length and tension. The unit for linear density is dtex (decitex).

Equipment used for linear density test:

- Lenzing Vibroscope (figure 6.4),
- pretension weight,
- forceps.

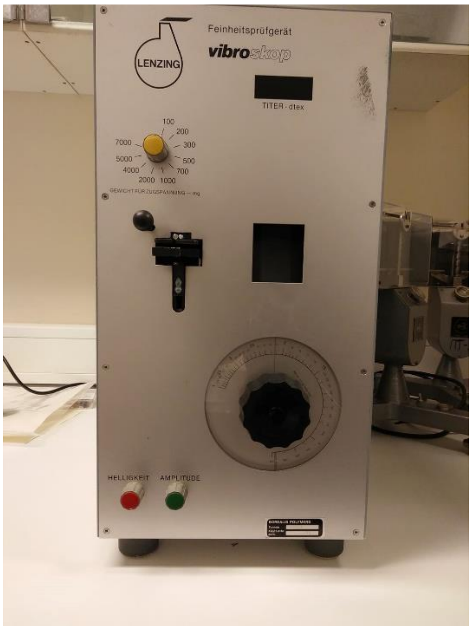


Figure 6.10 Lenzing vibroscope.

Test procedure:

- 25 fibres were taken as specimen from fibre sample.
- Specimen were conditioned according to the ISO 139.
- Pretension weight was set on the vibroscope based on selected tension weight. The applied pretension weight was 100mg for cotton, 200 mg for regular polyester, 500 mg for LMP and 200 mg for PLA.
- The fibres were clamped with pretension weight into the instrument.
- The frequency was gradually increased, and the amplitude of vibration was observed.
- When maximum vibration was observed, linear density was recorded directly in dtex from vibroscope.

Fibre length was tested according to ISO 6989:1981, Textile fibres - determination of length and length distribution of staple fibres (by measurement of single fibres). Measurement of individual fibre length was measured by straightening fibre under a light applied tension with help of forceps.

Apparatus used for fibre length measurement

- ruler,
- velvet fabric,
- forceps,
- Dino-Lite digital microscope (for type 1 recycled fibres),
- Dino capture imaging software (for type 1 recycled fibres).

Test procedure:

- Specimens were conditioned under standard atmosphere according to ISO 139.
- 25 fibres were taken randomly from fibre sample.
- Fibres were placed one by one on velvet fabric and straightened by applying tension with the help of forceps.
- The length of individual fibre was measured with ruler and recorded in mm.
- For measuring recycled fibre (type 1) images were taken with digital microscope and the length was measured by using imaging software. (figure 6.5)

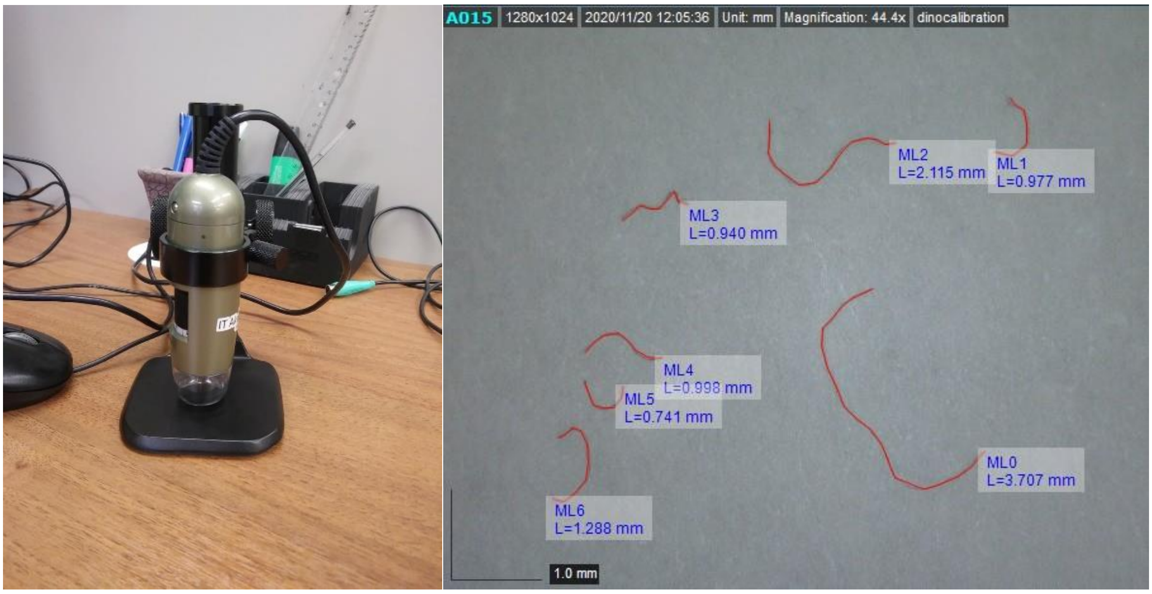


Figure 6.11 Digital microscope and image of recycled cotton at 44.4x magnification.

The hot stage microscope is a polarizing microscope with a stage compartment that is temperature controlled by a computer. Materials to be tested are mounted on a microscope slide, covered with a cover glass, and placed into the chamber of the hot stage. The compartment temperature could be controlled manually or automatically. By hot stage microscope analysis materials` melting point can be determined.

Required equipment:

- Zwiss primostar 3 microscope,
- Mettlar FP80 melting point apparatus (appendix 3).

Test procedure:

- The fibres were placed on to the glass slides.
- Then glass slides were placed into the hot-stage device and the microscope was adjusted to obtain a clear picture at 100x of magnification.
- The fibre was heated, and the temperature was controlled with the hot- stage device controller and photos were taken so that liquefaction of fibre could be observed.

Differential scanning calorimetry (DSC) is a technique that measures heat flow into or out of a material as a function of time or temperature. DSC analysis is also used for melting point determination.

Required equipment:

- PerkinElmer DSC 7.

Test procedure:

- The aluminium foil was placed as reference.
- Then the sample was placed for experiment and raised the temperature.

For nonwoven characterisation three types of tests were carried out. Those are mass per unit area, tensile strength, and air permeability. The following diagram (figure 6.12) was followed to cut the specimens for different testing and bending strength specimens were cut for future work.

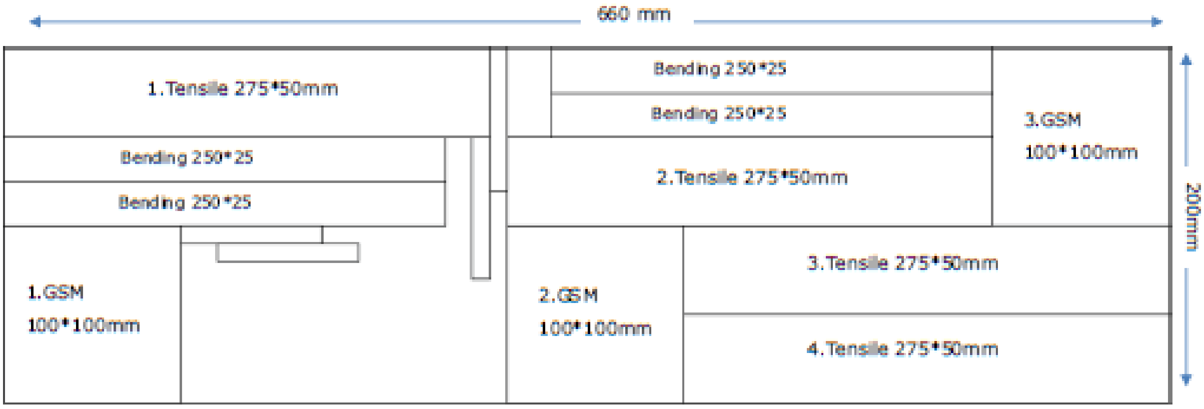


Figure 6.12 Scheme for specimens' preparation.

Mass per unit area of nonwovens was conducted according to EVS-EN-ISO ISO 9073-1:1989 Textiles — Test methods for nonwovens — Part 1: Determination of mass per unit area. This standard specifies the method for the determination of mass per unit area of nonwovens. The principle of this method is the measurement of the area and mass of test specimen and calculating the mass per unit area in gram per square meter (GSM).

Equipment used for mass per unit area test:

- scissor,
- ruler,
- KERN KB 6500-1NM balance (figure 6.13),
- marker pen.

Figure 6.13 Equipments used for mass per unit area test.

Test procedure:

- Three specimens were cut of 100 mm×100 mm with exception, 100mm×90mm, due to less width for some samples. (Figure 6.14)
- The specimens conditioned at standard temperature and humidity.
- Length and width each specimen were measured from three places and the results were rounded to 1 mm.
- Specimens were weighted and the results were rounded to the nearest 0.1g.

Figure 6.14 Test specimens for mass per unit area measurement.

Calculations:

The mass per unit area was calculated according to the equation 6.1.

$$G_s = \frac{m \cdot 10000}{A} \qquad (6.1)$$

G_s - mass per unit area, g/m^2,

m - mass of a test specimen, g,

A - area of the test specimen, cm^2.

Air permeability of nonwovens was tested according to EVS-EN-ISO 9073-15:2007 textiles — test methods for nonwovens — Part 15: Determination of air permeability. This standard specifies the method of determining the flow of air passing perpendicularly through a given area of nonwoven. This test method applies to the most nonwovens.

Used equipment:

- ruler,
- scissors,
- marker pen,
- TEXTEST FX 3340 MinAir (figure 6.15).

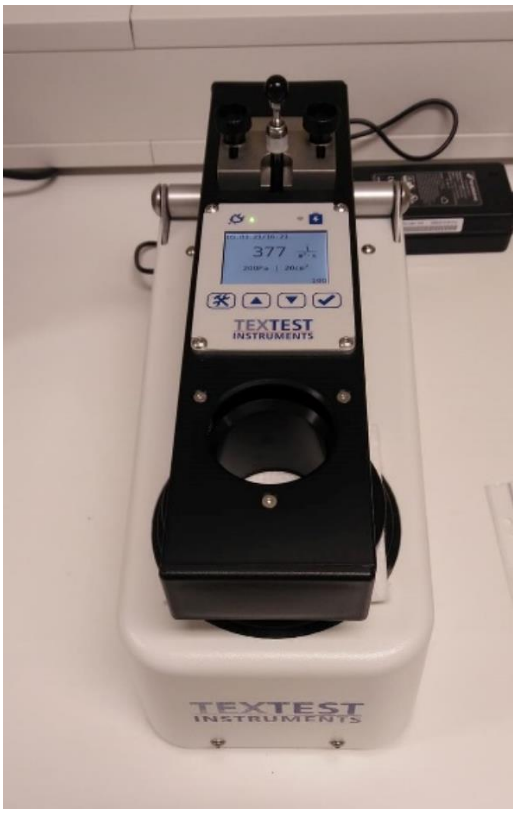


Figure 6.15 TEXTEST FX 3340 MinAir air permeability tester.

Test procedure:

- Three specimens with dimension of 100mm×100mm (100mm×90mm due to less width for some samples) were cut.
- The specimens were conditioned according to ISO 139.
- Measuring conditions: 20 cm^2 clamping area, and set the pressure drop 200Pa.
- The specimens were placed at the specimen holder and clamp them with the top clamper.
- After clamping the test continued automatically.
- When the digital screen showed stable reading, recorded the result in l/m^2·s unit.
- The same process was continued for next two specimens.
- The average value and standard deviation were calculated from five individual values.

Tensile strength of nonwovens was conducted according to EVS-EN 29073-3: Textiles - test methods for nonwovens. Part 3: Determination of tensile strength and elongation. This part of standard specifies determination of tensile properties of nonwoven by cut strip method. Application of force longitudinally on test specimen of specific length and width at constant rate of extension. This test was conducted in the TalTech Laboratory of Polymers and Textile Technology. Specimens were not conditioned.

Equipment used for tensile properties test:

- Instron 5866 tensile testing machine (figure 6.16)
- ruler,
- scissor,
- marker pen.

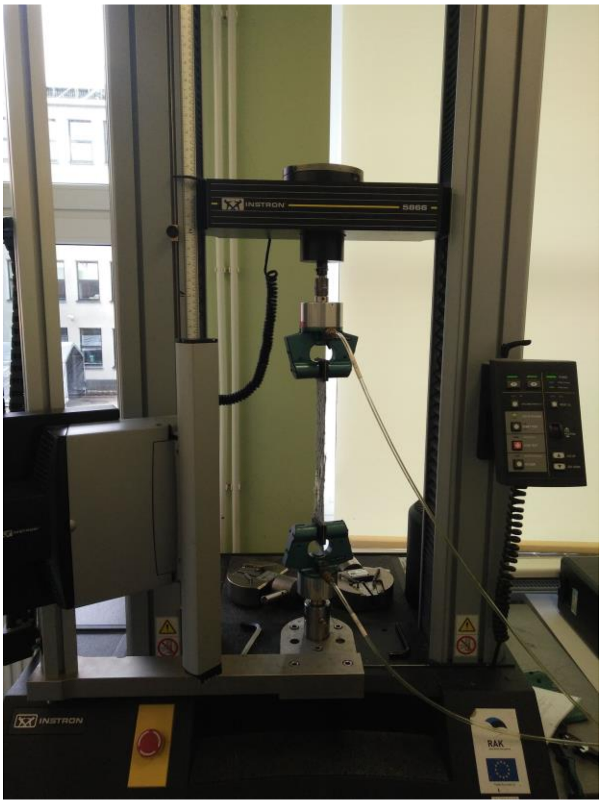


Figure 6.16 Instron 5866 tensile testing machine.

Test procedure:

- According to standard five specimens with size of 300 mm×50 mm. Due to limited sample dimensions of hand-carded nonwovens, four specimens of 275 mm×50 mm were prepared (Figure 6.17).
- 10000 N load cell was used for nonwovens that contained polyester base fibres and 500 N for other nonwovens.
- Constant test speed was 100 mm/min and 200 mm, respectively.

- Maximum load and extension at maximum load were recorded. To eliminate the dependence of tensile properties on mass per unit value, specific stress was calculated according to the equation 6.2.

Figure 6.17 Test specimen before and after tensile testing.

Calculations:

Calculate the specific stress (Nm/g) from maximum load by using the equation 5.2.

$$P_o = \frac{P_t \cdot 1000}{B \cdot G_s} \tag{6.2}$$

P_o - specific stress, Nm/g,
P_t - maximum load, N,
G_s - mass per unit area, g/m^2,
B - specimen width, mm.

7. RESULTS AND DISCUSSION

This chapter illustrates properties of fibres used for nonwovens preparation and nonwoven properties. In this work, fibre length and linear density of fibres used for NWMs preparation were determined. In addition, mass per unit area, air permeability, and tensile strength of NWMs were tested. Furthermore, the tested resulted were analyzed and compare with different NWMs with different NWMs.

7.1 Properties of raw materials

Test results of fibre linear density, length, and melting point are presented here. Since nonwovens are directly produced from fibre through a simple mechanism, fibres properties greatly influenced nonwoven properties.

Figure 7.1 illustrates the linear density of different fibres. The linear density of bonding fibre was higher than base fibres. Therefore, the standard deviation (S.D) of LMP and PLA were higher than others, which indicates that the large variation of individual values from the mean. On the other hand, polyester showed lower linear density than others. Due to the short length, the linear density of RCO, R'CO, and RMF could not be measured.

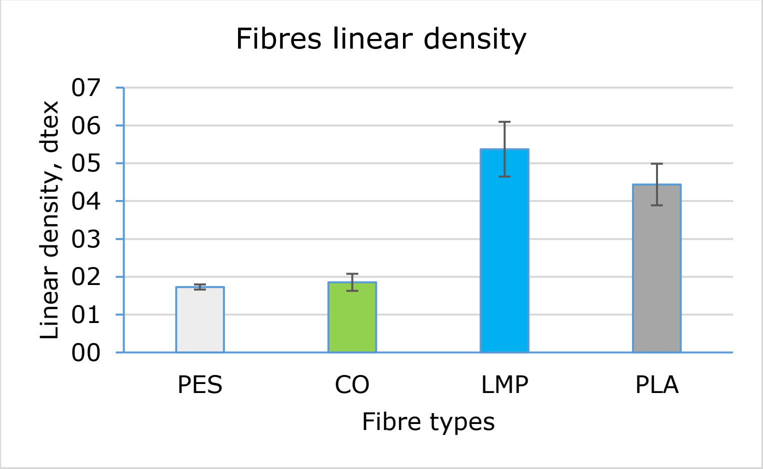


Figure 7.1 Linear density of different virgin fibres.

Figure 7.2 shows the length and length distribution of different fibres with error bar. The average length of virgin cotton was 26 mm with high standard deviation (0.2 mm), that indicates fibres had wide range of individual values. The length of virgin cotton fibre varied from 18mm to 36mm. RCO had the smallest average length, and even some fibres were less than 1 mm long. Out of 25 fibres most fibres had lengths less than 5 mm. The average length of RCO, R'CO and RMF were 4, 10, and 14 mm with standard deviation of 2.7, 7.7, and 10.7 mm, respectively (appendix 1). The higher standard deviation indicates large deviation of individual values from the mean. Synthetic fibres had a higher average length with low standard deviation. From fibre length distribution graph (Appendix 2) it is visible that out of 25 fibres, length of most synthetic fibres was at least 50mm. Carding process could be easy when processing longer fibre. It was not possible to make carded web with only RCO because of its shorter length.

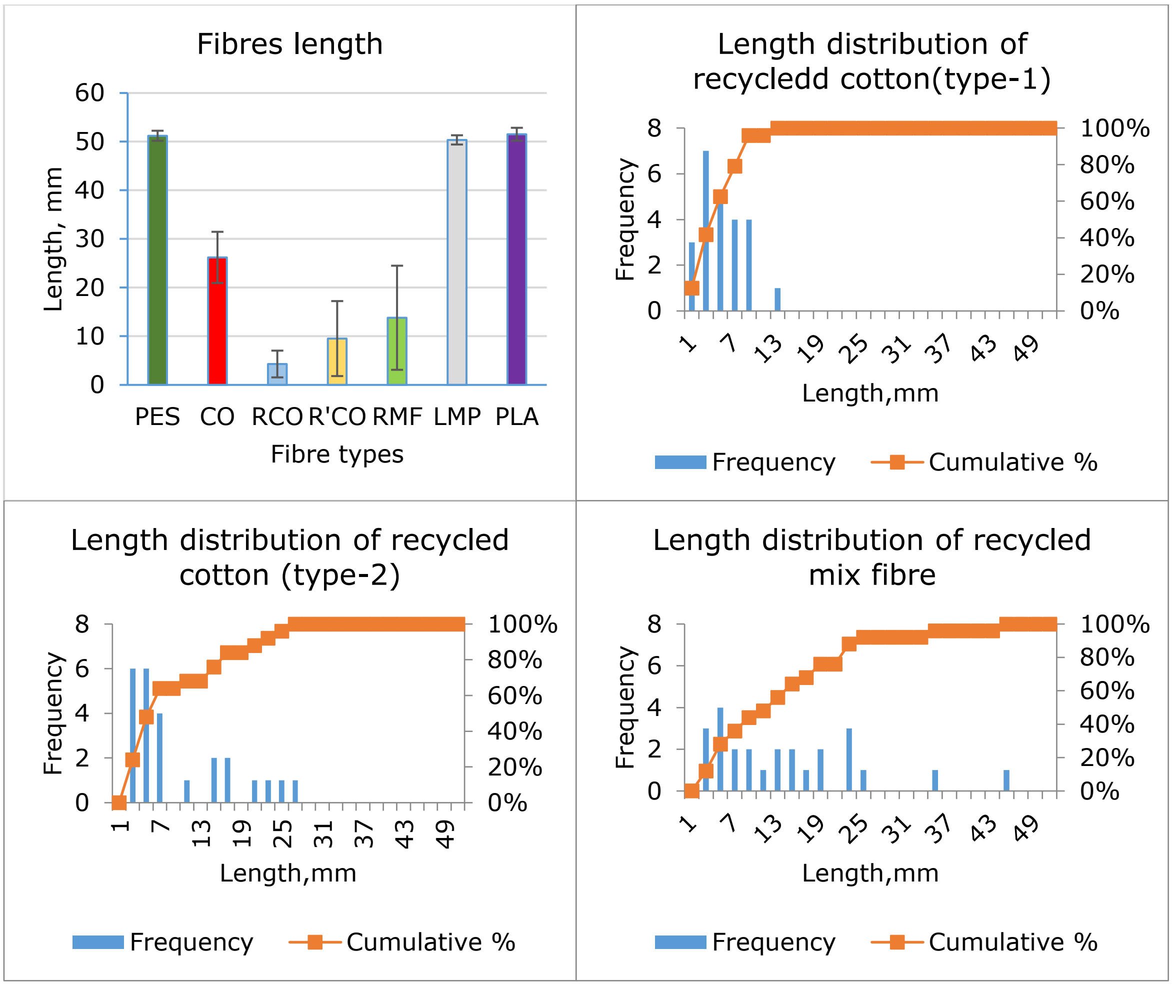


Figure 7.2 Length and length distribution of different fibres.

Figure 7.3 shows hot stage microscopy images of PLA and LMP fibres at different temperatures. From these figures it could be stated that LMP started to soften at 110 °C and the sheath part of LMP was fully molten at 150 °C. PLA became soften at 125 °C and molten around 160 °C. DSC analysis also showed almost similar result for PLA, where the softening and melting temperature were respectively 133.26 °C and 169.29 °C (Appendix 4).

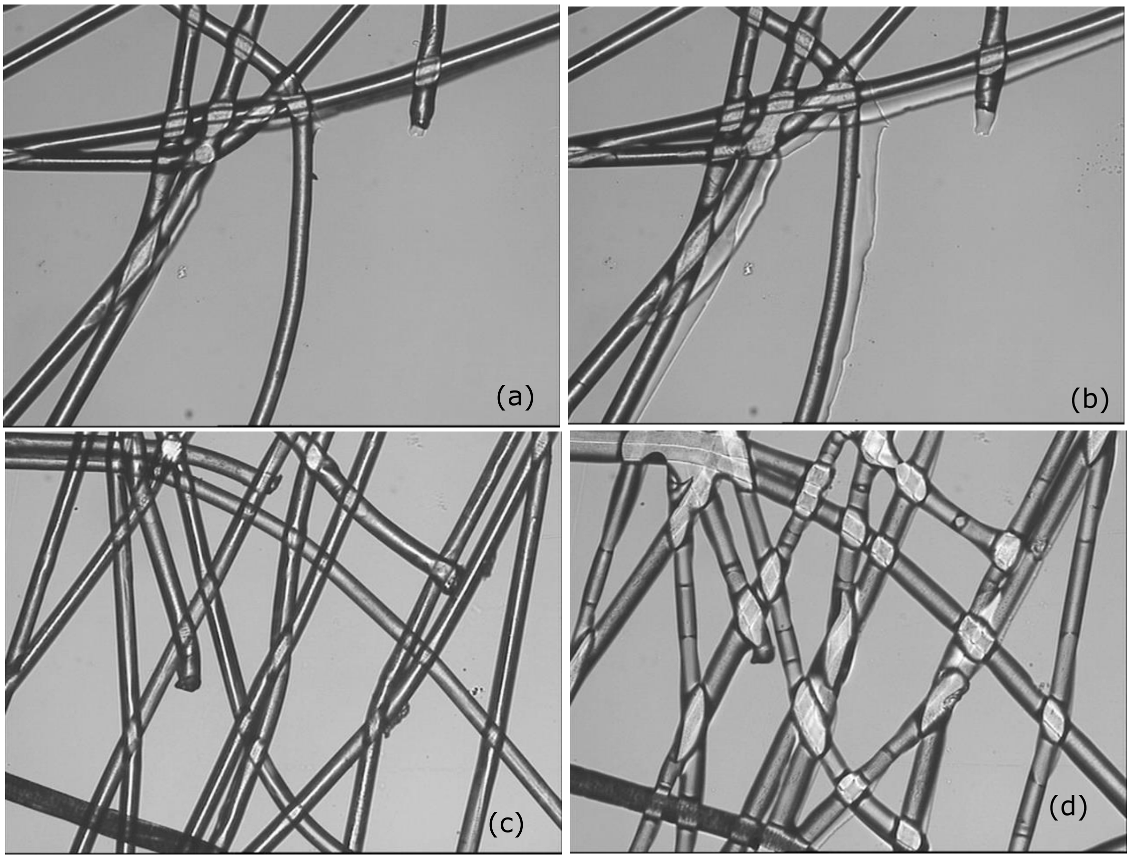


Figure 7.3 Hot stage microscope images (a) LMP at 110 °C (b) LMP at 150 °C (c) PLA at 125 °C and (d) PLA at 150 °C.

7.2 Properties of hand-carded nonwovens

7.2.1 Mass per unit area

Figure 7.3 illustrates mass per unit area of HC nonwovens. Most of the P:LMP nonwovens had the mass per unit area around 350 g/m^2, while HC9 (appendix 5) showed a high value (363.8±45.1) g/m^2, and HC4 had the lowest value (284.5±24.6) g/m^2. The mass per unit area of CO:P:PLA and CO:P:LMP nonwovens were below 300 g/m^2. However, standard deviation values were high for most CO:P:PLA nonwovens, but CO:P:LMP nonwovens showed the S.D below 20 g/m^2. RCO:PLA nonwovens had a mass per unit area of more than 250 g/m^2, but the highest value was (322.0±9.3) g/m^2. Standard deviation values were less than 20 g/m^2 except for two materials. RCO-LMP nonwovens had various GSM (gram per square meter), but standard deviations were less than 20 g/m^2. Moreover, standard deviation values were less than 20 except for three nonwovens. Mass per unit area range of CO:RCO:PLA nonwovens between 200 to 300 g/m^2, and most of them showed an error bar less than 20. Nonwovens of CO:RCO:LMP had GSM between 200 to 250 other than HC74, which had (261.1±20.7) gm^2.

Polyester nonwovens had high mass per unit area. On the other hand, cotton nonwovens had a low mass per unit area. GSM of most of the NWMs was more than 200 except five materials, while material HC50 has GSM of 183.8±30.2. During carding operation, cotton fibres tended to be stacked with the back drum, which could be the reason for lower weight of cotton nonwoven materials. Though the standard deviation for some materials was higher than 30 g/m^2, most results showed the S.D below 20 g/m^2. The high standard deviation values express that the prepared NWMs were uneven. This unevenness could be caused by the uneven fibres' distribution during carding. Appendix 7 and appendix 8 show some examples of prepared nonwovens.

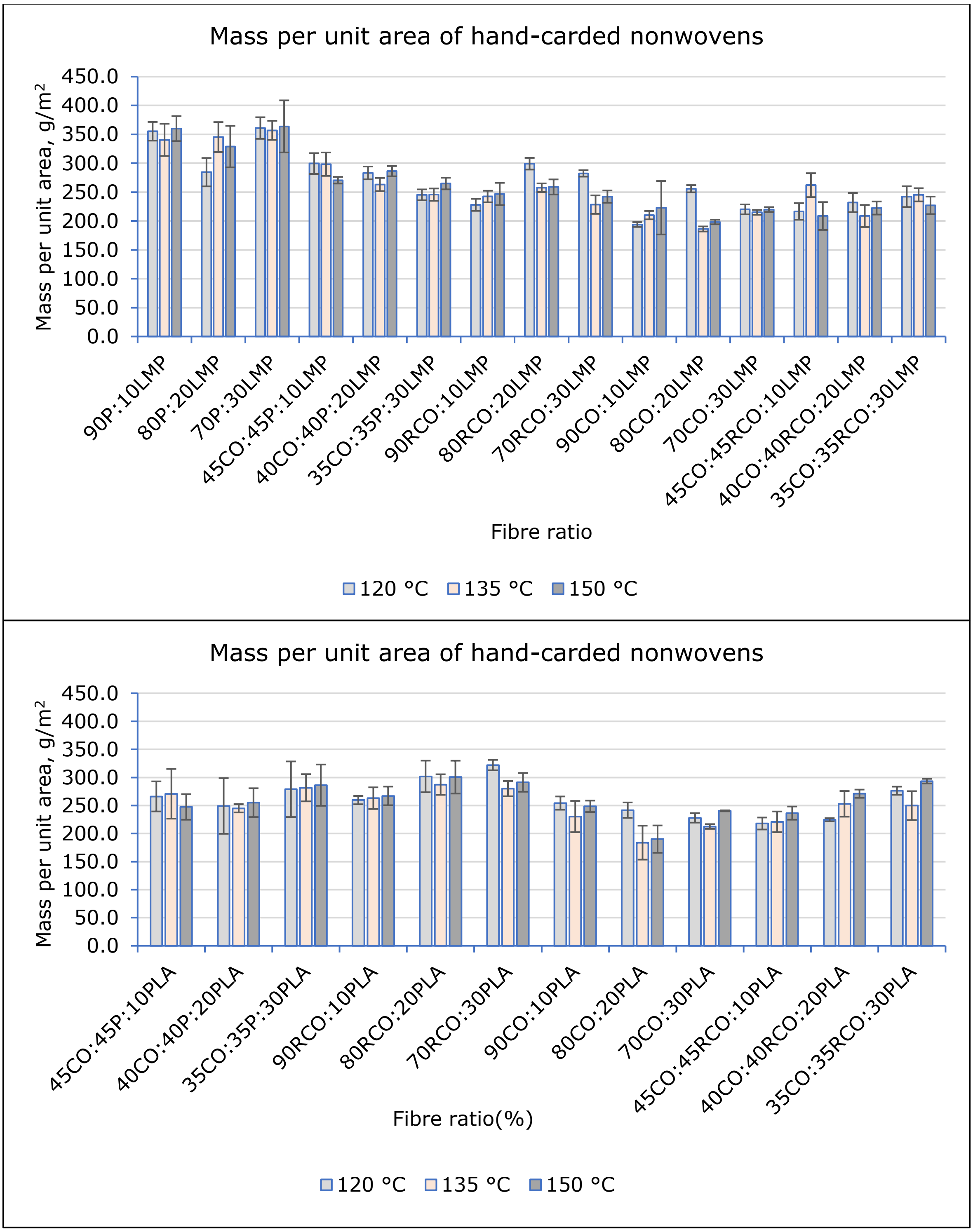


Figure 7.4 Mass per unit area of HC nonwovens.

7.2.2 Air permeability

Figure 7.5 presents air permeability of HC nonwovens with standard deviation. Among P:LMP NWMs the air permeability of HC1 was highest (4241±8.2) l/m^{2}·s, and HC9 shows lowest value (292±25.4) l/m^{2}·s than other P:LMP nonwovens. Air permeability of CO:P:LMP nonwovens varied from around 600 l/m^{2}·s to around 700 l/m^{2}·s. On the other hand, the air permeability of CO:P:PLA varied from 911 l/m^{2}·s to 544 l/m^{2}·s depending on fibre ratio and TTT. Figure 7.10 shows the air permeability of recycled cotton nonwovens. Among RCO:LMP and RCO:PLA nonwovens, HC28 had the highest air permeability, and HC36 had the lowest value. In addition, air permeability of CO:LMP nonwovens were below 800 l/m^{2}·s. Air permeability of most CO:PLA nonwovens was from 850 to 1050 l/m^{2}·s. However, CO:LMP had the air permeability of more than 900 l/m^{2}·s. Most results showed the error bar of more than 50 l/m^{2}·s. Most CO:RCO blends nonwovens had air permeability of more than 900 but below 1200 l/m^{2}·s. However, four CO:RCO:PLA nonwovens had the air permeability of less than 900 l/m^{2}·s.

Air permeability varied significantly with fibre content and TTT. P:LMP nonwovens had the lowest air permeability compared to others. Air permeability of nonwovens made from virgin cotton is comparatively high. Nonwovens made from recycled cotton less air permeable than virgin cotton nonwovens. It is evident from the graph that the standard deviation was high, which indicates different portions had different air permeability values, and the deviations were large.

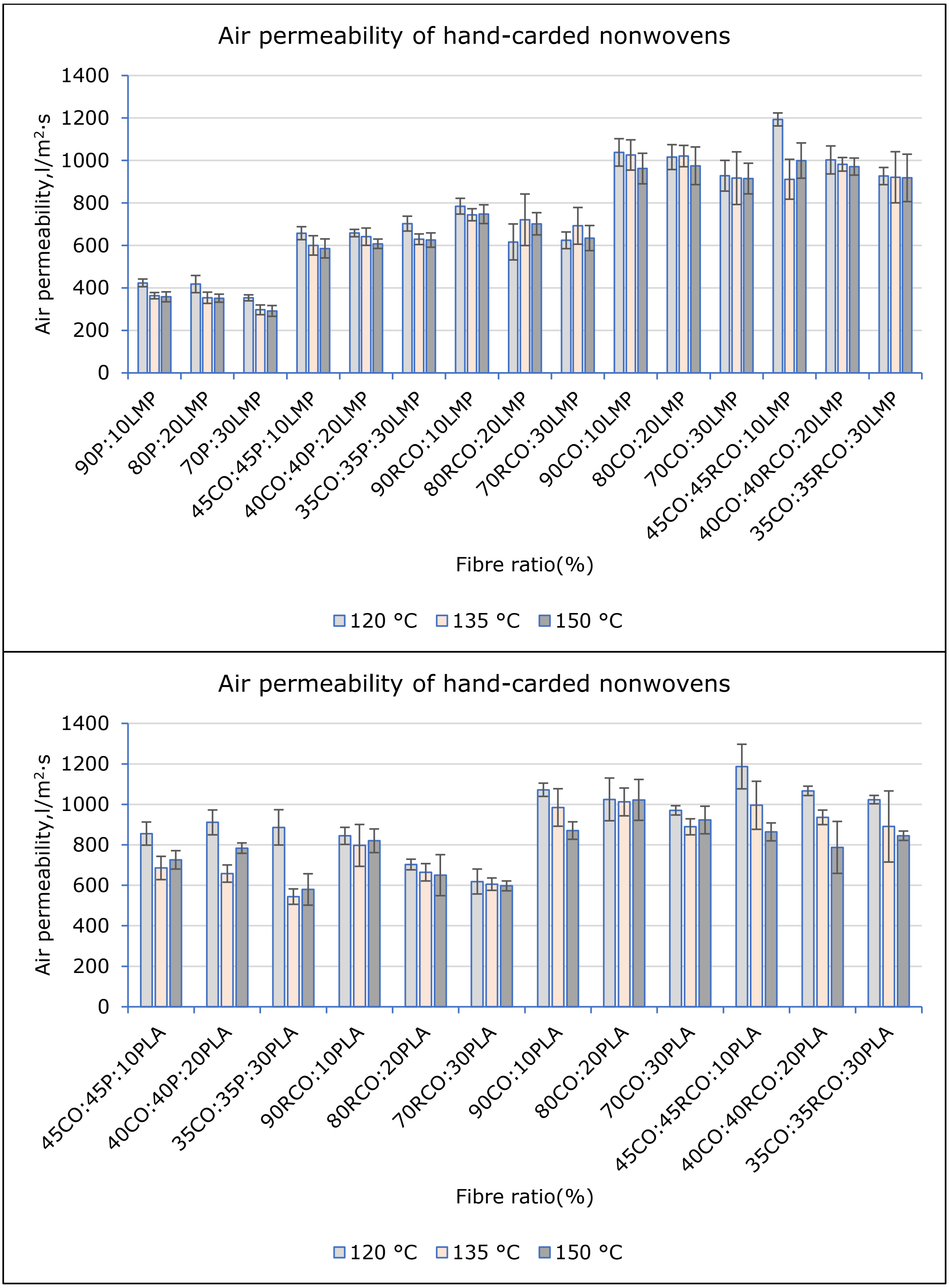


Figure 7.5 Air permeability of HC nonwovens.

7.2.3 Tensile properties

Figure 7.6 illustrates tensile properties of hand-carded nonwovens. The maximum specific stress of hand-carded P:LMP nonwovens was (44.9±4.2) Nm/g, and the lowest specific stress was 5.2±0.6 Nm/g. Nonwovens of CO:P:PLA had specific stress less than 20 Nm/g, and HC10 had the lowest value compared to other CO:P:PLA nonwovens. Specific stress of CO:P:LMP nonwovens had a value of more than 5.0 Nm/g and increased depending on the processing parameters and fibre ratio. Some results showed a standard deviation of more than 1.0 Nm/g. CO:PLA nonwovens showed stress below 15 Nm/g. On the other hand, CO:LMP nonwovens had increased value compared to CO:PLA nonwovens. HC45 showed the maximum specific stress among cotton nonwovens. Specific stress of CO:LMP nonwovens varied from around 2.0 to 14.0 Nm/g. On the other hand, the strength of CO:PLA remained below 12.0 Nm/g. Most results showed an error bar below 1.0 Nm/g. Nonwovens made from CO:RCO blend showed greater strength when LMP was used as bonding fibre. CO:RCO:LMP had maximum strength around 12.0 Nm/g, but all CO:RCO:PLA nonwovens showed specific stress less than 12.0 Nm/g. P:LMP nonwovens showed high specific stress compared to others when all other parameters were identical.

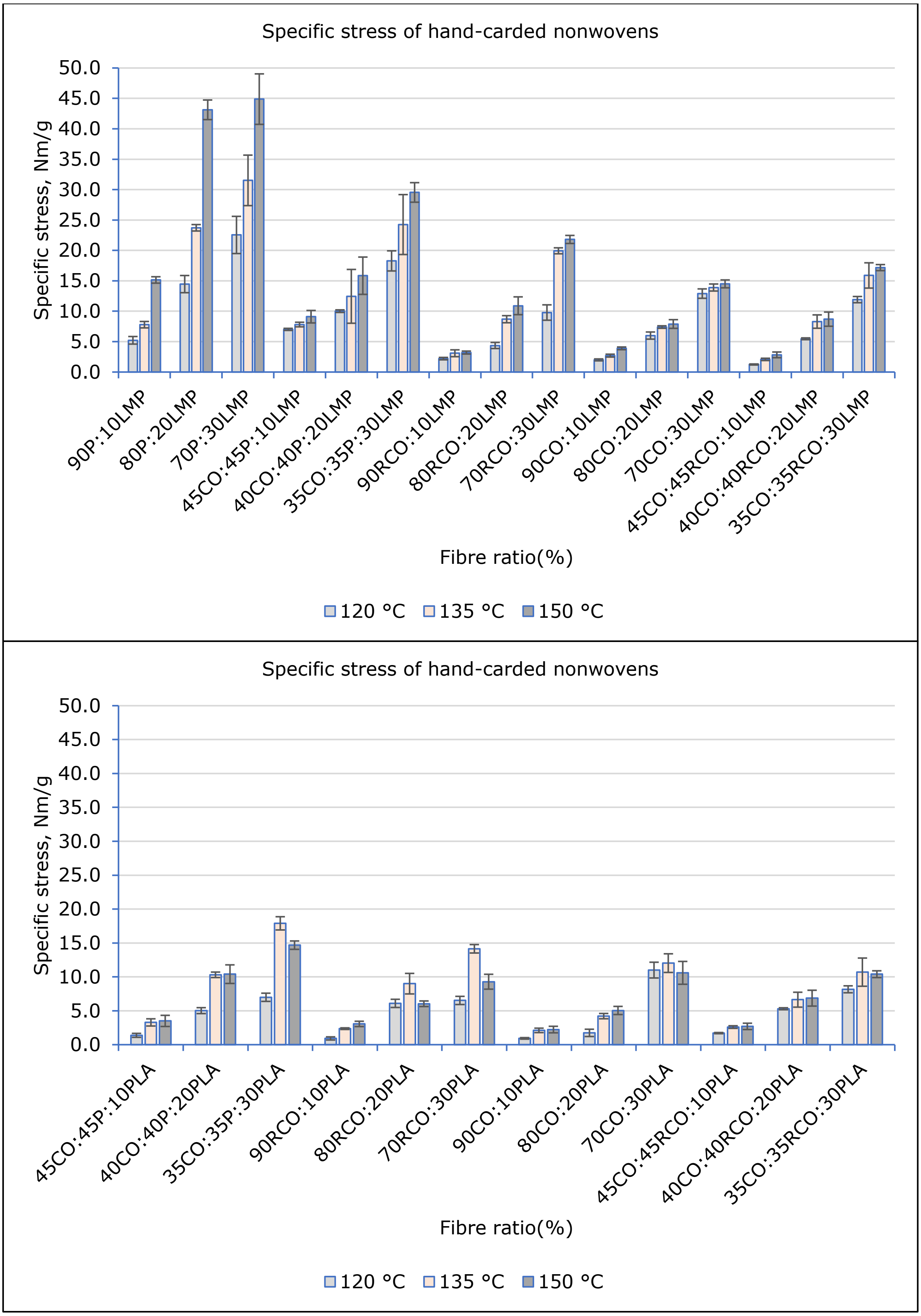
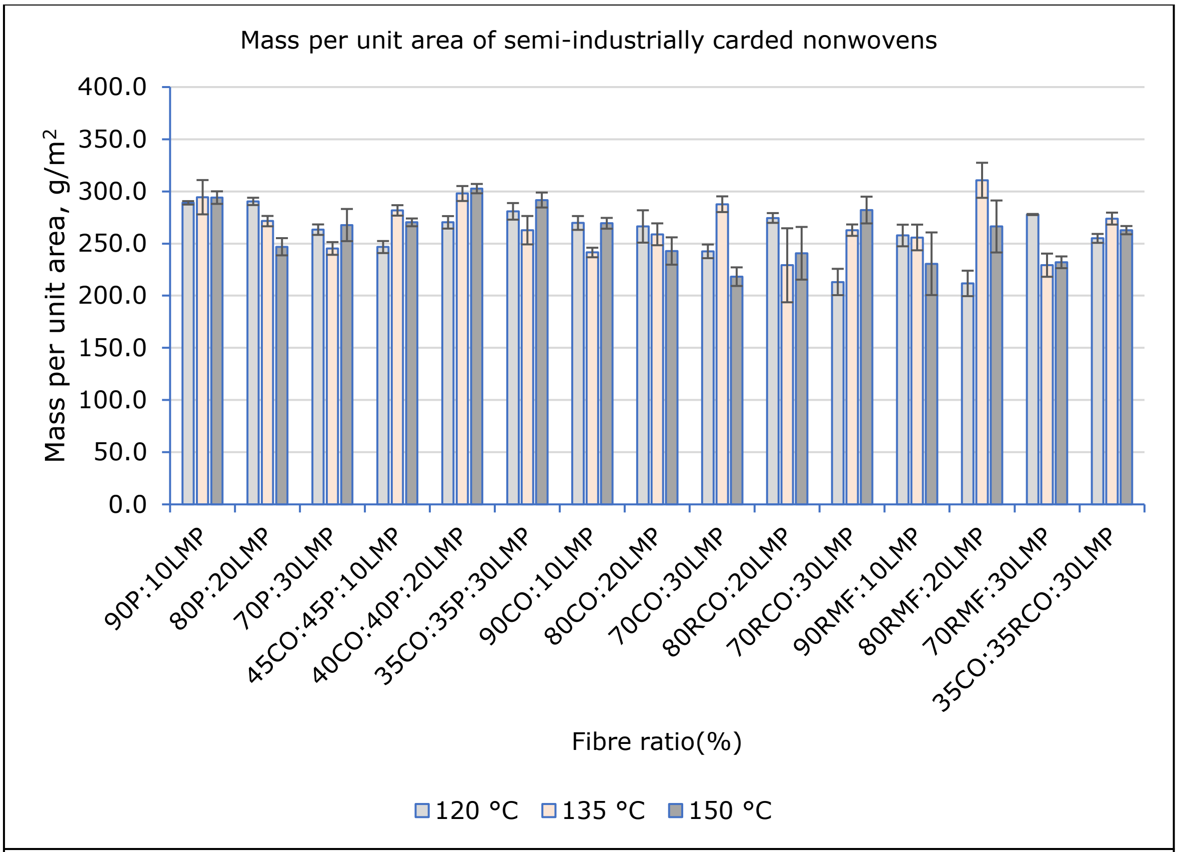


Figure 7.6 Specific stress of HC nonwovens.

7.3 Properties of semi-industrially carded nonwovens

7.3.1 Mass per unit area

Mass per unit area of IC nonwovens is illustrated in figure 7.7. Mass per unit area of most of P:LMP nonwovens was from 250 to 300 g/m^2, and the standard deviations were also not larger than 20 g/m^2. Thus, most nonwovens made of CO:P blend had the GSM from 250 to 300, with some exceptions. IC15 (appendix 6) had maximum mass per unit area of nonwovens made with CO:P blend. All CO:PLA nonwovens had GSM around 250 except IC33, which had mass per unit area (301.3±11.4) g/m^2. On the other hand, nonwovens of CO:LMP had mass per unit area ranging from (218.3±8.9) g/m^2 to (287.7±7.5) g/m^2. All nonwovens of RCO:PLA had mass per unit more than 200 g/m^2 other than IC47, which had (142.9±5.8) g/m^2. Moreover, the standard deviations of RCO:PLA nonwovens were also below 20 g/m^2 except IC48. Materials of RCO:LMP had GSM more than 200 but below 300. Mass per unit area of semi-industrially cared nonwovens showed value between 250 to 300 g/m^2. However, some deviations were also existed. Mass per unit area of RMF:LMP lied from (301.8±16.8) g/m^2 to (211.8±12.2) g/m^2. Standard deviation of most of the IC nonwovens were below 30 g/m^2, indicating semi-industrially carder produced even NWMs. 90RCO10PLA150 and 35CO35P30PLA150 NWMs showed large S.D, which were 54.1 and 61.8 g/m^2, respectively. The evenness was due to uniform distribution of fibres over the area of NWMs, this was happened by equal feeding of fibres through the full width of the carder.



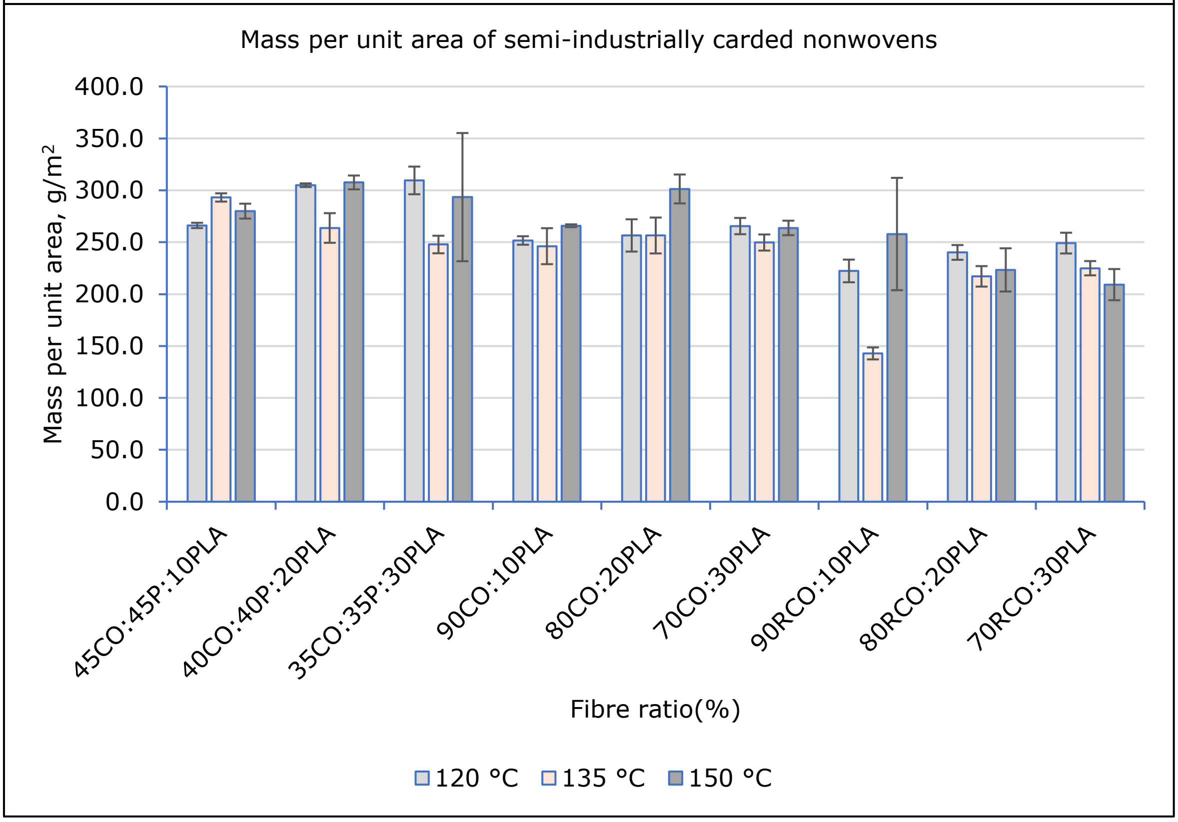


Figure 7.7 Mass per unit area of IC nonwovens.

7.3.2 Air permeability

Figure 7.8 represents the air permeability of IC nonwovens. The minimum air permeability value of P:LMP nonwoven was around 650 l/m^2·s and the maximum value was about 950 l/m^2·s. Most P:LMP results showed an error bar below 50 l/m^2·s. CO:P blend nonwovens showed the air permeability of more than 700 l/m^2·s, and less than 1000 l/m^2·s. However, CO:P:LMP nonwoven had a maximum air permeability of (903±26.3) l/m^2·s. The standard deviation values of all materials were below 50 l/m^2 except IC18. Though the highest air permeability of CO:PLA and CO:LMP nonwoven was more than 1000 l/m^2·s, the lowest value was below 750 l/m^2·s. The air permeability of other CO:PLA nonwoven materials lied from 800 to 950 l/m^2·s. Some NWMs had s standard deviation of more than 50 l/m^2·s. Most RCO:PLA materials had the air permeability of more than 900 l/m^2·s and below 1100 l/m^2·s. The standard deviation for some nonwovens was higher than 200, which indicates an extensive data range. RCO:LMP nonwovens showed the air permeability from (694±2.1) l/m^2·s to (1056±203.7) l/m^2·s. Air permeability of RMF:LMP nonwovens varied from 809 to 1246 l/m^2·s. Some of them showed S.D of more than 50 l/m^2. CO:RCO:LMP nonwovens had permeability of less than 1000 l/m^2·s.

Air permeability was influenced greatly by fibre type than fibre ratio and TTT. Recycled mix fibre showed highest air permeability. NWMs made from virgin cotton were slightly higher air permeable than nonwovens made from recycled cotton.

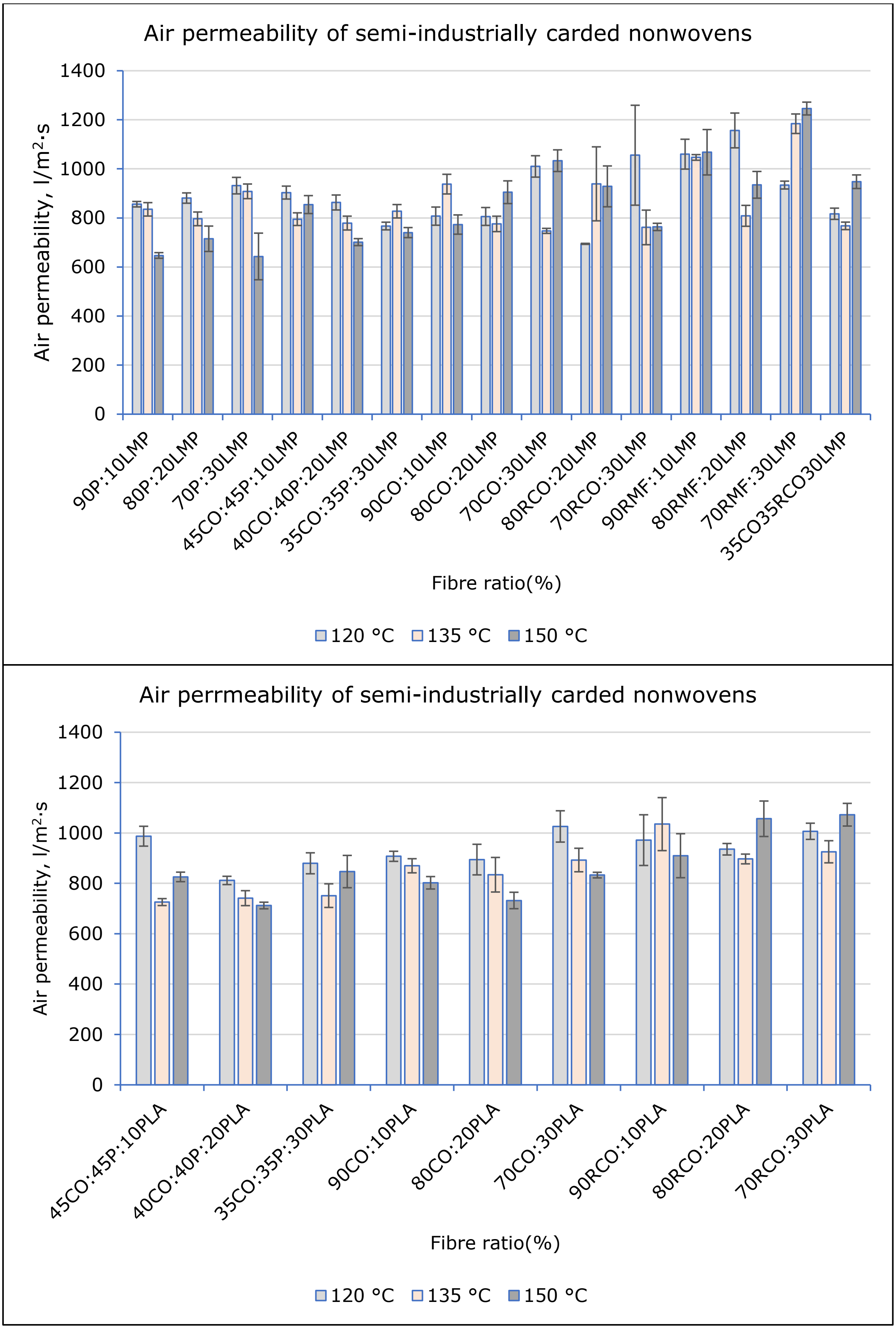


Figure 7.8 Air permeability IC nonwovens.

7.3.3 Tensile properties

The specific stress of IC is demonstrated in figure 7.9. IC9 showed the highest stress and IC28 showed the lowest specific stress of all IC nonwovens. The standard deviation of most P:LMP nonwovens had a higher value than 1.0 Nm/g, indicates that individual values had large dispersion from the mean value. The specific stress of CO:P:PLA nonwovens lied below 20 Nm/g but CO:P:LMP had higher stress than CO:P:PLA. Most results showed standard deviation of more than 1.0 Nm/g indicates individual values had big dispersion from the average value. The highest average specific stress of CO:PLA nonwoven was below 16 Nm/g. On the other hand, CO:LMP nonwoven had the highest stress of more than 30 Nm/g. Most results showed a standard deviation less than 1.0 Nm/g. Specific stress of RCO:PLA varied from (1.59±0.4) to (18.86±2.4) Nm/g. RCO:LMP showed stress more than 5 Nm/g. Some results showed standard deviation of more than 2 Nm/g, indicating dispersion from the average value. Maximum specific stress of RMF:LMP nonwovens was observed at 70:30 ratio and at 135 °C TTT.

The higher S.D expressed that NWMs were uneven. This unevenness could be because of uneven fibre distribution during carding and TTT variation in different places. Nonwoven materials with different fibre content show different tensile properties. Moreover, thermal treatment temperature also affects the specific stress. For most NWMs, it is observed that specific stress was increase with the increase of TTT and bonding fibre ratio. However, some different trends were also existed.

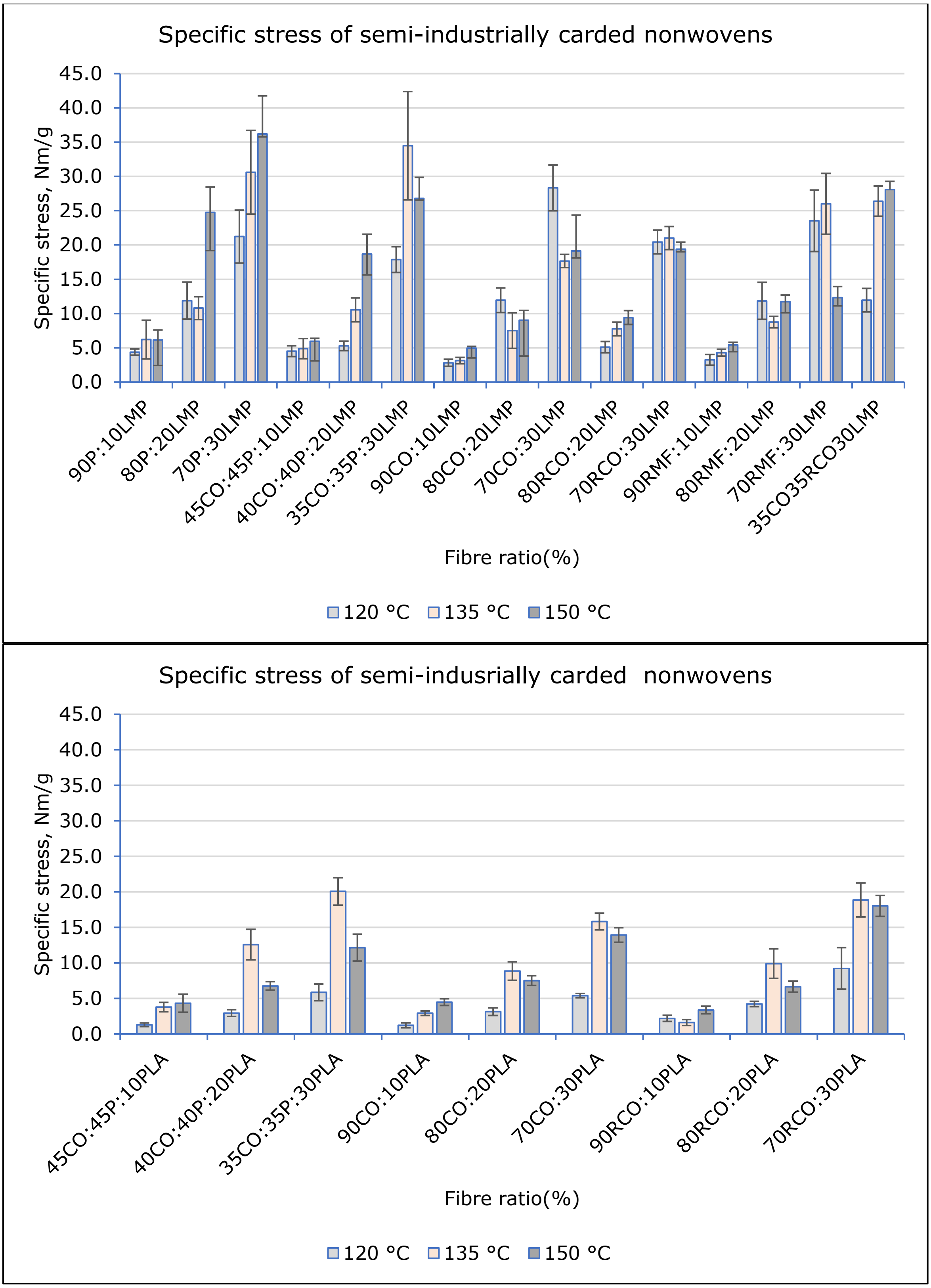


Figure 7.9 Specific stress of IC nonwovens.

7.4 Analysis

In the analysis part, the effect of bonding fibre types and ratio will be discussed. In addition, impact of recycled fibres and carding process on the properties of nonwovens will also be analysed.

7.4.1 Effect of thermal treatment temperature

Effect of temperature on tensile properties: The effect of temperature on tensile properties of LMP bonded NWMs is illustrated in figure 7.10. Nonwovens made with LMP fibre showed different specific stress at different TTT though fibre ratio was identical. Furthermore, the specific stress was lowest at 120 °C and highest at 150 °C for all fibre contents. For example, 70CO30LMP120 had specific stress of (8.2±0.8) Nm/g, which raised to (10.7±0.6) Nm/g for 70CO30LMP135 and 10.4±06 Nm/g for 70CO30LMP150. The difference was high when nonwoven contained 30% LMP and the difference was low when LMP fibre is 10%. Other LMP bonded nonwovens, including semi-industrially carded NWMs were also affected similarly when TTT was changing. Due to heating, the degree of crystallinity of bicomponent fibre was increased; therefore, the breaking load was increasing [84][110][111].

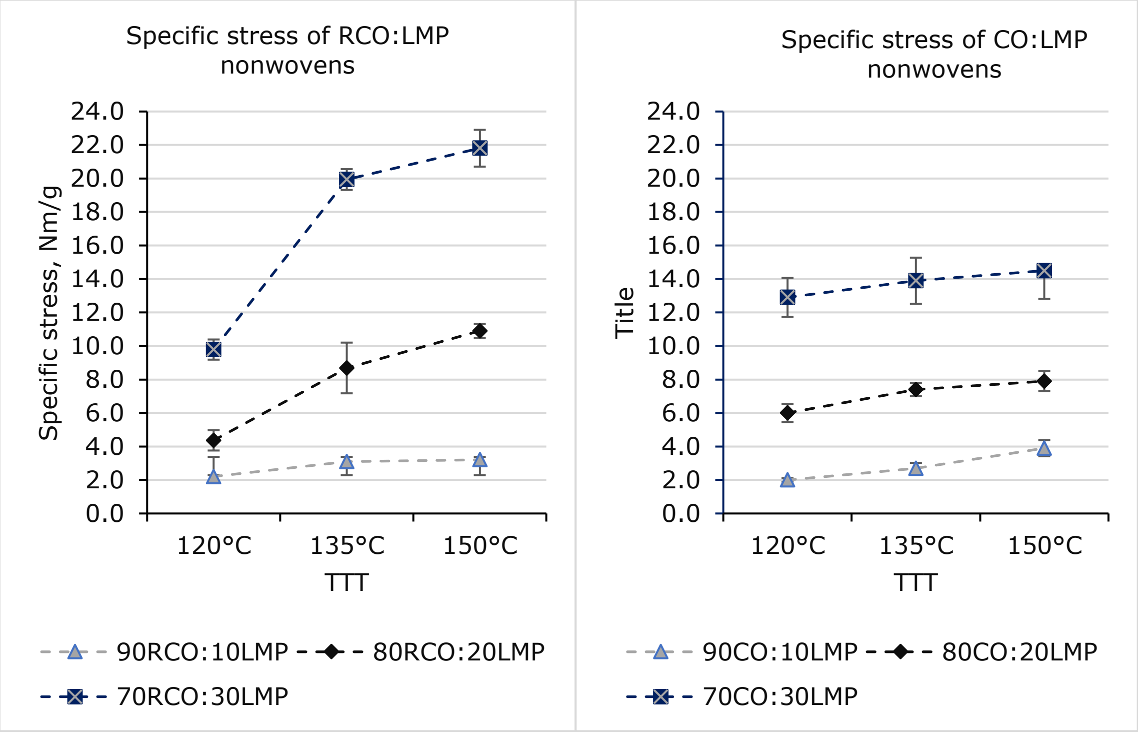


Figure 7.10 Effect of thermal treatment temperature on tensile properties of LMP bonded HC nonwovens.

Figure 7.11 illustrates the influence of thermal treatment temperature on the specific stress value of nonwovens bonded with PLA fibres. Specific stress of nonwovens bonded with 10% and 20% PLA fibres was higher while TTT was higher except 80RCO:20PLA. The stress of nonwovens containing of 30% PLA, was increased if temperature increased from 120 °C to 135 °C but decline while TTT is 150 °C. This was because of thermal degradation of PLA at the contact with nonwoven [84][111]. Puchalski et al. studied the influence of calender temperature on PLA spun-bonded nonwovens and found that the stress of nonwovens decreased when the calendaring temperature was above 100°C[111]. All PLA bonded nonwovens contain 30% PLA had the highest specific stress at 135 °C. However, other nonwovens showed maximum stress at 150 °C except 80RCO:20PLA, similar to those containing 30% PLA.

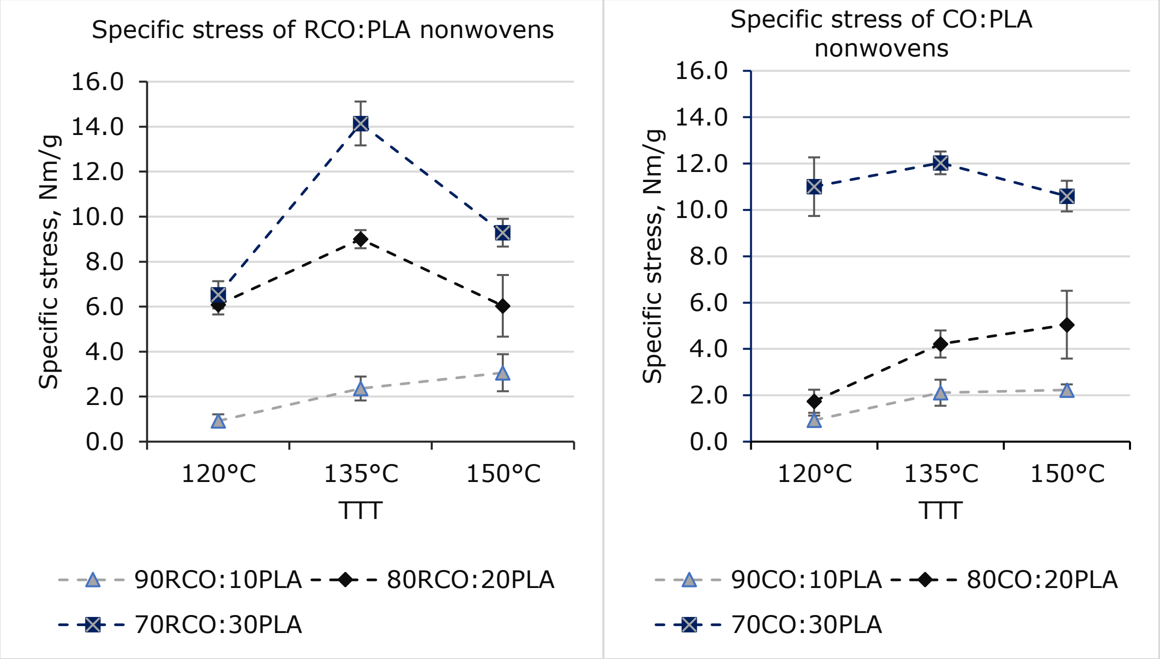


Figure 7.11 Effect of thermal treatment temperature on tensile properties of PLA bonded HC nonwovens.

Effect of temperature on air permeability: Figure 7.12 demonstrates the effect of TTT on air permeability of NWMs bonded with LMP fibres. With the rise of TTT the air permeability of CO:P:LMP and CO:LMP nonwovens showed continuous declining except 45CO:45RCO:10LMP. Studies of Yeon et al. showed that the air permeability decreased with the rise of TTT [112]. CO:LMP and CO:P:LMP nonwovens showed falling a rate of less than 15% while temperature increased from 120 °C to 150 °C. It can be concluded that with the increase of TTT NWMs became less air permeable. Similarly, all other nonwovens showed same trends of changing air permeability including semi-industrial carded nonwovens.

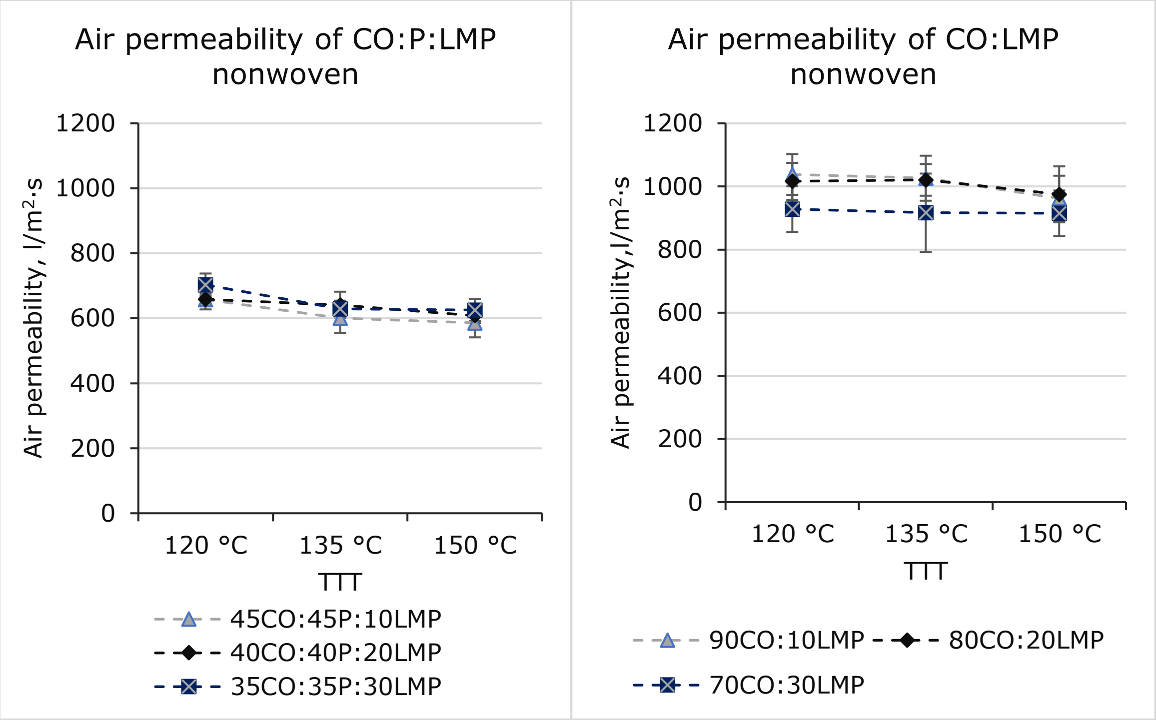


Figure 7.12 Effect of thermal treatment temperature on air permeability of HC nonwovens.

Effect of temperature on dimensional stability: TTT had significant effects on the dimensional stability of nonwoven materials. Due to heating, the bicomponent fibres shrink up to a certain percent depending on the TTT [84][111][113]. Therefore, NWMs shrink, according to bicomponent fibre ratio and TTT. In this work, NWMs were made from blending of bicomponent fibre with base fibre. Since base fibres and bicomponent fibres had different thermal shrinkage after thermal treatment, some NWM showed ripple effect (figure 7.13).

Figure 7.13 Ripple effect on nonwoven material.

7.4.2 Impact of bonding fibres

Impact of bonding fibres of specific stress: With the increase of bonding fibre the specific stress of NWMs was increased. For nonwovens bonding with LMP the rate of increasing was higher than nonwovens bonded with PLA. The impact of bonding fibres nonwovens is presented in figure 7.14. For nonwovens bonded with LMP the specific stress was around double when the bonding fibres was increased 10%. For example, if TTT was 135 °C and the amount of LMP raised from 10% to 20%, the specific stress increased from (3.1±1.1) to (8.7±1.7) Nm/g. The impact of bonding fibres on tensile properties were also similar for other nonwovens, including semi-industrially carded NWMs.

At all conditions, RCO:LMP nonwovens showed higher stress than RCO:PLA nonwovens. Moreover, in some conditions, the differences were more than 1.5 times. For instance, 70CO30LMP120 nonwoven had specific stress (9.8±0.6) Nm/g but 70CO30PLA120 had (6.5±0.6) Nm/g, which was more than three times lower. RCO:LMP and RCO:PLA nonwovens also showed similar trends but with some exceptions. For example, while fibre ratio was 80:20, and TTT was 120 °C and 135 °C PLA bonded nonwovens showed higher stress.

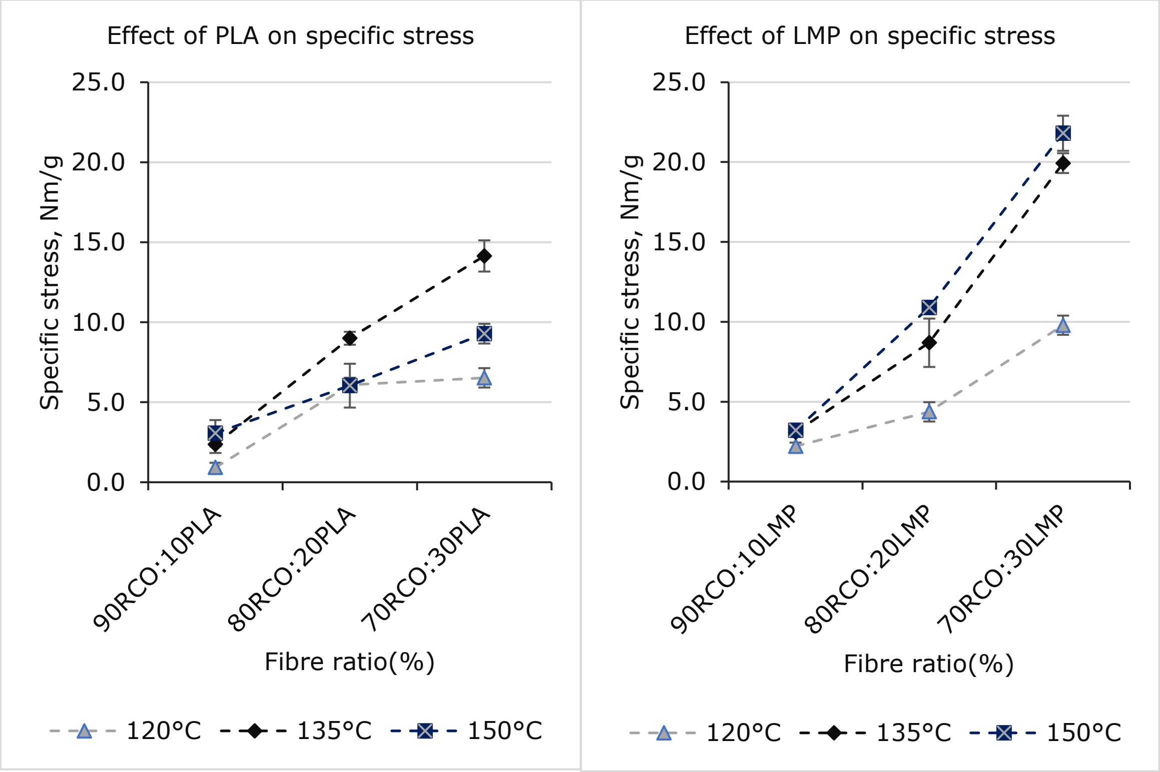


Figure 7.14 Impact of PLA and LMP on specific stress of HC nonwovens.

Impact of bonding fibres on air permeability: Figure 7.15 illustrates the influence of bonding fibres on the air permeability of different nonwovens. With the incorporation of bonding fibre the air permeability was declined, however the rate of decreasing was not significant. For example, 80RCO20PLA had air permeability of (703±26) l/m²·s and 90RCO10PLA had (619±61) l/m²·s. When nonwovens were made from RCO:PLA and RCO:LMP the difference was less than 15%, similarly for CO:PLA and CO:LMP was not greater than 10%. The difference was not always constant and specific. At some points, PLA bonded nonwovens showed higher permeability and vice versa. Moreover, with the increase of bonding fibre the permeability was declining slowly [89]. Lin et al. have also found similar results while investigated thermal insulation properties of nonwoven composite made from bamboo [115].

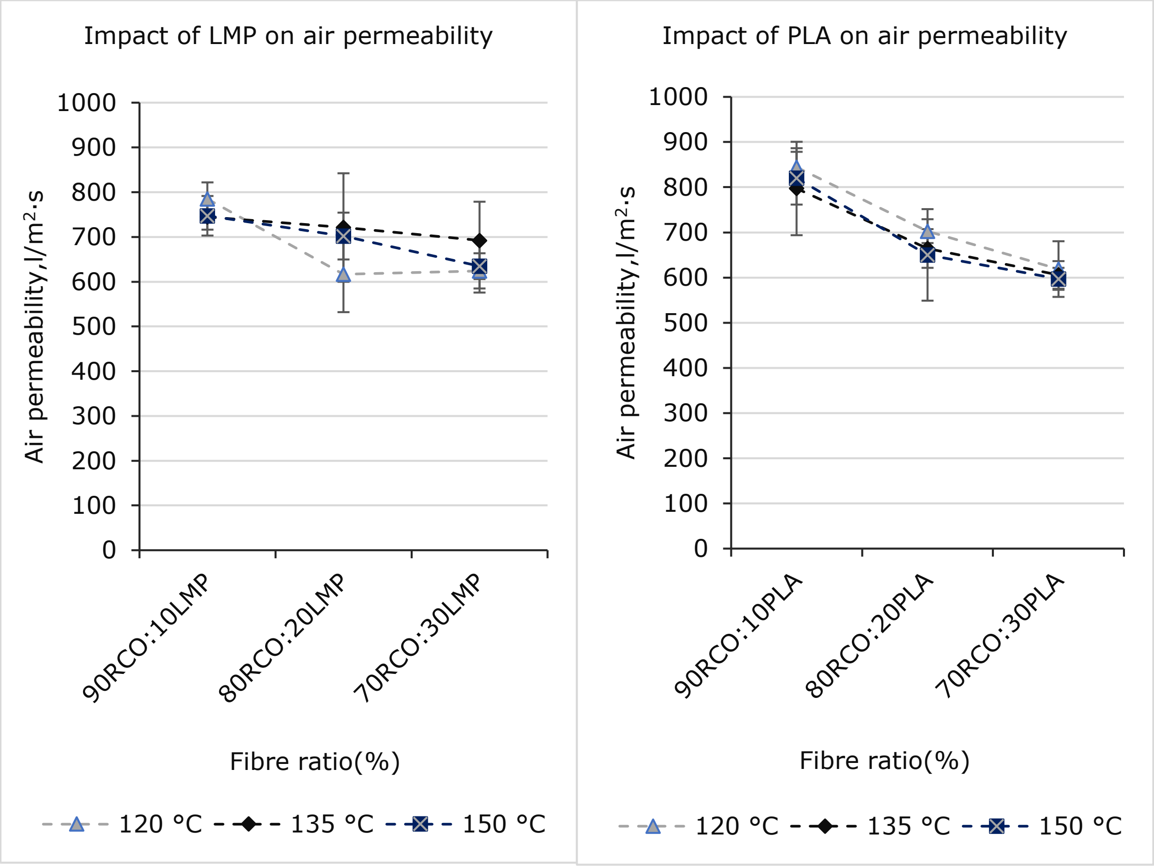


Figure 7.15 Effect of bonding fibres on air permeability of HC nonwovens.

7.4.3 Effect of recycled fibres

Impact of recycled fibres on tensile properties: The incorporation of recycled fibres had an impact on nonwovens properties. In figure 7.16 effect of RCO fibre is presented while nonwovens are made with LMP bonding fibre. Differences between the stress of CO:LMP, RCO:LMP, and CO:RCO:LMP were not the same at all conditions. For some parameters, CO:LMP showed higher stress but in some conditions, other nonwovens showed higher stress. However, RCO:LMP nonwoven showed the stress level above CO:LMP and CO:RCO:LMP nonwovens in most conditions. For instance, while fibre ratio was 80:20 and 70:30 with TTT 135 °C and 150 °C, RCO:LMP had the superior specific stress than CO:LMP and CO:RCO:LMP, where CO:RCO:LMP showed higher stress than CO:LMP. For example, NWMs of RCO7030LMP135 (19.9±0.6 Nm/g) and RCO70LMP30150 (21.8±1.8 Nm/g) had around 43% and 51% higher stress than CO70LMP30135 (14.5±0.6) and CO70LMP30150 13.9±0.6 Nm/g.

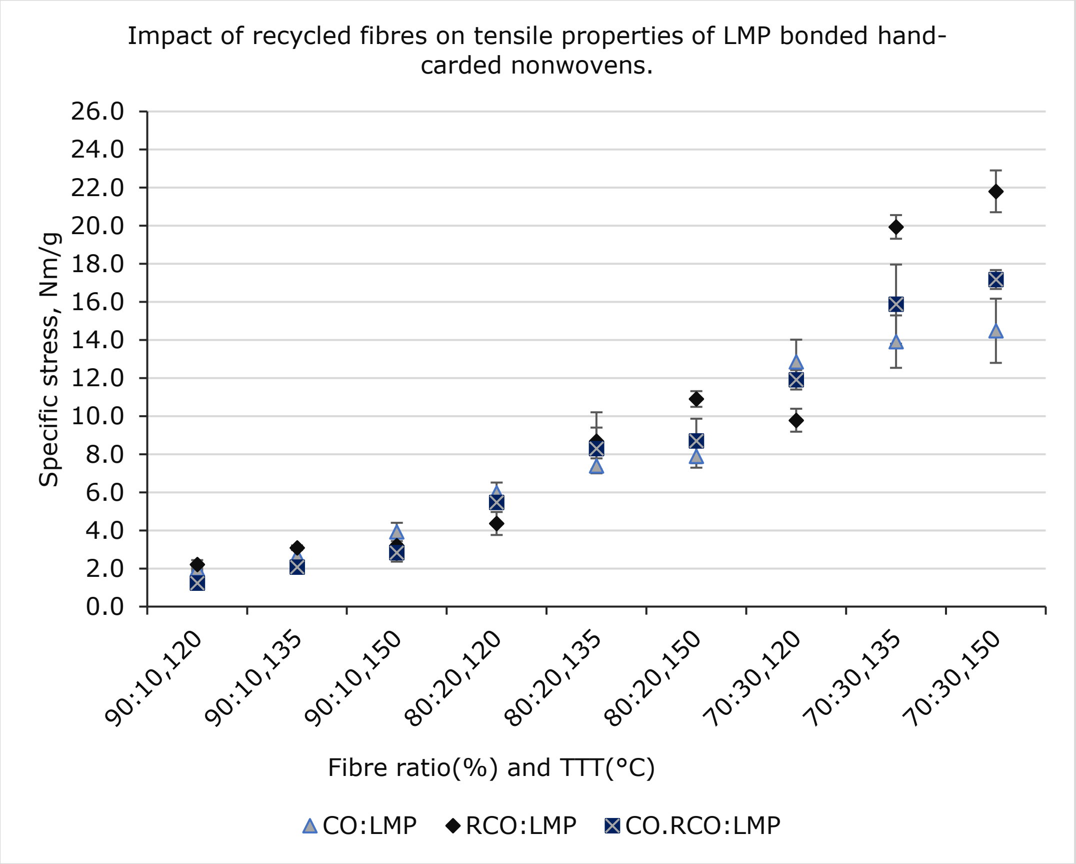


Figure 7.16 Impact of recycled fibres on tensile properties of LMP bonded HC nonwovens.

Nonwovens made from CO:PLA, RCO:PLA and CO:RCO:PLA showed almost similar trend as LMP. Figure 7.17 demonstrates comparison between tensile properties of CO:PLA, RCO:PLA and CO:RCO:PLA. In most cases nonwovens made with RCO or blend of

CO:RCO showed higher stress than virgin CO. 80RCO20PLA150 and 70RCO30PLA135 had 20% and 80% higher specific stress than nonwoven made from virgin CO by similar parameters.

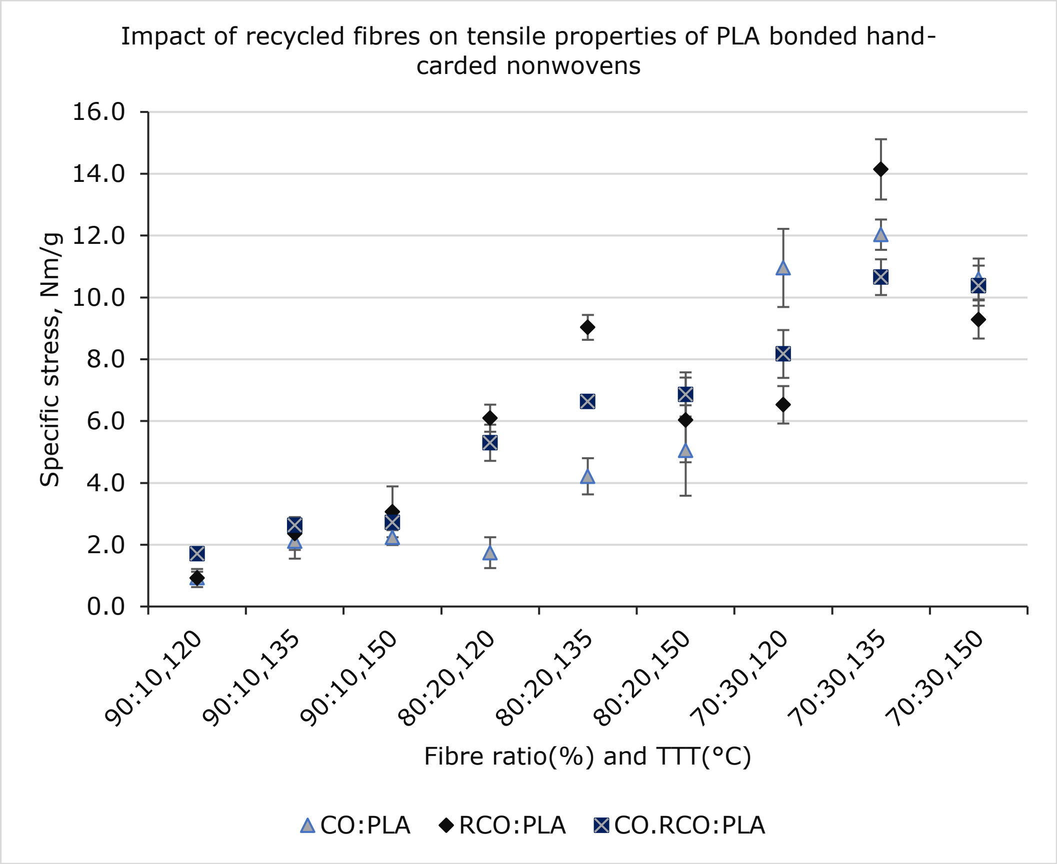


Figure 7.17 Impact of recycled fibres on tensile properties of PLA bonded HC nonwovens.

Impact of recycled fibres on air permeability: Nonwovens showed different air permeability levels with the incorporation of recycled fibre. Figure 7.18 presents air permeability of CO, RCO and CO:RCO nonwovens made with LMP bonding fibre. NWMs made from recycled fibre showed less air permeability than virgin cotton and recycled cotton blended nonwovens. Air permeability of RCO:LMP nonwovens was 29% to 65% less than CO:LMP. On the other hand, CO:RCO:LMP nonwovens had almost similar permeability levels with CO:PLA and CO:LMP nonwovens, except some deviations. All other nonwovens including IC nonwovens showed similar difference, where NWMs made from recycled fibres were more air permeable than NWMs made from virgin fibres.

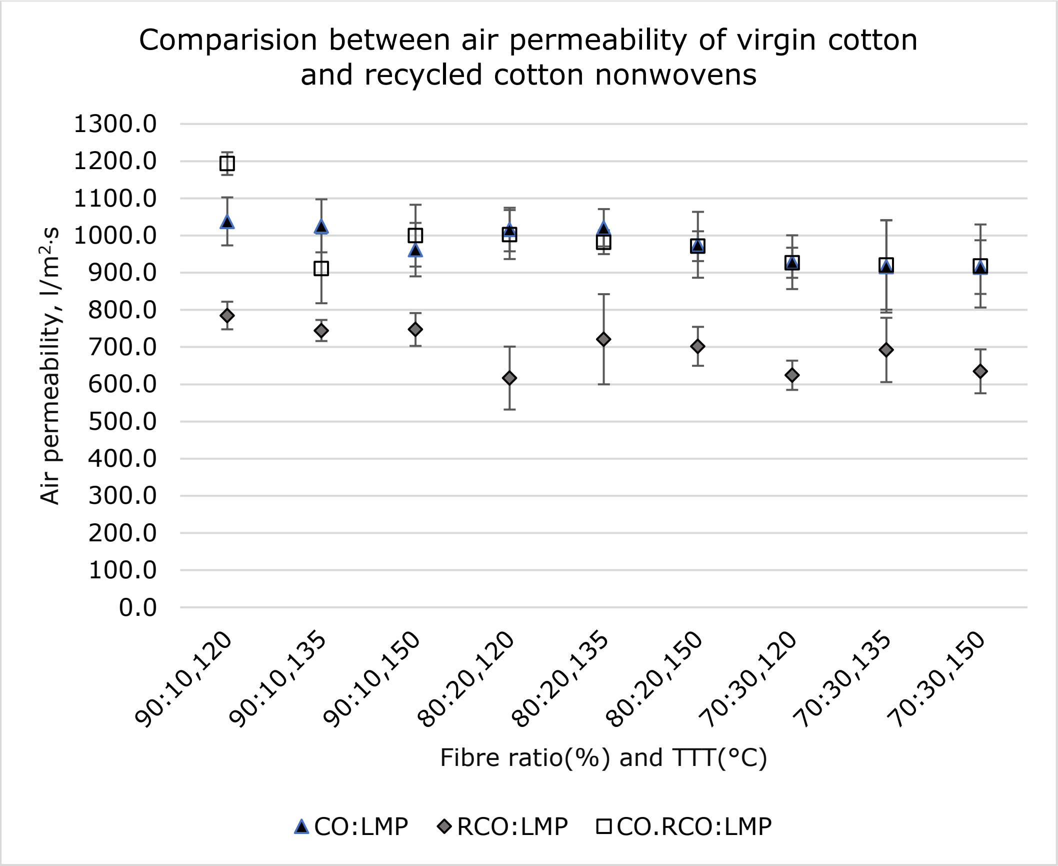


Figure 7.18 Impact of recycled fibre on air permeability HC nonwovens.

7.4.4 Comparison between hand-carded and semi-industrial carded nonwovens

Hand carder and semi-industrial carder showed different impacts on synthetic and natural fibres nonwovens. Figure 7.19 illustrates the influence of hand and semi-industrial carding system on CO:LMP and P:LMP nonwovens. Semi-industrial carded CO:LMP nonwovens had superior stress than hand-carded CO:LMP nonwovens. During nonwoven preparation through hand carder, 6 times carding was applied but 1 times carding was applied for semi-industrial carding. Due to frequent mechanical action during hand carding cotton fibre broke down and formed neps (entangled fibre), which caused reducing the stress and length. On the other hand, P:LMP nonwovens showed a different trend than CO:LMP nonwovens. This is because mechanical actions do not have significant impact on manmade fibres.

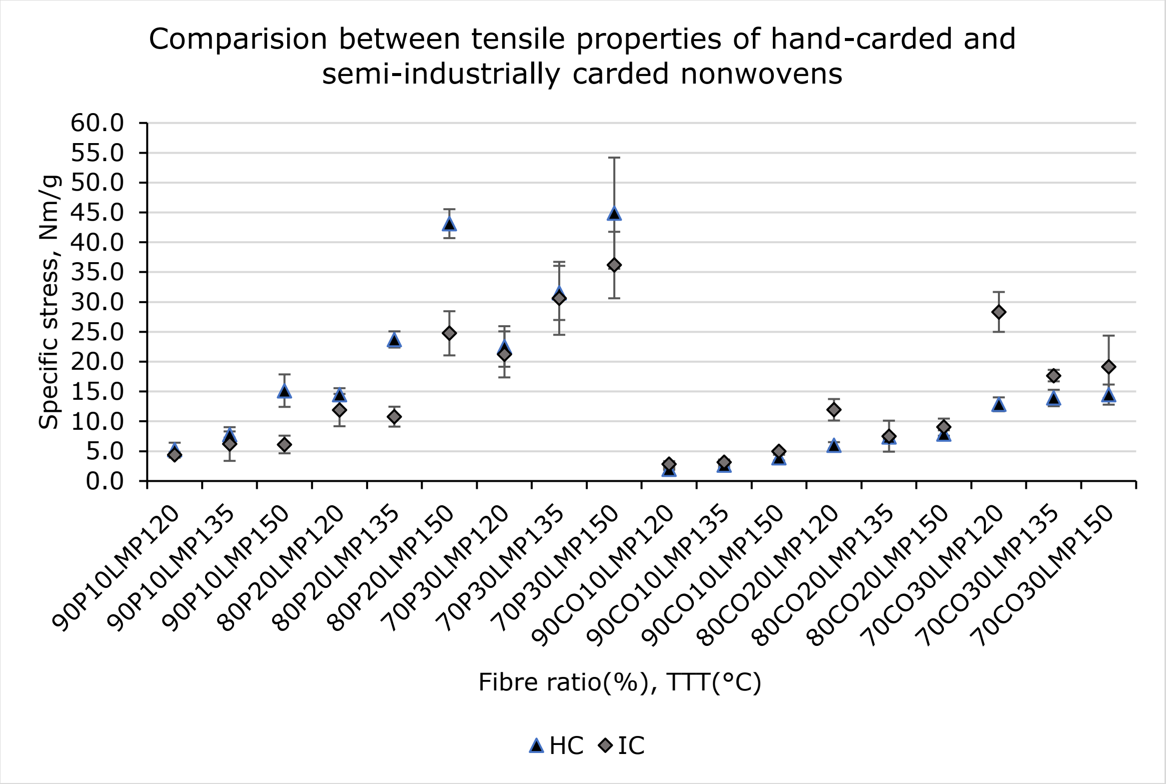


Figure 7.19 Comparision between tensile properties of HC and IC nonwovens.

Figure 7.22 demonstrates the comparison between air permeability of HC and IC nonwovens. Air permeability of semi-industrial carded nonwoven was almost two times higher than hand-carded nonwovens, if nonwovens were made from P:LMP. On the other hand, if nonwoven made from CO:LMP hand-carded nonwovens showed approximately 10% to 20% higher air permeability than semi-industrial carded nonwovens.

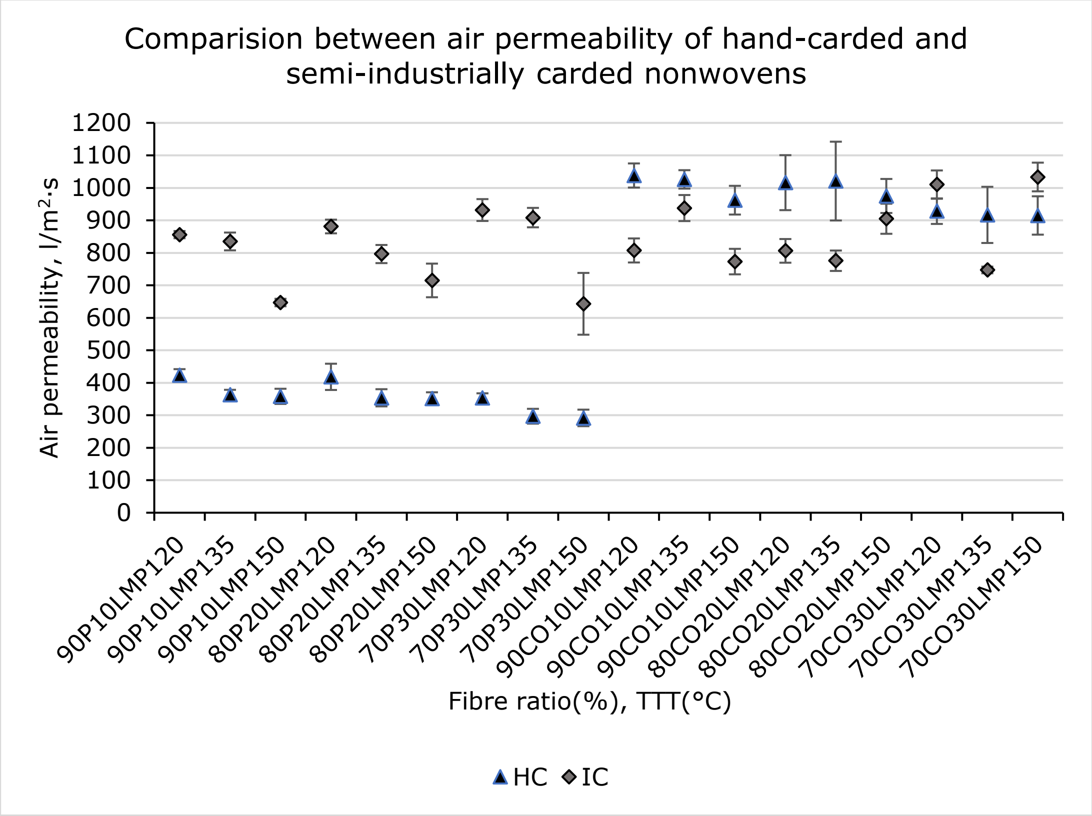


Figure 7.20 Comparision between air permeability of HC and IC nonwovens.

7.5 Main conclusions from the experimental part

- **Mass per unit area** of the most hand-carded NWMs lays between 200 to 300 g/m^2 except polyester nonwovens. Nonwovens made from virgin cotton had a comparatively lower mass per unit area due to some fibre loss during carding. However, most semi-industrially carded nonwovens had mass per unit area above 250 g/m^2. **In addition, HC nonwovens showed bigger S.D than IC nonwovens, which indicates that IC nonwovens were more even.**

- **Tensile properties. Overall, both HC and IC nonwovens made from recycled cotton had higher specific stress than nonwovens made from virgin cotton. For example, 70RCO30PLA120 had higher specific stress of (14.1±1.5) Nm/g and 70CO30PLA120 (12.2±0.5 Nm/g).** Moreover, RCO:LMP nonwovens showed higher stress value than RCO:PLA nonwovens. These results conclude, that fibres length did not significantly affect the tensile stress, since the length of recycled fibres used for nonwovens preparation were smaller than virgin cotton.

- **At most conditions RMF:LMP nonwovens showed higher specific stress than other IC carded nonwovens made from recycled fibres.** Semi-industrially carded RMF:LMP show lower specific stress compared to P:LMP. However, semi-industrially carded RMF:LMP had higher stress than CO:LMP at most conditions. For example, 80RMF20LMP135 had stress of (8.8±0.8) Nm/g and 80CO20LMP135 had (7.5±2.6) Nm/g. At most conditions' IC nonwovens showed higher specific stress than HC nonwovens.

- RMF:LMP nonwovens had overall higher air permeability than other IC nonwovens. Comparatively low air permeability was observed by R'CO:LMP nonwovens. For example, 80R'CO20LMP120 had minimum air permeability, which was (694±2.1) l/m2·s. The highest air permeability was observed for 70RMF30LMP150. This could be because of low thickness.

- **Overall, with the increase of bonding fibre ratio and TTT, the specific stress was increased but the air permeability was decreased. Nonwovens showed the highest stress at 70:30 ratio and 150 °C TTT.** Those nonwovens made from PLA bonding fibre had maximum stress at 135 °C TTT. Specific stress of 70RCO30PLA135 was (14.1±1) Nm/g and (9.3±06) Nm/g for 70RCO30PLA150. nonwovens made from recycled cotton could be an alternative for nonwovens made from virgin cotton.

- **Air permeability of hand-carded NWMs made from RCO was comparatively lower than the air permeability of virgin cotton nonwovens.** For example, 70RCO30PLA (619±62 $l/m^2{\cdot}s$) was less air permeable than 70CO30PLA (970±22 $l/m^2{\cdot}s$). However, these results were different for semi-industrially carded nonwovens, where recycled cotton nonwovens had slightly higher air permeability. Therefore, NWMs made from recycled fibres with high TTT could be used for insulation where stress is necessary. In addition, if stress is not necessary, NWMs made from recycled fibres with low TTT might be suitable.

SUMMARY

Textile production and consumption are increasing sharply; therefore, the amount of textile waste is also rising worldwide. This waste has a detrimental impact on the environment and economy. Due to growing awareness of the circular economy in textile manufacturing, many studies have been revealed since the last century to recycle textile waste. However, most of them are in the development phase owing to some challenges, and, globally, the recycling rate is low. Moreover, the application of recycled fibres is also limited because of inferior quality compared to virgin fibres and availability and low cost of virgin fibres.

An approach for producing nonwoven materials (NWMs) from mechanically recycled textile fibres was introduced in this thesis. In the theoretical part, the general overview of the current situation of textile waste, recycling technologies, application of recycled fibres, and background information about raw materials, manufacturing methods, and properties was given. In the experimental part, a variety of nonwoven materials were prepared with different fibre content and thermal treatment temperature. Eighty-one nonwoven materials through hand carder and seventy-two nonwovens through semi-industrial carder were prepared from both virgin and recycled fibres. Semi-industrially carded nonwovens were made from the University of Tartu Viljandi Culture Academy. First, the impact of fibre types, fibre ratio, and thermal treatment temperature (TTT) on air permeability and tensile properties of nonwovens as explored. Later the comparison between the properties of hand-carded (HC) nonwovens and semi-industrially carded (IC) nonwovens was also discussed. For the preparation of nonwovens cotton (CO), polyester (PL), two types of recycled cotton (RCO and R’CO) and recycled mixed (RMF) fibres were used. RCO was received from TalTech Department of Mechanical and Industrial Engineering, R’CO and RMF were received from *Lounais-Suomen Jätehuolto* (LSJH), Finland. Two different types bonding fibres were used – low-melt polyester (LMP) and polylactic acid (PLA) fibres.

Bonding fibre types and ratio influenced greatly the properties of NWMs. LMP bonded NWMs showed comparatively higher specific stress values than PLA bonded NWMs. For example, hand-carded CO:LMP nonwovens showed up to 53% higher stress value than CO:PLA NWMs, and specific stress of RCO:LMP was up to 58% higher than RCO:PLA. Nonwovens made from the higher amount of boding fibres showed higher strength than those nonwovens made from lower amount of bonding fibres.

The impact of TTT on NWMs tensile properties was significant while other parameters were identical. For all NWMs, the tensile stress was high if the TTT was high. However,

a different result was observed when NWMs were made from PLA bonding fibre. PLA bonded NWMs showed decreased specific stress when the TTT was increased from 135 °C to 150 °C because at 150 °C PLA started to degrade. The difference was high when the ratio of bonding fibre was high.

Though recycled fibres had smaller length than virgin fibres, the specific stress value of NWMs made from recycled cotton was higher than NWMs made from virgin cotton. The reasons could be that the virgin raw cotton was untreated, on the other hand, the extensive mechanical and chemical treatment were applied to improve the properties on recycled cotton during cloth processing. Though some HC nonwovens had superior stress than IC nonwovens, most IC nonwovens showed higher specific stress than HC nonwovens. This is because of even fibre distribution over the nonwovens.

Though air permeability is affected by other factors, it could be stated based on this study that TTT dramatically affects the air permeability. If the TTT was high, the air permeability was low. Furthermore, air permeability of NWMs made from higher bonding fibre ratio showed less air permeability, but the impact was not significant. By heating, the bonding fibres were molten and reduced the pore size and number. On the other hand, the air permeability of NWMs made from recycled cotton was less than virgin cotton nonwovens. Air permeability of semi-industrially carded NWMs was higher than hand-carded NWMs, though few differences were also observed. As fibres were comparatively well organised in IC nonwovens, it was more air permeable than HC nonwovens. On the other hand, neps were formed during six times HC nonwovens preparation, which might hinder the air permeability.

NWMs with higher stress and lower air permeability could be used as automotive interior noise control. However, for thermal insulation least air permeable NWMs are suitable. On the other hand, high air permeability is preferred for ventilation or comfort, such as clothes. Moreover, by applying lower thermal treatment temperature it could be possible to produce high air permeable NWMs for filtration or ventilation application. Overall it can be said that the main aims of the thesis were achieved, nonwoven materials from recycled post-consumer textile waste were produced and characterised. Also the optimum process parameters and possible applications were proposed.

KOKKUVÕTE

Tekstiilmaterjalide tootmine ja tarbimine kasvavad üha kiirenevas tempos, seetõttu suurenevad ülemaailmselt ka tekstiilijäätmete kogused. Tekstiilijäätmetel on keskkonnale ja ka majandusele suur mõju. Viimastel aastakümnetel on teadlikkus ringmajanduse põhimõtetest oluliselt suurenenud, seetõttu on suurenenud ka teadus- ja arendustööde hulk tekstiilijäätmete ümbertöötlemise valdkonnas. Kuna antud valdkond on väga väljakutsete rohke, siis paljud uurimis- ja arendustööd on alles arendusfaasis ning globaalselt saab öelda, et ümbertöötlemise määr on küllaltki madal. Ümbertöödeldud tekstiilkiudude kasutusvaldkond on piiratud, kuna võrreldes uute kiudude on nende kvaliteet madalam, samas on uued kiud on parema kättesaadavusega ning madalama maksumusega.

Käesolev magistritöö keskendus ümbertöödeldud tekstiilkiududest lausmaterjalide valmistamisele. Magistritöö teoreetilises osas anti ülevaade tekstiilijäätmete hetkeolukorrast, erinevatest ümbertöötlemise tehnoloogiatest, ümbertöödeldud tekstiilkiudude kasutusvaldkondadest, samuti anti ülevaade kasutatavatest tekstiilkiududest, erinevatest lausmaterjalide tootmismeetoditest ja nende omadustest. Magistritöö praktilises osas valmistati erineva kiulise koostisega lausmaterjalid, mille kuumtöötlemisel kasutati mitut erinevat temperatuuri. Käsikraasil valmistati 81 erineva koostisega lausmaterjali ning pooltööstuslikul kraasil valmistati 72 erineva koostisega lausmaterjali. Pooltööstuslikul kraasil toodetud materjalid valmistati Tartu Ülikooli Viljandi Kultuuriakadeemias. Esmalt analüüsiti kiudude päritolu, kiulise koostise vahekorra ja kuumtöötlemise temperatuuri mõju õhuläbilaskvusele ning lausmaterjalide tugevusomadustele. Samuti võrreldi käsikraasil kraasitud ning pooltööstuslikul kraasil kraasitud materjalide kvaliteeti ning erinevusi. Lausmaterjalide valmistamisel kasutati põhikiuna puuvilla (CO), polüestrit (PL), TalTech'is ümbertöödeldud puuvilla (RCO) ning Soome jäätmekäitlejalt (*Lounais-Suomen Jätehuolto*) saadud ümbertöödeldud puuvilla (R'CO) ning segakiudusid (RMF). Sidekiuna kasutati kergsulavat polüestrit (LMP) ja polülaktiidkiudusid (PLA).

Saadud lausmaterjalide omadusi mõjutas oluliselt see, milliseid kiudusid ja millises vahekorras oli kasutatud nende valmistamiseks. Materjalide suhteline koormus maksimaalse jõu juures oli tunduvalt kõrgem kui sidekiuna oli kasutatud LMP-d võrdluses PLAga. Näiteks käsikraasil valmistatud puuvillast ja kergsulavast polüestrist lausmaterjalide suhteline koormus oli 53% suurem kui puuvilla ja polülaktiidkiudu sisaldavatel lausamaterjalidel. Ümbertöödeldud puuvillast (RCO) ja kergsulavast polüestrist valmistatud lausmaterjalide suhteline koormus oli aga 58% suurem kui

ümbertöödeldud puuvilla (RCO) ja PLAd sisaldavatel lasumaterjalidel. Mida kõrgem oli sulava kiu osakaal lausmaterjalides, seda paremad oli materjalide tugevusomadused.

Termilise töötlemise temperatuur mõjutas oluliselt lausmaterjalide tugevusomadusi, temperatuuri tõustes paranesid oluliselt materjalide tugevusomadused. Samas võis näha mõnevõrra teistsugust mõju, kui kasutati PLA kiudusid, mille puhul temperatuuri tõustes (135 °C kuni 150 °C) suhteline koormus langes, kuna ilmselt PLA kiud hakkasid lagunema. Mida suurem oli sidekiu hulk seda suurem erinevus oli kahe sidekiuga valmistatud lausmaterjali vahel.

Kuigi ümbertöödeldud kiudude pikkused olid väiksemad uute kiudude pikkustest, siis ümbertöödeldud kiududest valmistatud lausmaterjalide suhtelise koormuse väärtused olid kõrgemad. See võib olla tingitud asjaolust, et ümbertöödeldud tarbijajärgsetest jäätmetest saadud kiud on juba oluliselt eelnevalt töödeldud, kuid uued puuvillakiud olid töötlemata. Kuigi ka mõned käsikraasil valmistatud lausmaterjalid näitasid häid tugevusomadusi, siis pooltööstuslikult valmistatud lausmaterjalide suhtelise koormuse väärtused oli kõrgemad. See võib olla tingitud asjaolust, et pooltööstuslikult valmistatud lausmaterjalid oli ühtlasema struktuuriga.

Õhuläbilaskvust mõjutavad erinevad tegurid, kuid selle magistritöö raames tehtud katsetustest võib järeldada, et termilise töötlemise temperatuuril on oluline mõju materjalide õhuläbilaskvusele. Kõrgematel temperatuuridel valmistatud lausmaterjalide õhuläbilaskvus oli pigem madal. Õhuläbilaskvus oli madalam lausmaterjalidel, mis sisaldasid suuremal määral sidekiudusid. Temperatuuri tõustes sidekiud sulasid ning see põhjustas lausmaterjalis olevate pooride suuruse ja arvu vähenemist. Teisalt võib välja tuua, et ümbertöödeldud puuvillast valmistatud lausmaterjalide õhuläbilaskvus oli madalam uutest puuvillakiududest valmistatud lausmaterjalide õhuläbilaskvusest. Pooltööstuslikul kraasil valmistatud lausmaterjalide õhuläbilaskvus oli reeglina suurem käsikraasil valmistatud lausmaterjalide õhuläbilaskvusest. See võis olla tingitud asjaolust, et pooltööstuslikult valmistatud materjalide struktuur on ühtlasem. Käsikraasil valmistatud lausmaterjale kraasiti läbi aga 6 korda ning see põhjustas sasinenud kiudude kogumikke, mis omakorda võivad mõjutada õhuläbilaskvuse väärtusi.

Kõrge suhtelise koormuse ning madala õhuläbilaskvusega materjale võiks kasutada näiteks autotööstuses helisummutavate materjalidena. Soojusisolatsioonimaterjalideks võiksid olla sobivad vähese õhuläbilaskvusega lausmaterjalid. Samas hea õhuläbilaskvus on oluline näiteks rõivaste valmistamiseks kasutatavate materjalide puhul. Madalama termilise töötlemise temperatuuri juures on võimalik toota hea õhuläbilaskvusega materjale näiteks filtrite valmistamiseks. Kokkuvõttes said antud magistritöö põhieesmärgid täidetud. Magistritöö käigus valmisid lausmaterjalid tarbijajärgsetest tekstiilijäätmetest ning iseloomustati saadud materjalide omadusi. Leiti ka optimaalsed lausmaterjalide valmistamise parameetrid ning samuti pakuti välja saadud materjalidele erinevaid kasutusvaldkondi.

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APPENDICES

Appendix 1 Length and linear density of textile fibres

Table A1.1 Length and linear density of textile fibres.

	Linear density, dtex			**Length, mm**		
	Average	S.D	CV%	Average	S.D	CV%
PES	1.73	0.07	3.9%	51	1.04	2.0%
CO	1.85	0.23	12.1%	26	5.27	20.1%
RCO	:	:	:	4	2.7	64.0%
RCO2	:	:	:	10	7.7	81.0%
RMF	:	:	:	14	10.7	78.0%
LMP	5.37	0.72	13.5%	50	0.95	1.9%
PLA	4.44	0.55	12.4%	52	1.33	2.6%

Appendix 2 Length distribution of textile fibre

Figure A2.1 Length distribution of cotton.

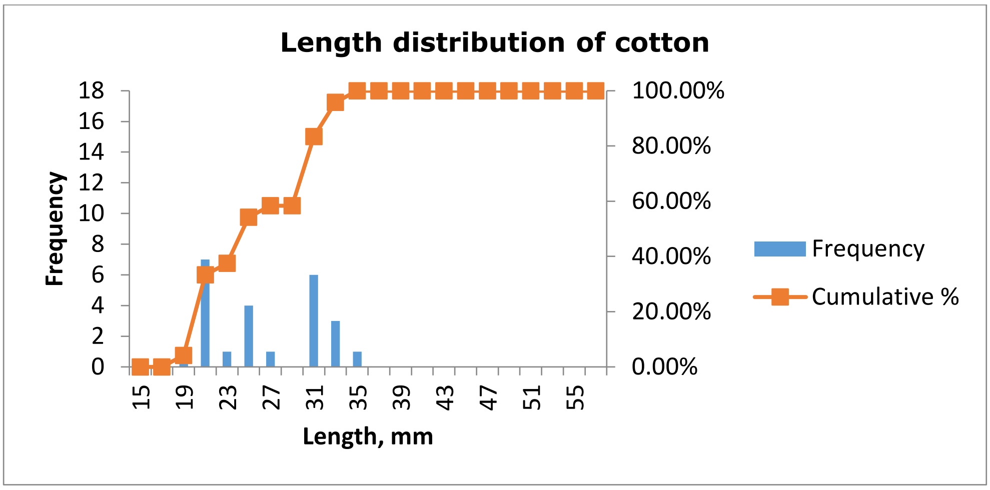


Figure A2.2 Length distribution of regular polyester.

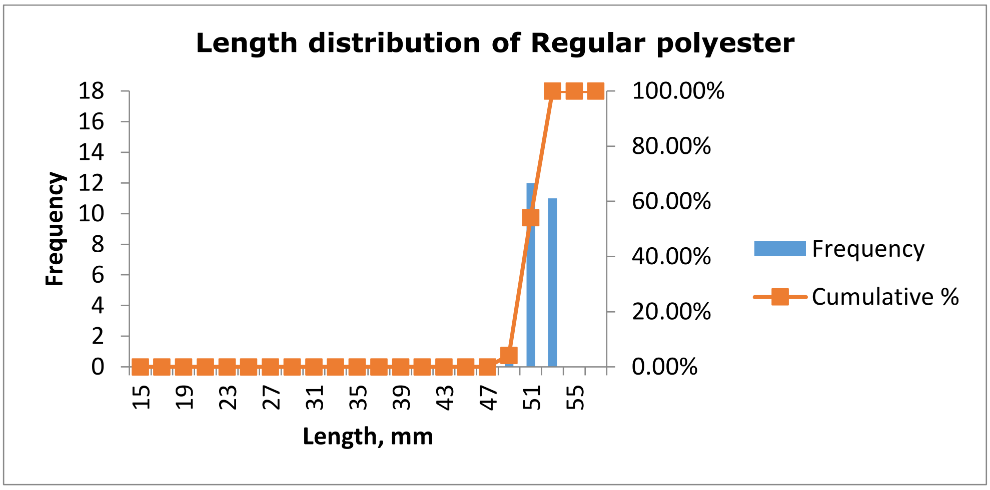


Figure A2.3 Length distribution of low melt polyester.

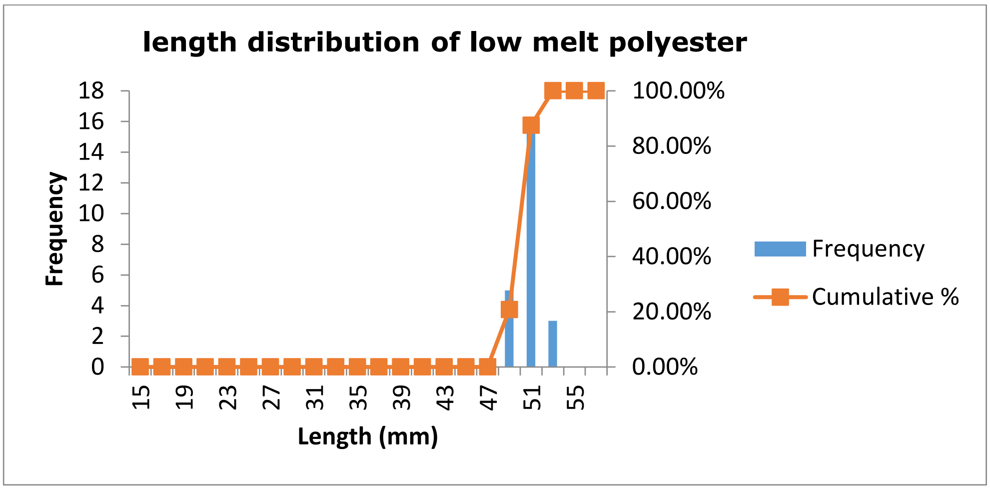
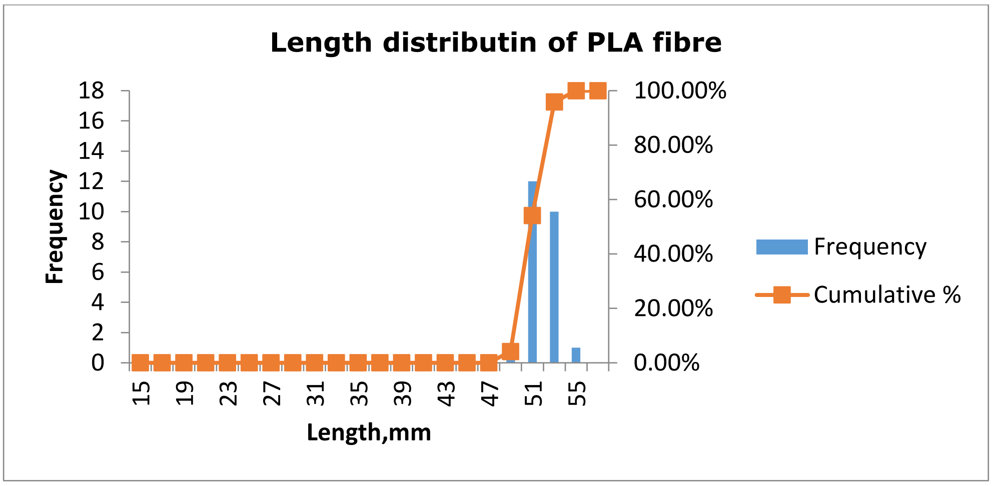
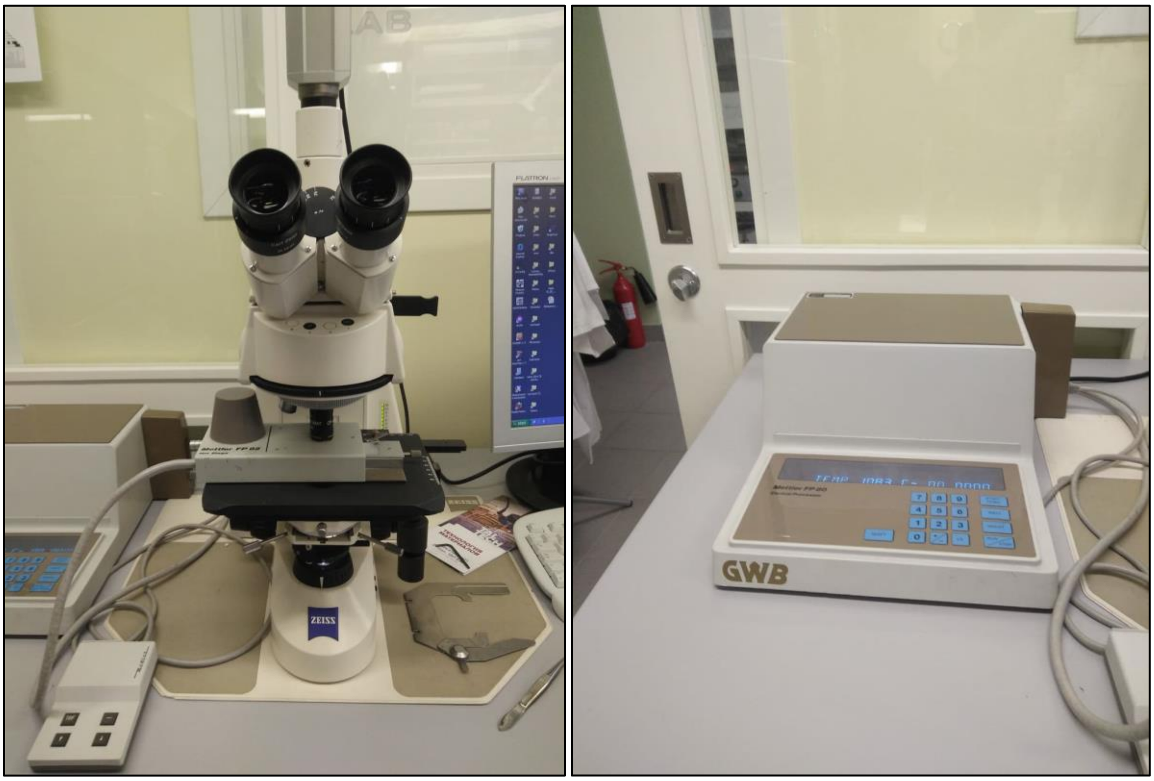


Figure A2.4 Length distribution of PLA.



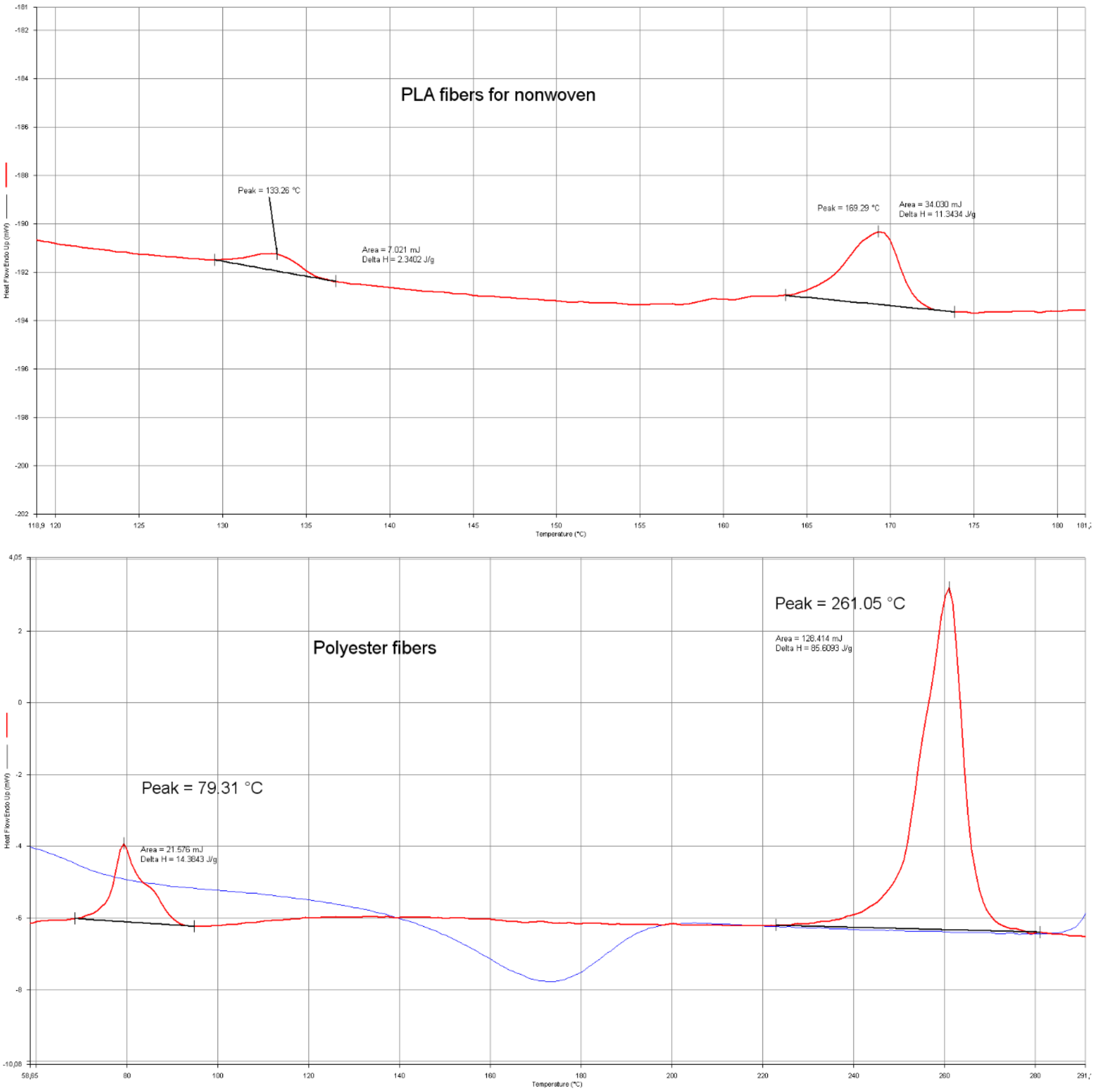
Appendix 3 Apparatus for hot stage microscopy analysis

Figure A3.1 Apparatus for hot stage microscopy analysis.



Appendix 4 DSC analysis images of PLA and low melt polyester

Figure A4.1 DSC analysis of PLA and low melt polyester.



Appendix 5 Sample identification for hand-carded nonwovens

Table A5.1 Sample identification for hand-carded nonwovens.

SL	Fibre content	Thermal treatment temperature	Sample ID
HC1	90%Polyester+10%LMP	120 °C	90P10LMP120
HC2	90%Polyester+10%LMP	135 °C	90P10LMP135
HC3	90%Polyester+10%LMP	150 °C	90P10LMP150
HC4	80%Polyester+20%LMP	120 °C	80P20LMP120
HC5	80%Polyester+20%LMP	135 °C	80P20LMP135
HC6	80%Polyester+20%LMP	150 °C	80P20LMP150
HC7	70%Polyester+30%LMP	120 °C	70P30LMP120
HC8	70%Polyester+30%LMP	135 °C	70P30LMP135
HC9	70%Polyester+30%LMP	150 °C	70P30LMP150
HC10	45%Cotton+45%polyester+10%PLA	120 °C	45CO45P10PLA120
HC11	45%Cotton+45%polyester+10%PLA	135 °C	45CO45P10PLA135
HC12	45%Cotton+45%polyester+10%PLA	150 °C	45CO45P10PLA150
HC13	40%Cotton+40%polyester+20%PLA	120 °C	40CO40P20PLA120
HC14	40%Cotton+40%polyester+20%PLA	135 °C	40CO40P20PLA135
HC15	40%Cotton+40%polyester+20%PLA	150 °C	40CO40P20PLA150
HC16	35%Cotton+35%polyester+30%PLA	120 °C	35CO35P30PLA120
HC17	35%Cotton+35%polyester+30%PLA	135 °C	35CO35P30PLA135
HC18	35%Cotton+35%polyester+30%PLA	150 °C	35CO35P30PLA150
HC19	45%Cotton+45%polyester+10%LMP	120 °C	45CO45P10LMP120
HC20	45%Cotton+45%polyester+10%LMP	135 °C	45CO45P10LMP135
HC21	45%Cotton+45%polyester+10%LMP	150 °C	45CO45P10LMP150
HC22	40%Cotton+40%polyester+20%LMP	120 °C	40CO40P20LMP120
HC23	40%Cotton+40%polyester+20%LMP	135 °C	40CO40P20LMP135
HC24	40%Cotton+40%polyester+20%LMP	150 °C	40CO40P20LMP150
HC25	35%Cotton+35%polyester+30%LMP	120 °C	35CO35P30LMP120
HC26	35%Cotton+35%polyester+30%LMP	135 °C	35CO35P30LMP135
HC27	35%Cotton+35%polyester+30%LMP	150 °C	35CO35P30LMP150
HC28	90%Recycled cotton+10%PLA	120 °C	90RCO10PLA120
HC29	90%Recycled cotton+10%PLA	135 °C	90RCO10PLA135
HC30	90%Recycled cotton+10%PLA	150 °C	90RCO10PLA150
HC31	80%Recycled cotton+20%PLA	120 °C	80RCO20PLA120
HC32	80%Recycled cotton+20%PLA	135 °C	80RCO20PLA135
HC33	80%Recycled cotton+20%PLA	150 °C	80RCO20PLA150
HC34	70%Recycled cotton+30%PLA	120 °C	70RCO30PLA120
HC35	70%Recycled cotton+30%PLA	135 °C	70RCO30PLA135
HC36	70%Recycled cotton+30%PLA	150 °C	70RCO30PLA150
HC37	90%Recycled cotton+10%LMP	120 °C	90RCO10LMP120
HC38	90%Recycled cotton+10%LMP	135 °C	90RCO10LMP135
HC39	90%Recycled cotton+10%LMP	150 °C	90RCO10LMP150
HC40	80%Recycled cotton+20%LMP	120 °C	80RCO20LMP120
HC41	80%Recycled cotton+20%LMP	135 °C	80RCO20LMP135
HC42	80%Recycled cotton+20%LMP	150 °C	80RCO20LMP150
HC43	70%Recycled cotton+30%LMP	120 °C	70RCO30LMP120
HC44	70%Recycled cotton+30%LMP	135 °C	70RCO30LMP135

SL	Fibre content	Thermal treatment temperature	Sample ID
HC45	70%Recycled cotton+30%LMP	150 °C	70RCO30LMP150
HC46	90%Cotton+10%PLA	120 °C	90CO10PLA120
HC47	90%Cotton+10%PLA	135 °C	90CO10PLA135
HC48	90%Cotton+10%PLA	150 °C	90CO10PLA150
HC49	80%Cotton+20%PLA	120 °C	80CO20PLA120
HC50	80%Cotton+20%PLA	135 °C	80CO20PLA135
HC51	80%Cotton+20%PLA	150 °C	80CO20PLA150
HC52	70%Cotton+30%PLA	120 °C	70CO30PLA120
HC53	70%Cotton+30%PLA	135 °C	70CO30PLA135
HC54	70%Cotton+30%PLA	150 °C	70CO30PLA150
HC55	90%Cotton+10%LMP	120 °C	90CO10LMP120
HC56	90%Cotton+10%LMP	135 °C	90CO10LMP135
HC57	90%Cotton+10%LMP	150 °C	90CO10LMP150
HC58	80%Cotton+20%LMP	120 °C	80CO20LMP120
HC59	80%Cotton+20%LMP	135 °C	80CO20LMP135
HC60	80%Cotton+20%LMP	150 °C	80CO20LMP150
HC61	70%Cotton+30%LMP	120 °C	70CO30LMP120
HC62	70%Cotton+30%LMP	135 °C	70CO30LMP135
HC63	70%Cotton+30%LMP	150 °C	70CO30LMP150
HC64	45%Cotton+45%Recycled cotton+10%PLA	120 °C	45CO45RCO10PLA120
HC65	45%Cotton+45%Recycled cotton+10%PLA	135 °C	45CO45RCO10PLA135
HC66	45%Cotton+45%Recycled cotton+10%PLA	150 °C	45CO45RCO10PLA150
HC67	40%Cotton+40%Recycled cotton+20%PLA	120 °C	40CO40RCO20PLA120
HC68	40%Cotton+40%Recycled cotton+20%PLA	135 °C	40CO40RCO20PLA135
HC69	40%Cotton+40%Recycled cotton+20%PLA	150 °C	40CO40RCO20PLA150
HC70	35%Cotton+35%Recycled cotton+30%PLA	120 °C	35CO35RCO30PLA120
HC71	35%Cotton+35%Recycled cotton+30%PLA	135 °C	35CO35RCO30PLA135
HC72	35%Cotton+35%Recycled cotton+30%PLA	150 °C	35CO35RCO30PLA150
HC73	45%Cotton+45%Recycled cotton+10%LMP	120 °C	45CO45RCO10LMP120
HC74	45%Cotton+45%Recycled cotton+10%LMP	135 °C	45CO45RCO10LMP135
HC75	45%Cotton+45%Recycled cotton+10%LMP	150 °C	45CO45RCO10LMP150
HC76	40%Cotton+40%Recycled cotton+20%LMP	120 °C	40CO40RCO20LMP120
HC77	40%Cotton+40%Recycled cotton+20%LMP	135 °C	40CO40RCO20LMP135
HC78	40%Cotton+40%Recycled cotton+20%LMP	150 °C	40CO40RCO20LMP150
HC79	35%Cotton+35%Recycled cotton+30%LMP	120 °C	35CO35RCO30LMP120
HC80	35%Cotton+35%Recycled cotton+30%LMP	135 °C	35CO35RCO30LMP135
HC81	35%Cotton+35%Recycled cotton+30%LMP	150 °C	35CO35RCO30LMP150

Appendix 6 Sample identification for Semi-industrially carded nonwovens

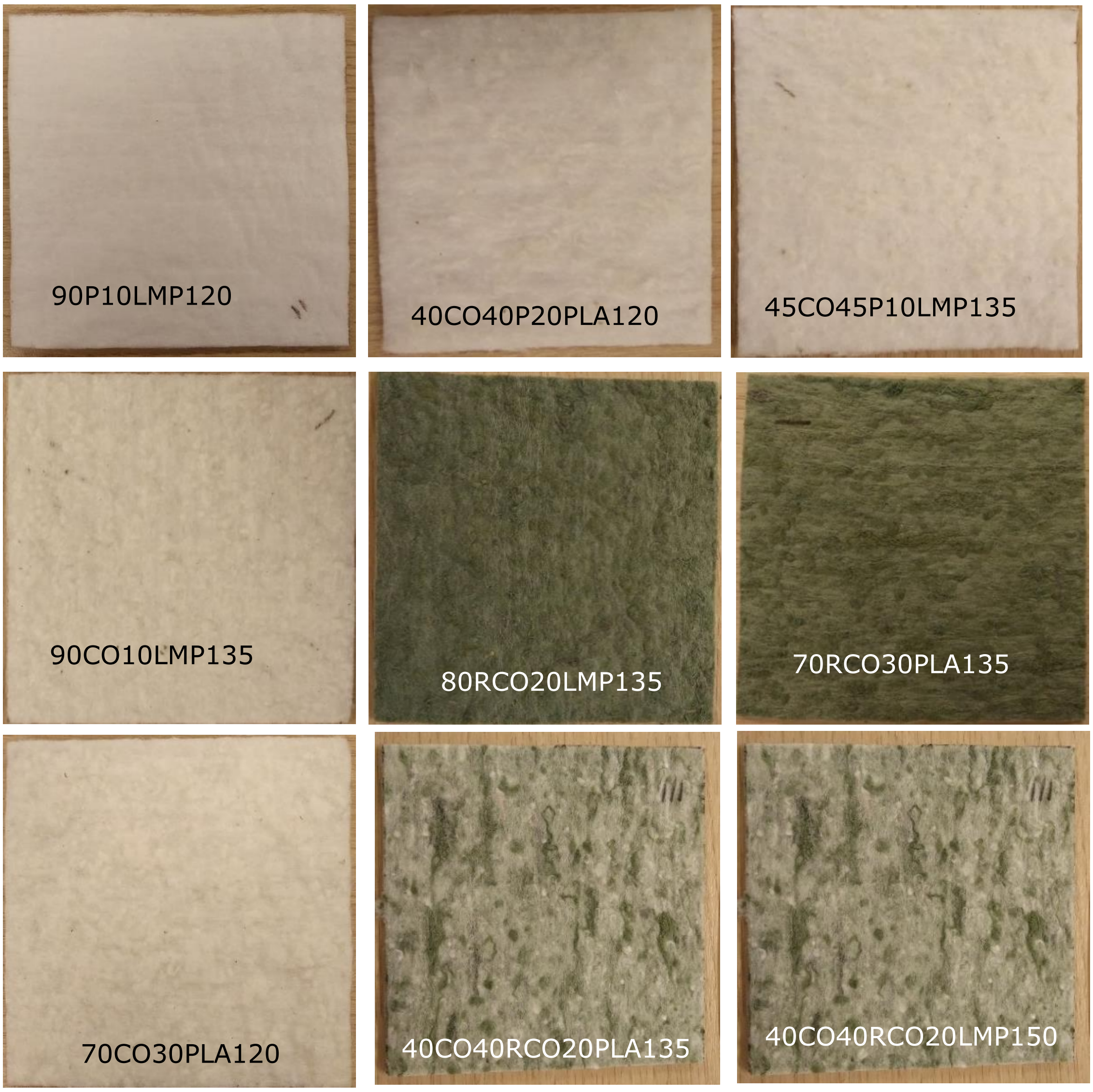
Table A6.1 Sample dentificatin for semi-industrially carded nonwovens.

SL	Fibre content	Thermal treatment temperature	Materials ID
IC1	90%Polyester+10%LMP	120 °C	90P10LMP120
IC2	90%Polyester+10%LMP	135 °C	90P10LMP135
IC3	90%Polyester+10%LMP	150 °C	90P10LMP150
IC4	80%Polyester+20%LMP	120 °C	80P20LMP120
IC5	80%Polyester+20%LMP	135 °C	80P20LMP135
IC6	80%Polyester+20%LMP	150 °C	80P20LMP150
IC7	70%Polyester+30%LMP	120 °C	70P30LMP120
IC8	70%Polyester+30%LMP	135 °C	70P30LMP135
IC9	70%Polyester+30%LMP	150 °C	70P30LMP150
IC10	45%Cotton+45%polyester+10%PLA	120 °C	45CO45P10PLA120
IC11	45%Cotton+45%polyester+10%PLA	135 °C	45CO45P10PLA135
IC12	45%Cotton+45%polyester+10%PLA	150 °C	45CO45P10PLA150
IC13	40%Cotton+40%polyester+20%PLA	120 °C	40CO40P20PLA120
IC14	40%Cotton+40%polyester+20%PLA	135 °C	40CO40P20PLA135
IC15	40%Cotton+40%polyester+20%PLA	150 °C	40CO40P20PLA150
IC16	35%Cotton+35%polyester+30%PLA	120 °C	35CO35P30PLA120
IC17	35%Cotton+35%polyester+30%PLA	135 °C	35CO35P30PLA135
IC18	35%Cotton+35%polyester+30%PLA	150 °C	35CO35P30PLA150
IC19	45%Cotton+45%polyester+10%LMP	120 °C	45CO45P10LMP120
IC20	45%Cotton+45%polyester+10%LMP	135 °C	45CO45P10LMP135
IC21	45%Cotton+45%polyester+10%LMP	150 °C	45CO45P10LMP150
IC22	40%Cotton+40%polyester+20%LMP	120 °C	40CO40P20LMP120
IC23	40%Cotton+40%polyester+20%LMP	135 °C	40CO40P20LMP135
IC24	40%Cotton+40%polyester+20%LMP	150 °C	40CO40P20LMP150
IC25	35%Cotton+35%polyester+30%LMP	120 °C	35CO35P30LMP120
IC26	35%Cotton+35%polyester+30%LMP	135 °C	35CO35P30LMP135
IC27	35%Cotton+35%polyester+30%LMP	150 °C	35CO35P30LMP150
IC28	90%Cotton+10%PL	120 °C	90CO10PLA120
IC29	90%Cotton+10%PLA	135 °C	90CO10PLA135
IC30	90%Cotton+10%PLA	150 °C	90CO10PLA150
IC31	80%Cotton+20%PLA	120 °C	80CO20PLA120
IC32	80%Cotton+20%PLA	135 °C	80CO20PLA135
IC33	80%Cotton+20%PLA	150 °C	80CO20PLA150
IC34	70%Cotton+30%PLA	120 °C	70CO30PLA120
IC35	70%Cotton+30%PLA	135 °C	70CO30PLA135
IC36	70%Cotton+30%PLA	150 °C	70CO30PLA150
IC37	90%Cotton+10%LMP	120 °C	90CO10LMP120
IC38	90%Cotton+10%LMP	135 °C	90CO10LMP135
IC39	90%Cotton+10%LMP	150 °C	90CO10LMP150
IC40	80%Cotton+20%LMP	120 °C	80CO20LMP120
IC41	80%Cotton+20%LMP	135 °C	80CO20LMP135
IC42	80%Cotton+20%LMP	150 °C	80CO20LMP150
IC43	70%Cotton+30%LMP	120 °C	70CO30LMP120
IC44	70%Cotton+30%LMP	135 °C	70CO30LMP135
IC45	70%Cotton+30%LMP	150 °C	70CO30LMP150
IC46	90%Recycled Cotton+10%PLA	120 °C	90RCO10PLA120
IC47	90%Recycled Cotton+10%PLA	135 °C	90RCO10PLA135
IC48	90%Recycled Cotton+10%PLA	150 °C	90RCO10PLA150
IC49	80%Recycled Cotton+20%PLA	120 °C	80RCO20PLA120
IC50	80%Recycled Cotton+20%PLA	135 °C	80RCO20PLA135
IC51	80%Recycled Cotton+20%PLA	150 °C	80RCO20PLA150
IC52	70%Recycled Cotton+30%PLA	120 °C	70RCO30PLA120
IC53	70%Recycled Cotton+30%PLA	135 °C	70RCO30PLA135

SL	Fibre content	Thermal treatment temperature	Materials ID
IC54	70%Recycled Cotton+30%PLA	150 °C	70RCO30PLA150
IC55	80%Recycled Cotton+20%LMP	120 °C	80RCO20LMP120
IC56	80%Recycled Cotton+20%LMP	135 °C	80RCO20LMP135
IC57	80%Recycled Cotton+20%LMP	150 °C	80RCO20LMP150
IC58	70%Recycled Cotton+30%LMP	120 °C	70RCO30LMP120
IC59	70%Recycled Cotton+30%LMP	135 °C	70RCO30LMP135
IC60	70%Recycled Cotton+30%LMP	150 °C	70RCO30LMP150
IC61	90%Recycled Mixed Fiber+10%LMP	120 °C	90RMF10LMP120
IC62	90%Recycled Mixed Fiber+10%LMP	135 °C	90RMF10LMP135
IC63	90%Recycled Mixed Fiber+10%LMP	150 °C	90RMF10LMP150
IC64	80%Recycled Mixed Fiber+20%LMP	120 °C	80RMF20LMP120
IC65	80%Recycled Mixed Fiber+20%LMP	135 °C	80RMF20LMP135
IC66	80%Recycled Mixed Fiber+20%LMP	150 °C	80RMF20LMP150
IC67	70%Recycled Mixed Fiber+30%LMP	120 °C	70RMF30LMP120
IC68	70%Recycled Mixed Fiber+30%LMP	135 °C	70RMF30LMP135
IC69	70%Recycled Mixed Fiber+30%LMP	150 °C	70RMF30LMP150
IC70	35%Cotton+35%Recotton+30%LMP	120 °C	35CO35RCO30LMP120
IC71	35%Cotton+35%Recotton+30%LMP	135 °C	35CO35RCO30LMP135
IC72	35%Cotton+35%Recotton+30%LMP	150 °C	35CO35RCO30LMP150

Appendix 7 Examples of hand-carded nonwovens materials

Figure A8.1 Photos of hand-carded nonwoven materials.



Appendix 8 Examples of semi-industrially carded nonwoven materials

Figure A9.1 Photos of semi-industrially carded nonwoven materials.