Tampereen yliopisto

Ella Kärkkäinen

CHARACTERISATION OF SELECTED MECHANICALLY OPENED COTTON FIBRES

A study on the feasibility of spinning the staple fibres into recycled yarn

Master of Science Thesis
Faculty of Engineering and Natural Sciences
Examiners: Professor Jurkka Kuusipalo
M.Sc. Taina Kamppuri (Research team leader, VTT)
October 2023

ABSTRACT

Ella Kärkkäinen: Characterisation of selected mechanically opened cotton fibres – A study on the feasibility of spinning the staple fibres into yarn
Master's thesis
Tampere University
Engineering Materials Science
October 2023

With the upcoming EU directive and the recent Finnish waste legislation it has become necessary to find ways to collect, sort and recycle textile waste. Textile waste is now collected nationwide in Finland, with reusable items directed to second hand sales, and non-reusable waste directed into recycling centres. Two mechanical opening lines were opened in Paimio in 2021 with a shared theoretical opening rate of 50 tonnes of fibre per year. While the theoretical recycling rate is high, the problem arises with the poor reputation of recycled fibres on the textile market. It has been reported that fibres should have a certain tenacity and length to suit the yarn production needs. Telavalue is a Business Finland (BF) project that aims to create value for the textile waste and offer solutions for circularity of the textile economy. The project is coordinated by VTT, LAB University of Applied Sciences and Turku University of Applied Sciences and executed in partnership with other research centres, companies, and other organisations. The commercial actors in the textile industry are interested in the quality of recycled fibres for future textile solutions. This study aims to show the value in fibre-to-fibre recycling and in mechanically opened (MO) fibres further processed into yarn by staple fibre spinning.

This study utilises both quantitative and qualitative methods to characterise six different types of MO cotton fibres: PRE-KNIT, PRE-WOVEN, POST-B2B, POST-n, POST-s and POST-ea. The cotton types include both pre- and post-consumer derived fibres. Pre-consumer fibres are obtained from garment production of knitwear (KNIT) and denim (WOVEN). The post-consumer textiles are collected from workwear companies (B2B) and from municipal waste collection with either neutral (n) sorting and opening, softener (s) used in the opening, or with up to 10% elastane (ea) and other fibres allowed in sorting. A reference of 100% virgin cotton, REF-CO, was used. The fibres were obtained from a fibre collection belonging to the Telavalue BF.

In general, the results showed shortened fibre lengths for the mechanically opened fibres. While the REF-CO average length was calculated to be 18.8 millimetres, the longest mechanically opened fibres were 25-27 mm long. The shortest fibre contents were established for the sample PRE-KNIT, with average length of 8.6 mm. Although the fibre lengths were weak, the fibre uniformity indexes (UI) of the MO fibres were from 54 to 59% and the UI of REF-CO was 64%. The PRE-WOVEN and POST-B2B were made up of a greater content of long fibres than the other MO samples. The linear densities were near equal to the values of REF-CO. Tenacities at break were generally greater for post-consumer samples than any other samples. POST-ea was found with greatest elongation at break and PRE-KNIT with the weakest. The surfaces of the fibres were inspected with scanning electron microscopy (SEM). The inspection showed some damaging of the MO fibres. However, this damage was sparse and only visible on individual fibres. Additionally, a 50-year-old bedsheet was hand-opened into fibres to look out for surface wear. There was some surface opening on those fibres, as well as on some post-consumer fibres. Moreover, the post-consumer samples were dirtier than REF-CO or the pre-consumer samples. SEM imaging revealed other fibres than cotton in the samples. Furthermore, a Fourier transform infrared spectroscopy (FT-IR) and differential scanning calorimetry (DSC) were applied to investigate the composition of the cotton qualities. It was discovered that alongside REF-CO, PRE-KNIT and PRE-WOVEN did not have any melting points between 0 to 300 ºC whereas all post-consumer samples showed peaks. A cross-examination with FT-IR hinted that the post-consumer samples include e.g., polyester, which is a common fibre in denim garments.

A discussion of a classification of mechanically opened cotton fibres is included as a result of the experimental work. The multiple factors affecting MO fibre properties make it challenging to draw conclusions without neglecting some properties.

Keywords: mechanical opening, opened fibres, recycled fibres, post-consumer textile waste

TIIVISTELMÄ

Ella Kärkkäinen: Valittujen mekaanisesti avattujen puuvillalaatujen karakterisointi – Tutkimus mahdollisuuksista käyttää kierrätyskuituja langankehräyksessä
Diplomityö
Tampereen yliopisto
Materiaalitekniikan DI-ohjelma
Lokakuu 2023

Tulevan EU-direktiivin ja Suomen uuden jätelainsäädännön myötä on tullut tarpeelliseksi löytää keinoja tekstiilijätteen keräämiseen, lajitteluun ja kierrätykseen. Tekstiilijätettä kerätään nyt valtakunnallisesti Suomessa. Käyttökelpoiset tekstiilit ohjataan käytetyn tavaran myyntiin ja käyttöön kelpaamattomat tekstiilit kierrätykseen. Paimioon avattiin vuonna 2021 kaksi mekaanista kuidunavauslinjastoa, joiden jaettu teoreettinen kapasiteetti on 50 tonnia avattua kuitua vuodessa. Vaikka teoreettinen avauskapasiteetti on korkea, ongelmaksi nousee kierrätyskuitujen huono maine tekstiilimarkkinoilla. Aiemmin on raportoitu, että kuiduilla tulisi olla tietty lujuus ja pituus, jotta ne sopivat langankehräykseen. *Telavalue* on *Business Finlandin* (BF) hanke, jonka tavoitteena on luoda lisäarvoa tekstiilijätteelle ja tarjota ratkaisuja tekstiilien kiertotalouteen. Hanketta koordinoivat VTT, LAB-ammattikorkeakoulu ja Turku AMK, ja se toteutetaan yhteistyössä yritysten, muiden tutkimuskeskusten ja organisaatioiden kanssa. Tekstiiliteollisuuden kaupalliset toimijat ovat kiinnostuneita kierrätyskuitujen laadusta tulevaisuuden tekstiiliratkaisuissa. Tämän tutkimuksen tavoitteena on lisätä arvoa kuitukierrätykselle ja mekaanisesti avattujen (MO; *mechanical opening*) kuitujen jatkojalostukselle.

Tässä tutkimuksessa on karakterisoitu sekä laadullisin että määrällisin menetelmin kuusi erilaista MO-puuvillakuitulaatua: PRE-KNIT, PRE-WOVEN, POST-B2B, POST-n, POST-s ja POST-ea. Puuvillalaatuihin sisältyy sekä tuotantovaiheesta (*pre-consumer)* että kulutusjätteestä (*post-consumer)* kerätystä tekstiilijätteestä saatuja kuituja. Kulutusjätteestä saadut kuitulaadut on saatu työvaatteista (B2B), ja yhdyskuntajätteen keräyksestä joko neutraalein (n) lajittelu- ja avausmenetelmin kerätyistä ja avatuista, pehmentimen (s; *softener*) avulla avatuista, ja jopa 10 % elastaania (ea) sisältävistä avatuista tekstiileistä. Vertailuun on käytetty 100 % neitseellistä puuvillanäytettä, REF-CO. Kuidut on saatu *Telavalue BF*:än kuitukokoelmasta.

Yleisesti ottaen tulokset osoittivat MO-kuitujen olevan lyhyempiä kuin vertailunäytteen kuitujen. Kun REF-CO:n keskipituus oli 18,8 mm painon mukaan laskettuna, pisimmät mekaanisesti avatut kuidut olivat 25–27 mm pitkiä. Lyhyimmät kuitupitoisuudet määritettiin PRE-KNIT-näytteelle, jonka keskipituus oli 8,6 mm. Vaikka näiden kuitujen pituudet olivat lyhyitä, MO-kuitujen yhtenäisyysindeksit (UI; *uniformity index*) olivat 54–59 % ja REF-CO:n UI oli 64 %. PRE-WOVEN- ja POST-B2B-näytteet sisälsivät enemmän pitkiä kuituja kuin muut MO-kuidut. MO-kuitujen pituusmassat olivat liki samansuuruisia kuin REF-CO:n pituusmassa. Kulutusjätteestä saatujen kuitujen murtolujuudet olivat yleisesti suurempia kuin muiden näytteiden. POST-ea-näytteiden murtovenymä oli suurin, ja PRE-KNIT-näytteiden heikoin. Kuitujen pinnat tarkastettiin pyyhkäisyelektronimikroskoopilla (SEM). Koe osoitti vaurioita MO-kuiduissa. Vauriot olivat kuitenkin vähäisiä ja näkyvissä vain yksittäisissä kuiduissa. Lisäksi 50-vuotias puuvillalakana avattiin käsin kuiduiksi pinnan kulumisen tarkastelemiseksi. Näissä kuiduissa, samoin kuin joissakin kulutusjätteestä saaduissa kuiduissa, oli näkyvissä kuidun pinnan avautumista. Lisäksi kulutusjätteestä saadut kuidut olivat likaisempia kuin muut kuidut. SEM-kuvauksessa näytteistä löytyi muitakin kuituja kuin puuvillaa. Fourier-muunnosinfrapunaspektroskopiaa (FT-IR) ja differentiaalista pyyhkäisykalorimetriaa (DSC) käytettiin puuvillalaatujen morfologian tutkimiseen. Havaittiin, että REF-CO:n ohella PRE-KNIT- ja PRE-WOVEN-kuiduilla ei ollut sulamispisteitä tarkasteluvälillä 0–300 ºC, kun taas kaikissa kulutusjätteestä saaduista näytteissä oli sulamispiikkejä. FT-IR-tulokset varmistivat, että kulutusjätteestä saaduissa näytteissä voisi olla mm. polyesteria.

Kokeellisen työn perusteella tuloksien arviointiin sisältyy pohdintaa MO-kuitujen mahdollisesta luokittelumenetelmästä. MO-kuitujen ominaisuuksiin vaikuttaa moni tekijä, minkä takia kattavan luokittelumenetelmän takaaminen on vaikeaa.

Avainsanat: mekaaninen avaus, avatut kuidut, kierrätyskuidut, kulutusjätetekstiili

POPULAR SCIENTIFIC SUMMARY

Textiles are made to be used, and clothing is made to be worn. The growing demand for textiles has, however, lead to the piling up of used, non-reusable clothing on landfills, and left society searching for ways to minimize the negative effects of over-consumption. Sales of second-hand clothing have established their status on the market, and now the research is focusing on ways to *recycle* the garments that cannot be *reused*.

January 2025 marks the start of an EU-wide, separate collection of textile waste as it is to slow down the rate of textile material going to waste and divert it into recycling. The current methods for recycling of textiles can principally be listed under chemical, biological, thermo-mechanical and mechanical methods. The waste to be recycled can be obtained from both consumers in the form of e.g., a worn-out t-shirt (post-consumer textile waste) or from the industry in the form of e.g., scraps from garment cutting (pre-consumer textile waste).

This report digs into fibre-to-fibre recycling with mechanical methods. Fibre-to-fibre recycling is a recycling method that values the textile. The collected textile waste is turned into a new textile product, such as yarn or further into a garment. Fibre-to-fibre recycling can be executed with the principal recycling methods, but mechanical recycling is the method that gives a new fibre as an output material without chemical modifications of the material. Mechanical recycling methods consist of the textile waste being fed into the opening line and shredding it into smaller pieces, and further into new, mechanically opened fibres. It has been estimated that a fibre-to-fibre recycled yarn is the most valuable end-product of the mechanical recycling industry.

Be that as it may, the mechanically opened fibres suffer from a poor reputation in the market. Their length and strength are observed to reduce in the mechanical opening process, thus making it more difficult to spin yarn with properties required for weaving or knitting. There has recently been research about the properties of such mechanically opened fibres and yarn spun using them. This report reviews some of those papers that study the properties of mechanically opened cotton. The general result is that mechanically opened cotton fibres should be blended with virgin fibres to obtain yarns better suited for their end-purpose. Nevertheless, there have been research utilizing 100% mechanically recycled cotton, suggesting there is value in mechanical fibre-to-fibre recycling.

This report consists of a literature review of the recent research and an experimental part characterising the properties of selected mechanically opened cotton fibres. The selected mechanically opened cotton fibres are obtained from both pre- and post-consumer textile waste and are opened on different opening lines. The experimental part of this report shows the reduced length of mechanically opened cotton fibres. The mechanical properties are observed to be similar to those of virgin cotton, and the fibre surface is perceived to inhibit little to no change caused by mechanical opening. The compositions of the mechanically opened fibres are observed to be 100% cotton for the pre-consumer cottons, whereas some deviating values are observed for the post-consumer cottons suggesting the composition is other than 100% cotton.

The chemical composition identification methods are observed to work well in defining the different compositions of the cotton qualities, although no information about the quantified contents can be given. The methods for measuring length and mechanical properties are time-consuming and give little value to characterisation. However, differences can be seen in the lengths and length uniformities between pre- and post-consumer cottons. As a general result, it can be observed that the mechanically opened fibres obtained from pre-consumer waste are cleaner and more homogenous than post-consumer fibres.

ACKNOWLEDGEMENTS

Finishing this thesis feels wonderful. I have been lucky to acquire help and support throughout my studies in *Materials science and engineering*, and now even more during this writing. Therefore, I take this chance, and dedicate this preface to the help I have been given and all the helpers along the way.

My greatest *thank you* goes to my involved and well knowledgeable supervisor at VTT – Taina Kamppuri, you have been both the questioning research partner and the supportive friend. Thank you for your trust and time. The whole team at VTT has been warmly welcoming on both research matters and during coffee breaks. Thank you must be given to Pirjo Heikkilä and Eetta Saarimäki, too; you have blessed me with a fraction of your expertise and guidance on research practises. I would also like to thank my fellow master's thesis worker, Susanna Raiskio, for your peer support and advice. Additional thank-yous go to the supportive team at VTT, and anyone who has helped me in obtaining results or data, your flexibility with schedules is appreciated.

Thank you, professor Jurkka Kuusipalo, my supervisor at Tampere University, for your time and interest in the subject. The time at Tampere University has gone past quickly, and I leave with fond memories. Additionally, was there ever only one teacher worth thanking (there are undoubtedly more), it is Sanna Auvinen for me. Thank you for the conversations, the laughter, and the empathy you bring to teaching.

The world of textile recycling is vast, and my thesis can only cover a part of it. Thank you to Miira Ojanen and Anna Garton for showing me around in Paimio and giving me the opportunity to visit the textile refinement centre. After this thesis, I can confidently say I have gained expertise on the mechanical recycling of fibres.

And lastly, thank you to my nearest and dearest for being there for me and sharing ideas with me. Thank you to my partner Joonatan for reminding me of my strength. A grateful thank you to my mother Kirsimari for my lifelong interest in textiles, and a grateful thank you to my father Juha for my lifelong interest in mathematics and engineering.

Tampere, 10.10.2023

Ella Kärkkäinen

TABLE OF CONTENTS

TABLES AND FIGURES

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

AFIS	advanced fibre information system
ATR-FT-IR	attenuated total reflectance-FT-IR
CO	cotton
c_v	coefficient of variation
DFO	degree of fabric opening
DP	degree of polymerisation
DSC	differential scanning calorimetry
EFO	efficiency of the fibre opening
GRS	Global recycled standard
FT-IR	Fourier-transform infrared spectroscopy
HVI	high-volume instrumentation
IR/IRS	infrared (spectroscopy)
LSJH	*Lounais-Suomen jätehuolto;* the South-west Finland waste management company
ML	mean length
MO fibre	mechanically opened fibre
NIR/NIRS	near-infrared (spectroscopy)
PEG	polyethylene glycol
PES	polyester
POST-	*refers to samples obtained from the mechanical opening of post-consumer waste*
PRE-	*refers to samples obtained from the mechanical opening of pre-consumer waste*
r-FT-IR	reflectance-FT-IR
RCS	Recycled claim standard
SEM	scanning electron microscope/microscopy
SFC	short fibre content
UHML	upper half mean length
UI	uniformity index; the ratio of ML to UHML
UQL	upper quartile length
$\bar{x}$	average length
-B2B	*refers to samples obtained from workwear garment waste*
-ea	*refers to samples obtained from municipal waste, including up to 10 % elastane and other fibres than cotton*
-KNIT	*refers to samples obtained from knitwear waste*
-n	*refers to samples obtained from municipal waste; neutral sorting and opening*
-s	*refers to samples obtained from municipal waste; softener used in opening*
-WOVEN	*refers to samples obtained from woven waste*

1. INTRODUCTION

In 2019, 40 thousand tonnes of textile were discarded from private households in Finland. This number is based on the approximations made by comparing the total amount of mixed waste and their average composition. During 2019, when the data was collected, there was no separate textile collection, and all discarded textile was diverted into incineration. According to the same study, approximately 131 thousand tonnes of textiles were in use in Finland the same year. This number is derived from the statistical data related to the tracking numbers of textile parcels moving in and out of Finland. The domestic use in Finland is calculated by adding up the import and the domestic sales of textiles and removing the weight of the export textiles. (Dahlbo et al. 2021)

Globally the textile fibre production was at 113 million tonnes in 2021 (Textile Exchange 2022), and it is estimated that 5.4 million tonnes of textiles entered the European market in 2019 (Trzepacz et al. 2023). While approximately 1.7 to 2.1 million tonnes of post-consumer textiles are collected separately yearly in Europe, it is estimated that the outstanding 3 million tonnes are discarded in household waste (Köhler et al. 2021), partly due to the lack of functional collection systems. A directive concerning the collection of some previously not affected waste types, including textiles, to be organized by municipalities came into effect on the 1st of January 2023 in Finland (Ympäristöministeriö 2022) and is set to come into effect EU-wide on the 1st of January 2025 according to Directive (EU) 2018/851 of the European Parliament and of the Council[1]. One of the aims of the directive is to reduce the amount of textile waste ending up in the landfills by redirecting it. The directives suggest additional progress is necessary in the textile collection, sorting and recycling technologies. The directives highlight the significance of reuse and recycling of materials in general.

In line with the waste collection directive, Trzepacz *et al*. (2023) review that by 2030 the amount of collected textile waste could be as high as 9 million tons per year in Europe. According to a study conducted in Sweden (Östlund et al. 2015) the textile industry is expected to offer a viable collection system of textiles by then, but the challenge remains

---

[1] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance). (OJ L 150, 14.6.2018, pp. 109–140)

in the unpredictability of the future. Textile Exchange (2022) estimate the global fibre market to expand to a yearly production of 149 million tonnes by 2030 with production of polyester increasing more rapidly than production of any other fibre quality. Trzepacz *et al.* (2023) review that the mandatory textile waste collection will in all probability increase the supply of textiles but ultimately worsen the quality of textiles that are suitable for reuse or recycling. Collection is one step towards circularity, but processing and finally recycling the waste after the collection has been carried out are other critical steps.

There are several ways of approaching the recycling of textiles. Kahoush and Kadi (2022) establish four main methods with which textile waste can be recycled: i) pre-consumer textiles, such as production scraps, used to make products with same value as the waste material initially is, ii) mechanical opening and recycling of post-consumer textile to produce fibres, iii) chemical recycling of post-consumer textiles through depolymerisation in order to achieve monomers or polymers, and finally iv) energy recovery. On the other hand, Harmsen, Scheffer and Bos (2021) divide the recycling methods into i) mechanical, ii) physical and iii) chemical methods, but the physical recycling methods are also often called thermomechanical recycling (Heikkilä et al. 2023). Furthermore, the *R strategies (refuse – reduce – reuse – recycle – recover*) are a well-known concept aiming to decrease the amount of waste. Even this allows room for a misconception. In second hand markets, a reused piece of clothing may be perceived as “recycled” by some consumers. In addition, as opposed to the division described by Kahoush and Kadi (2022), energy recovery is its own *R strategy* that does not fall under recycling. Therefore, recycling can be seen as an umbrella of different concepts. The many possibilities of classifying the recycling methods is one of the challenges facing the textile industry, as the previous life of the recycled product can be of significance for both the businesses and the consumers. Ultimately, recycling is the use of material from one thing transformed into the raw materials of another.

1.1 Problem description

Mechanical recycling of textiles involves the waste collection, mechanical opening of the fibres and the use of the opened fibres in for example spinning into new yarns with no use of chemicals. Extracting a fibre from a textile product and using it in a new textile product is closed loop recycling, and called *fibre-to-fibre recycling*, or sometimes *textile-to-textile recycling*. Fibre-to-fibre recycling involves a staple fibre as the main object of the recycling. The problems associated with the mechanical opening include but are not limited to the difficult sourcing of often heterogeneous raw material and limitations of technologies. (Heikkilä et al. 2023; Lu et al. 2022)

Riemens, Lemieux, Lamouri and Garnier (2021) found that the small number of available technologies for textile-to-textile methods is the main hinder for it to succeed. The study highlights the lack of viable technologies for closed loop recycling. Often the mechanically recycled fibres become parts of nonwovens or other composites (Riemens et al. 2021) and mechanically recycled cotton is often used in other, lower value products, such as insulation and blankets (Ütebay, Çelik and Çay 2019). Moreover, Ütebay, Çelik and Çay (2019) report that while there have been several research on recycling polyester, there is need for cotton recycling research. Fibre-to-fibre recycling is all about not losing value on the process, and therefore it is important to utilise the whole mechanically opened (MO) fibre. Riemens *et al*. (2021) also observe the demand for more automated systems for sorting, claiming that the current shortcomings of manual sorting lie in the reliability. According to a study conducted in the Netherlands (Wilting & van Duijn 2020), up to 41 % of blend material labels are incorrect. This adds to the problem of heterogeneity of the raw material, as well as to the unreliability of the obtained fibre and its properties. Moreover, MO fibres have often been identified weaker and shorter than virgin fibres due to the stresses of mechanical opening (Kahoush & Kadi 2022; Kamppuri et al. 2019a). Tenacity and length have been claimed some of the most important prerequisites for a successful yarn spinning (Kamppuri et al. 2019a).

This paper contributes to the aspects of mechanical recycling, and namely fibre-to-fibre recycling of cotton. Heikkilä *et al*. (2023) raise the question of how mechanical fibre-to-fibre recycling could be implemented best knowing impurities of textile waste and unpredictable quality of output fibres. They report that the heterogeneity of the textile waste, difficult sourcing and finally the restrictions of current recycling methods are the challenges that need to be overcome to achieve both an economically and an environmentally sustainable fibre-to-fibre recycling industry.

1.2 Telavalue

Telavalue is a Business Finland funded project that aims to establish “value chains for sustainable production, use and cycles of Textiles” (Telaketju 2023). The project is executed partly as public research and partly as independent projects for specific companies. The project is coordinated by VTT, LAB University of Applied Sciences and Turku University of Applied Sciences and conducted in close partnership with other research institutes and companies working in the textile field. This report aims to offer more information for one of the main objectives of the public research, namely to “ensure efficient textile material circulation via recycling of different kinds of discarded textiles from households as well as companies including also technical textiles” (Telaketju 2023).

The textile materials used for this work are obtained from partners in the Telavalue consortium. Three of the post-consumer samples are obtained from *Lounais-Suomen jätehuolto* (LSJH) – the local municipality waste management company in South-west Finland. LSJH opened their mechanical textile opening line in 2021 in the same building as Rester, a commercial company working in the same product field (LSJH 2021b). For comparison, one of the textile materials studied in this report is obtained from Rester. The other two mechanically opened fibre materials are obtained from Pure Waste and Citeve (Technological centre for textile and clothing of Portugal). Citeve also provided the reference cotton used in the experiments.

The LSJH opening line was recently sold to Rester (LSJH 2023). LSJH will continue to collect and sort raw material for various recycling solutions, while Rester will invest in engineering the processes and MO fibre quality. The mechanical opening lines of the two companies are different, as they were manufactured for their specific purposes: one for opening post-consumer textile waste from consumers, and one from companies. The shared theoretical opening capacity of the two opening lines is 50 tonnes per year but this is observed relatively high considering the actual opening capacity at the facility[2].

1.3 Research questions and expected contribution

The research questions discussed in this report are shown in Table 1.1. The report discusses the properties of MO cotton and aims to offer a point of view in understanding their place in the textile market. The properties such as average fibre length, breaking tenacity, elongation, and linear density are researched quantitatively, whereas SEM imaging, DSC and FT-IR offer a qualitative picture of the MO cotton fibres. The analysing methods used for fibre testing are looked at from the perspective of recycled fibres. Furthermore, the feasibility of using MO cotton fibres in yarn spinning and the spinning parameters are weighed up.

Table 1.1: The research questions.

Can mechanically opened (MO) fibres be characterised?
Can the characterisation of MO fibres give valuable information about their properties?
How can the fibre composition of mechanically opened fibres be established?
Does the mechanical opening damage the fibre surface?
Are the mechanically opened fibres suitable for yarn spinning?
How can the fibre length of mechanically opened fibres be improved?

[2] Anna Garton, LSJH. Personal communication over e-mail, 29th of August 2023.

1.4 Limitations

While the report aims to offer a broad characterisation of the selected samples, the quality of the acquired MO fibre is different from day to day, depending on many variables such as where the waste was collected, what the waste was, what settings were used on the opening line and how many rounds of shredding the fibre went through. While it is only assumed that the quality between batches of opened fibres varies, it is unclear how much the quality varies. It needs to be noted that the samples used in these experiments are rather small and obtained from one batch each, so even the quantitative results speak more for a possibility than universal results. It is therefore difficult to presume the researched properties apply for every batch of the respective fibre types. A question remains also whether universally applicable conclusions could be drawn even if results were obtained from several bales in several batches.

The characterisation of MO fibres may prove inefficient or even impossible with the standard methods. For example, the American standard for fibre length measurement by photoelectric measurement (ASTM D1447-07) states that the method is “applicable to fibers taken from raw or partially processed cotton or some types of cotton waste, but not to fibers from blends of cotton with other fibers or to fibers recovered from cotton yarns or fabrics”. Moreover, Ütebay, Çelik and Çay (2023) studied the properties of dark MO cotton and discovered it could not be measured for its length using an optical method due to the colour. In this report, the length is measured manually adjusting the American standard (ASTM D1440-07). The limitations of the methods regarding fibres obtained from waste are not only a hinder for this report, but for the whole industry of recycled fibres.

The literature in the given research is still limited, and therefore any results presented in this report are often non-comparable to results that already exist. However, new research is being published all the time. As the textile industry are now trying to find solutions to the sometimes poor quality of MO fibres, new questions will be presented in the future; *how will the second mechanical opening of a once-recycled garment affect the fibre quality, how will the collection of textile waste affect the recycling rates and textile waste quality, and what fibre will make up the majority of textile waste in 10, 20, or 30 years?*

2. THEORETICAL BACKGROUND

The textile businesses involved in the Telavalue project were asked about their preferences of material qualities the mechanically reclaimed fibres should exhibit. On top of that, some material properties can be seen as the basic material requirements for further processing of the fibres. Those properties include the fibre length, tensile strength and the degree of fibre opening. The fibre properties are often described to deteriorate during mechanical recycling, as opposed to chemical recycling (Wang & Salmon 2022).

The first end-of-life textile refinement plant was opened in Finland in 2021 for mechanical recycling of textile waste. It is estimated that the plant can recycle up to 10 % of the Finnish textile waste stream (LSJH 2021b), which is a direct sign there is a need for more effective recycling manners, more capacity to take over and therefore more market share available in the industry. Some of the recycled fibre market is taken up by chemical recycling, with industrial scale development just during the recent years. The world's first industrially scaled fibre-to-pulp facility opened in Sweden in 2021. The facility is responsible for the manufacturing of Renewcell and has the permit to recycle 60 000 tons of textile annually (Valmet 2021). For the time being, there is no effective waste collection system in Sweden, and the company is importing its raw material from for example Asia (Vetenskapsradion Klotet 2023). The solutions to the problem of obtaining raw material are currently being considered at EU level, where new separate waste collection laws regarding textile waste will come into effect on the 1st of January in 2025, as stated in the article 12, point (b) in Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste[3]. Still, problems in textile material collection and recycling are caused by many factors, including unreliable material tags (Wilting & van Duijn 2020), blend materials (Kahoush & Kadi 2022), and the use of undesirable, unrecyclable materials (European Commission 2022).

---

[3] OJ L 150, 14.6.2018, p. 129

Figure 2.1: A schematic illustration of mechanical fibre-to-fibre recycling: collection of textiles, sorting, mechanical opening and yarn spinning.

Figure 2.1 shows the characteristic steps of mechanical fibre-to-fibre recycling and the typical products along the production chain. This report focuses on the fibre product and the feasibility of turning it into yarn using mechanical technologies. Mechanical recycling for cotton can be defined as follows:

> Mechanical recycling of waste cotton involves decomposition or crushing of waste cotton through mechanical actions, such as opening, spinning, weaving, and other physical approaches, without affecting or modifying the native chemical structure, and then reusing the recycled cotton for fibers, yarns, fabrics or nonwovens. The following products, such as blended yarns and composite reinforcements, can be obtained through the mechanical recycling of waste cotton. (Lu et al. 2022)

According to a study conducted in Sweden (Östlund et al. 2015, p.47) one of the main challenges for the broader implementation of mechanical recycling of fibres lie within the clothing design sector i.e., the clothes are not designed to be recycled. The study suggests that the use of mono-materials and easily removable metal parts are key factors in making fibre-to-fibre recycling economically viable. Similarly, a study conducted by Riemens *et al.* (2021) found the “lack of eco-design” to be the main reason hindering the textile-to-textile recycling. The EU has reported the lack of design for quality, longevity, and recyclability alongside the linear economy and its “low rates of use, reuse, repair and fibre-to-fibre recycling of textiles” to have negative environmental effects (European Commission 2022). Regarding the use of blends versus mono-materials, Kahoush and Kadi (2022) point out the incomplete knowledge concerning the separation of cotton and polyester fibres from one another in a blend, although the said blend is the most common textile fibre blend. This chapter gives insight to the mechanical opening processes, the fibre requirements for different types of spinning and the problematics of current mechanical recycling processes, and possible solutions for more effective and economically viable recycling. Some of the recent research literature is briefly introduced in this chapter and analysed in greater depth in chapter *3. Literature Review*.

2.1 Mechanical opening of fibres

In theory, mechanical recycling can be used for all kinds of collected textile waste, including fibre blends. Mechanical opening is the act of loosening the fabric structure and tearing it down to fibre level. The new textile fibres can then be spun into new yarn, given some requirements. Östlund *et al*. (2015) estimate that fibre-to-fibre recycled yarn is the most valuable end-product in the mechanical recycling industry. The disadvantages of mechanical recycling are the shortened fibre length and the often unknown composition of *post-consumer* textiles especially (Heikkilä et al. 2023, Riemens et al. 2021). These properties make the spinning of new yarn more unpredictable and more difficult to optimize.

Chapter *2.1.1 Sorting* presents the current sorting mechanisms used in the industry, and chapter *2.1.2 LSJH mechanical opening line* presents the mechanical opening line at the *Lounais-Suomen jätehuolto* refinement facility. The process is a summary of what is described by LSJH in their media (LSJH 2021a) and personal communication with LSJH. Östlund *et al.* (2015, p. 31) estimated earlier that mechanical recycling will remain a niche sector in textile recycling, unless the design steps, consumers' attitudes and the effectivity of the recycling processes change. They estimated that fibre-to-fibre recycling will be economically viable first in 2030 if these changes apply.

2.1.1 Sorting

The sorting of the incoming textile waste is the first step in maintaining the quality of the fibre. The sorting can be done manually or automatically and by colour, by fibre contents, by garment type etc. This chapter presents some of the common identification methods used in material identification.

Wang and Salmon (2022) report the use of infrared (IRS) and near-infrared (NIRS) spectroscopy methods, Fourier-Transform infrared Spectroscopy (FT-IR), and colour detecting cameras in the recent years. One of the NIRS-based sorting methods is the sorting line developed by LAB University of Applied Sciences, REISKAtex (Cura & Rintala 2019; Cura, Rintala, Kamppuri, Saarimäki & Heikkilä 2021). The NIR spectroscopy is a non-destructive identifying method that does not require sample preparation. Cura *et al.*

(2021) found that the identification problems with NIRS are related to the thin or loose structures of some fabrics, thick structures, and some dark colourants, which make it difficult for the NIR sensor to correctly identify the composition of the fabric.

FT-IR is a type of a non-destructive infrared identification method. There are three main types of FT-IR techniques i.e., transmission-FT-IR, attenuated total reflectance (ATR-FT-IR) and reflectance (r-FT-IR). Transmission FT-IR measurements are made by letting the IR light to pass through the material where some of it is absorbed, and the light transmission is detected by a sensor on the other side, so transmittance or absorbance of the material can be calculated. ATR-FT-IR applies a technology where the sample is placed on a crystal, and the IR light is aimed through the crystal to the sample, then the sample absorbs some of the IR light and the IR light is directed again through the crystal to the sensor. Disadvantageously, ATR-FT-IR can only detect the first layers of the sample surface against the crystal. The sensor in r-FT-IR measures the IR light reflected off the sample, unlike the other two methods where the sensor measures the IR light transmission through the sample. (Bruker 2023)

Peets, Kaupmees, Vahur and Leito (2019) discuss the use of r-FT-IR in identifying textile fibres, comparing it to ATR-FT-IR and ATR-FT-IR microspectrometer. They conclude what is similarly disadvantageous for many of the FT-IR technologies; the samples can only be examined at the surface level which is dependent on having clean fibre surface without additives or dirt. The study excessively lists the differences in ATR-FT-IR, ATR-FT-IR microspectrometer and r-FT-IR with regards to different sample types. The study reports that for example elastane proved difficult sample to examine given its distorted spectrum due to the sample size often being smaller than the measured area. However, the study found that the r-FT-IR is a more accurate method in telling apart the different amide-based textile fibres than the other two methods. (Peets et al. 2019)

The world's first large-scale automatic sorting line, Siptex, was developed and built in Sweden, in Malmö. The sorting line was the result of Siptex project, A Vinnova funded project that was led by the Swedish research institute *IVL Svenska Miljöinstitutet* and partnered Swedish brands such as IKEA, H&M, Stadium and Renewcell. The sorting is based on NIRS technology as well as visual spectroscopy. The sorting line is 260 meters long in total and has the potential of sorting 4.5 tons of textile per hour (24 000 tons per year). The sorting line is nowadays owned by Sysav, a municipally owned waste collection and recycling organisation. (Sysav 2023)

Fibersort is another commercial scale sorting line developed in a joint project by Valvan in Belgium and Circle Economy in the Netherlands. It was the first commercially offered sorting line when it was developed. The sorting line relies on NIRS and RGB camera technologies. Fibersort can sort six different types of textile fibres correctly: wool, cotton, polyester, viscose, acrylic and nylon. The RGB camera can sort the incoming garments or fabrics by precise colour or single vs. multi-colour. The data library is computed with the help of the care labels, and the line is guaranteed to recognise the material 82-96 % correctly according to its care label. The sorting line can sort garments with the speed of 1 garment per second. (Fibersort 2023, Kamppuri et al. 2019b)

At the LSJH sorting facility there is an automatic sorting device based on NIR technology, but the staff at the sorting facility tells that manual sorting is faster and thus a more effective method[4]. The sorting at the LSJH centre is done often according to the material contents or the structure type of the garments, e.g., cotton, linen, wool, cellulosic materials, polyester, denim and knitted. The sorting can be customised for example by colour, to exclude elastane or to exclude hard parts. Figure 2.2 shows sorted textiles at the LSJH storage. The LSJH fibre product portfolio consists of cellulose mixes, synthetic mixes, knitted, denim, cotton, black cotton, wool, linen, and polyester. (LSJH 2022)

Figure 2.2: Sorted and baled textiles at the LSJH storage.

2.1.2 LSJH mechanical opening line

The textile material arrives to the LSJH opening line after sorting and possible storing. The textile is fed onto the opening line manually, after which the material is led through two guillotines on a conveyor belt. The guillotines are placed in cross-machine direction, and a 90° turn of the textile ensures that the fabrics are cut in two respective directions

[4] Personal communication with the LSJH sorting personnel. Paimio, 26th April 2023.

and the remaining pieces are as small as possible. The blades are made of titanium so they will not break even if they hit metal buttons, but they will cut through plastic zippers. Buttons, zippers etc. are separated after the guillotine by suction: the lighter fabric pieces move along the line through a tube, while the heavier details will not be sucked up and will fall in a container. Figure 2.3 shows the two guillotines at the start of the opening line (left) and some hard parts and heavier pieces that are removed from the opening line by gravity after the guillotines (right).

Figure 2.3: The guillotines at the start of the LSJH opening line (left). The textile material is transported through the guillotines and cut in two directions. Hard parts and heavier textile scraps are removed from the opening line after the guillotine (right).

After the cutting, the pieces move on a mixing chamber, where other recycled fibres can be added into the fibre mix. The main task of the mixing chamber alongside fibre blending is to loosen up the shredded textile and prepare it for opening. The fibres are then led through the first opening rollers during a so-called *pre-opening*. The parameters for the opening of the textile materials can be altered to better suit the requirements of further processing. For example, the LSJH samples studied in this report are opened with a *re-spinning* setting, but other settings (e.g., nonwoven suitable opening) are available. After the pre-opening, the fibres can be collected into a drum, where a softener may be applied. According to the staff at the facility[5], water is a common softener that both eases the opening, but also removes the conductivity in synthetic fibre opening. The fibres may also be removed from the opening line if the desired quality is reached. Often during the pre-opening, fine fibre i.e., dust-like fibre, is collected in the cyclonic separators (LSJH 2021a).

---

[5] Personal communication with the LSJH opening line personnel. Paimio, 26th April 2023.

The fibres are then continuing their journey onto the main tearing line that consists of four cylinders. Figure 2.4 shows the main opening line at the LSJH refinement centre. The shredded fabric pieces are pulled apart due to the pressure between the rollers. After complete opening, the fibres are moved onto the automatic baling area for baling, after which the product is ready to be used in for example yarn spinning or web forming for nonwoven products.

Figure 2.4: The main opening line at the LSJH refinement centre. At the front, the vertical intake of material, and at the back, the horizontal cylinder line.

The opening line at LSJH in Paimio is manufactured according to its purpose: opening the variation of post-consumer textile waste collected municipally from households nationwide. The opening line would have looked different if it was designed exclusively for opening of cotton fibres, or for opening fibres for re-spinning, etc. The number of opening cylinders is an example of a mechanical factor that should be taken into consideration when designing the opening line and its desired output, as some materials require more and some fewer shredding cylinders. On top of the number of cylinders, the speed of the opening line can be altered to provide for rougher or gentler opening. Moreover, the quality of the input material affects the quality of the output fibre greatly.[6][7]

---

[6] Miira Ojanen, LSJH. Paimio, 26th April 2023

[7] Anna Garton, LSJH. Personal communication over e-mail, 29th of August 2023.

2.2 Key fibre properties for spinning

Spinning using recycled yarns has been reported successful with both open-end spinning (Gun & Oner 2019) and ring-spinning (Arafat & Uddin 2022), although the literature is strongly focused on blending reclaimed material with virgin fibres, especially cotton or polyester (Ütebay, Çelik & Çay 2023). While Lu *et al.* (2022) claim that the short fibre length and poor mechanical properties make it impossible to spin yarns with only mechanically recycled cotton waste, Lindström, Sjöblom, Persson and Kadi (2020) found a way to use lubricated MO fibres in a 100% recycled rotor-spun yarn. Jamshaid, Hussain, Mishra, Tichy and Muller (2021) claim that it is possible to make yarn out of 100% reclaimed or recycled materials and use it in e.g., towels and denim fabrics. However, their study is based on utilizing cotton waste from both mechanically opened rags and yarns and industrial side streams already in fibre form, such as yarn spinning process waste. This means that while the cotton lost in processing can be classified as "waste", it is not recycled, but virgin cotton. This chapter and the report are focused on utilizing the MO cotton fibres in yarn solutions, but it should be noted that the literature is focused on creating value for MO fibres through blending with virgin fibres, yet there is value in utilizing the fibre waste. Kamppuri *et al.* (2019a) report that fibre length, fibre fineness and fibre tenacity are the most important factors in open-end spinning. The frictional behaviour of the waste textile is also important, as friction has been detected to affect the occurrence of neps and shortening of the fibre length during mechanical opening (Arafat & Uddin 2022). Moreover, Wang and Salmon (2022) report that only fibres at least or longer than 13 millimetres can be taken advantage of in staple fibre yarn spinning. This chapter presents the most mentioned fibre properties required for spinning.

2.2.1 Fibre length and fibre fineness

Fibre length is one of the most crucial aspects of a staple fibre. It dictates the fibre's suitability for yarn spinning and the yarn strength and elongation (Jamshaid et al. 2021). Sayeed *et al.* (2021) report that a high short fibre content (SFC) has a negative impact on the manufacturing methods of textiles, at least for raw cotton, and Jamshaid *et al.* (2021) report that while longer fibres offer better technical performance, even fibre uniformity should be considered: when short fibre content increases, so does the yarn irregularity. Heikkilä *et al.* (2023) report that ring spinning fibres should favourably be over 45 millimetres long, and that for open-end spinning 25-26 millimetres long fibres are considered good.

The common methods for fibre length measurement are different manually executed methods and automated, optical methods. The methods are often designed to be used with longer fibres, as the sample sizes are standardised for typical virgin fibres. Similarly, the machines used for the quality control of virgin fibres may often not be suitable for fibres that have been processed before; Ütebay, Çelik and Çay (2019) used Textechnos Length Control Tester (LCT) to study the lengths of recycled fibres but had to consider that the machine can successfully process only greige cotton fibres. The fibres in secondary use are often dyed, which means similar machines are inadequate in the future. In a later experiment by Ütebay, Çelik and Çay (2023), they reported the use of optical systems for length measurements did not work for their dark-coloured recycled fibres.

High-volume Instrumentation (HVI) is used to measure some key properties in raw cotton. Those properties include e.g., the micronaire, fibre length and fibre length distribution, trash content and short fibre content of the fibre sample (Morton & Hearle 2008, pp. 82-83), but the HVI method or machinery does not consider the length variation in the shorter fibres (Sayyed et al. 2021). Instead, the HVI often describes only the longer population of the fibres with the parameters *upper half mean length* (UHML) and *uniformity index* (UI) (Sayyed et al. 2021). The advantages of the HVI method are its rapidness and fully computerised analysis (Morton & Hearle 2008, p. 159), but the method is created for raw cotton and therefore it has been reported that the testing of other colours than grey cotton fibres is difficult or impossible (Arafat & Uddin 2022). However, Arafat and Uddin (2022) report testing of recycled, colour fibres successful with the Uster Advanced Fibre Information System (AFIS). The AFIS is a fibre fineness testing method that can scan individual fibres and determine their fibre lengths (Morton & Hearle 2008, p. 161).

Sayeed *et al.* (2021) review that the high SFC negatively affects the yarn tenacity, yarn fineness and the yarn manufacturing options. The problems related to high SFC are not just related to MO cotton, but for virgin cotton as well. Sayeed *et al.* (2021) propose the cotton industry should have a reliable method for quantifying the short fibre contents of raw cotton for improvement of economic value.

There are varying results of how the waste textile quality affects the obtained fibre. Aronsson and Persson (2020) found that the looser, coarser yarns are easier to detangle and therefore allow for a better mean length and yield of fibres. Östlund *et al*. (2015) found somewhat similarly, that looser structures were easier to detangle. However, they suggested that the difference was between the knitwear and woven structures rather than the yarn structure. Ütebay, Çelik and Çay (2019) found that the number of shredding passages, shred size and the pre-treatments of the recycled cotton played important roles in the reclaimed fibre quality.

As described earlier, ring spinning is a challenge for the short fibres. Therefore, rotor spinning, and other open-end spinning technologies are to favour with short staple fibres. Spatafora and Schwippl (2020) have reported a rotor spinning method more suitable for a high SFC. While the classical process involves a blowroom followed by carding and two draw frame passages before the rotor spinning itself, two alternative processes are introduced; either a single draw frame passage (shortened process) or a drawing module attached to the carding machine and no separate draw frame passage at all (direct process). The direct process is found to be more effective for a high SFC as often short fibres are more prone to package build-ups in the sliver with every draft. While the direct process benefits the spinning of a high SFC yarn, the excessive parallelisation caused by several drafts may result in drafting faults for the low SFC content, too. The adhesive strength of the sliver was the same or better for all the tested fibre blends with the direct mode as it was with the classical process. Even the 100 % cotton with low/no SFC lost some of its adhesive strength with the second drawing. Spatafora and Schwippl (2020) found that with up to 50 % SFC, a classical process may be used as it provides a more even sliver. However, a higher SFC fibre benefits from the direct process as it provides more strength than a classical process does. They also found that if the SFC is more than 65 % a direct process must be used as the adhesive strength of the fibre web is too low with the classical and shortened processes, and therefore spinning proves ineffective or results in uneven yarns.

Textile Ecxhange, a global non-profit organisation that controls and supervises the use of standards such as *Recycled Claim Standard* (RCS) and *Global Recycled Standard* (GRS) has released a guide to the recycling standards. The guide states that the RCS and GRS standards cannot be granted to products that are made up of fibres with staple lengths longer than 25 millimetres, or of yarn with a yarn count higher than 40 Ne, as the high values cannot be substantiated with knowledge of the limitations of the modern mechanical recycling technologies. Moreover, the Textile Exchange guide rules that no combed types of Vortex or rotor spun yarn can be granted the RCS or GRS standards, as those types of yarns are listed “not possible to make” with recycled fibres. (Textile Exchange 2021)

2.2.2 Fibre tenacity and degree of polymerisation

Degree of polymerisation (DP) is the number of the repeating monomers in the polymer chain, and its value is directly related to the strength of the fibre (Albertsson, Edlund, Odelius 2012). The DP does not change during mechanical opening, and it can only be altered with chemical treatment. Wang and Salmon (2022) review that for a virgin cotton, the DP is between 9000 and 15000, and that for cotton waste or cotton textiles after industrial laundering the DP is 3500 or lower, before mechanical recycling. Palme, Idström, Nordstierna and Brelid (2014) report that the DP is shortened due to the alkaline detergents used in industrial laundering, causing the polymer chains to break. They suggest that even if longer fibre lengths can be obtained in mechanical opening, the yarns made of those fibres suffer from the shortened DP and therefore exhibit low strengths.

2.2.3 Degree of opening

A textile technology report by Rieter (Schwippl 2020) suggests a phenomenon or a measurable characteristic called *degree of opening* as one of the main factors influencing a successful recycling. The degree of fabric opening or the of the fibre opening could be calculated to help evaluating the quality of the MO fibres. The degree of fabric opening (DFO) is calculated as shown in Equation 1.1:

$$DFO = \frac{input\ fabric - output\ fabric}{input\ fabric} * 100\% \qquad (Equation\ 1.1)$$

It is suggested that the optimal value for the degree of fabric opening is 98%. The Rieter report continues to elaborate why the degree of fibre opening is also important: yarns that are opened into fibres in the mechanical processing are suitable for staple fibre yarn spinning. The efficiency of the fibre opening (EFO) can be calculated as shown in Equation 1.2:

$$EFO = \frac{raw\ material - nonopened\ fibres - fibre\ fragments}{raw\ material} * 100\% \quad (Equation\ 1.2)$$

The suggested EFO to be obtained in the future is 70%. The testing was found to be applicable by using a ‘Shirley’ test device. (Schwippl 2020)

2.2.4 Frictional behaviour

The friction between the fibres is a problem causing factor in mechanical recycling. The mechanical opening causes the fibres to be spun into a bundle where fibres are tangled upon each other and exposed to frictional forces that cause the loss of longer fibres (Lindström et al. 2020). Lindström *et al*. (2020) studied the effect of a lubricant in enhancing the parallel alignment of the fibres thus decreasing the frictional cohesion.

Arafat and Uddin (2022) produced yarns with varying contents of MO fibres and found that the neps increase in with increasing MO fibre content. They estimate this is due to the different surface properties, namely the frictional property of dyed fibres compared to those of virgin cotton fibres. The frictional property of dyed fibres increases the likelihood of neps and short fibre content (Arafat & Uddin 2022). Likewise, Ütebay, Çelik and Çay (2019) report that SFC is increased in dyed fabrics.

2.3 Future for mechanically opened fibres

The nature of cotton sets its own boundaries for processing. While synthetic fibres can be engineered and shaped to fit the exact needs of the processes and the end-user, different quality control methods are necessary for cotton and other natural fibres. Synthetic fibres are different from manufacturer to another, but cotton, for instance, can be different from one plant to the other besides it. Given the already varying qualities of virgin cotton, recycled cotton increases the variation. Chapter *2.3.1 Fibre classification* elaborates the fibre classification for cotton and bring attention to the lack of it recycled fibres, and chapter *2.3.2 Change towards eco-design* reviews the eco-design questions related to the possibilities of mechanical opening lines.

2.3.1 Fibre classification

When it comes to mechanical properties such as length, fibre uniformity and fibre strength, virgin cotton has widely standardised measuring and classification systems (Cotton Incorporated 2021). Moreover, cotton qualities are sold under market names such as *Sea Island cotton*, *Egyptian cotton*, *Pima cotton* and *American Upland Long Staple cotton*, names that refer to the growing place or the quality of the respective fibres. The classification of which fibre length is considered “long”, how high a certain uniformity is, and what strength makes a “strong” fibre gives the fibres invisible value on the fibre market. For an economically viable future for the mechanically opened fibres and other recycled fibres, a classification method should be developed. While the classification of virgin cotton is conventionally based on the mechanical properties, the absence of a classification for recycled fibres allows for freedom in designing one.

Moreover, Harmsen, Scheffer and Bos (2021) mention there is no classification of textile recycling methods. Textile recycling processes are often classified according to the used processes, i.e., mechanical recycling, thermo-mechanical recycling, and chemical recycling (Heikkilä et al. 2023). However, a question can be raised whether the classification of any recycling method should be done according to its processes or its end-products. Harmsen, Scheffer and Bos (2021) suggest the recycled fibres be allocated according to their chemical components instead of the conventional classification between natural and artificial and their respective sub-classes. The reasoning behind this is that fibres with the same chemical groups and bonds often share similar properties and therefore could be processed together. The study presents a division of the raw material according to the essential linkages, namely: cellulose, ester amide, urethane, alkane, and acrylonitrile (Harmsen, Scheffer & Bos 2021).

2.3.2 Change towards eco-design

Riemens *et al*. (2021) conducted a thorough empirical study about the disruptors of textile recycling. The study was conducted with a so-called Delphi-Régnier method, where a questionnaire was sent to the respondents, whereafter the questionnaire was refined according to the obtained answers and more concise information could be obtained. The questionnaire consisted of statements regarding the hinders of textile recycling, and the respondents indicated their agreement vs. disagreement to the statements with a colour scheme. The study found that the respondents shared a high consensus (82 %) that the industry lacks eco-design ignoring the end-of-life processes. Other main factors identified for a slow progress in textile recycling were the presence of material blends and hard parts (zippers etc.) in clothing. (Riemens et al. 2021)

As described earlier in chapter *2.1.1 Sorting*, the sorting methods in Paimio rely strongly on manual labour. The problems with textile waste collected from households are related to the textile market focus on polyester, cotton and their blends (Wang & Salmon 2022, Textile Exchange 2022), the difficulty in recycling the components of blends separately (Kahoush & Kadi 2022), the sometimes-poor quality of the collected clothing, and the care labels that are possibly not as accurate as thought (Wilting & van Duijn 2020). Firstly, these aspects cause difficulty in manual sorting, and secondly, the quality of the retrieved fibre is unpredictable.

Wilting and van Duijn (2020) studied and compared the care labels and the material composition of 7454 pieces of clothing. The composition was established with the help of NIR and with a reasonable error margin it was compared to the composition provided in the care label. They found that 41% of all the garments had a label that did not match the real composition, and that the error was greater in blends than it was in pure compositions. Care labels claiming a 100 % cotton composition were inaccurate at approximately 25 % of the times. On the contrary, cotton and polyester blends were accurate in less than 25 % of the cases. The researchers discuss several causes for the inaccurate labels and claim it might be due to both accidents and intentional behaviour: while the complex supply chains of textile production are identified as reasons for unintentional mistakes, aim for profit connotated with natural fibres could be a reason a garment care label shows a higher percentage of e.g., cotton than its actual contents. (Wilting & van Duijn 2020)

The concept of comparing the NIR identification to what is stated on the care label can work for some fibre compositions and be more debatable for others. Regulation (EU) No 1007/2011 of the European Parliament and of the Council of 27 September 2011 on textile fibre names and related labelling and marking of the fibre composition of textile products[8], in accordance with the SFS standard (SFS 4876), states that a description of "100 %" may only be used when the whole product is made up of one fibre type, and no active blending of other fibres is performed. Moreover, for example embroidery made with another fibre type, that is up to 7 % of the total weight of the final product is allowed on 100 % mono-fibre products. For blends the standard for reporting of used fibres is different; all blended fibres need to be listed with their percentage shares in a decreasing order, unless the percentage of one fibre type is maximum 5 % or the sum of their weight is up to 15 %, if the actual weight percentages of these fibres are difficult to control during textile production. Moreover, the SFS standard (SFS 4876) was published in 2000, when it was declared that for textile products that had no fibres with at least 85 % weight share only the two most used fibres with their percentages had to be disclosed, while the other percentages were voluntary.

Lu *et al.* (2022) suggest that using the dyed textile waste for the market advantage can also prove successful from the environmental point of view, when the dyes will not have to be bleached out. Ütebay, Çelik and Çay (2023) report that blending of recycled fibres with virgin fibres in spinning often produce a mélange yarn that can be of value in the knitting industry and knitted garments. They also highlight the positive effect of recycled fibres already exhibiting a colour, and therefore no dye processes are necessary.

---

[8] Regulation (EU) No 1007/2011 of the European Parliament and of the Council of 27 September 2011 on textile fibre names and related labelling and marking of the fibre composition of textile products and repealing Council Directive 73/44/EEC and Directives 96/73/EC and 2008/121/EC of the European Parliament and of the Council Text with EEA relevance. (OJ L 272, 18.10.2011, pp. 1–64)

Arafat and Uddin (2022) suggest the cost for producing a yarn made of 10-30 % MO fibres could be up to 8.5 % cheaper than virgin fibre yarn production, and that the fibre cost could be up to 21.4 % smaller. Their calculations are based on the raw material costs of the US cotton market, and the ring-spun yarn production. It has also been reported that the cost of blended yarn i.e., produced with virgin and recycled fibres, can be up to 33.5 % smaller than for 100% virgin fibres (Wanassi et al. 2016 se Lu et al. 2022).

3. LITERATURE REVIEW

This chapter discovers some of the recent research regarding MO fibres and yarns spun from them. Chapter *3.1 Fibre length of mechanically opened fibres* and its subchapters review studies on fibre length of MO fibres and the factors affecting it. Chapter *3.2 Fibre fineness and tenacity of mechanically opened fibres* briefly reviews some studies regarding fineness and tenacity results, although the research in this area is still scarce. Chapter *3.3 Yarn from recycled fibres* presents some results obtained by several studies where yarns were spun using MO fibres. There is an increasing trend in the literature regarding the mechanical fibre-to-fibre recycling. The studies are often conducted in different units and therefore Table 3.1 provides the most common conversions between the different tenacity units mentioned in this chapter.

Table 3.1: A conversion table of the most used tenacity units for fibres and yarns.

	g/tex	g/dtex	g/den	cN/tex
g/tex =	1	$[\frac{g}{dtex}] * 10$	$[\frac{g}{den}] * 9$	$[\frac{cN}{tex}] * 1.02$
g/dtex =	$\frac{[g/tex]}{10}$	1	$[\frac{g}{den}] * 0.9$	$[\frac{cN}{tex}] * 0.102$
g/den =	$\frac{[g/tex]}{9}$	$[g/dtex] * \frac{10}{9}$	1	$[\frac{cN}{tex}] * 0.113$
cN/tex =	$\frac{[g/tex]}{1.02}$	$\frac{[g/dtex]}{0.102}$	$\frac{[g/den]}{0.113}$	1

3.1 Fibre length of mechanically opened fibres

Fibres obtained from textile waste are usually 10 – 25 millimetres long (Esteve-Turrillas & de la Guardia 2017 se Lu et al. 2022), while for example virgin cotton fibres are available between 13 and 50 millimetres, and synthetic fibres are available in any desired length as a staple fibre or a filament (Morton & Hearle 2008, p. 134). Virgin cotton fibres shorter than 25 millimetres are widely replaced with longer varieties (Morton & Hearle, p. 135). As noted earlier, Textile Exchange only permits their RCS and GRS standards to be used for MO fibres shorter than 25 millimetres, as they claim it is not possible to obtain fibres longer than that by shredding textile waste (Textile Exchange 2021). Their standard is set for maximum length of 18 millimetres for post-consumer denim waste.

Ütebay, Çelik and Çay (2019) studied the effect of mechanical opening on fibre length of pre-consumer knitted cotton waste. They sorted the different knits according to the fabric structure i.e., interlock or single-jersey, and whether they were dyed or not, but also controlled the size of the pieces fed into shredding and how many shredding passages the pieces went through. They found that the SFC in the dyed cottons were high (18-28 %) and only researched the fibre lengths of the untreated fabrics.

Arafat and Uddin (2022) characterized virgin cotton, pre-consumer cotton waste and post-consumer cotton waste with an AFIS Pro-2. They found that the UQL was shorter, and likewise the SFC was higher for the MO fibres than the other fibre types. They estimated the UQL of virgin cotton at 28.3 cm and the SFC at 10 %. The UQL values for pre- and post-consumer textile fibres were 22.2 cm and 18.9 cm respectively, and the SFC's were established at 35 % and 45 %. (Arafat & Uddin 2022)

3.1.1 Short fibre content

Thibodeaux, Senter, Knowlton, Mcalister and Cui (2008a) studied the accuracy of three different methods for measuring SFC in cotton bale samples with 5 % to 25 % SFC. Their results suggest that the Suter-Webb array method is the most accurate method providing with the most differentiation between the bales, while HVI and AFIS give greatly related measurements and results. According to the study, these relations can be used to estimate the SFC in the samples with good proximity thus proving the tedious Suter-Webb array method ineffective compared to HVI and AFIS. The methods were explored with bales of virgin cotton. (Thibodeaux et al. 2008a)

Thibodeaux, Senter, Knowlton, Mcalister and Cui (2008b) also studied the effect of SFC on the quality of ring-spun yarns. They found that an increasing SFC has a correlation with the yarn tensile strength, the number of yarn thick and thin spots and the coefficient of variation (c_v) of yarn mass. Their results suggest that an increase from 8 % SFC to 14 % SFC can lower the tensile strength of the yarn by 10 %.

Ütebay, Çelik and Çay (2019) studied mechanical opening and the properties of MO fibres. They found that when smaller sizes were shredded the waste ratio i.e., SFC, increased. It was also observed, that the SFC decreased when the number of shredding passages was increased. Furthermore, they review that the dyed fibres had increased SFC compared to the undyed fibres. In their study, it was concluded that at least three shredding passages for larger pieces of greige cotton provide the least waste ratio suitable for spinning processes. (Ütebay, Çelik and Çay 2019)

3.1.2 Improving fibre length

A study by Aronsson and Persson (2020) found that knitted structure suffers more from the mechanical opening than denim structures. They manually deconstructed rather worn and barely worn cotton t-shirts and denim fabrics, and then performed a mechanical opening on respective materials and compared the fibre lengths measured after the manual deconstruction and after the mechanical opening. While the mean lengths (ML) after manual deconstruction were as long as 22 millimetres for both single-jersey knits and denim yarns, the fibre lengths dropped notably after mechanical opening line. The barely worn single jersey obtained an ML of 10.4 mm and thus a 53% length loss in the mechanical opening. The denim fibres in rather worn garments suffered the smallest length loss, namely 29% in the mechanical opening. Aronsson and Persson estimate that the opening of looser yarns results in better fibre lengths than opening of tighter, twisted yarns. Denims are often made up of rotor spun yarns with less entanglement of the fibres. Moreover, the study claims that the rather worn garments may exhibit as good or better fibre lengths than barely worn garments, suggesting that even more heavily worn garments are suitable for mechanical opening. (Aronsson & Persson 2020)

Ütebay, Çelik & Çay (2019) had earlier discovered that while the fabric tightness may not have had a significant effect on the fibre waste, the single-jersey fabrics obtained in general higher values for 50% span length, mean fibre length and uniformity of the fibres than the tight interlock fabrics. They suggest that this is due to the easier unravelling of the looser knit. They also found that the properties of the waste fabrics, and the opening line parameters affected the quality of the obtained MO fibre. (Ütebay, Çelik and Çay 2019)

Lindström *et al.* (2020) found that lubricating the MO fibres with polyethylene glycol (PEG) improved the fibre length. The PEG 4000 lubricant was used in different concentrations on cotton, polyester, and CO/PES blend fibres. The fibres were produced by mechanical opening and carded into a web. Then a solution prepared by mixing PEG 4000 and deionized water at 60 ºC was sprayed on the web and let dry for 2 hours. After drying, the web was carded twice more, after which the tests were performed. The amount of neps and unopened fibres was decreased with a higher concentration of lubricant on all samples. Similarly, the mean fibre length was improved for all samples with a higher concentration of PEG. The MO cotton fibres with a 0.0 wt.% PEG treatment obtained a mean length of 9.1 mm, and the 0.3 wt.% concentration of PEG gave a mean length of 13.4 mm. (Lindström et al. 2020)

3.2 Fibre fineness and tenacity of mechanically opened fibres

Arafat and Uddin (2022) did not find significant differences in the fineness of the virgin cotton compared to MO fibres. The found finenesses were 1.58 dtex for the virgin cotton and 1.64 and 1.68 dtex for pre- and post-consumer MO fibres respectively. Memon, Ayele, Yesuf and Sun (2022) obtained a fineness of 1.75 dtex for the MO fibre blend of approximately a half acrylic, a third cotton and the rest other fibres.

The literature is limited in reporting values for tensile properties of mechanically opened cotton fibres, or any recycled cotton fibres for that matter. Yuksekkaya, Celep, Dogan, Tercan and Urhan (2016) found a strength of 31.6 g/tex for a bundle of virgin cotton fibres, and a strength of 30.6 g/tex for a bundle of mechanically opened, white pre-consumer cotton fibres. They also report finenesses of 4.3 and 4.4 micronaire [1.69 and 1.73 dtex] for virgin cotton and MO cotton respectively. The properties were tested on an Uster HVI machine. Whereas the literature is sparse regarding the fibre properties, there are multiple works presenting the tenacity values for yarns made utilising mechanically opened fibres (Arafat & Uddin 2022; Jamshaid et al. 2021; Ütebay, Çelik and Çay 2019). Some tenacity and fineness values for yarns are reported in the following chapter.

3.3 Yarn from recycled fibres

While fibre properties affect the quality and appearance of the yarn, the yarn structure should be considered for its end application. Arafat and Uddin (2022) review that a soft feel and a good moisture absorbance are desirable properties for yarns used in t-shirt production, whereas more coarse yarns with rather harsh feel could be used in denim, towels, or other home textiles. Yarns used in t-shirt production are often ring-spun while for example denim production can utilise rotor spun yarns (Arafat & Uddin 2022).

Ütebay, Çelik and Çay (2019) made two types of yarn, with counts Ne 20/1 and a Ne 10 (approximately 30 and 60 tex, respectively) by ring spinning the mechanically opened pre-consumer cotton knit waste fibres (rCO) with virgin cotton (CO) and polyester (PES) fibres. The composition of Ne 20/1 yarn was 50/30/20 rCO/CO/PES and the composition of Ne 10 yarn was 80/20 rCO/PES. The testing of the Ne 20/1 yarn showed the quality of the undyed fabrics resulted in stronger yarn, suggesting the treatments worsen the fibre quality. The observations and variance analysis for the latter yarn type, Ne 10, showed that the previous fabric structure had a significant effect on yarn evenness, yarn hairiness, yarn tenacity and elongation at break, suggesting that a looser structure gives a higher tenacity and elongation. They studied whether small or large sizes of fabric should be used for shredding and found that the size does not play a significant role on the yarn tenacity, although small pieces were attributed to increased SFC. They found that Ne 20/1 yarn produced with recycled dyed fibres had lower tenacities due to the decreased strength caused by dying. Moreover, it was observed that the number of shredding passages or the fabric structure did not have a significant effect on the yarn tenacity. On the other hand, for the Ne 10 yarn the fabric structure, shredding size and the number of shredding passages were observed to have a significant effect on the yarn tenacity. This was attributed to the increased contents of MO fibres. (Ütebay, Çelik and Çay 2019)

In a more recent study by Ütebay, Çelik and Çay (2023), they spun fine yarns, 20 tex and 30 tex, on an open-end spinning machine and a compact spinning machine. The yarns were made partly from pre-consumer knitted waste (100% cotton) and partly from virgin cotton, as no yarn could be spun with just fibres obtained from waste in their settings.

Riemens *et al.* (2021) who conducted a Delphi-Régnier method study, review that the greatest challenges in mechanical textile-to-textile recycling are the shortened fibre length and the difficulty in controlling colour or material of post-consumer waste. They further review that the eco-design is important, as the initial fibre quality is an important factor affecting the re-spinnability of textiles, even more important than the use phase of the textile.

Rabbi, Banna, Mia, Islam and Hasan (2023) spun yarns with open end spinning. The yarns consisted of 10-30 % post-consumer textile waste in fibre form blended with virgin cotton fibres. The yarns were tested for unevenness, imperfection, hairiness, tensile strength, and elongation. The prepared yarns were also used for denim production, and their tensile strength and tearing strength were determined. Attributes such as unevenness, imperfection and tensile strength were found to be worse with increasing post-consumer waste contents, while hairiness and elongation were not significantly different from 100 % virgin cotton yarn. Rabbi *et al.* (2023) noticed that hairiness may first increase with introduction of post-consumer waste-derived fibres, namely in the 90/10 virgin/post-consumer waste yarn, but with increasing contents of post-consumer waste, the hairiness was more controlled by the spinning parameters. Moreover, the denim fabrics had better tensile strength and tearing strength the less waste-derived fibres were blended into the yarn. The study concluded that with up to 30 % contents of fibres obtained from post-consumer waste the qualities of the produced denim fabrics were acceptable. They also found that the ratio of recycled and virgin fibre should be considered, and further studies should be executed to optimize those ratios and the processes. (Rabbi et al. 2023)

While Rabbi *et al.* (2023) used open-end spun yarns in their experiment, other studies investigating the effect of yarn structure in denim fabrics have found that denim fabrics woven with ring-spun yarns have better tensile and tear strength than open-end rotor spun yarns. Hailemariam and Muhammed (2022) studied some properties of altering ring-spun and open-end rotor spun yarns in warp and weft. In their study, the yarns were produced with virgin cotton fibres. They observed that the denim fabrics are stronger in the warp direction, and that ring-spun yarns in the testing direction contribute to better tensile and tear strengths than open-end rotor spun yarns. However, open-end rotor spun yarns contribute to better abrasion resistance, pilling resistance and higher air permeability than ring-spun yarns (Hailemariam & Muhammed 2022). Open-end spun yarns are often used for their shorter processing times and thus smaller economic cost.

Arafat and Uddin (2022) produced ring-spun yarn with varying contents of recycled fibre. Their aim was to produce a yarn that was fine and smooth enough for soft knitwear or woven production, namely a yarn with a 30 Ne (approximately 20 tex) fineness. They blended two main types of yarns: pre-consumer fibres with white virgin cotton, and post-consumer fibres with virgin cotton. The waste-derived fibre contents were altered between 10, 20, 25, 30 and 35 % in the yarns. The ratio of 35 % MO fibre to 65 % of virgin fibre proved, however, unsuccessful, as the tenacity of the yarn was too low in knitting and weaving. The study found that the colour of the yarn darkens with increased contents of MO fibres, provided that the MO fibres are not white. They also found that the coefficient of mass variation increases with increasing MO fibre contents, as do the hairiness, the amount of neps, and the deviations in yarn thickness. The study concludes that a yarn of 30 Ne count is possible to produce by ring spinning with 30 % MO fibres, and that that yarn is suitable for knitwear production. They estimate that if the virgin/MO fibre blend yarn is produced with pre-consumer derived fibres, the contents of MO fibres can be higher than what it can if post-consumer derived fibres are used. They also conclude none of the produced yarns with post-consumer waste-derived fibres could be used for weaving. The researchers propose a weft yarn should exhibit a tenacity of at least 14 g/tex [13.73 cN/tex] and an elongation of 2 %. For a yarn used in knitting, the corresponding values are 13.5 g/tex [13.25 cN/tex] and 3 %. (Arafat & Uddin 2022)

Memon *et al.* (2022) spun yarns with a blend of MO fibres and virgin cotton on a rotor spinning machine. The recycled fibres were obtained from pre-consumer waste, namely knitwear garment cutting and stitching. Additionally, hard waste acrylic yarn was mixed with the knitwear cuts before mechanical opening. The blend of the MO fibre was identified with a help of a chemical solvent. The MO fibre blend consisted of approximately 32.5 % cotton fibres, 49.8 % acrylic fibres, and other fibres. The blend was mixed with virgin cotton in varying degrees, and it was discovered the optimal blend was 39 % recycled fibre and 61 % virgin cotton. The recycled yarn was then used in denim production as a weft yarn. The study found correlations between the varying contents of recycled fibres in a yarn and the strength, elongation, yarn unevenness, thin places, thick places and neps of the yarn. The conclusions were that the increased percentage of recycled fibre reduced values in strength and elongation but increased the yarn unevenness and the presence of yarn irregularities. (Memon et al. 2022)

Although the recent research is greatly focused on blending recycled cotton with other fibres, it has been reported successful to use 100% recycled or recovered cotton to produce recycled yarns. Jamshaid *et al.* (2021) prepared rotor spun yarn out of 100% recycled or reclaimed waste. The types of cotton they used in their yarn samples were partly from hard waste that was mechanically opened, and partly from cotton processing, and already in a fibrous form. They blended 40 % of mechanically opened yarn or rags with reclaimed cotton to prepare open-end yarns with a yarn count of Ne 10 ± 0.02 (approximately 60 tex).

Lindström *et al.* (2020) found that it was possible to rotor spin yarn from 100% recycled, mechanically opened, pre-treated lubricated fibres. The PEG 4000 lubricant treatment sprayed on a once-carded web of MO fibres helped to increase the percentage of long fibres in cotton and polyester and their blend, reduce neps and other irregularities and reduce the friction force so that yarn could be spun. Nevertheless, the yarns were found somewhat difficult to spin, and a rather high linear density value was sought after to compensate. The linear densities for the cotton yarns were between 92 and 99 tex (920-990 dtex), and tenacities between 6 to 8 cN/tex. After spinning, the yarns were washed, and the study found that their tensile strength was increased by washing off the softener. (Lindström et al. 2020)

Furthermore, Lindström *et al*. (2020) found that processing of 100% MO, untreated PES fibres after shredding became difficult as no sliver could be formed. The defects were described as the presence of neps, and molten fibres fused together, which did not allow for easy handling. They also found that the sliver-forming of MO cotton-polyester blend was difficult and argued this is due to the dissimilarities in fibre length for the two materials.

4. MATERIALS AND METHODS

4.1 The samples

The cotton materials studied in this report, including the reference cotton, are presented in Table 4.1. All the materials are from VTT's sample collections in the *Telavalue* project. The presented materials were chosen amongst those materials, as it was decided that it would be most beneficial to focus on one fibre type (cotton) and find out more about the characteristics of the different cotton samples given their different backgrounds.

Table 4.1: The cotton qualities used in the experimental work.

Cotton ID	Composition; definition	Mechanical opening	Sample appearance
REF-CO	100% cotton (virgin); origin: unknown	[reference; virgin cotton]	
PRE-KNIT	100% cotton; knitted pre-consumer textile scraps, dark blue	Pure Waste processes	
PRE-WOVEN	100% cotton; denim, woven pre-consumer textile scraps	Citeve opening line, Vila Nova de Famalicão, Portugal	

Table 4.1: The cotton qualities used in the experimental work. (Continued)

POST-B2B	100% cotton; post-consumer **work-wear** waste in varying colours	Rester opening line, Paimio, Finland	
POST-n	98-100% cotton with ≤2% other fibres; post-consumer blue denim waste, **“neutral” (n)**	Opening quality re-spinning, LSJH opening line, Paimio, Finland	
POST-s	98-100% cotton with ≤2% other fibres + **softener (s)**; post-consumer blue denim waste	Opening quality re-spinning, LSJH opening line, Paimio, Finland	
POST-ea	90-100% cotton with ≤10% other fibres, especially **elastane (ea)**; post-consumer black denim waste	Opening quality re-spinning, LSJH opening line, Paimio, Finland	

All the mechanically opened post-consumer cotton samples were cleaned with the help of ‘Shirley’ Trash Analyzer earlier in the *Telavalue* project, resulting in three different types of sample forms: **uncleaned, accept and reject**. The ‘Shirley’ Trash cleaning is explained in chapter *4.2 ‘Shirley’ Trash: cleaning the fibres*. Additionally, REF-CO and

PRE-WOVEN and an additional sample of POST-B2B were cleaned during the experimental works for this report. PRE-KNIT was already an “accept” by the providing company’s standards and thus it needed no cleaning. Table 4.2 shows the different forms of sample materials used in the different tests. Generally, accepts vs. uncleaned samples and accepts vs. rejects were compared for the qualitative analysis of the samples. For quantitative testing i.e., length and tensile testing, accepts were preferred. However, uncleaned samples were used for the length measurements of REF-CO and for the tensile testing of PRE-WOVEN due to scheduling conflicts. Additionally, an old cotton bedsheet was acquired for the surface inspection done with SEM.

Table 4.2: The detailed sample/test breakdown. Uncleaned, accept or reject types of samples, or two different sample types of each cotton were used in the tests described in their respective columns. The dark grey blanks indicate no sample type described on the respective row was used in the test.

Main sample	Sample form used in the following test:				
	Length	Tensile testing	SEM	DSC	FT-IR
REF-CO	uncleaned	accept	accept		accept
PRE-KNIT	accept (company controlled)	accept (company controlled)	accept (company controlled)		accept (company controlled)
PRE-WOVEN	accept		accept		accept
		uncleaned	uncleaned		reject
POST-B2B	accept	accept	accept		accept
			uncleaned		reject
POST-n	accept	accept	accept		accept
			uncleaned		reject
POST-s	accept	accept	accept		accept
			uncleaned		reject
POST-ea	accept	accept	accept		accept
			uncleaned		reject
Bedsheet, cotton (70+ years old)			hand-opened		

4.2 ‘Shirley’ Trash: cleaning the fibres

Prior to testing the fibres obtained from the mechanical opening lines they were cleaned with the help of a ‘Shirley’ Analyzer Mk2 manufactured by SDL Atlas. The analyser is conventionally used for separating lints, dust and other trash from virgin cotton. For this report, the fibres were cleaned using the machine: the machine removed the heaviest unopened threads and small fabric pieces which ensured an easier measuring of e.g., fibre length. Additionally, the opening efficiency of the cotton types or their respective opening lines was established.

In the cleaning process the sample is laid on a feeder (Figure 4.1 left), from where it moves into the machine. At this point, the sample is referred to as *uncleaned*. When all the material has been processed into the machine, it is let to work for a short moment before the cleaned fibre can be collected. The material is sorted into *accept* (Figure 4.1 centre) and *reject* (Figure 4.1 right) in their respective compartments.

Figure 4.1: Photos of REF-CO sample being cleaned. The uncleaned fibre being fed into the 'Shirley' Analyzer Mk2 (left) and accept fibre (centre) and reject (right) separated in their own compartments.

The cleaning was executed in standard testing conditions. The opening was performed for samples REF-CO, PRE-WOVEN and POST-B2B during this experiment, and for POST-n, POST-s and POST-ea during earlier experiments. Only one sample of each cotton quality was used for comparison. After the cleaning, the ratio between the accept and the fed raw material, the efficiency of opening (EFO), was calculated according to the Equation 1.2 presented in chapter *2.2.3 Degree of opening*. All the results are presented in chapter *5.1 'Shirley' Trash opening*.

4.3 Fibre length

The length of the fibres was measured by adjusting the American standard (ASTM D1440-07) and the Suter-Webb Comb Sorter method (Webb 1932 se Morton & Hearle 2008, pp. 151-152). The apparatus that was used is a Baer comb sorter, suitable for the array method explained in the American standard (ASTM D1440-07). No specific conditioning was executed prior to the length measurements. Three specimen of size 75 ± 2 milligrams were used to evaluate each sample.

Baer sorter is a manually operated apparatus with upwards pointing combs. In laboratory, the apparatus was first placed on the table with the screw tops pointing towards the tester. A fibre tuft was prepared by gently pulling the tuft apart in two and laying the two separated bundles doubled on top of each other, and progressively doing so until the fibres were aligned parallel. The fibres were then laid on the far-right side perpendicular to the combs so that the ends of the fibres were easily graspable. The fibres were pushed down with a teethed depressor so that the fibres were rather between than on top of the combs (Figure 4.2a). The outermost fibres were pulled away from the bundle with the help of a wide grasp forceps, gently brushed in the middle of the combs to get rid of any non-parallel fibres and neps, and finally laid on the left side of the apparatus (Figure 4.2b) with the forceps coming as close to the combs as possible. This process was carried out for the whole of the sample. The fibres left on the far right and the middle of the combs (Figure 4.2b) were collected and processed again to obtain any remaining fibres. This was done twice, resulting in a total of three times of withdrawal.

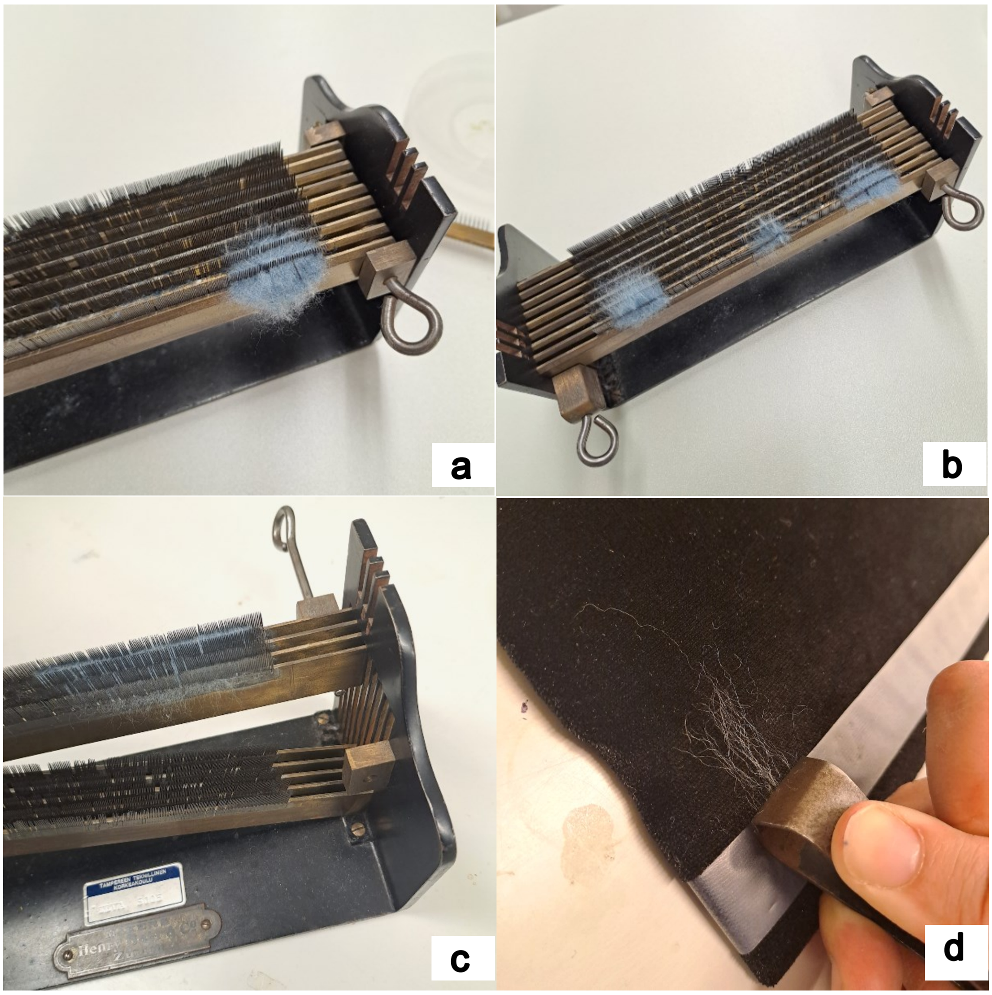


Figure 4.2: Photos of the phases of fibre length measurement. The fibres are first laid on the combs (a), picked up from the fringe and moved successively to the right end of the combs (b), with the aim of getting the fibre ends even. Once all fibres are moved up, the combs are turned 180º and dropped down successively until the fringe of the longer fibres is visible (c). The fibres are picked up with a pair of wide-grasp forceps and laid down on a velvet board (d) for array formation and length measurement.

Then, the apparatus was pivoted 180º so that the screw tops were pointing away from the tester. The combs were dropped down successively until the longest fibres, the fringe was visible (Figure 4.2c). These fibres were picked up with the help of the wide grasp forceps and placed on a velvet board (Figure 4.2d). All the fibres were picked up and in successive length order laid down on the velvet board in an array form.

The fibres were then divided into length categories *i* = (1-3, 4-6, 7-9, 10-12, 13-15, 16-18,… millimetres). Each length group was weighed, and the results were recorded to calculate the average length ($\bar{x}$), and the approximate fibre distribution. Moreover, the approximate number of fibres was calculated after tensile testing with methods presented in chapter *4.3.2 Mean length, upper half mean length and length uniformity*. This allowed for comparisons of standard deviation and coefficient of variation of the lengths between the different cotton qualities. The main results are presented in chapter *5.2 Fibre length results*, and some results related to the approximations are presented in *Appendix A*.

The described method was tested first with samples weighing 200 ± 20 milligrams, but it proved ineffective with its rather large sample size. The method was altered so that a more accurate approach described as the Suter-Webb array method and a smaller sample size, 75 ± 2 milligrams, was used. In literature (Morton & Hearle 2008, Thibodeaux et al. 2008a) the Suter-Webb array method is described as accurate, tedious and requiring of skill in order to obtain reliable results. It is an applicable method for cotton due to the short fibre length (Morton & Hearle 2008, p. 151).

The Suter-Webb comb sorter method applies a three-step combing process to ensure the parallelism of the fibres (Morton & Hearle 2008, p. 152). Morton and Hearle (2008) further point out that even with a high degree of parallelism, some fibre breakage will always take always take place with comb sorting methods. In this laboratory experiment, the fibres were combed slightly and prepared three times, and thus instead only a small fraction of the specimen was left unmeasured due to the described method. The weight-based average fibre length ($\bar{x}$) was calculated with the help of the following Equation 4.1. The unmeasurable fibres were left out of the calculation.

$$\bar{x} = \frac{\Sigma\,(m_i * l_i)}{\Sigma m_i} \qquad (Equation\ 4.1)$$

where m_i is the mass of the length group and l_i the average length in the length groups, thus l_i = (2, 5, 8, 11,…).

4.3.1 Upper quartile length and short fibre content

Additionally, an upper quartile length (UQL) and short fibre content (SFC) were determined. UQL was calculated by establishing the point where over 25 % of the fibres were weighed, starting from the longest fibre groups. UQL is defined as the shortest length of the longest 25% of fibres. It can be calculated for both the whole weight and per number of fibres. In this experiment, the number of fibres was unknown. SFC includes all fibres that are under 0.5 inches (12.7 millimetres) (Morton & Hearle 2008, p. 144), i.e., the length groups 1-3, 4-6, 7-9 and 10-12 mm. Like UQL, SFC can be calculated for both the whole weight and per number of fibres. For a direct approach, the SFC is calculated as a percentage of weight, not considering the decitex for this experiment. The short fibres were weighed and their percentage share of the weight of all the length groups was calculated. The results are presented in chapter *5.2.1 UQL and SFC*.

4.3.2 Mean length, upper half mean length and length uniformity

The approximate number of fibres (*n*) was calculated after the tensile testing when the dtex number of the fibres was obtained. The number of fibres in each length group was approximated as shown in Equation 4.2. The total number of fibres in the sample was estimated by adding all the length groups together.

$$n_i = \frac{m}{dtex} * \frac{10000}{l_i} \qquad (Equation\ 4.2)$$

Then, the mean length (ML) by fibres was calculated with the help of the estimation of the number of fibres, *n* (Equation 4.3).

$$ML = \frac{\Sigma(m_i * l_i)}{n} \qquad (Equation\ 4.3)$$

The average length $\bar{x}$ was used for almost all the presented results and graphs, while mean length (ML) was obtained to estimate the staple lengths, length uniformities and fibre distribution (*Appendix A*) of the cotton qualities.

Upper half mean length (UHML) is defined as the mean length by number of fibres of the longer weight-half of the sample (Morton & Hearle 2008, p. 144). UHML is often referred to as the *staple length*, the length describing the most frequent length of the cotton quality. However, Morton and Hearle (2008, p. 143-144) point out that staple length is a subjective visual attribute that only correlates with the most frequent length of the cotton. The UHML was calculated once the decitex number was obtained for the samples. It needs yet to be noted, that the UHML values presented in this report are based on approximations of the number of fibres.

The uniformity index (UI) of cotton is an industry standard describing the relation between the mean length and the upper mean length (Equation 4.4), describing the quality of the cotton. In the industry, a uniformity UI > 85% is considered as “very high” and a UI < 77% “very low” (Cotton Incorporated 2021). The calculated values are presented in chapter *5.2.2 ML, UHML and uniformity*.

$$UI\ (\%) = \frac{ML}{UHML} * 100 \qquad (Equation\ 4.4)$$

4.4 Tensile testing

The tensile testing of the fibres was performed on a Textechno machine Favimat+ that also measures the linear density of the fibres. The testing conditions and machine settings are reported in Table 4.3. The testing was carried out according to ISO standard (SFS EN-ISO 5079:2020). The standard defines the testing to be performed at 20-millimeter gauge distance, but due to the lack of long fibres in the MO fibres, the gauge distance was set to 10 millimetres. All the different cottons were measured with the 10-millimeter distance. Additionally, a 20-millimeter distance was used for those fibres that were long enough. The standard also mentions that natural fibres, such as cotton and wool should be measured in bundles rather than individually. Due to the short nature of MO fibres this was not possible, and only singular fibres were measured.

Table 4.3: Testing conditions and machine settings for tensile testing with Favimat+.

Standard testing conditions		Test	Machine settings			
Relative humidity	Temperature		Load cell	Pretension	Testing speed	Gauge length
65 RH%	20 ºC	Linear density	210 cN	1 cN/dtex	5 mm/min	10 mm
						20 mm
		Tensile strength	210 cN	0.5 cN/dtex	20 mm/min	10 mm
						20 mm

A small fibre bundle was taken on a velvet board. A pretension weight clamp of 1 cN was used to find a fibre end. The fibre was clamped and pulled separate. The free end of the clamped fibre was then picked up with a pair of tweezers and lifted in the testing position above the upper gauge of the machine. The upper gauge was closed to lock the fibre in its place, and with the pre-weight clamp successfully hanging under the lower gauge, also the lower gauge was closed. The machine then performed the testing automatically for both the linear density and the tensile strength of the fibres. The machine reported the results numerically and with graphs. The numerical results were used to perform a statistical analysis on the samples. The results are reported in chapter *5.3 Tensile testing results* and in *Appendix B*.

4.5 Statistical analysis for quantitative results

Single factor ANOVA was carried out for the results of average length, breaking tenacity, elongation, and linear density between the different cotton qualities. Only the results of the tensile testing experiments with 10-millimetre gauge distances were compared i.e., no statistical analysis was performed for the results measured with the standardised 20-millimetre gauge distance. The critical values were obtained from a studentized range statistic, and the analysis was performed on a confidence level $\alpha = 0.05$. If an attribute was found statistically significant, further statistical testing was executed in the form of Tukey-Kramer pairwise testing. The results are presented in chapter *5.4 Statistical analysis results*.

4.6 Surface inspection

The surface inspection of the fibres was done with scanning electron microscopy (SEM). Both accepts and uncleaned samples were studied to observe any differences in the surface structure before and after the 'Shirley' Trash treatment. The REF-CO was pictured to see difference between a virgin fibre and a mechanically opened one. Finally, an extra sample made up of an old bedsheet was added to further observe any surface wear caused by the long lifecycle, as listed earlier in Table 4.2. A small piece of the bedsheet was cut and pulled carefully apart with hands and tweezers. The obtained threads were twisted open carefully by hand and the exposed fibres were picked up with tweezers.

A SEM sample was built by picking a small tuft of the fibrous material and spreading it out on a clean surface so that as many fibres as possible were exposed. Then, cylinder shaped specimen stubs that are standardised for e.g., the SEM imaging of wool and silk (SFS-ISO 17751-2:2016, p. 7) were used. A small, double-sided tape with the same area as the top of the stub was glued on top of the stub, after which the separated fibres or small pieces of yarns were placed on top of it. Fibre or yarn ends that ended up over the tape area and were thus not adhered were carefully cut with scissors.

The stubs were then placed in the sputtering machine, Leica EM ACE100. The machine was first pumped into a vacuum of $2.0*10^{-2}$ mbar, as the samples were to be sputtered with a directional mode. Directly after the pumping a magnetron sputtering was conducted: the samples on the stubs were targeted with a gaseous plasma of argon, during which a 20 nm thick layer of gold was depositioned. The coating deposition was done twice.

After the sputtering, four samples at a time were placed on a stub tray and into the machine. The samples were studied scarcely visually to find a well representing area. The area was pictured with 2000x, 1000x, 500x, 200x and 100x magnification. Additional interesting areas were pictured with altering magnifications. The SEM was operated at 10 kV voltage and the samples were pictured with a 15 mm working distance. The photos were slightly re-touched for brightness and contrast to better indicate the desired attributes. The results of the surface inspection are presented in chapter *5.5 Surface inspection results* and in *Appendix C*.

4.7 Fibre composition

The composition of the cotton qualities was observed with scanning electron microscopy (SEM), differential scanning calorimetry (DSC) and Fourier-transform infrared spectroscopy (FT-IR). SEM was used to observe the shape of the fibres possibly revealing something about the composition, while DSC and FT-IR were used as a cross-examination to quantitatively say how the chemical composition of the cotton qualities may look like. The main results for the fibre compositions are reported in chapter *5.6 Fibre composition results* and additionally in *Appendices D* and *E*.

For SEM, 13 different samples were prepared, as listed earlier in Table 4.2. The main goal with SEM was surface inspection, but the fibre shapes were additionally observed to see any deviations from the typical cotton fibre and its convolutions. For DSC and FT-IR, accepts and rejects were tested, as listed in Table 4.2.

DSC is a method to observe the behaviour of materials upon heating and cooling. The device is an oven where a reference material and the examined material are heated simultaneously. A computer monitoring the heat flow will regulate the heat flow so that it happens at similar rates in both the sample materials. The computer plots the difference of required heat in the samples and displays the difference as plots with endothermic and exothermic peaks. The peaks can be seen where the examined material requires more energy to be heated at the required pace (endothermic reaction) or where the material gives off energy because it is taking longer to cool (exothermic reaction). The peaks can then reveal the melting temperatures and crystallisation temperatures of the material, among other things.

All the samples were heated to 300 ºC, as it was suspected that other materials than cotton exist in some of the samples. Cotton will not show any special behaviour up to 300 ºC nor will it melt after, but its decomposing can be seen at approximately 350 ºC (Langley et al. 1980 se Yasin et al. 2017). Polypropylene, polyester and polyamide-66, other fibres often used in denim production, melt at approximately 165 ºC, 265 ºC and 264 ºC respectively (Albertsson, Edlund & Odelius 2012). The testing was conducted with both accepts and uncleaned samples and three specimens of each cotton type were examined. For uncleaned sampling, unopened yarns were preferred to get a more distinctive idea of their qualities. None of the samples were conditioned prior to the testing. The peaks were determined with the help of NETZSCH Proteus Thermal Analysis 8.0.3 software.

FT-IR is a method based on measuring the absorbance or transmittance of light of a given material. The material is exposed to a narrow beam of infrared (IR) radiation, and the vibrating atoms of the material absorb some of that radiation at a certain intensity, and the non-absorbed IR is detected by a special detector. The absorbance happens when the radiation energy is equivalent to the atomic vibration. The vibrations have their specific frequencies, wavenumbers. Wavenumbers are linearly scaled to the energy difference between an atom at a neutral state and at an excited state. The FT-IR spectrum is obtained by plotting the intensity against the wavenumber. (Calabrò & Magazù 2017; Larkin 2011)

IR can be observed on frequencies between 14300 and 20 cm^{-1}, but the mid region from 4000 to 400 cm^{-1} is the most important for the analysis of chemical composition. In addition to absorbance and transmittance, the chemical composition of the material can be observed with attenuated total reflection-FT-IR (ATR-FT-IR). In using transmittance FT-IR the sample must be prepared so that the sample is not too thick and can transmit some of the IR. 100% absorbance will result in poor analysis of the peaks. ATR-FT-IR method takes advantage of an ATR crystal. The material is exposed to the IR through the crystal, and the light that is not absorbed by the material, is once more passed through the crystal, and detected. Although the transmission-FT-IR and ATR-FT-IR methods are rather different, the resulting spectra can be compared with each other, as similar chemical bonds display similar peaks at similar frequencies. (Bruker 2023; Calabrò & Magazù 2017)

The FT-IR inspection was conducted with Nicolet iS50 Spectrometer. The testing was performed with a resolution of 4 cm^{-1}. No conditioning was conducted for any samples prior to FT-IR testing.

5. RESULTS

5.1 'Shirley' Trash opening

The 'Shirley' Trash cleaning was performed with all the cotton qualities apart from PRE-KNIT. The cleaning separates the sample in two; cleaner, more homogenous *accept* fibres and dirtier, less homogenous *reject* fibres. The efficiency of opening is calculated as the ratio of the accept to the fed raw material, as described in chapter *2.2.3 Degree of opening*. Figure 5.1 shows the percentage weights of the accept, reject and lost fibres for samples REF-CO, PRE-WOVEN, POST-B2B, POST-n, POST-s and POST-ea. Figure 5.2 shows examples of three different cotton qualities after the 'Shirley' Trash opening. The cotton qualities were cleaned with the machine to provide for an easier length measuring and tensile testing. The analyser is meant to be used for virgin cotton cleaning and analysing, which shows in the results presented hereafter.

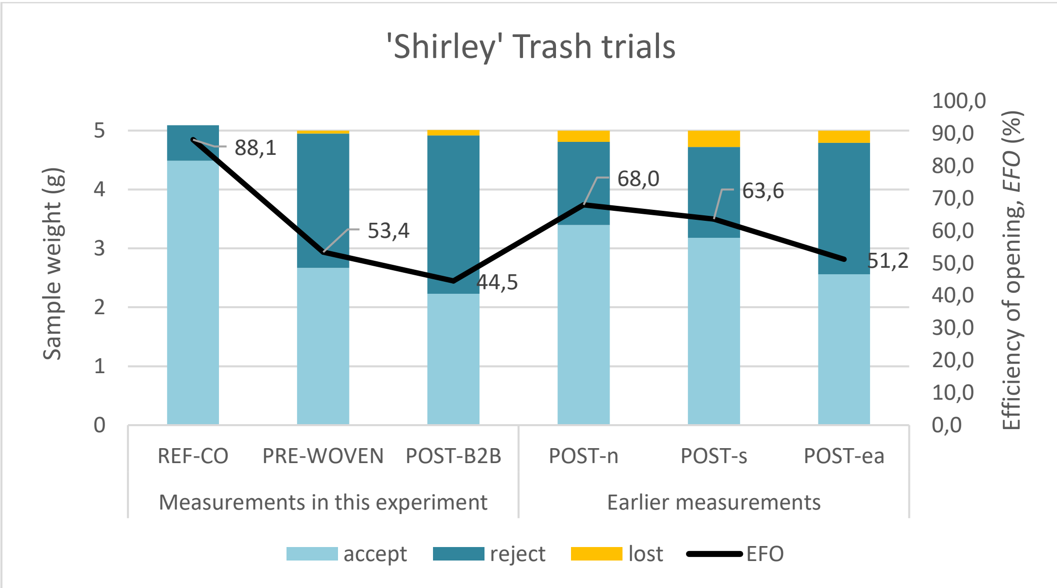


Figure 5.1: The weights of the accept, reject and lost fibres in 'Shirley' Trash opening. The black line graph represents the efficiency of opening, EFO.

Figure 5.2: Photos of selected cotton samples after 'Shirley' Trash opening. Each photo shows the accept fibres on the left, and the reject fibres on the right.

5.2 Fibre length results

The fibre lengths were measured adjusting the American standard (ASTM 1440-07) and a Suter-Webb array method. The combed fibres were laid on a velvet board by small tufts in a length order and each length group is weighted. In this experiment, the length groups were 1-3 mm, 4-6 mm, 7-9 mm and so forth. The average length of the fibres was calculated based on weight and the assumption that the linear density is homogenous throughout the sample. Moreover, upper quartile length was calculated based on weight.

Figures 5.3 – 5.9 show the array forms of a specimen of each cotton. It should be noted that Figure 5.3 displays a different ruler scale from the other pictures. The longest fibres reached approximately 35 millimetres for the reference cotton, while the longest MO fibres were approximately 25 millimetres long. The weight-based average lengths and the max lengths are reported for each cotton, not for the individual specimens in the pictures. The shortest measured fibres were in the length group *1-3 millimetres* for all the samples.

The fibre length measurement using the Suter-Webb array method is a tedious process with each specimen taking 1-2 hours to measure. The method was altered slightly due to the shortness of the recycled fibres; on the first round of drawing, there are many fibres tangled in the combs in cross-direction, as the hand-drawing and paralleling of the short fibres prior to the combs is not as easy as it is for longer fibres. Therefore, the fibres were withdrawn three times through the combs to get as many fibres out of the sample and thus as accurate a picture of the fibre lengths as possible.

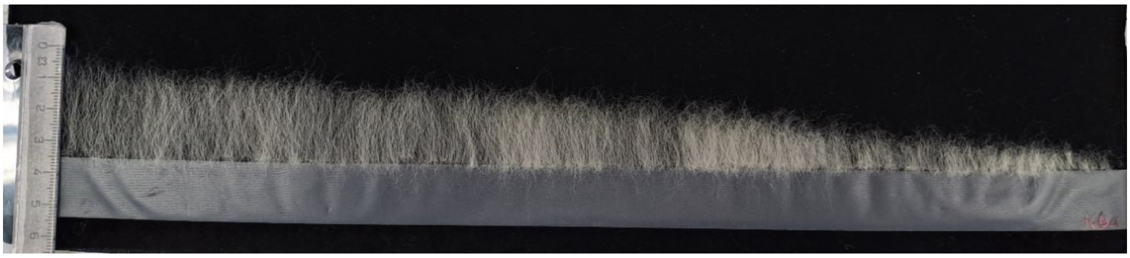


Figure 5.3: Photo of REF-CO (uncarded) uncleaned fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 18.8 mm, max length 31-33 mm.

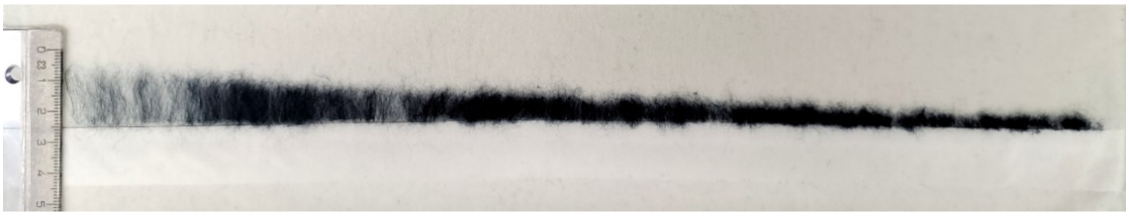


Figure 5.4: Photo of PRE-KNIT accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 8.6 mm, max length 19-21 mm.

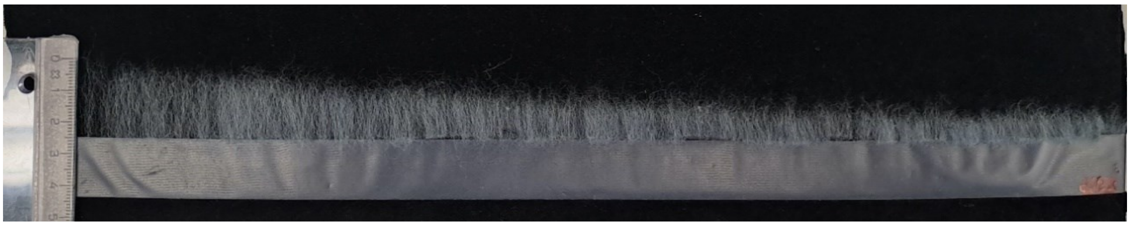


Figure 5.5: Photo of PRE-WOVEN accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 11.3 mm, max length 25-27 mm.

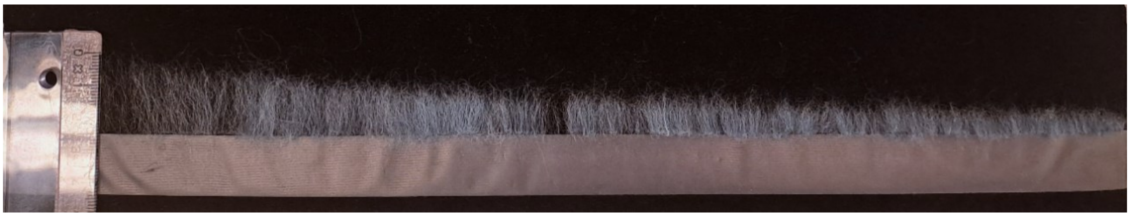


Figure 5.6: Photo of POST-B2B accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 11.5 mm, max length 25-27 mm.

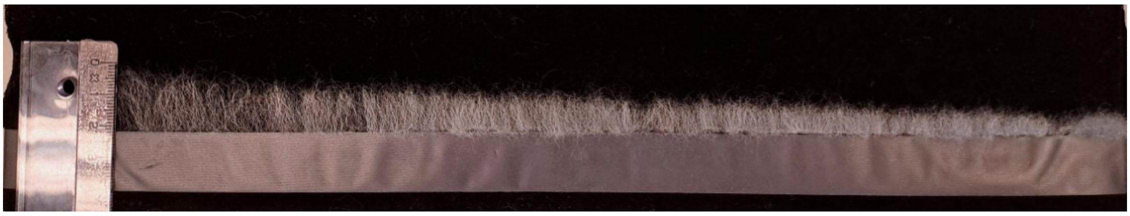


Figure 5.7: Photo of POST-n accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 9.8 mm, max length 22-24 mm.

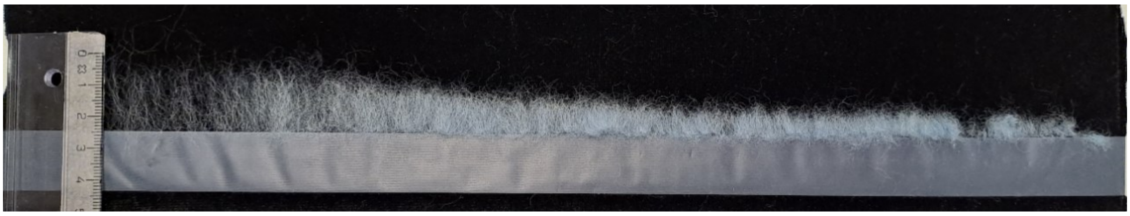


Figure 5.8: Photo of POST-s accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 9.9 mm, max length 25-27 mm.

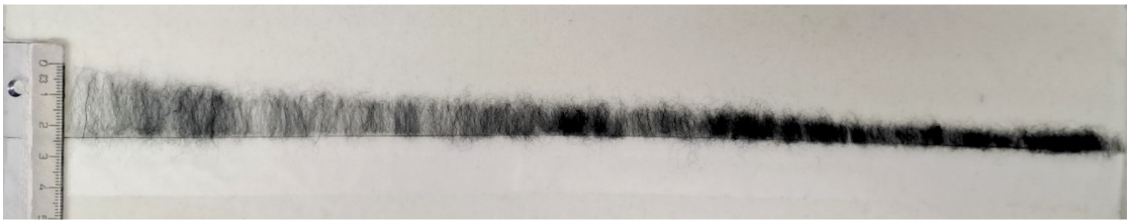


Figure 5.9: Photo of POST-ea accept fibres laid down in successively shortening length order according to Suter-Webb array method. Average length 9.9 mm, max length 25-27 mm.

The approximate calculations for number of fibres allow for speculation of mean length, variance, coefficient of variation (c_v), confidence interval and fibre distribution. These are presented more in detail in *Appendix A*. Chapter *5.2.2 UQL and SFC* shows the comparison between the weighted average length, calculated mean length and the staple length.

5.2.1 UQL and SFC

The results for UQL and SFC are presented in Figures 5.10 and 5.11. Due to the chosen fibre length measurement method, no accurate information of the number of fibres in each length group can be obtained. Therefore, both the SFC and the UQL are calculated as the percentage of weight of fibres. The graphs in Figures 5.10 and 5.11 display the values of fibres that were measured for their length and exclude the threads, neps and unmeasurable fibre dust. Figure 5.12 shows the quality of the sample tufts in terms of measurable fibre and other matter.

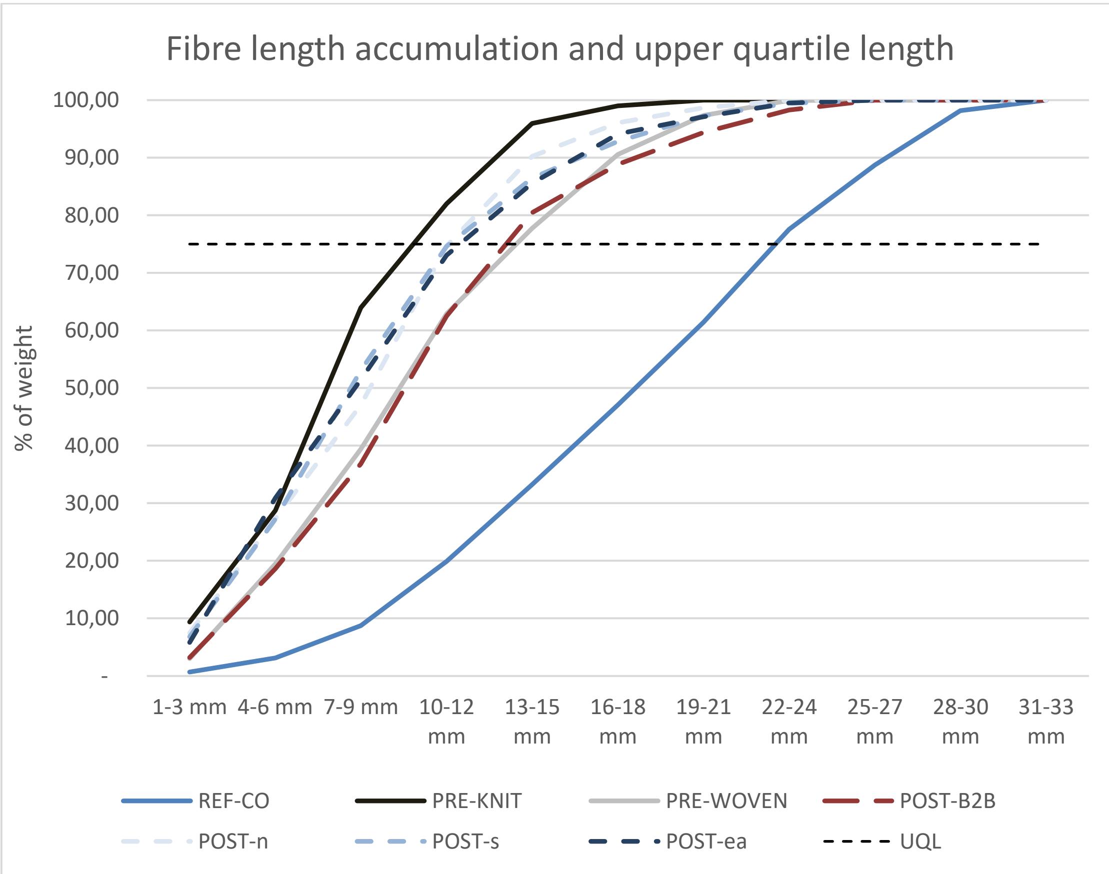


Figure 5.10: Fibre length accumulation by percentage of weight. The graphs indicate the increasing weight per fibre length group. The horizontal dash line shows the upper quartile length, UQL. The longest 25 % of the fibres are above that point.

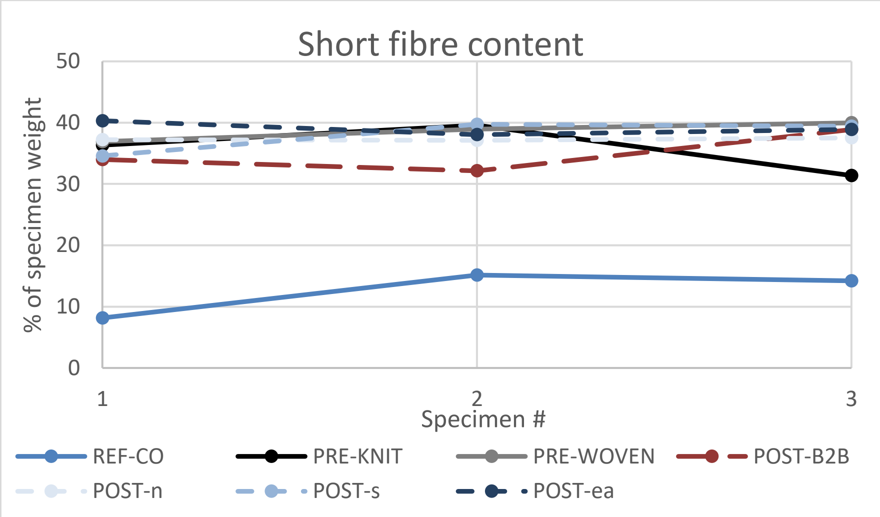


Figure 5.11: The short fibre content (SFC) in the three specimens for each cotton quality. The SFC is calculated by comparing the weight of the shorter length groups (1-3, 4-6, 7-9 and 10-12 mm) to the total weight of the measured sample.

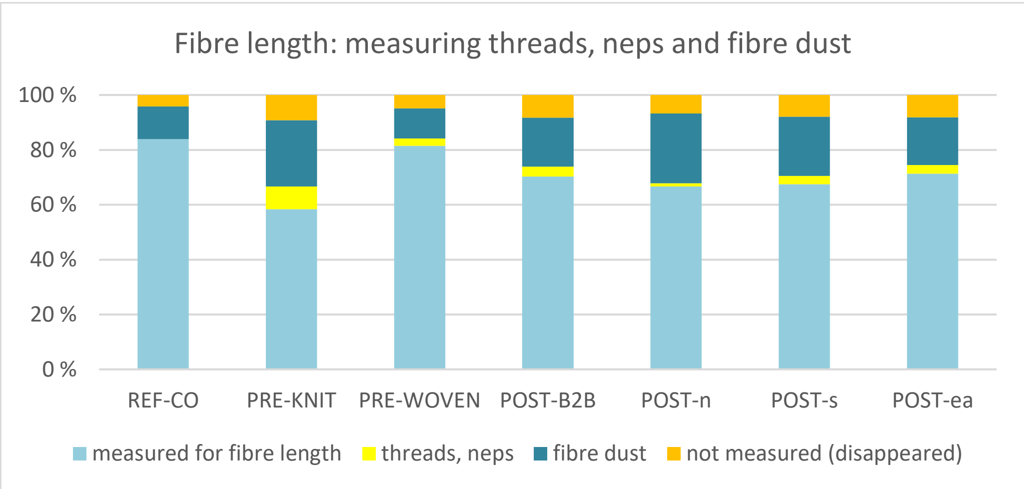


Figure 5.12: Cotton fibre quality breakdown. The fibres measured for their length, threads and neps, unmeasurable fibre dust and the disappeared fibres shown as the percentages of the total sample (75±2 mg).

5.2.2 ML, UHML and uniformity

The mean lengths (ML) and upper half mean lengths (UHML) were calculated as shown in chapter *4.3.2 Mean length, upper half mean length and length uniformity*. The values are thus based on approximations of the number of fibres. UHML is an industry-wide known measure for the quality of the cotton. The previously given weight-based average length, calculated mean length, upper-half mean length and the calculated uniformity index are shown in Figure 5.13.

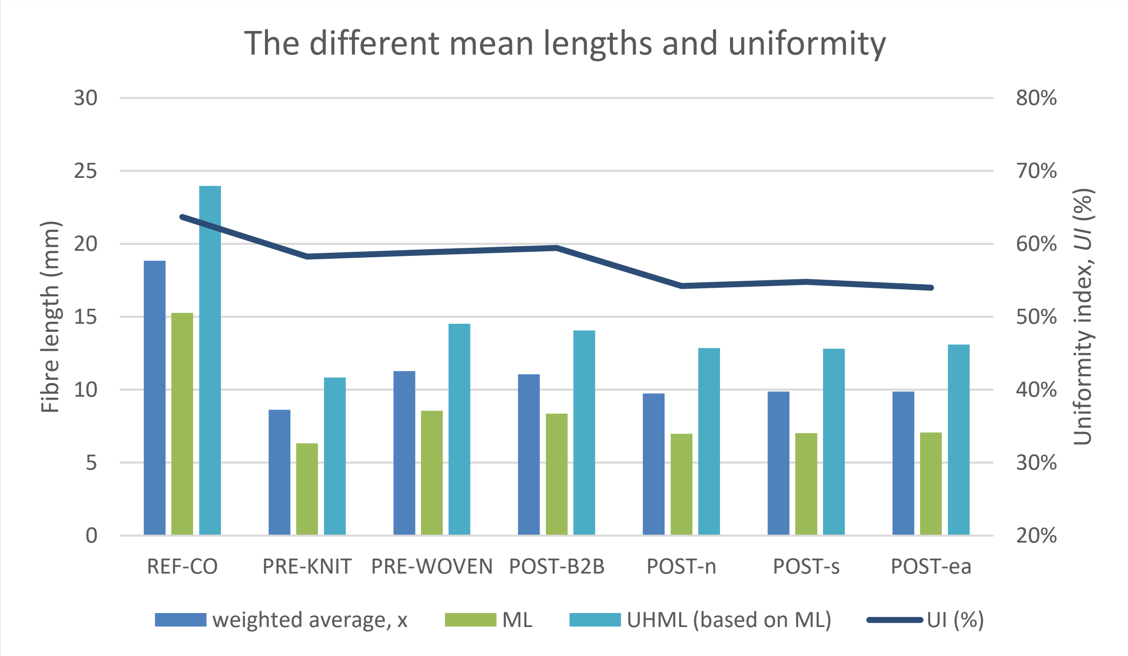


Figure 5.13: The different mean lengths of the cotton qualities. The weight-based average length, and the approximated mean length (ML) and upper half mean length (UHML) are shown in comparison to each other. The line graph shows the uniformity index (UI), which is the ratio between ML and UHML.

5.3 Tensile testing results

The tensile testing was performed with Textechnos Favimat+. The samples were individual fibres, mostly measured on a 10-mm gauge length. The standardised sample is a tuft of fibres measured with a 20-mm gauge length. Figure 5.14 shows the average tensile testing plots measured with 10-millimeter gauge distance and additionally the reference cotton with 20-millimeter gauge distance. The curves present the means of all measured fibres and were given by the computer. Table 5.1 shows the numerical values obtained for breaking elongations, tenacities, and linear densities of the samples. The grey column shows the overall means of the measurements for reference cotton as average of 10 measurements and recycled fibres as average of 20 measurements. The white column shows the values obtained by erasing the deviating fibres. Some single fibre result showing great deviation from the mean were removed from the results to best describe the properties of cotton fibres. As the hypothesis was that recycled fibres may contain other than cotton fibres, such as polyester, the erased measurements were chosen carefully, compared to reference values in literature, and removed one by one until a $c_v \leq 0.5$ was obtained for the remaining fibres. The erased values implicated there can be other fibres than cotton in the mixes. All the tensile testing results including the removal of deviating fibres can be found in *Appendix B*.

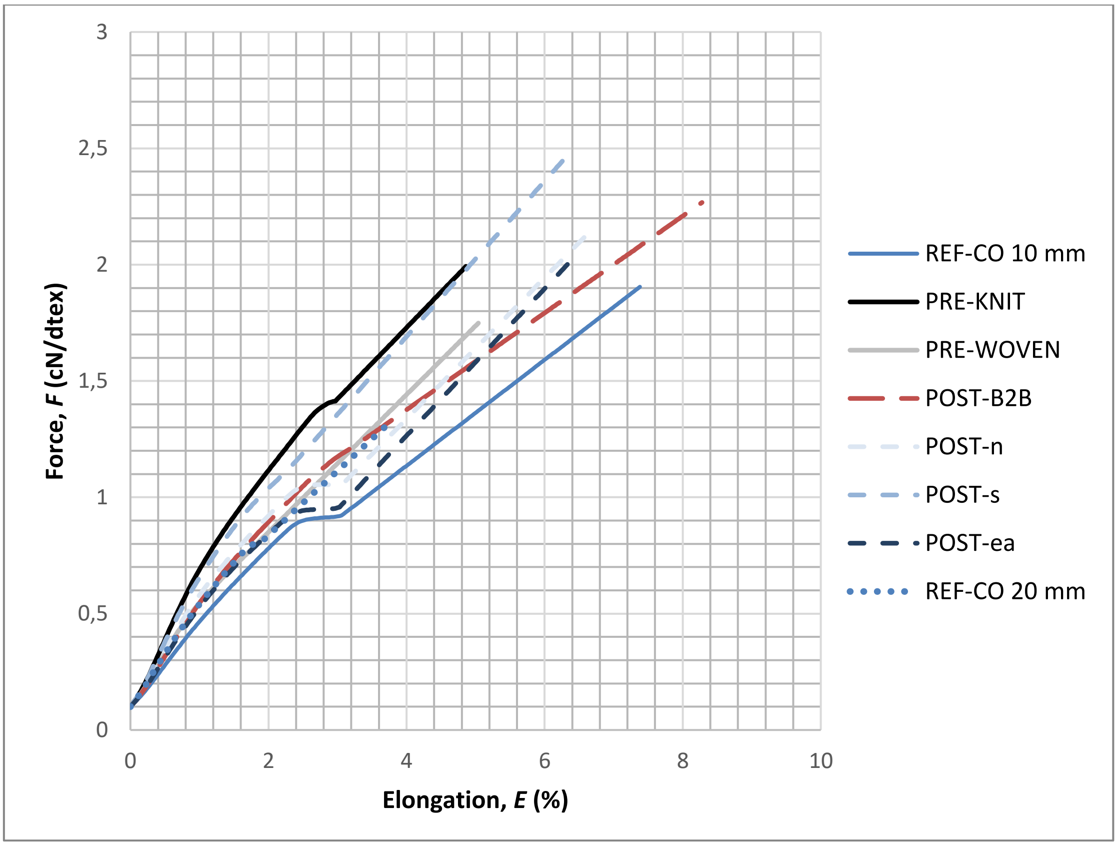


Figure 5.14: Average tenacity-elongation plots for the cottons measured with 10-mm gauge length, apart from the REF-CO 20 mm that was measured on the 20-mm gauge length.

Table 5.1: The mean values for breaking elongation, tenacity, and linear density of the samples with 10-mm gauge distance. The columns with the grey back-ground show the results for all the tested specimen, i.e., n= [10,20] specimens. The columns with the white background show the results of the selected speci-mens, i.e., the ones that had a coefficient of variation ≤ 50% (see Appendix B).

sample	all specimen				selected specimen			
	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)
REF-CO	10	7.40	1.91	2.18	6	4.10	1.97	2.19
PRE-KNIT	20	4.25	1.89	2.16	19	3.73	1.84	2.18
PRE-WO-VEN	20	5.67	1.87	1.99	20	5.67	1.87	1.99
POST-B2B	20	8.30	2.27	2.25	17	5.55	2.01	2.24
POST-n	20	5.70	1.87	2.21	19	5.26	1.74	2.24
POST-s	20	6.78	2.39	2.17	18	5.11	2.18	2.15
POST-ea	20	9.89	2.48	2.23	17	6.95	1.95	2.19
Reference values for virgin cotton in literature at 10-mm gauge distance (Morton & Hearle 2008, p. 290)						5.60– 7.10	1.90– 4.50	
Commercial reference values (Textile Learner 2022)						5–10	2.5–5	1–4

For reference, the same properties measured with a 20-millimeter gauge distance are reported in Table 5.2. It was possible to measure only POST-B2B and POST-n of the MO fibre samples with the longer, standardised gauge distance. All samples were given a minimum of 10 minutes of time trying to find a fibre that was long enough before the testing was terminated and thus marked unsuccessful.

Table 5.2: The mean values for breaking elongation, tenacity, and linear density of the samples with 20-mm gauge distance. The columns with the grey background show the results for all the tested specimen, i.e., n=10 specimens. The columns with the white background show the results of the selected specimens, i.e., the ones that had a coefficient of variation ≤ 50% (see Appendix B).

sample	all specimen				selected specimen			
	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)
REF-CO	10	3.85	1.35	1.67	8	2.90	1.19	1.63
POST-B2B	10	10.84	2.43	1.73	9	8.96	2.32	1.53
POST-n	10	10.28	2.55	1.99	6	4.23	1.74	1.76

5.4 Statistical analysis results

A single factor ANOVA was executed for the weight-based average lengths, breaking tenacities, elongations, and linear densities to evaluate whether the MO fibres compare to or differ from each other or the reference cotton. Table 5.3 shows a statistically significant difference for *average length* and *elongation* with both all and selected specimen. There is no statistical significance between the tenacities or the linear densities of the different cotton qualities with α = 0.05, which indicates that at least in this study, the mechanical opening or the quality of the textile waste did not influence the different cotton qualities' tenacity or linear density. However, the quality of the textile waste seemed to somewhat affect elongation. The pairwise comparison was carried out for the elongation results measured at 10 millimetres for both all *and* selected specimen. The Tukey-Kramer test showed there is a statistical significance between the pair PRE-KNIT and POST-ea with a confidence level α = 0.05 in both groups.

The Tukey-Kramer test further reveals that the weighted average lengths of sample REF-CO are statistically significantly different in all pairwise comparisons as was clearly suggested by the fibre length measurement results in chapter *5.2 Fibre length results*. Moreover, the pairwise comparisons suggest that pairs PRE-KNIT/POST-B2B and PRE-KNIT/PRE-WOVEN are statistically significantly different with a confidence level α =

0.05. PRE-KNIT was observed to obtain shortest average length and shortest UQL compared to the other MO cotton qualities in the results given in Figure 5.10. The statistical analysis highlights its difference in length to the other MO fibres.

Table 5.3: The single factor ANOVA results for average length, breaking tenacity, breaking elongation, and linear density.

	SOURCE OF VARIATION	SS	DF	MS	F	P-VALUE	F CRIT
AVERAGE LENGTH X, ALL SPECIMEN	Between Groups	211.4712	6	35.2452	95.13801	1.55E-10	2.847726
	Within Groups	5.186495	14	0.370464			
TENACITY, ALL SPECIMEN (10 MM)	Between Groups	8.493295	6	1.415549	1.349186	0.240605	2.173112
	Within Groups	129.05	123	1.049187			
TENACITY, SELECTED SPECIMEN (10 MM)	Between Groups	2.096159	6	0.34936	0.703831	0.647126	2.182862
	Within Groups	54.10419	109	0.496369			
ELONGATION, ALL SPECIMEN (10 MM)	Between Groups	419.9604	6	69.99341	2.425018	0.029948	2.173112
	Within Groups	3550.155	123	28.86305			
ELONGATION, SELECTED SPECIMEN (10 MM)	Between Groups	106.106	6	17.68434	3.499469	0.003333	2.182862
	Within Groups	550.8243	109	5.053434			
LINEAR DENSITY, ALL SPECIMEN (10 MM)	Between Groups	0.88007	6	0.146678	1.481184	0.190028	2.173112
	Within Groups	12.18041	123	0.099028			
LINEAR DENSITY, SELECTED SPECIMEN (10 MM)	Between Groups	0.842862	6	0.140477	1.425918	0.211192	2.182862
	Within Groups	10.73834	109	0.098517			

5.5 Surface inspection results

The surfaces of the cotton fibres were inspected with SEM. The 200x magnifications of all the cottons are presented in *Appendix C*. Selected cropped images are presented in this chapter, and uncropped images of those are shown in the same *Appendix C*. For surface inspection, an additional sample of an old bedsheet was prepared, as described in the chapter *4.1 The samples*. The hand-opened fibres of the bedsheet are pictured in Figure 5.15.

Figures 5.16 – 5.18 show some additional details of chosen fibre samples. Figure 5.16 shows some damaged fibres in two samples. Figure 5.17 shows some surface opening in a post-consumer sample compared to undamaged pre-consumer sample. Cuts, tearing, and other surface damage was observed in individual fibres on MO fibre samples, somewhat more on the post-consumer fibres. The observations related to fibre contents of the cotton qualities are presented in chapter *5.6.3 SEM observations*.

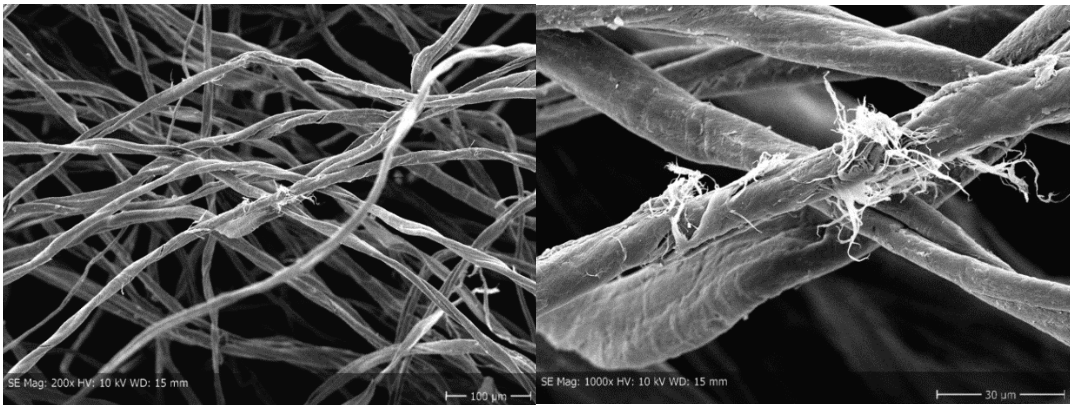


Figure 5.15: SEM images of the fibres in the old bedsheet with 200x (left) and 1000x (right) magnifications. The pictures can additionally be found in Appendix C in Figures C.13 and C.14.

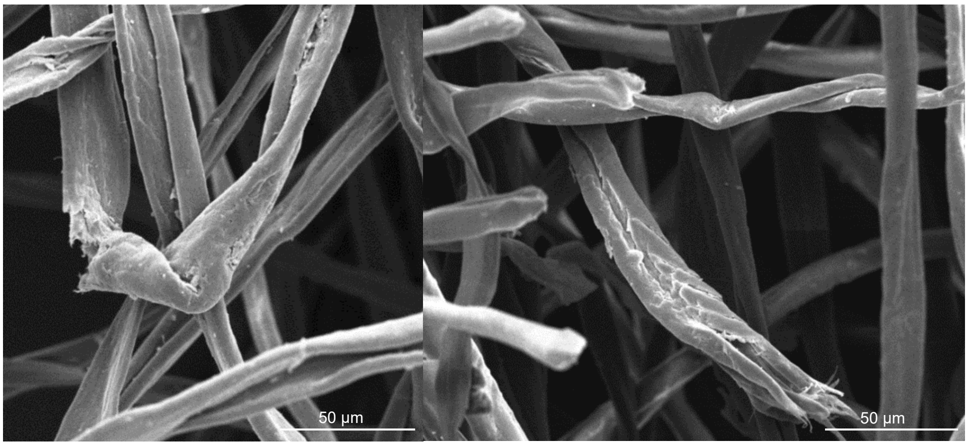


Figure 5.16: SEM images of individual damaged fibres on POST-s accept (left) and POST-B2B uncleaned (right). 500x magnifications. The uncropped images are presented in Appendix C in Figures C.15 and C.16

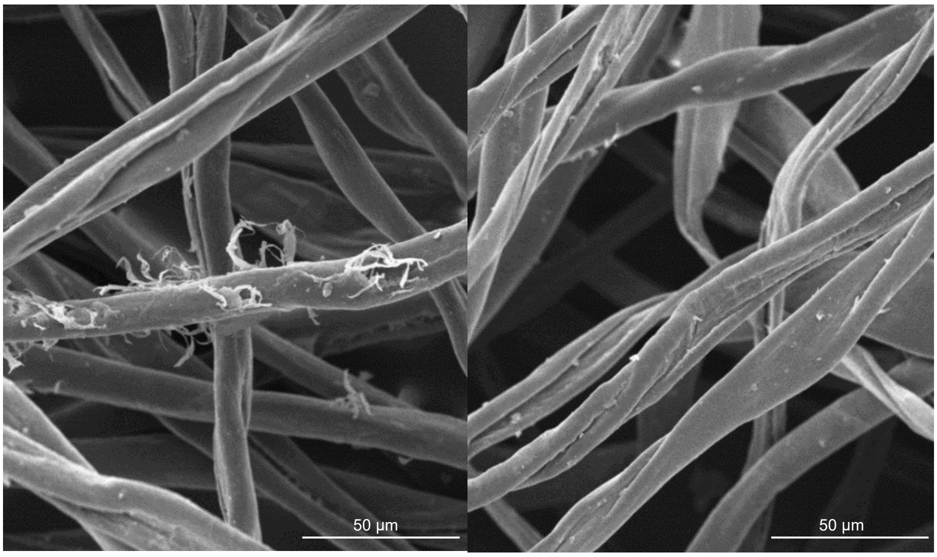


Figure 5.17: SEM images of POST-n accept (left) and PRE-KNIT (right). 500x magnifications. The uncropped images are presented in Appendix C in Figures C.17 and C.18.

Figure 5.18 shows the dirtiness of the post-consumer fibres compared to reference and pre-consumer fibres. In general, post-consumer fibres were observed to be more dirty than other observed fibres. No observations of difference in dirtiness in accept or uncleaned samples was made.

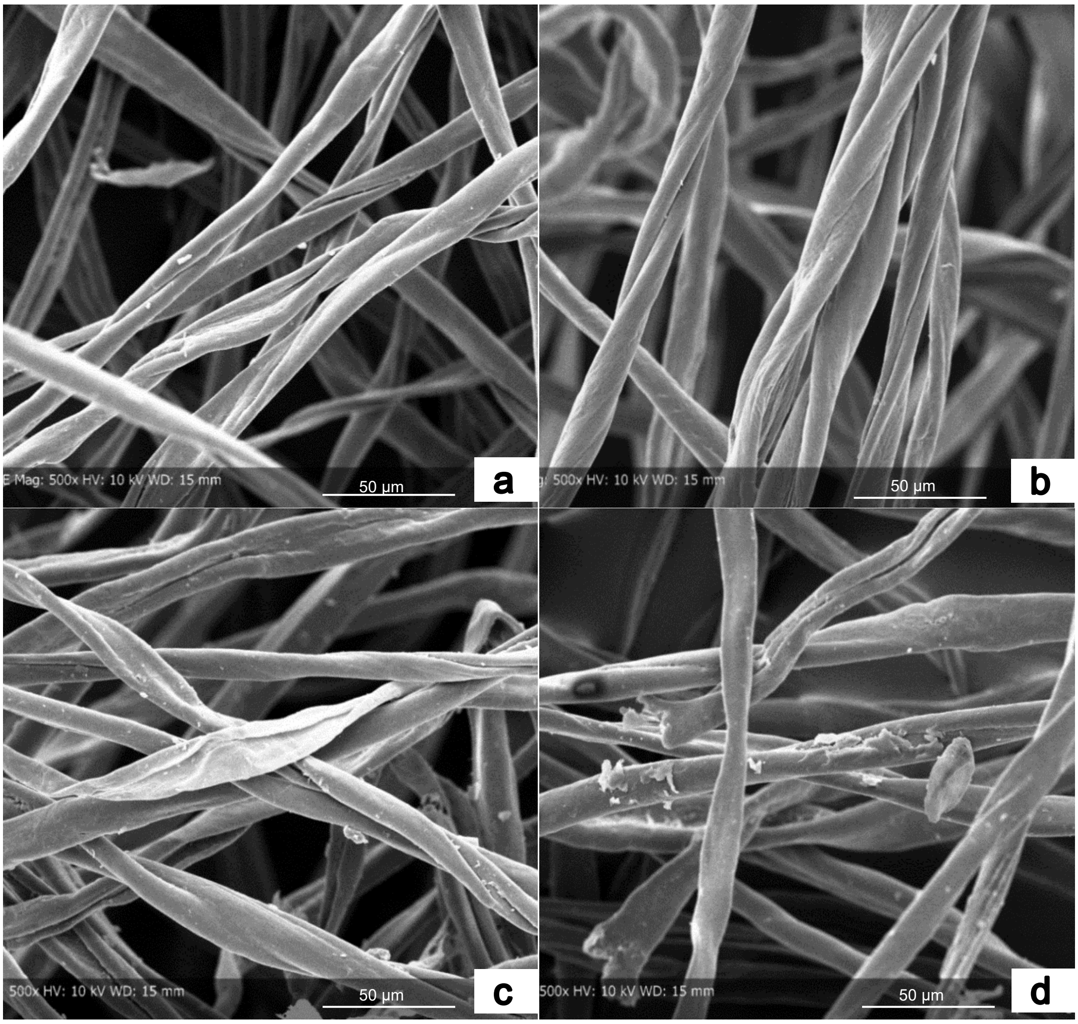


Figure 5.18: Some fibres were dirtier than others. SEM images of PRE-WOVEN accept (a), REF-CO accept (b), POST-ea accept (c) and POST-n accept (d). 500x magnifications. The uncropped images are presented in Appendix C in Figures C.19-C.22.

5.6 Fibre composition results

The fibre compositions of the different cotton qualities were observed with DSC, FT-IR and SEM. DSC was used to identify the possible melting points of the material, and its brief results are presented in chapter *5.6.1 DSC results*. FT-IR spectroscopy was used to identify chemical components in the cotton samples. Similar to the DSC results, only the brief results of FT-IR spectroscopy are presented in the following chapter *5.6.2 FT-IR results*. Finally, SEM imaging was used to observe fibres with shapes different to the cotton fibre shape, and these results are presented in chapter *5.6.3 SEM observations*.

5.6.1 DSC results

Figures 5.19 and 5.20 show selected DSC heating curves. The focus of the presented results is on recognising the melting peaks, and therefore no cooling peaks are presented in the figures in this chapter. Figure 5.19 shows the peaks of first and second heating in all the accept cottons, one specimen per sample and Figure 5.20 shows similarly observed peaks with similar sampling, but with uncleaned cottons. The peaks at approximately 10-minute mark are attributed to moisture evaporating from cotton (Trivedi et al. 2015) and can be seen in all the samples at approximately 80-100 ºC (*Appendix D*). For a closer look, all the accept and uncleaned cottons with three specimen each are presented on their own in *Appendix D*, and selected curves are presented in *Discussion* in chapter *6.1.5 Fibre composition.*

On top of the moisture evaporation peaks, some peaks are observed on higher temperatures. These peaks are more pronounced for the uncleaned samples than they are for accept samples, and no peak during second heating can be obtained for REF-CO, PRE-KNIT or PRE-WOVEN (Figure 5.20). Figure 5.19 shows that the computer determined certain peaks for all the accept cottons, but looking at the shapes of the heating curves, the peaks for REF-CO, PRE-KNIT and PRE-WOVEN are more subtle than for the post-consumer cottons.

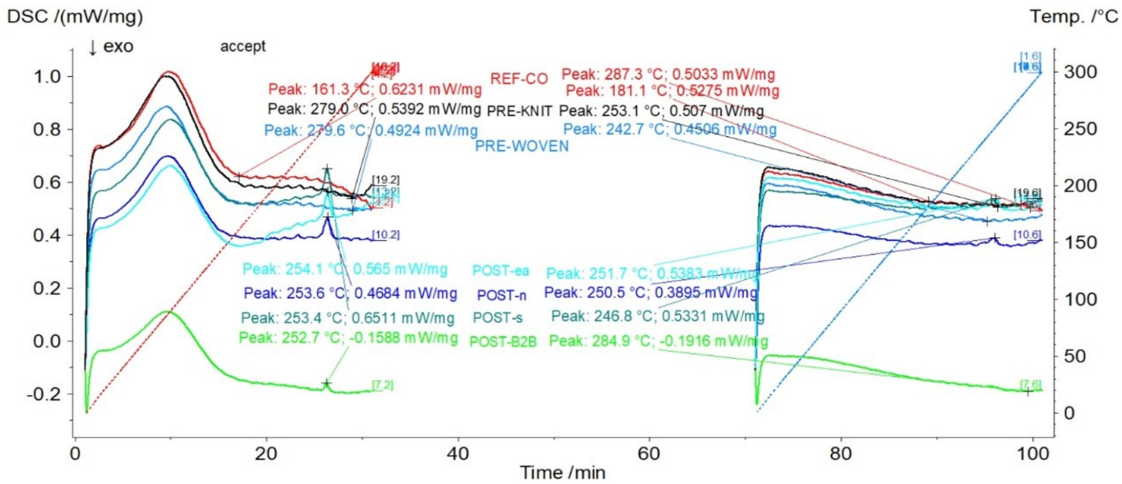


Figure 5.19: The DSC heating curves for accept samples of each cotton quality. The graphs and their detected peaks are displayed in sample-coordinated colours displayed in the picture.

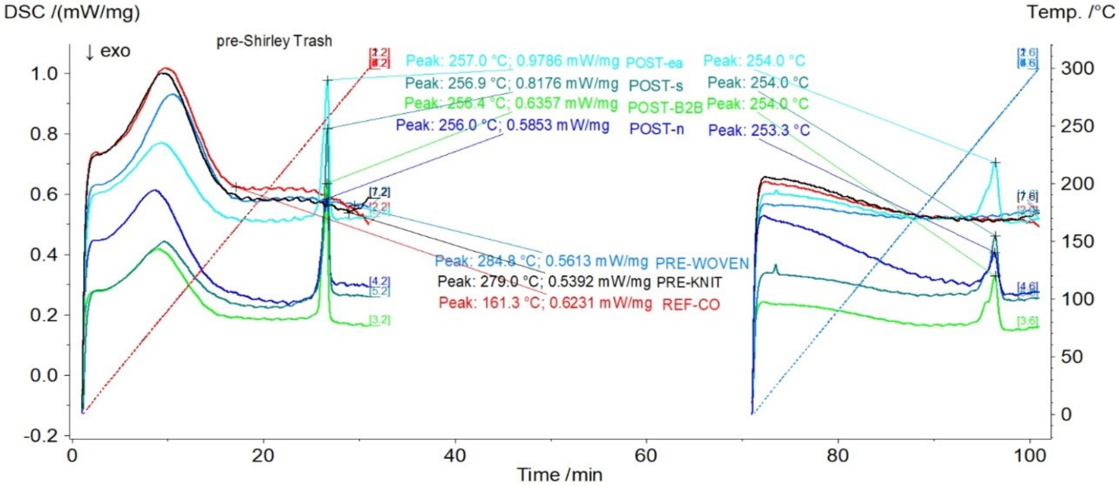


Figure 5.20: The DSC heating curves for uncleaned samples of each cotton quality. The graphs and their detected peaks are displayed in sample-coordinated colours displayed in the picture.

5.6.2 FT-IR results

The three spectra for REF-CO accept specimen are presented in Figure 5.21. The broad peaks at 3331 cm^{-1} have earlier been identified as the stretching vibrations of intramolecular hydroxyl groups in other studies researching cellulosic materials (Hospodarova, Singovszka & Stevulova 2018; Tamanna, Belal, Shibly & Khan 2021; Lourdin et al. 2016). All the studied materials in this report showed the said peaks. Due to excessive amount of data, all the FT-IR spectra are presented in *Appendix E*, and selected spectra are presented in *Discussion* in chapter 6.1.5 *Fibre composition*.

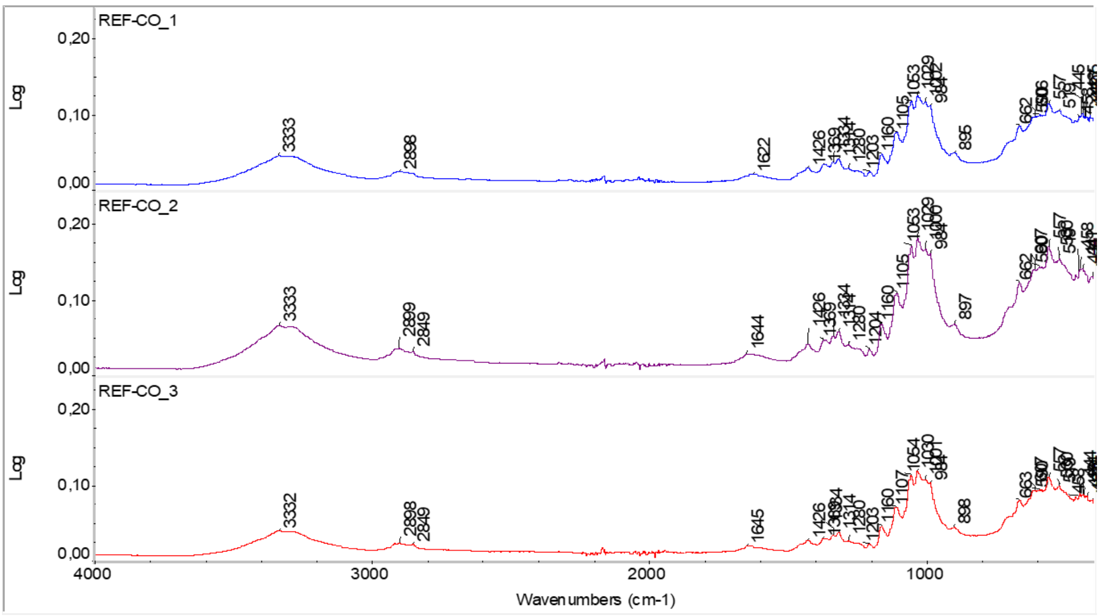


Figure 5.21: The FT-IR spectra for REF-CO (accept) specimen.

5.6.3 SEM observations

Figure 5.22 shows selections of fibres in three different samples. Some of the pictured fibres do not have the typical cotton convolutions that can be seen throughout most of the samples, which indicates there are man-made, synthetic fibres involved. In Figure 5.22 (centre) and (right) the man-made fibres are in yarn constructions. Man-made fibres were difficult to identify in the accept samples, and the fibre in Figure 5.22 (left) was one of the few exposed examples. All the easily visually identified synthetic fibres were in post-consumer samples. This result suggests that the man-made fibres are often used in the yarns in the seams of the garments and are therefore not opened as easily as the fabric. The unopened yarn and neps are easily removed from the fibre blend with the help of 'Shirley' Trash analyser. The full pictures of the cropped pictures of Figure 5.22 are presented in *Appendix C:* Figures C.23 – C.25.

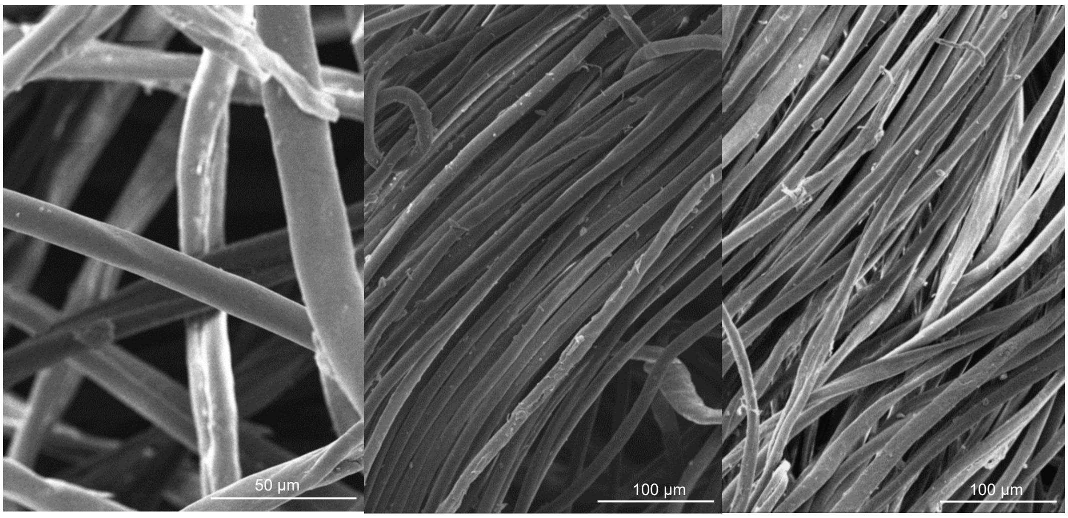


Figure 5.22: Man-made fibres? SEM images of POST-s accept (left) at 500x magnification, and POST-s uncleaned (centre) and POST-ea (right) at 200x magnifications. The uncropped images are presented in Appendix C in Figures C.23-C.25.

Figure 5.23 shows two 500x magnifications of POST-n uncleaned. In both pictures there are different thicknesses of fibres visible. Cotton is a natural fibre which gives it an intrinsic unevenness in length, thickness, and other dimensional properties. The size of the fibres in the samples can and will, however, affect the mechanical properties, such as breaking tenacity and breaking elongation, thus resulting in more unpredictability in terms of processing.

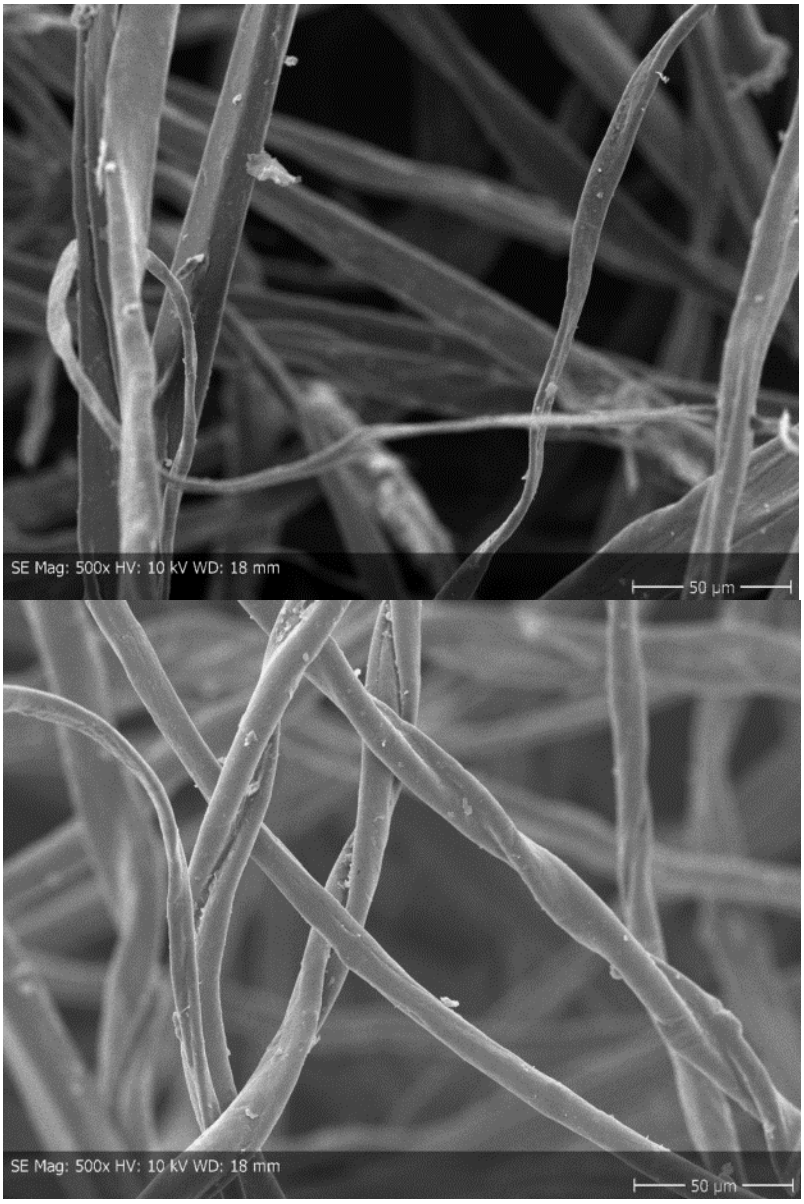


Figure 5.23: Two SEM images of POST-n uncleaned showing the uneven and deviating thicknesses of the fibres.

6. DISCUSSION

6.1 Experimental results

6.1.1 ‘Shirley’ Trash opening

As described in the text, the ‘Shirley’ Trash Analyzer is used in the industry for the purposes of analysing the foreign matter in virgin raw cotton. In this experiment the machine was used to clean the mechanically opened cotton i.e., separating fabric pieces and yarn fragments from opened fibres. Based on masses of accept and reject the efficiency of opening was calculated. The EFO reaches an 88.1 % rate for the reference cotton, whereas the MO fibres reach between 44-68 % EFO. During the ‘Shirley’ Trash analysis, small part from the sample is lost, most likely in form of very short fibre dust. The most fibres were lost for the post-consumer denim samples POST-n, POST-s and POST-ea, which have all been opened on the same opening line. POST-B2B is also obtained from post-consumer waste, and while its ‘lost’ rate is not as high as for the other post-consumer samples, its accept to reject ratio is the weakest between all the samples.

Given that the EFO is measured with ‘Shirley’ Trash Analyzer, Schwippl (2020) reports an efficiency of opening of >70 % to be desirable in the future. POST-n and POST-s obtain highest EFO’s in this report, 68 % and 63.6 % respectively, while POST-ea obtains an EFO at 51.2 %. Provided the fact that POST-n, POST-s and POST-ea were not statistically significantly different from one another in terms of average length, breaking elongation, tenacity or linear density, it was surprising that their ‘Shirley’ Trash EFO differed from each other, and it seemed that the use of softener did not have an effect on EFO. However, the results of the ‘Shirley’ Trash cleaning are based on one sample each, and more elaborate testing could be performed. Additionally, MO fibres as such were inhomogeneous and the sampling procedure may have affected the result.

Interestingly, the darker samples obtained the lowest EFO’s. Ütebay, Çelik and Çay (2019) observed in their trials that the mechanical opening of greige cotton resulted in fewer short fibres than the mechanical opening of dyed cotton fabrics, and the produced yarn of greige cotton fibres had better strength properties than the yarn with fibres from dyed fabrics. Similar results were observed in another study (Moghassem 2007), where three yarns were spun with grey, dyed or a 50-50 blend of grey and dyed virgin cotton fibres were spun. The study found no significant difference in the breaking elongations of the different yarns, but the tenacity of the yarn spun with grey fibres was the highest.

The study reviewed the dyed fibres, or the blend of the grey and dyed fibres also obtained the most neps, which is most likely due to the mechanical fibre damage caused by the dying processes. The neps increase the SFC and negatively affect the strength properties. Figure 6.1 shows the uncleaned cottons next to each other with their respective EFO's. The decreasing of EFO with a darkening fibre colour can somewhat be observed in these results, but more research is necessary to determine the effect of colour. Further research should consider a higher number of samples opened at the same opening line, as EFO is an opening line property rather than a material property.

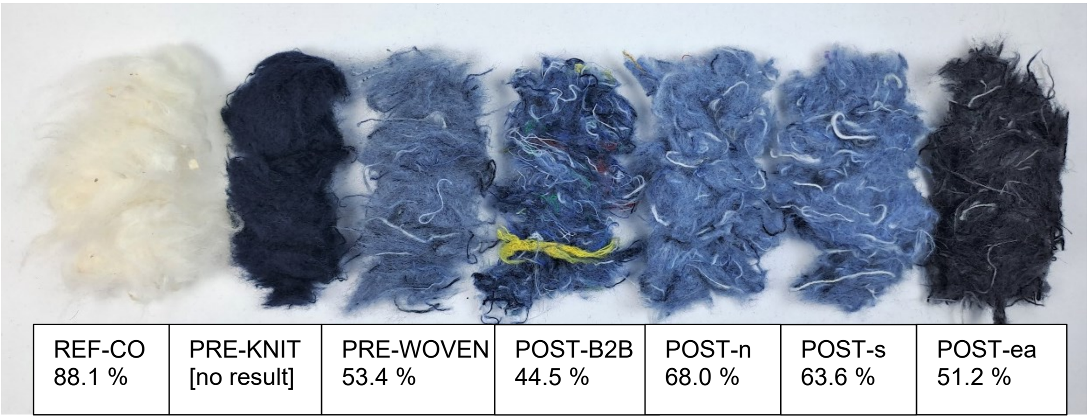


Figure 6.1 The cottons studied in this report with their respective opening lines' efficiencies of opening (EFO).

6.1.2 Fibre length

The fibre length measurements were made with a slightly adjusted weight-based method, and the results obtained in studies where the number of fibres was recorded are not directly comparable. According to the standard (ASTM D1440-07), cotton length is measured with just the first prepared fringe. In this report, the fringe was prepared three times, as the samples were not combed prior to the experimenting. The aim of preparing the fringe three times was to get out unparallel fibres, but it may have resulted in a higher content of short fibres and thus a lower mean length than normally would be observed.

Still, the values from the literary review serve as a reference, as the length measurement of MO fibres is not standardised, and the many parameters affecting the results must be considered. It can be noted that with the Suter-Webb comb method used in this study some of the MO fibres get tangled in the combs, as the MO fibres are not as easy to get parallel as the longer virgin cotton fibres. The method chosen for this report hints at a higher SFC than what would be acquired were the standardised method used: by measuring as many fibres as possible leads inevitably to a higher SFC, as many of the short fibres as possible are forced for length measuring. In the results of this report, the SFC was found to be between 31.4 and 40.3 % for the MO fibres and 8.2 to 15.2 % for the virgin cotton, but for example Yuksekkaya *et al.* (2016) found the SFC values to be at 11.3 % for MO cotton fibres and 8.4 % for the virgin cotton fibres. The testing by Yuksekkaya *et al.* (2016) was conducted with an Uster HVI instrument, whereas the results in this report are based on manual measurements. Additional inaccuracy of the method can be seen in for example the approximated UHML and length uniformity index of the virgin cotton, as presented in Figure 5.13: REF-CO obtains a UHML of 23.98 millimetres and a UI of 64 %. According to commercial reference values presented by the U.S. non-profit company Cotton Incorporated (2021), cotton fibres with UHML shorter than 25.4 millimetres are considered “short”, and a UI lower than 77 % is “very low”. It is possible that REF-CO is a cotton fibre of a weaker quality, but it is also possible that the adjusted measuring system affected the measured average length, ML, UHML and finally UI. Although the fibre lengths could need a re-evaluation with another type of method, it can be constituted that the fibre length uniformity index suffers a drop from REF-CO to the pre-consumer cottons, and a further drop moving onto the post-consumer cottons. Further evaluation could reveal whether the drop would be more pronounced with a correct method, for example an optical, automated method.

However, it has been reported that some of the optical methods are unsuitable for testing of darker, dyed, mechanically opened fibres (Arafat & Uddin 2022) although the testing of light-coloured MO fibres has been reported successful (Yuksekkaya et al. 2016). The observations made by Thibodeaux *et al.* (2008a) confirm that the Suter-Webb array method gives a higher SFC content variation between cotton bales. According to their study of virgin cotton bales, they estimate that SFC could be measured more efficiently with HVI and AFIS systems. On the contrary, Arafat and Uddin (2022) found the use of HVI systems impossible of MO fibres due to the many unopened threads and neps, whereas AFIS proved successful.

In this study, the fibre length results showed that the MO fibres are shorter than the virgin REF-CO: the longest individual fibres for any mechanically opened samples are 25-27 millimetres, while the longest reference fibres are 31-33 millimetres. The fibre length accumulation was slowest for the REF-CO meaning more of its weight consists of generally longer fibres than any other sample. REF-CO was statistically significantly different from all the other cottons. Moreover, PRE-KNIT was statistically significantly shorter than PRE-WOVEN and POST-B2B. Knitwear was found more difficult to detangle than woven fabric on a mechanical opening line by e.g., Aronsson and Persson (2020). The effects of yarn structure were observed in this study, too, as PRE-KNIT obtained the shortest lengths of all the samples.

The study by Aronsson and Persson (2020) showed that yarn construction of post-consumer textile waste and its level of wear affect the obtained fibre length. The yarn construction of ring-spun yarns is twisted and therefore tighter than that of rotor spun denim yarns. As Hailemariam and Muhammed (2022) observed on their experiments, ring-spun yarns provide with more tensile strength than open-end rotor spun yarns. The twist of the ring spun yarn may very well be the main factor affecting the tensile strength of a yarn, but unfortunately it results in poor opening of the yarns. The yarns and textile shreds are under the stretching motions caused by the cylinders in the opening line, and a looser structure can be more beneficial. Aronsson and Persson (2020) described how the rather worn garments did not obtain as drastic fibre length losses as the barely worn garments, suggesting that the worn-out structure can be seen as an advantage in mechanical textile recycling. The wearing-out of fabric structures while in use can result in loosening of the textile structure and therefore both reduce the friction and make it easier for a single fibre to separate in mechanical action.

Although, in this study, PRE-KNIT obtains visibly the lowest mean lengths in total (Figure 5.13) and its fibres are weighted on the short side (Figure 5.10), its uniformity index is the third highest of all the observed mechanically opened qualities. The said fibre is designed to be used in recycled textile products, which partly proves that even a short fibre is suitable for use if its properties (i.e., length) are controlled. When the length is controlled, the behaviour of the cotton fibres in spinning can be approximated, thus resulting in regular qualities of yarn.

Conclusively, the results for the reference fibre differ from the other fibres: the obtained fibre lengths are approximately longer, and the weight of the fibres left unmeasured is lower, as can be seen in Figures 5.10 – 5.12. Arguably, the MO fibres contain some unopened threads that weaken the result. Most of the unopened threads are removed in the ’Shirley’ Trash cleaning. Still, some of the unopened threads are left in the ‘accept’ sample, which ultimately results in them being either neps or threads in length measurement.

6.1.3 Tenacity, breaking elongation, linear density

As described in chapter *5.3 Tensile testing results*, some of the individual tensile testing results were removed from the measurements. Figure 6.2 shows the curves for the 20 specimens measured off sample POST-ea. It was due to the varying results that the individual fibres were looked at more closely, and it was decided to drive the coefficient of variation between the fibres down. Hence, the most deviating fibres were removed from the results to better indicate the properties of the cotton fibres in the recycled fibre samples. For POST-ea the c_v was 0.82 before the selection, and 0.38 after removing four of the most deviating fibres still visible in Figure 6.2. The selection and removal of the fibres is specified in *Appendix B: Table B.7*.

However, it is crucial to recognize two things; most likely there are other fibres than cotton in the recycled bundles, and whether there are more deviating fibres in some samples than others. It could be suggested that the deviating fibres in POST-ea (Figure 6.2) are for example polyester and elastane, which are widely present in jeans (Yousef et al. 2020). The breaking elongations of 10 % or more are uncommon for cotton, and more common for selected synthetic fibres (Tables 6.1 and 6.2). POST-ea is also the sample with the lowest control in material composition i.e., it is collected as “denim with up to 10 % other fibres”. Therefore, it is safe to assume that not all the fibres in the sample are cotton. Instead, sample POST-B2B is a more controlled post-consumer sample. However, even some of its individual fibres showed deviation in breaking tenacity and elongation (Figure 6.3 and Table B.4 in *Appendix B*) which led to the removal of some of the individual fibre results for a closer cotton property inspection.

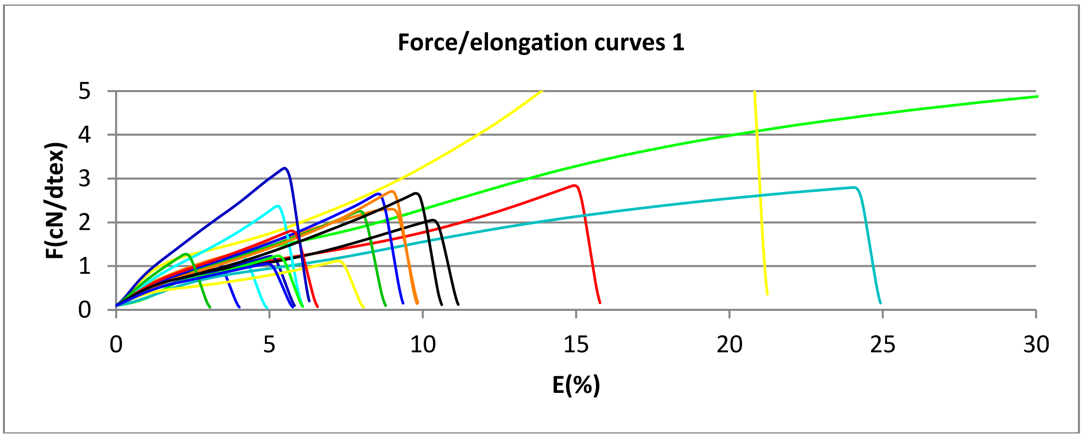


Figure 6.2: The tensile testing curves for POST-ea with 10-mm gauge length; 20 specimen

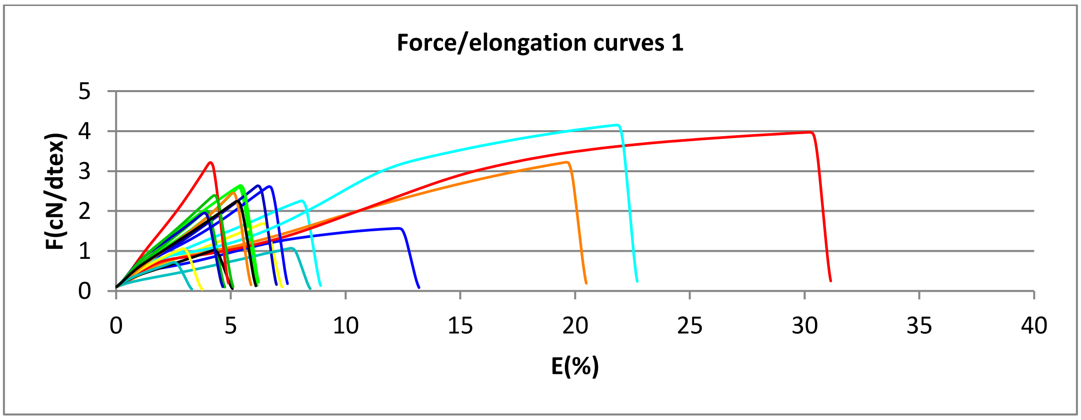


Figure 6.3: The tensile testing curves for POST-B2B with 10-mm gauge length; 20 specimen.

The smallest number of deviating fibres in tensile testing results were obtained for PRE-KNIT, PRE-WOVEN and POST-n with the 10-mm gauge length (Table 5.1 and *Appendix B*: Figures B.1 – B.7). Interestingly, the reference cotton received initially a c_v at approximately 0.75 with the 10-millimeter gauge length and that of 0.6 with the standardised 20-millimeter gauge length (Tables B.1 and B.8 in *Appendix B)*. Table 6.1 shows how the removed fibres mainly affect the elongation, suggesting there is little difference in the tenacity and linear density of the individual REF-CO fibres. The greatest singular elongation for REF-CO is at 16.12 % (Table B.1 in *Appendix B*), which is rather too high for cotton (Morton & Hearle 2008, p. 290; Cotton Incorporated 2021).

However, the rather considerable c_v between the individual REF-CO fibres, the mean breaking elongations, tenacities, and linear densities of the REF-CO fibres fall somewhat within the limits presented by Morton and Hearle (2008, p. 290) and Textile Learner (2022), as can be seen in Table 6.1. The standard 20-mm gauge distance gives lower values than the 10-mm gauge distance. Furthermore, selecting specimen i.e., removing some of the measurements generally lowers the values.

Table 6.1: REF-CO tensile testing results of both 10- and 20-mm gauge lengths and reference values from literature. Put together from Tables 5.1 and 5.2.

sample	all specimen				selected specimen			
	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)	n	breaking elongation (%)	tenacity (cN/dtex)	linear density (dtex)
REF-CO 10 mm	10	7.40	1.91	2.18	6	4.10	1.97	2.19
REF-CO 20 mm	10	3.85	1.35	1.67	8	2.90	1.19	1.63
Reference values for virgin cotton in literature at 10-mm gauge distance (Morton & Hearle 2008, p. 290)						5.60– 7.10	1.90–4.50	
Commercial reference values (Textile Learner 2022)						5–10	2.5–5	1–4

The standard gauge length of 20 millimetres (SFS EN-ISO 5079:2020) is set for cotton fibres that are often at least 15 millimetres long, and often the most popular cotton varieties are even longer. The standard, however, states that the gauge length can be altered to 10 millimetres, although the results may not be as reliable. In this study, the average length of REF-CO was 18.84 mm. The tensile testing is also often performed with samples of multiple fibres in a tuft (SFS EN-ISO 5079:2020), which was not possible with the rare number of suitable fibres. It is estimated that when measuring a longer fibre, it is more probable that the weak point of the fibre is present in the testing area and vice versa (Rollins 1965). This may partly explain why the tenacity results for the longer REF-CO samples are weaker than for the shorter samples. Moreover, cotton's quality is different from plant to plant which may give a high, yet acceptable coefficient of variation.

The fibre length results implicated that not all MO fibres could be measured with the longer, 20-mm gauge length. For the 20-millimetre distance the fibres should be at least 20 millimetres long and cover the size of the gauges i.e., approximately 26 millimetres and longer. In the end, only POST-B2B and POST-s of the recycled fibres had enough of longer fibres to be able to execute the testing with 10 samples. PRE-WOVEN was tested with a few fibres but regardless of its overall fibre length results the testing proved unsuccessful. The main reason for this is probably that the other samples (apart from PRE-WOVEN) were measured for their length prior to tensile testing and therefore longer fibres were in bunts, i.e. more easy to be found.

POST-B2B was more difficult to measure than POST-s with the 20-mm gauge distance. Considering the length results, this does not make sense, but it could be explained with e.g., the more homogenous fibre composition of POST-B2B, the more composition-wise controlled post-consumer cotton. POST-s is most likely a fibre blend, and it could be that the synthetic staple fibres were longer from the beginning. This can be seen in the varying shapes of the force-strain curves in Figure 6.4. Similarly, the elongations of specimens #5, #6 and #7 are rather high for cotton, as cotton obtains elongations between 5.6 – 7.1 % depending on its type and growth area (Morton & Hearle 2008, p. 290).

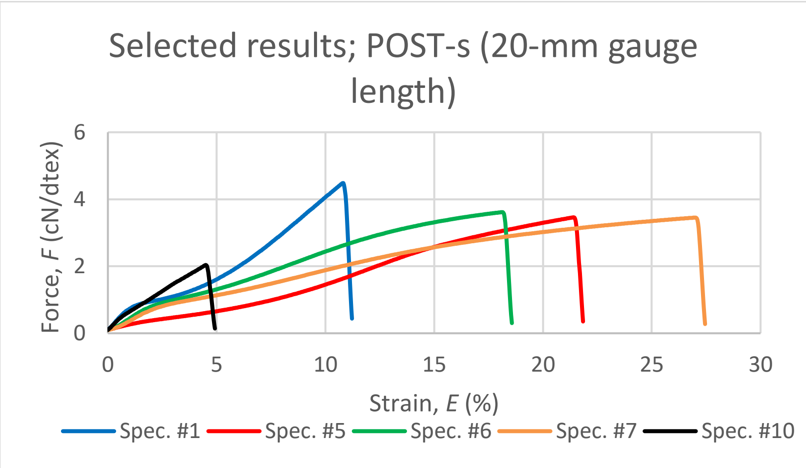


Figure 6.4: The tensile testing curves for selected POST-S specimen with 20-mm gauge length.

Table 6.2: Some common textile fibres' tensile properties reviewed by Morton and Hearle (2008, pp. 290, 292).

Fibre	Tenacity (cN/dtex)	Breaking elongation (%)
Cotton	1.9-4.5	5.6-7.1
Viscose rayon (high-tenacity)	4.1	12
Nylon 6.6 (medium-tenacity)	4.8	20
Polyester (Terylene) (medium-tenacity)	4.7	15
Acrylic (Orlon 42 staple-fibre	2.7	25

Based on the curve form, the specimen #10 displays a common cotton tenacity and elongation, while the other fibres could be polyester, viscose, polyamide or acryl considering their shape and higher tenacity and elongation. Table 6.2 reviews different tenacities and breaking elongations of some common textile fibres for comparison. Additionally, the selecting of the test specimen is supposed to be random, and it could be pure luck, that the longer of the POST-s fibres were picked up and tried out for the tensile testing. This is supported further by the detail that POST-s has similar fibre lengths to POST-n and POST-ea, both of which proved unsuccessful with the longer gauge length.

Although the literature regarding the tensile testing of fibres is scarce, the reviewed research in chapter *3.2 Fibre fineness and tenacity of mechanically opened fibres* and the results presented in this report show that the breaking tenacities, elongations, and linear densities do not differ significantly between the virgin cotton fibres and MO cotton fibres in general. In chapter *5.4 Statistical analysis results*, it was concluded that the only pairwise comparison proving statistically significant difference was between the elongation values for samples PRE-KNIT and POST-ea. Moreover, the differences in tenacities and linear densities were insignificant. The results suggest favourable tensile properties regarding spinning feasibility.

6.1.4 Surface inspection

The SEM picturing is an accurate, yet time consuming process when executed properly. Some defects may be sought after, while some may be found spontaneously. In this experiment, an interesting spot was first searched for, and then images from that area were taken with the previously discussed settings.

Generally, the surfaces of many of the MO fibres do not look more worn out than the surface of reference cotton. However, there are some scarce occasional surface defects. The MO fibre samples, especially the post-consumer samples seem to be dirtier than the pre-consumer samples. Additionally, it seems that most of the pictured defects were found in the post-consumer samples. It could be suggested, that for example the abrasive defects on the surface of the fibres are somewhat due to the wear and laundering part of the fibres' previous lifecycle. Palme *et al.* (2014) suggest that the wet abrasion during laundering causes fibrillation, and dry abrasion during tumble drying causes cracking of the fibres. The same abrasive defects can be found in many of the mechanically opened post-consumer samples, and the additional bedsheet sample. Some abrasive defects may be noticed on the PRE-KNIT fibres, suggesting there could be difference between the knit vs. weave opening. However, the abrasive type of surface defect is scarce, and so are any other defects. Other types of defects include torn fibre ends and slashing.

6.1.5 Fibre composition

Denim is a cotton-rich fabric, although polyester and elastane are widely present in jeans (Yousef et al. 2022). Sometimes viscose fibres or other cellulosic fibres such as hemp or linen may be blended with cotton to obtain special types of denim (Paul 2015, p. 2). Thus, it was plausible to assume that the samples in this study contained mainly cotton, but other materials as well. The aim of the DSC and FT-IR studies was to verify the cotton rich composition of the samples, and to additionally study if these methods were able to identify any other materials in the samples.

The DSC curve for the reference cotton, as well as the curves for the pre-consumer cotton samples PRE-KNIT and PRE-WOVEN were lacking any melting points, thus suggesting the composition for these samples is 100% cotton or made up of e.g., other cellulosic or non-synthetic material. Figure 6.5 shows all the observed heating curves for REF-CO, PRE-KNIT and PRE-WOVEN (accept). The water evaporation peak around 80-100 ºC was seen during the first heating and then, during the second heating it was absent, as expected. It should be noted that the PRE-KNIT and PRE-WOVEN samples did not contain any sewing threads as the material was obtained from opened fabrics.

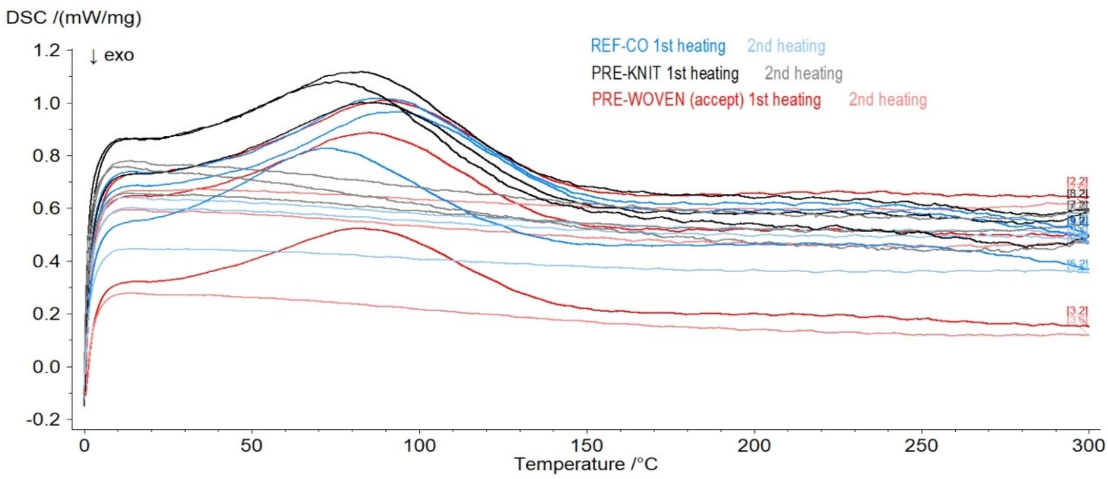


Figure 6.5: The DSC heating curves for the 1st and 2nd heating of REF-CO and pre-consumer cottons. The graphs are colour-coordinated according to the data above the graphs.

The DSC results showed melting peaks for samples POST-B2B, POST-n, POST-s and POST-ea (Figures 6.6 – 6.9). These results showed what was suggested and partly known; the post-consumer samples included both cotton and other fibres. Figure 6.6 shows the behaviour of the accept samples of the post-consumer cottons during the first heating, and Figure 6.7 the behaviour of those during the second heating. The uncleaned samples of the post-consumer cottons are presented in similar manner in Figures 6.8 and 6.9.

The melting peaks at around 250 ºC were present both in the first and second heating. For example, polyester (more specifically polyethylene terephthalate) has typical melting peaks around 530 – 540 K (i.e., 256 – 266 ºC) (Kong & Hay 2003). This may be the case also in this study, as polyester is a common material in denim. However, based on the results presented here, other synthetic materials cannot be ruled out.

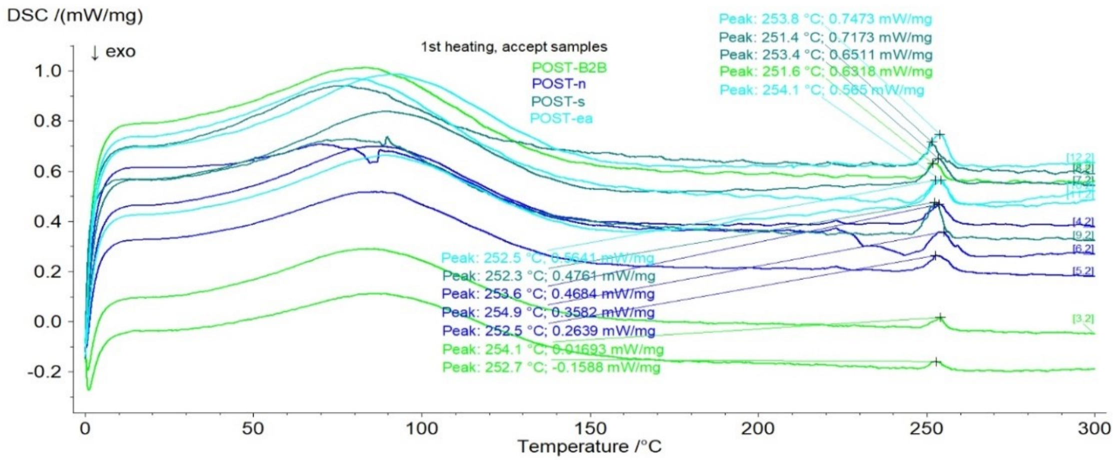


Figure 6.6: The DSC heating curves for the 1st heating of all post-consumer cottons (accept). The graphs are colour-coordinated according to the data above the graphs.

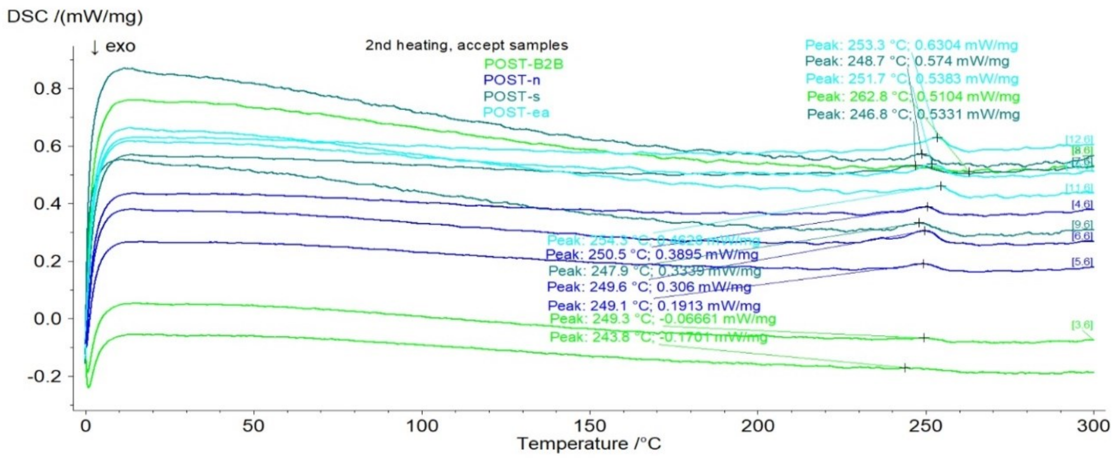


Figure 6.7: The DSC heating curves for the 2nd heating of all post-consumer cottons (accept). The graphs are colour-coordinated according to the data above the graphs.

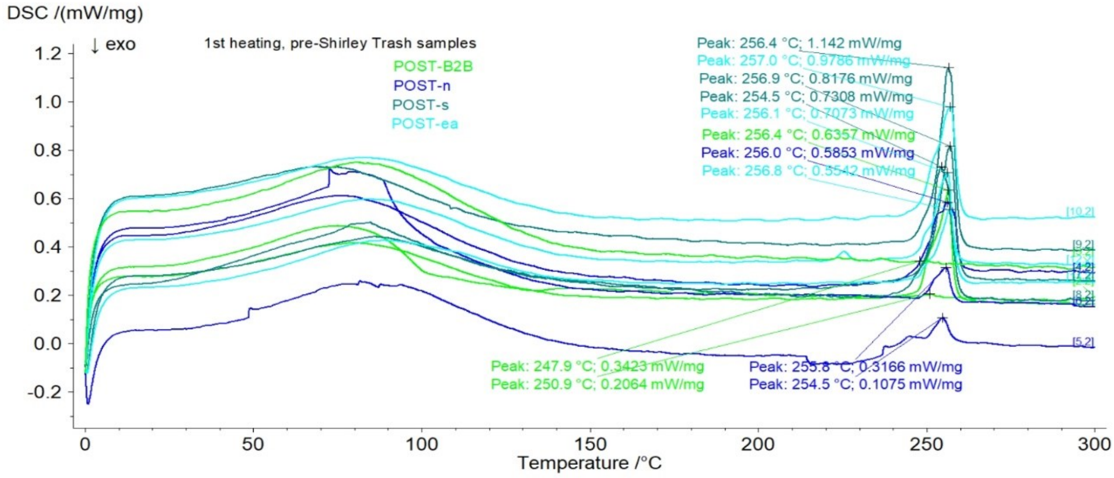


Figure 6.8: The DSC heating curves for the 1st heating of all post-consumer cottons (uncleaned). The graphs are colour-coordinated according to the data above the graphs.

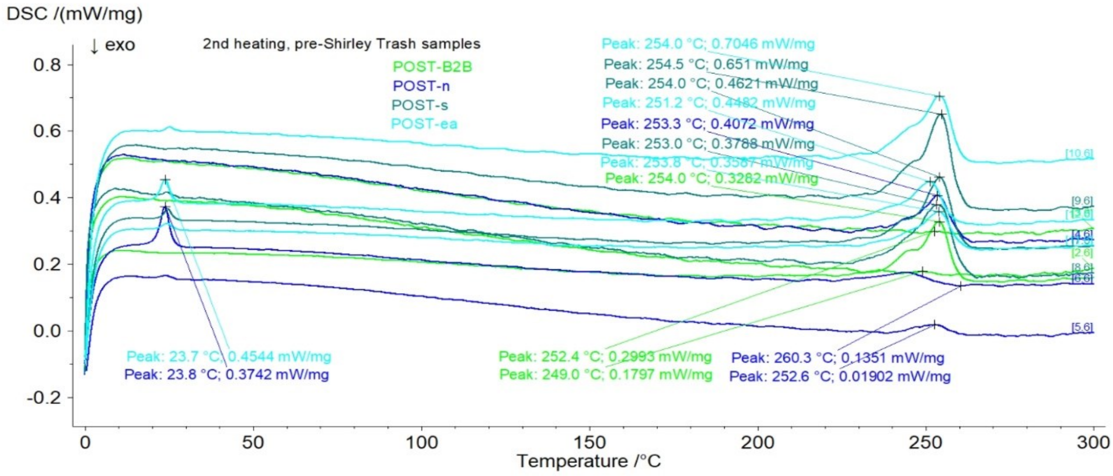


Figure 6.9: The DSC heating curves for the 2nd heating of all post-consumer cottons (uncleaned). The graphs are colour-coordinated according to the data above the graphs.

The curves for the post-consumer samples showed more energy-requiring melting peaks for the thread samples (i.e., uncleaned) than for the accept samples, 0.84 mW/mg and 0.65 mW/mg as average during the first heating, respectively. One reason for this could be that the uncleaned specimens were chosen so that it was prioritised to pick unopened yarns. These yarns could be the seam yarns that are often polyester even if the clothing would be made of cotton fabric. Other possible explanation is that the unopened yarns are denser, which requires more energy to melt them. All in all, the peaks look less energy requiring for the accept samples, compare Figures 6.6 and 6.7 with Figures 6.8 and 6.9, suggesting that the ‘Shirley’ Trash treatment removes a small deal of synthetic fibres from the blend.

The SEM pictures supported the suggestion, as it was noticed it was more difficult to find polyester or other synthetic-shaped, round, fibres on the accept samples, than it was to find them on the uncleaned samples. Even with the latter mentioned samples, the supposed polyester fibres were often parts of the building material for the yarns and thus the accept fibres may have obtained smaller melting peaks on the DSC.

As FT-IR is a qualitative method, the spectra must be very carefully analysed. Certain peaks can be attributed to a material, while some other material might be present and its peaks be suppressed by the other, dominating material. One of the materials may be dominating due to its relatively higher contents or better position in front of the IR beam. Therefore, FT-IR offers only qualitative analysis, and while certain materials' presence in the sample may be possible to confirm with a cross-examination, it is difficult to rule out a presence of another material. The peaks of FT-IR results can be compared with ATR-FT-IR results although the two methods are differently executed.

The typical cotton peaks can be seen in many of the samples. The peak at 1428 cm^{-1} can be attributed to the -CH and $-CH_2$, and C=O bonds' vibrations (Hospodarova, Singovszka & Stevulova 2018). The FT-IR spectra for all the samples show an approximate equivalent at either 1426 or 1427 cm^{-1}. Other relevant peaks for cellulosic materials are the peaks where for example the C-O-C bond is stretching. These peaks have been found to be at 1155 cm^{-1} (Carrillo, Colom, Suñol & Saurina 2004) or at 1164 cm^{-1} (Rosa et al. 2010). Similarly, the stretching of the glucose rings can be found at approximately 1111-1114 cm^{-1} (Carrillo et al. 2004, Rosa et al. 2010). Peaks around these areas can be found in all the samples, implicating the samples contain cotton, as expected. Figure 6.10 shows one of the cotton specimens with the described peaks.

Peets *et al.* (2019) found peaks for cotton at 3423, 2904, 1647, 1130, 1091 and 898 cm^{-1} with r-FT-IR method, and 3336, 2920, 1732, 1055, 1034 and 903 cm^{-1} with mATR-FT-IR. The said report researched whether r-FT-IR serves as a comparable method to mATR-FT-IR in fibre identification and concluded that it does. As an example, The REF-CO specimen #2 in this experiment display comparable peaks at 3333, 2899, 1644, 1053, 1029 and 897 cm^{-1} (Figure 6.10). The proposed mATR-FT-IR peak at 3336 cm^{-1} (Peets et al. 2019) is close to the peak at 3333 cm^{-1} while the proposed r-FT-IR peak at 1647 cm^{-1} is closer to the peak at 1644 cm^{-1} and no comparable peak has been obtained with the mATR-FT-IR method. Among others, Hospodarova, Singovszka and Stevulova (2018) and Rosa *et al.* (2010) report that peaks around 1633 to 1648 cm^{-1} could be due to the O-H bonds of water molecules in cellulosic fibres, and the broad band at approximately 3200-3400 cm^{-1} can be attributed to the stretching vibration of the hydrogen group

(Chen, Zhao, Wang & Wang 2013). The fibres were not dried prior to the testing so it is reasonable to assume that the obtained peaks at 1622-1645 cm^{-1} and 3333 cm^{-1} are results of the intrinsic moisture in cellulose.

Looking for cotton, it should also be noted, that cellulosic fibres are difficult to tell apart with the help of IR methods due to their similar chemical composition (Peets et al. 2019). Therefore, it can only be assumed that most of the samples give the FT-IR spectrum for cotton, although sometimes viscose fibres or other cellulosic fibres such as hemp or linen may be blended with cotton to obtain special types of denim (Paul 2015, p. 2). Cura *et al.* (2021) found similarities in the FT-IR spectra of mercerised cotton and viscose, which makes it more difficult to tell the two apart just by using FT-IR or DSC. The viscose peak at approximately 3300 cm^{-1} is often round, whereas the cotton has a double peak at that wavelength (Vahur, Teearu, Peets, Joosu & Leito 2016). Moreover, cotton exhibits more peaks between 950-1100 cm^{-1} than viscose (Vahur et al. 2016). Due to the small contents of viscose in presumably cotton-rich samples, the presence of viscose is difficult to show.

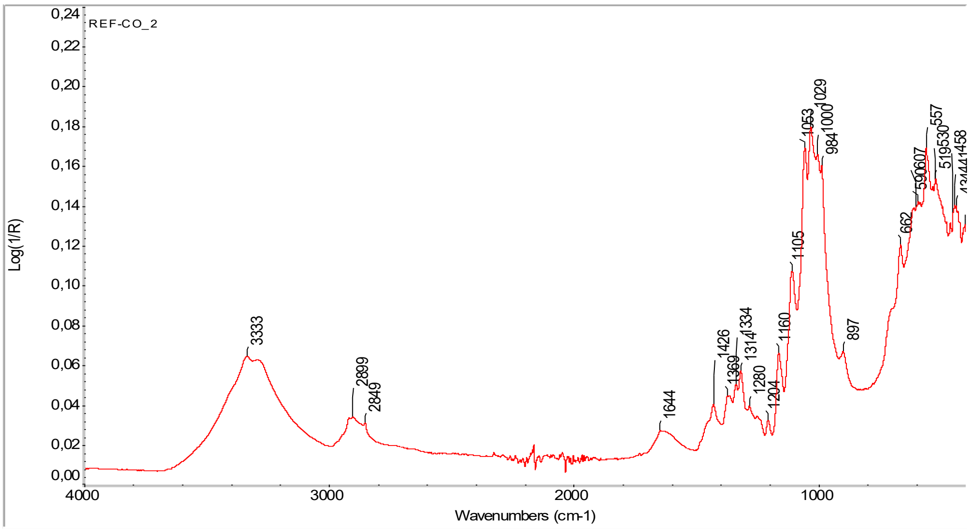


Figure 6.10: The FT-IR spectrum for REF-CO #2.

The peaks visible between 1709 to 1713 cm^{-1} can be identified as the strong, symmetrical C=O bonds of the aromatic ring of the polyester chain, usually vibrating at 1712 cm^{-1} (Ghosh, Roy & Singh 2021; Parvinzadeh & Ebrahimi 2011). These peaks can be seen in almost all the post-consumer samples, but none in the pre-consumer samples or the REF-CO sample spectra. For some of the post-consumer samples the carbonyl peak can be seen in the accept samples, and for some in the reject, see Figures 6.11 and 6.12. Additionally, many of the specimen displaying the ~1712 cm^{-1} peak also display a slight peak at approximately 871 cm^{-1} which is said to be due to the strong out-of-plane vibrations of the C-C bonds in the polyester's benzene ring (Parvinzadeh & Ebrahimi 2011). This slight peak can be detected at 872 cm^{-1} in for example Figure 6.12.

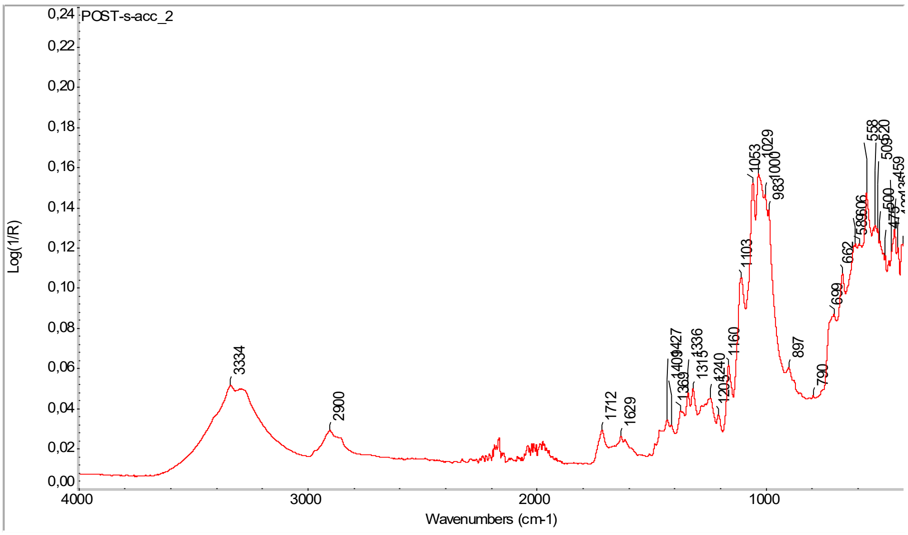


Figure 6.11: The FT-IR spectrum for POST-s-accept #2.

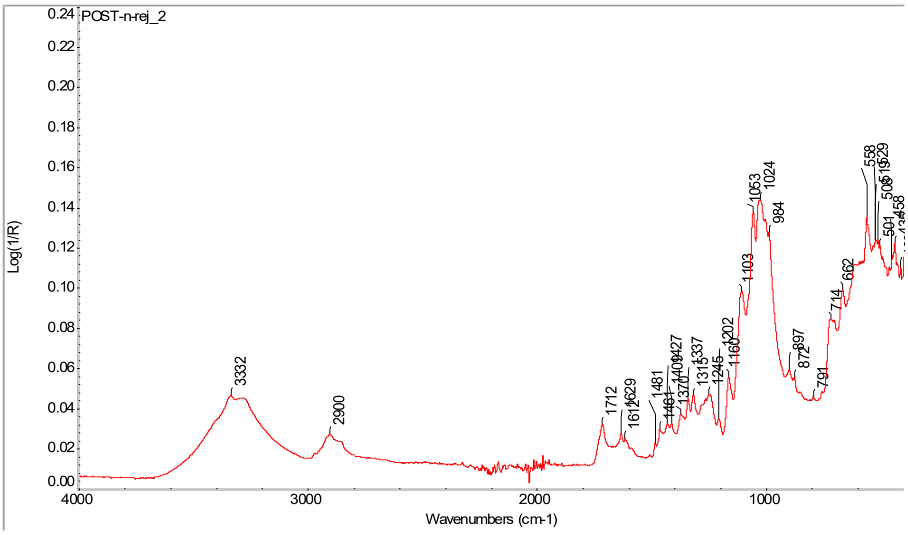


Figure 6.12: The FT-IR spectrum for POST-n-reject #2.

The peak between 1627 and 1630 cm^{-1} on all of the PRE-WOVEN, POST-B2B-accept, POST-n-reject and POST-s samples (*Appendix E*: Figures E.3 – E.5 and E.8 – E.10), as well as on occasional POST-B2B-reject, POST-n-accept and POST-ea samples (*Appendix E*: Figures E.6 – E.7 and E.11 – E.12) could be due to C=O stretching of the indigo dye (Baran, Fiedler, Schulz & Baranska 2010). However, the most intense peak covered with ATR-IR at 1065 cm^{-1} caused by indigo's five-membered carbon ring (Baran et al. 2010) is not intensely visible in the FT-IR spectra in this experiment. Should there be indigo dye in the fibres, it can remain undetected due to the low level of dye in the fibres and the nature of low IR absorbance by components that comprises of less than 5 % of the material (Goodpaster & Liszewski 2009). Still, it is likely that the peak at around 1627-

1630 cm^{-1} is attributed to the indigo dye. The suggestion is further supported by the absence of the same peak in samples REF-CO (white virgin cotton) and PRE-KNIT (dark blue knit), and by the narrow presence in sample POST-ea (black denim). The peaks at 1622, 1644 and 1645 cm^{-1} for the respective REF-CO specimen can be attributed to cotton's moisture, as discussed earlier. The indigo peak is close to the moisture peak, so it is not possible to exclude the possibility of other dyes in the samples, nor is it to exclude the presence of indigo, see Figures 6.13 – 6.15 for reference.

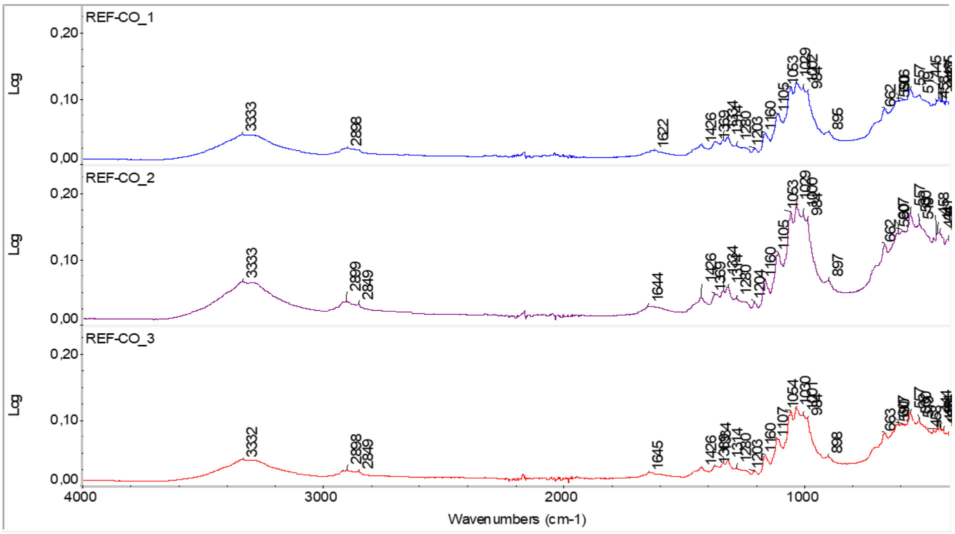


Figure 6.13: The FT-IR spectra of REF-CO specimen. The O-H defibrillation of water molecules may peak at around 1644 cm^{-1}.

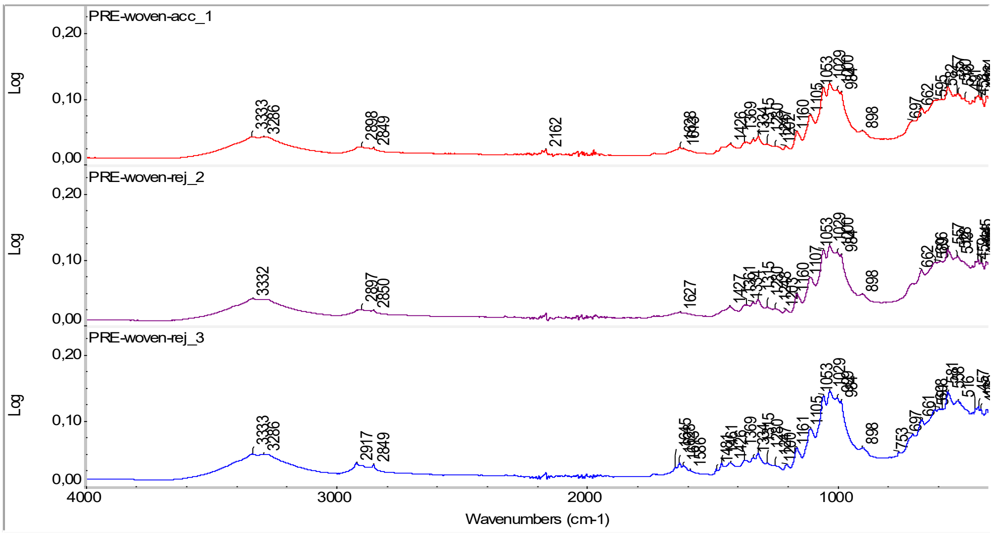


Figure 6.14: The FT-IR spectra for PRE-WOVEN-accept specimen. The peaks at 1627-1628 cm^{-1} may be due to O-H bonds of moisture or indigo dye.

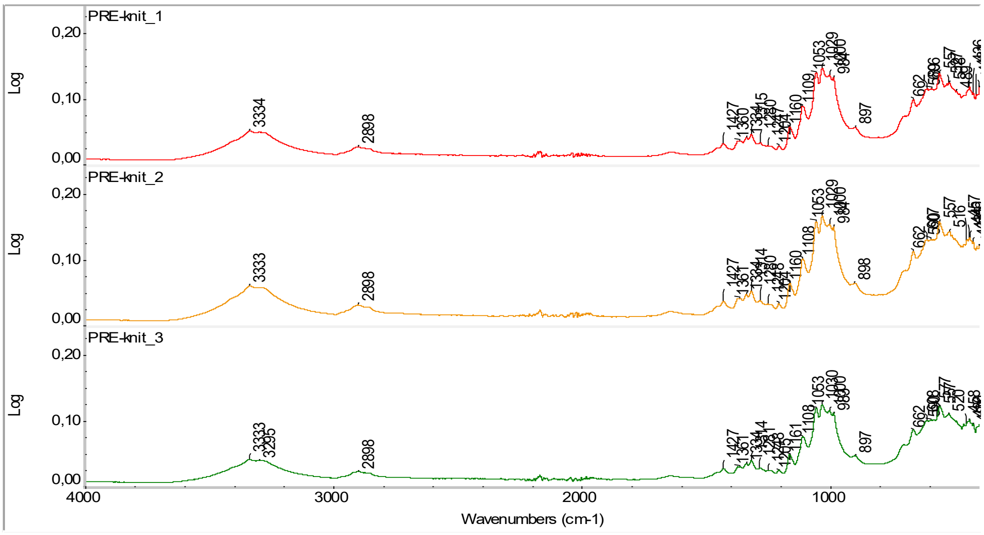


Figure 6.15: The FT-IR spectra for PRE-KNIT specimen. There are no observed peaks at around 1633-1648 cm^{-1}.

Cincinelli *et al.* (2017) experimented with microfibres found in the sea and reported that only 2.9 % of the rFT-IR examined fibres were polyamide. The characteristic peaks for polyamide are made up by the N-H bonds stretching, the amides I, II and III, and the CH_2 bending and twisting (Porubská et al. 2012; Pockett 2004 se Cincinelli et al. 2017). The same study reported an intense peak at 3291 cm^{-1} attributed to the stretch of the N-H bond and other significant peaks at 3050 and 1722 cm^{-1} for the polyamide microfiber. These peaks are not clearly visible on any of the spectra in this experiment, see *Appendix E*. According to the study, it has been earlier noted that mapping polyamide with the r-FT-IR method can be difficult due to the uneven surface of the PA fibres causing possible scattering of infra-red light (Tagg et al. 2015 se Cincinelli et al. 2017). Although polyamide could be used in jeans, its total market share of the textile fibre manufacturing is 5 %, while polyester carries a total of 54 % of all fibre manufacturing (Textile Exchange 2022). This means that even though polyamide was present, it is possible it could be used in small fractions only.

When it comes to elastane, it is more complex to point out its presence. The relevant peaks for ether-based polyurethane are at around 3454, 3317, 1730, 1705, 1600, 1532 and 1102 cm^{-1} (Boschmeier, Archodoulaki, Schwaighofer, Lendl & Bartl 2023). The peaks at 1730 cm^{-1} and 1705 cm^{-1} are attributed to carbonyl and can be thus found in e.g., polyester too. The peaks at 3454, 3317, 1600 and 1532 cm^{-1} are due to the N-H bindings stretching and bending and can be thus found in polyamide or protein fibres, such as wool and silk. The peak at 1102 cm^{-1} is caused by the stretching of the ether-based C-O-C binding (Boschmeier et al. 2023). None of the spectra in this experiment show pronounced peaks that speak for the presence of elastane, but it needs to be noted, that elastane is only fractionally present in the samples, and the other dominating materials could suppress its peaks.

The resonating spectrum between 1800-2400 cm^{-1} is common for both cotton and polyester (Vahur et al. 2016). It is notable in all of the samples, yet only in the POST-s specimen the computer has picked up peaks near 2165 cm^{-1}, see Figure 6.16. POST-s is the softened sample, which may indicate a different behaviour and therefore sharper pronunciation of the aromatic rings due to the softener in this sample. However, also polyacrylic fibres display a peak at 2243 cm^{-1} (Peets et al. 2019) which may give insight into the material composition.

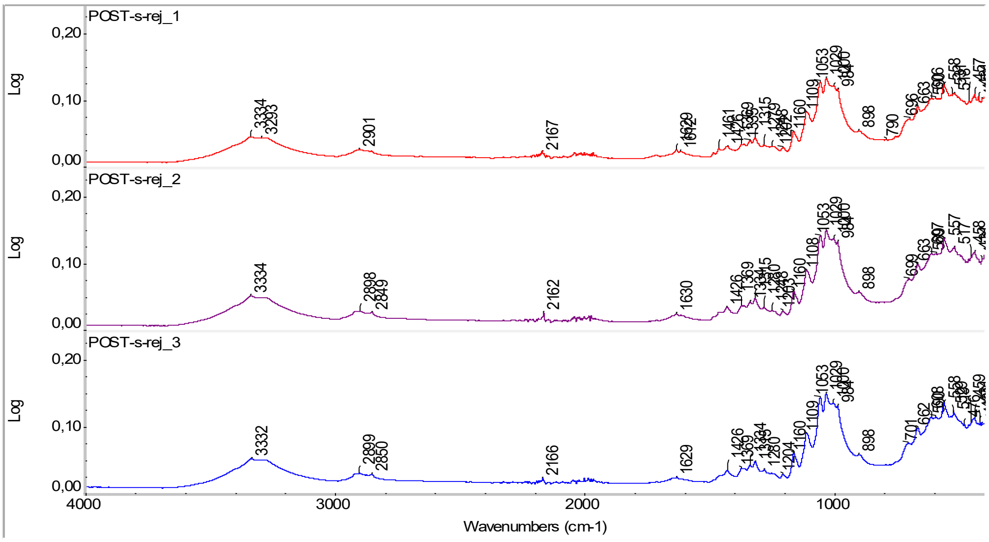


Figure 6.16: FT-IR spectra for POST-s reject.

6.2 Fibre feasibility for spinning

The results obtained in the experimental part of this report show reduced length, reduced uniformity and higher SFC for MO fibres than virgin cotton. Tenacity, breaking elongation, and linear density are not observed to decrease as strongly. In yarn production, length, fineness, and tenacity of the fibre are said to play the most important role. Open-end spinning is the more suitable method for MO fibres than ring-spinning, as it is more suitable for the high SFC (Heikkilä et al. 2023).

Rabbi *et al.* (2023) spun 9 different open-end rotor yarns and found that the mass variation in yarns increases when the percentage of post-consumer waste-derived fibres increases. They suggest this is likely due to reduction in fibre length, SFC, uniformity and fineness of recycled fibres. In several studies, the yarns with MO fibre content were coarser than yarns with 100 % virgin cotton fibres. For example, Lindström *et al.* (2020) were able to spin a yarn with 100% MO opened fibres with a 92-tex fineness, while Arafat and Uddin (2022) and Ütebay, Çelik and Çay (2023) were able to spin a finer yarn of approximately 20 tex using a blend of virgin cotton and MO fibres. The requirement for fineness of the yarn is relative to its end use. As it has been stated, knitted products such as t-shirts are often spun with finer yarns, whereas denim or home textiles could be produced with coarser yarns.

The results in this report suggest there is a necessity in developing methods for controlling the fibre length. While Lindström *et al*. (2020) found a method of increasing the fibre length with the help of a lubricant, similar results were not found for POST-s sample. The optimisation of the amount and concentration of softeners used in the opening line, and optimisation of the point where they are applied are further challenges to solve. Moreover, the cotton industry lacks a suitable manner of quantifying the SFC. The problem with high SFC is also identified for virgin cotton, and it leads to decreased strength of yarns. It is possible and rather necessary that a method for quantifying the short fibre contents of recycled fibres is developed. With the current methods, the SFC is sometimes difficult to measure, and when measured, it is rather too high compared to virgin cottons, and the economic value is thus decreased. The motivation to use recycled fibres could be changed through different methods.

On the other hand, the examined tensile properties of the MO fibres in this report do not indicate a poorer suitability for spinning than virgin fibres. There are multiple literary works showing the MO fibres can be used in yarn spinning blended with virgin fibres resulting in functioning yarns. The question remains whether the MO fibres can be used in yarn spinning on their own, and it seems that fibre length is the most limiting factor. As the short fibres do not give any added value in yarn spinning, they become a component that is not economically viable. For spinning, it would be suitable to find a method to separate the shortest fibres of the MO fibre. Otherwise, there could be a classification system which estimates the value of the SFC level, thus giving the different SFC-% different economic value. This would leave more responsibility to the buyer of MO fibres and the producer of MO fibre products.

6.3 Classification of recycled fibres

Currently recycled textile materials, especially from post-consumer textiles, are often downcycled and innovations in using recycled textile materials are hindered by the lack of common, clear material classification. Additionally, as presented in chapter *2.3.2 Change towards eco-design*, the unreliability of the care labels sets a challenge for the manual sorting and results in an uneven quality of obtained recycled fibre.

The table 6.3 shows a conclusive result table for the virgin cotton and the mechanically opened cotton fibres chosen for study for this report. The cotton qualities and their properties *tenacity, fibre length, length uniformity, cleanness,* and *the efficiency of opening (EFO)* are evaluated on a traffic light system, where green indicates a good or a strong property, orange is a medium quality and red indicates a bad or a weak property. The quantified values are presented where possibly. The colour grading is subjective to the findings in this report. For example, a fibre uniformity index of 80-82 % is considered average in the industry, and anything below 77 % is considered very low (Cotton Incorporated 2021), but the length measurements done for this report may have influenced the UI so that also the REF-CO falls under the lowest UI category. Therefore, the highest UI's obtained in the experiments are marked with green, even if objectively the results are not as strong as for virgin cotton fibres. The tenacities are considered good for all the MO cottons, the fibre lengths better for pre-consumer woven cotton and post-consumer cotton with controlled contents, the length uniformity is overall better for the more controlled cottons, and the cleanness is poorer for the post-consumer samples. The cleanness is a material property that was not quantified in this report, but a property that was visible in the SEM pictures.

Table 6.3: Conclusive characterisation results. Some fibre properties of MO fibres presented with a traffic light system grading. The REF-CO is presented for comparison.

ID	Controlled parameters				Output fibre properties				
	1st life	Collection method	Fabric structure	Cotton content (%)	tenacity (cN/dtex)	fibre length (mm)	length uni-formity (%)	clean-ness	EFO * (%)
REF-CO					1.91	18.8	64		88.1
PRE-KNIT	pre-consumer	production scraps	knit	100	1.89	8.6	58		n/a
PRE-WOVEN	pre-consumer	production scraps	woven	100	1.87	11.3	59		53.4
POST-B2B	post-consumer	controlled (B2B etc.)	woven	100**	2.27	11.5	59		44.5
POST-n	post-consumer	municipal collection	woven	≥ 98	1.87	9.8	54		68
POST-s	post-consumer	municipal collection	woven	≥ 98	2.39	9.9	55		63.6
POST-ea	post-consumer	municipal collection	woven	≥ 90	2.48	9.9	54		51.2

Explanations of the colours:								* measures the EFO of the opening line ** includes possibly other fibres due to embroidery, material tags, seam yarns
(green)	= good/ strong	(orange)	= medium	(red)	= bad/ weak	n/a	= data not available	

As noted, the colour grading is subjective, and only based on the results of this report. For example, the PRE-KNIT fibre may suffer a shorter fibre length than the other MO fibres, but its length uniformity is better than that of the post-consumer fibres. Jamshaid *et al.* (2021) have earlier reported a low UI leads to yarn irregularities. The different fibre lengths may also cause slippage of fibres during spinning, thus resulting in weaker yarns and more difficult spinning processes. The fibre slippage can sometimes be avoided by increasing the twist and tying the fibres tighter together (Lord 2003). Higher twist also increases the tenacity of the yarn. However, increasing and controlling the twist is more difficult in rotor spinning than in ring spinning (Tyagi 2010). This leads to fibre slippage and e.g., lower tenacities. Mechanically opened fibres are often spun into yarns with rotor spinning, suggesting fibre slippage is inevitable, but easier to control with better uniformity indexes between the fibres used in spinning.

However, uniformity index is only one property of textile fibres. The variety of properties for MO fibres and the variety of reasons behind the properties make it difficult to set numerical limits for a property and grade the MO fibres purely objectively. It also makes it controversial to set the fibres in an order where one quality is better than another. Good properties depend on the desired output product and therefore quality is subjective to a certain limit.

The results in this report suggest following summary of characterisation:

i) The tenacities of the MO fibres are enough to be used in yarn production, and there were no samples found statistically significantly different in this study,

ii) the fibre length, which is affected by multiple factors, is the most important parameter in added value and further processing,

iii) the length uniformity ensures an even yarn regularity and quality in terms of fibre length,

iv) the efficiency of opening depends greatly on the opening line parameters and settings, but also on the fabric and yarn structure of the waste textile,

v) and that the cleanliness is easier to control in pre-consumer cotton qualities, making them suitable for more applications and thus possibly more economically viable.

The pre-consumer fibres could be more economically viable because their compositions are easier to control, and they are cleaner than post-consumer fibres. MO fibres made from pre-consumer textile waste are made from fabrics and yarns, while MO fibres made from post-consumer waste are made from garments that contain embroidery, care labels, seam yarns etc., see Figure 6.17 for reference. For example, embroidery covers only a small fraction of the whole garment weight, and therefore its material does not have to be reported in the care label[9]. In other words, it is difficult to avoid the blending of other fibres in the MO fibre that is made from garments. The pre-consumer textile waste obtained fibres further lack the use-phase and are thus less prone to breakage, as it was shown by Palme *et al.* (2014) that laundering will have a negative effect on the fibre integrity.

Figure 6.17: Picture of uncleaned, mechanically opened POST-B2B fibres. The pictured cotton quality is a post-consumer MO cotton made from workwear garments, collected as 100 % cotton. The unopened yarns could be from embroidery or seams, and the white, torn care label at the left-top of the fibre tuft shows pre-consumer fibres often include other articles than the fabric material.

Drawing conclusions about the input textile materials and their effect on spinnability and output fibre properties is challenging. The results in this report suggest the PRE-KNIT sample has shorter fibre length than any other MO fibre, but it is a fibre that is already in use in the industry. There are a few reasons behind the shorter fibre length, and based on the results in this report, it is impossible to say all fibres obtained from knitted fabrics behave similarly. Aronsson and Persson (2020) observed the denim structure was easier to unravel than knitted fabric, but suggested this is due to the coarser yarn structure often used in denim fabrics as opposed to the tight ring spun yarns often used in knitted garments. One more factor affecting the fibre length is the colour of the collected textile waste. Ütebay, Çelik and Çay (2019) observed the SFC was higher for MO pre-consumer

---

[9] OJ L 272, 18.10.2011, p. 7

knit fibres that were dyed than for those who were unprocessed. However, Table 6.3 lacks *colour* as one of the controlled parameters as there was not enough data to prove its effect on the obtained MO fibre.

The EFO that was discussed in chapter *2.2.3 Degree of opening* is an important property of the obtained fibre, as it directly affects the quality of the yarn: when the EFO is low the yarns become more uneven and are more prone to breakage. However, the yarns can be cleaned in the combing stage or separately with the help of ‘Shirley’ Trash Analyser to avoid bulky yarn. The low EFO means thus that there is less material to take advantage of, and therefore a low EFO is economically unviable. It is, however, impossible to determine EFO based on only these experiments and the number of specimens. The goal with reporting EFO in this report is to explain the differences in the opening lines and its direct effect on the total amount of opened fibre.

Importantly, the conclusive results presented in Table 6.3 are based on the experimental results of this study, and its columns are limited to the chosen parameters and properties, even though multiple aspects could be examined. Although the conclusions are stated earlier in this chapter, it could eventually be difficult to make such assumptions to cover all opening lines and all cotton fabric types. A qualified classification of the MO fibres should somehow consider all aspects, or otherwise it may be neglecting crucial properties and create a status where one MO fibre type is more favourable than others.

7. CONCLUSIONS

This report focuses on the challenges regarding mechanically opened textile fibre waste and the characterisation of a selection of MO cotton fibres. The collection of textile waste is going to be mandatory on an EU-level from the beginning of the year 2025, although there are still no set strategies on how to utilise the collected waste. Mechanical recycling can be beneficial because it allows for recycling of fibre blends and worn-out textiles, and it can be more economically efficient and environment-friendly than chemical recycling. The disadvantages of mechanical recycling are related to the poor reputation and unpredictable quality of its output fibres. This report contributes to the increasing data of the properties of MO fibres, and the research about the characterisation methods. Qualitative research increases the value of the MO fibres and allows for an efficient fibre-to-fibre recycling.

Suter-Webb array method, used to characterise fibre length and length distribution, proved successful and results enabled the comparison of the different cottons with one another. However, the measuring of fibre length of MO fibres manually, such as the Suter-Webb array method used in this report is a time-consuming process. Additionally, the comb-based fibre length measuring technique used in this study might not be as accurate as the modern electronic machines. All in all, the length results suggest that MO fibres are always shorter than virgin fibres, as expected. Moreover, the post-consumer fibres were rather similar, and the only MO cotton quality with a shorter fibre length according to the statistical analysis is PRE-KNIT. The average length of PRE-KNIT was found statistically significantly different from PRE-WOVEN and POST-B2B. However, the number of average length values per cotton in the analysis of variance was small.

It was possible to measure the mechanical properties of MO fibres. Surprisingly, there were no clear differences between REF-CO and mechanically opened samples. There were no notable differences in the measured values, and especially the linear densities show favourable similarity. The greatest disadvantage with measuring the breaking tenacity, elongation, and linear density of MO fibres with Favimat+ or a similar machine is once more the slow operation. There are not enough long fibres in the samples studied in this report for the method to be time effective. It may be questioned whether tensile testing of MO fibres is necessary or brings any added value to the material.

There is a need for a standard or an automated system for measuring fibres with short fibre length. The manual methods are too slow for the quick responses necessary for added value, and the HVI based methods that neglect the short population of the fibres are not yet theoretically suitable. It has been reported that the automated identification systems, such as HVI or AFIS have problems identifying dark fibres and the short population of fibre samples. The MO fibre is often already dyed and as seen in the experimental results, MO fibres have rather high SFC. The shortness of MO fibre samples creates a further problem in tensile testing. Although the methods could be developed, it is possible to measure MO fibres with a tensile testing machine. A more interesting question regarding the characterisation is how much the properties change between cotton bales and batches. Further research could examine how much tenacity or another property of a sample changes from bale to bale, and how many bales of MO fibres opened with the same settings would be necessary to examine to conclude the exact parameters for the tensile properties.

Although for example dyeing processes and laundering are observed to cause mechanical damage on the fibre, somewhat surprisingly the surface inspection with SEM did not reveal the mechanical opening is unfavourable for the fibre quality in terms of appearance or integrity. However, it could not rule out the possibility of damage caused by the opening line. The damage was, however, scarce although it has been earlier speculated the knives ruin the fibre surfaces. The greatest impact of the opening line is the guillotine, the effect of which can be interpreted in the length results. SEM imaging showed that the post-consumer samples were dirtier compared to pre-consumer samples.

The DSC showed that the pre-consumer samples are made up of cotton and possibly some other materials with similar, non-melting behaviour. All the post-consumer samples have a melting point indicating the controlling of the material composition is not as easy as it is for pre-consumer fabrics. The FT-IR shows peaks that can be attributed to the presence of polyester, dye, polyamide etc. The small contents of some fibres may not be enough to show on the spectrum, and the fibre content that can be identified cannot be quantified. However, the cross-examination with DSC and FT-IR is rather fast and shows promising results in identifying whether the sample is 100% cotton or not. For some manufacturers, quality controllers or yarn spinners it may be enough to know that there are no polyester or other fibres in the sample, while on some occasions it is not as important. It has been estimated there are already viable recycling solutions for mono-materials, whereas there is not one fully suitable method for recycling blended textile waste. The lack of information about the composition of collected blended textile waste may be seen as a hinder in creating value for it, but new identification methods with quantifying abilities should reduce the problems related to blended textiles.

Although the DSC/FT-IR cross-examination shows promising ability in swiftly identifying the presence or absence of certain fibres in the samples, further research is necessary in quantifying the contents in a reliable way. The many optical methods for sorting the textile waste could be applied for fibre identification after the opening. Nevertheless, these methods are not able to quantify the quantities yet.

The quality of the MO fibres is reviewed to be affected by the structure of the opened fabric and especially its yarn, the colour of the opened fabric, the size of the piece textile fed into the opening line and the inherent tensile properties of the opened fibres, as well as the setting parameters of the opening line. Yarn spinning using MO fibres has been proven successful, although most of the research reviewed in this report focuses on blending MO fibres with virgin cotton fibres or other fibre types. Open-end spinning is a more favourable option than ring spinning for MO fibres, as the short fibre contents of mechanically opened fibres are relatively high. High short fibre content is reported to cause poor adhesive strength in drawing, cause neps in the yarn, and increase yarn irregularities. Other characteristics affecting the yarn quality are fibre length, tenacity, linear density, and frictional behaviour, and of course the spinning settings. Fibre length and frictional behaviour causing neps could be controlled by use of lubricants, although more research is necessary. The control of fibre tenacity and linear density may not be as relevant as the control of tenacity and linear density of the yarn; however, they play an important part in the yarn quality and cannot be neglected completely.

This report shows that the characterisation of MO fibres is possible. The characterisation was conducted by evaluating the efficiency of the opening lines, and the length, breaking tenacity, elongation, linear density, chemical composition of the selected cotton qualities. The collected data alongside the literature review gives valuable information that may enable and increase the use of MO fibres in fibre-to-fibre recycling. To confirm the suitability of MO fibres in fibre-to-fibre recycling, further studies related to yarn spinning, knitting, weaving, dyeing and other textile processes should be concluded. Similarly, more research is necessary for cotton qualities not presented in this report, such as post-consumer knitwear or a pre-consumer cotton-blend. This report studied four MO fibres obtained from denim materials and two MO fibres obtained from other textile types.

A classification system for MO fibres can be essential in the future so that the MO fibres can be seen as a valuable raw material in the textile fibre industry. Even if a feasible classification could be established, the problem in the uncertainty in predicting textile production and consumption remains. The results in this report suggest the pre-consumer fibres are cleaner and longer than post-consumer samples, but the new waste directive aims to collect the textiles from the consumers. Even if the settings of the mechanical opening line could be optimised to get as long fibres as possible, and the sorting be as accurate as possible, the contents and the quality of the MO post-consumer fibres depends on what is collected. The point of a well-established qualification may be that while it is often desirable to sell and buy 100% cotton, it is also possible to set other kinds of limits for MO fibres, as fractioning of cotton and other fibres has yet to prove accessible. On top of the material factor, other value adding factors can be the colour, the fabric structure, the collection methods, or the garment type. The most challenging part will be predicting the *what* and *how much* of a certain textile material will be collected from the consumers and the industrial waste streams in the next 10, 20 or 30 years.

REFERENCES

Albertsson, A., Edlund, U. & Odelius, K. (2012) *Polymerteknologi - Makromolekylär design*. Stockholm.

Arafat, Y., & Uddin, A. J. (2022) Recycled fibers from pre-and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning: A sustainable and eco-friendly approach. *Heliyon*, 8(11), e11275. https://doi.org/10.1016/j.heliyon.2022.e11275

Aronsson, J. & Persson, A. (2020) Tearing of post-consumer cotton T-shirts and jeans of varying degree of wear. *Journal of Engineered Fibers and Fabrics*, 15, 1-9. https://doi.org/10.1177%2F1558925020901322

ASTM D1440-07. *Standard Test Method for Length and Length Distribution of Cotton Fibers (Array Method).* (2012) American Society for Testing and Materials.

ASTM D1447-07. *Standard Test Method For Length And Length Uniformity Of Cotton Fibers By Fibrograph Measurement*. (2021) American Society for Testing and Materials.

Baran, A., Fiedler, A., Schulz, H., & Baranska, M. (2010) In situ Raman and IR spectroscopic analysis of indigo dye. *Analytical Methods*, 2(9), 1372-1376. https://doi.org/10.1039/c0ay00311e

Boschmeier, E., Archodoulaki, V. M., Schwaighofer, A., Lendl, B., & Bartl, A. (2023) A novel quantification tool for elastane in textiles using thermal treatment. *Polymer Testing*, 118, 107920. https://doi.org/10.1016/j.polymertesting.2022.107920

Bruker (2023) *Spectroscopy Basics – Guide to Infrared Spectroscopy*. Available at: https://www.bruker.com/en/products-and-solutions/infrared-and-raman/ft-ir-routine-spectrometer/what-is-ft-ir-spectroscopy.html [18.7.2023]

Calabrò, E. & Magazù, S. (2017) A Review of Advances in the Analysis of Biological Systems by means of Fourier Transform Infrared (FTIR) Spectroscopy in Moore, E. (ed.) *Fourier Transform Infrared Spectroscopy (FTIR): Methods, Analysis, and Research Insights*. Nova Science Publishers, Incorporated, pp. 1-32.

Carrillo, F., Colom, X., Suñol, J. J., & Saurina, J. (2004) Structural FTIR analysis and thermal characterisation of lyocell and viscose-type fibres. *European Polymer Journal*, 40(9), 2229-2234. https://doi.org/10.1016/j.eurpolymj.2004.05.003

Chen, Q., Zhao, T., Wang, M., & Wang, J. (2013) Studies of the fibre structure and dyeing properties of C alotropis gigantea, kapok and cotton fibres. *Coloration Technology*, *129*(6), 448-453. https://doi.org/ 10.1111/cote.12051

Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis, A., Fossi, M. C. & Corsolini, S. (2017) Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR. *Chemosphere*, 175, 391–400. https://doi.org/10.1016/j.chemosphere.2017.02.024

Cotton Incorporated (2021) *2021/2022 U.S. Cotton Fiber Chart: Ratings of Fiber Properties*. Available at: https://www.cottoninc.com/cotton-production/quality/us-cotton-fiber-chart/ratings-of-fiber-properties/ [17.7.2023]

Cura, K., & Rintala, N. (2019) Using NIR technology to identify value in waste textile streams. In *Proceedings of the 19th World Textile Conference—Autex, Gent, Belgium*, pp. 11-14. Available at: https://openjournals.ugent.be/autex/article/id/63731/

Cura, K., Rintala, N., Kamppuri, T., Saarimäki, E. and Heikkilä, P. (2021) Textile recognition and sorting for recycling at an automated line using near infrared spectroscopy. *Recycling*, 6(1), p.11. https://doi.org/10.3390/recycling6010011

Dahlbo, H., Rautiainen, A., Savolainen, H., Oksanen, P., Nurmi, P., Virta, M. & Pokela, O. (2021) *Textile flows in Finland 2019*. Reports from Turku University of Applied Sciences 276. Turku: Turku University of Applied Sciences. https://urn.fi/URN:NBN:fi-fe2021061738621

European Commission (2022) COM/2022/141. Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions: EU Strategy for Sustainable and Circular Textiles. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0141 [2023-01-19]

Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance). (OJ L 150, 14.6.2018, pp. 109–140. Available at: https://eur-lex.europa.eu/eli/dir/2018/851/oj

Regulation (EU) No 1007/2011 of the European Parliament and of the Council of 27 September 2011 on textile fibre names and related labelling and marking of the fibre composition of textile products and repealing Council Directive 73/44/EEC and Directives 96/73/EC and 2008/121/EC of the European Parliament and of the Council Text with EEA relevance. (OJ L 272, 18.10.2011, pp. 1–64). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32011R1007

Fibersort (2023) [Website] Available at: https://www.fibersort.com/en/ [8.9.2023]

Ghosh, S., Roy, S., & Singh, K. (2021) Effect of pH on antibacterial activity of textile fibers. *Journal of The Institution of Engineers (India): Series E: Chemical and Textile Engineering*, 102(1), 97-104. https://doi.org/10.1007/s40034-020-00202-0

Goodpaster, J. V., & Liszewski, E. A. (2009) Forensic analysis of dyed textile fibers. *Analytical and bioanalytical chemistry*, 394, pp. 2009–2018. https://doi.org/10.1007/s00216-009-2885-7

Gun, A. D., & Oner, E. (2019) Investigation of the quality properties of open-end spun recycled yarns made from blends of recycled fabric scrap wastes and virgin polyester fibre. *The Journal of the Textile Institute*, 110(11), 1569–1579. https://doi.org/10.1080/00405000.2019.1608620

Hailemariam, A. F. and Muhammed, N. (2022) Effect of ring and rotor spun yarns on denim fabric properties, *Research Journal of Textile and Apparel,* Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/RJTA-11-2021-0137

Harmsen, P., Scheffer, M., & Bos, H. (2021) Textiles for circular fashion: The logic behind recycling options. *Sustainability*, 13(17), 9714. https://doi.org/10.3390/su13179714

Heikkilä, P., Heikkilä, J., Kamppuri, T., Keskisaari, A., Määttänen, M., Saarimäki, E., Heikinheimo, L., Koivula, A., Rintala, N., Harlin, A. (2023) *Technologies and Model for Sustainable Textile Recycling.* VTT Technical Research Centre of Finland. VTT Tutkimusraportti No. VTT-R-00941-22 [to be published]

Hospodarova, V., Singovszka, E., & Stevulova, N. (2018) Characterization of cellulosic fibers by FTIR spectroscopy for their further implementation to building materials. *American journal of analytical chemistry*, 9(6), 303-310. https://doi.org/10.4236/ajac.2018.96023

ISO 17751-2:2016. *Textiles. Quantitative analysis of cashmere, wool, other specialty animal fibers and their blends. Part 2: Scanning Electron Microscopy method*. (2016) Suomen Standardisoimisliitto SFS ry.

ISO 5079:2020(en). *Textile fibres — Determination of breaking force and elongation at break of individual fibres*. (2020) Suomen Standardisoimisliitto SFS ry.

Jamshaid, H., Hussain, U., Mishra, R., Tichy, M., & Muller, M. (2021) Turning textile waste into valuable yarn. *Cleaner Engineering and Technology*, 5, 100341. https://doi.org/10.1016/j.clet.2021.100341

Kahoush, M. & Kadi, N. (2022) Towards sustainable textile sector: Fractionation and separation of cotton/polyester fibers from blended textile waste. *Sustainable Materials and Technologies*, 34, e00513. https://doi.org/10.1016/j.susmat.2022.e00513

Kamppuri, T., Heikkilä, P., Pitkänen, M., Saarimäki, E., Cura, K., Zitting, J., Knuutila, H., & Mäkiö, I. (2019a) *Tekstiilimateriaalien soveltuvuus kierrätykseen*. VTT Technical Research Centre of Finland. VTT Tutkimusraportti No. VTT-R-0091-19. Available at: https://cris.vtt.fi/en/publications/tekstiilimateriaalien-soveltuvuus-kierr%C3%A4tykseen

Kamppuri, T., Heikkilä, P., Pitkänen, M., Hinkka, V., Viitala, J., Cura, K., Zitting, J., Lahtinen, T., Knuutila, H., & Lehtinen, L. (2019b) *Tunnistusteknologiat tekstiilien kierrätyksessä*. VTT Technical Research Centre of Finland. VTT Tutkimusraportti No. VTT-R-00092-19. Available at: https://cris.vtt.fi/en/publications/tunnistusteknologiat-tekstiilien-kierr%C3%A4tyksess%C3%A4

Kong, Y. & Hay, J. N. (2003) Multiple melting behaviour of poly (ethylene terephthalate). *Polymer*, *44*(3), 623-633. https://doi.org/10.1016/S0032-3861(02)00814-5

Köhler A., Watson D., Trzepacz S., Löw C., Liu R., Danneck J., Konstantas A., Donatello S. & Faraca G., (2021) Circular Economy Perspectives in the EU Textile sector, EUR 30734 EN, *Publications Office of the European Union, Luxembourg*, 2021, ISBN 978-92-76-38646-9, https://doi.org/10.2760/858144

Larkin, P. (2011) *Infrared and Raman Spectroscopy: Principles and Spectral Interpretation.* Elsevier, pp.1-25. https://doi.org/10.1016/C2010-0-68479-3

Lindström, K., Sjöblom, T., Persson, A., & Kadi, N. (2020) Improving mechanical textile recycling by lubricant pre-treatment to mitigate length loss of fibers. *Sustainability*, *12*(20), 8706. https://doi.org/10.3390/su12208706

Lourdin, D., Peixinho, J., Bréard, J., Cathala, B., Leroy, E., & Duchemin, B. (2016) Concentration driven cocrystallisation and percolation in all-cellulose nanocomposites. *Cellulose*, 23(1), 529-543. https://doi.org/10.1007/s10570-015-0805-x

Lord, P. R. (2003) Common principles. In *Handbook of yarn production: Technology, science and economics*. Woodhead publishing, pp. 56-87.

LSJH (2021a) *Pilot-stage refinement line for end-of-life textiles in Paimio* [video] Available at: https://www.youtube.com/watch?v=xzIKpJlWZjQ [9.8.2023]

LSJH (2021b) Paimion poistotekstiilien kiertotalouslaitos on valmis aloittamaan toimintansa. *Lounais-Suomen jätehuolto*, 2nd November 2021. Available at: https://poistotekstiili.lsjh.fi/2021/11/01/paimion-poistotekstiilien-kiertotalouslaitos-on-valmis-aloittamaan-toimintansa/ [26.1.2023]

LSJH (2022) Our Products. https://poistotekstiili.lsjh.fi/wp-content/uploads/2022/09/LSJH_Product-portfolio-2022_online.pdf Available at: https://poistotekstiili.lsjh.fi/en/sales-and-partnerships/ [9.8.2023]

LSJH (2023) Rester OY ostaa LSJH:n poistotekstiilien kuidunavauslinjaston. *Lounais-Suomen jätehuolto*, 8th June 2023. Available at: https://lsjh.fi/uutiset/rester-oy-ostaa-lsjhn-poistotekstiilien-kuidunavauslinjaston/ [14.7.2023]

Lu, L., Fan, W., Meng, X., Xue, L., Ge, S., Wang, C., Foong, S. Y., Tan, C. S. Y., Sonne, C., Aghbashlo, M., Tabatabaei, M. & Lam, S. S. (2022) Current recycling strategies and high value utilization of waste cotton. *Science of The Total Environment*, 856, 158798. https://doi.org/10.1016/j.scitotenv.2022.158798

Memon, H., Ayele, H. S., Yesuf, H. M., & Sun, L. (2022) Investigation of the physical properties of yarn produced from textile waste by optimizing their proportions. *Sustainability*, *14*(15), 9453. https://doi.org/10.3390/su14159453

Moghassem, A. (2007) Study on the Damaging of Dyed Cotton Fibers with Direct Dye in Spinning Processes and its Effect on the Properties of Cotton Mélange Yarn*. International Journal of Engineering*, 20(2), 203-210.

Morton, W. E. & Hearle, W. S. (2008) *Physical properties of textile fibres.* Fourth edition. Woodhead Publishing Limited, Cambridge.

Palme, A., Idström, A., Nordstierna, L., & Brelid, H. (2014) Chemical and ultrastructural changes in cotton cellulose induced by laundering and textile use. *Cellulose*, *21*, 4681-4691. https://doi.org/10.1007/s10570-014-0434-9

Parvinzadeh, M., & Ebrahimi, I. (2011) Influence of atmospheric-air plasma on the coating of a nonionic lubricating agent on polyester fiber. *Radiation Effects & Defects in Solids*, 166(6), 408-416. https://doi.org/10.1080/10420150.2011.553230

Paul, R. (2015) Denim and jeans: an overview. In Paul, R. (ed.) *Denim manufacture, finishing and applications*. Woodhead Publishing, pp. 1-11.

Peets, P., Kaupmees, K., Vahur, S., & Leito, I. (2019) Reflectance FT-IR spectroscopy as a viable option for textile fiber identification. *Heritage Science*, 7(1), 1-10. https://doi.org/10.1186/s40494-019-0337-z

Rabbi, K. F., Banna, B. U., Mia, R., Islam, M. R., & Hasan, M. M. (2023) Utilization of post-consumer waste for sustainable denim manufacturing. *Case Studies in Chemical and Environmental Engineering*, 8, 100415. https://doi.org/10.1016/j.cscee.2023.100415

Riemens, J., Lemieux, A.-A., Lamouri, S. & Garnier, L. (2021) A Delphi-Régnier Study Addressing the Challenges of Textile Recycling in Europe for the Fashion and Apparel Industry. *Sustainability,* 13(21), 11700. https://doi.org/10.3390/su132111700

Rollins, M. L. (1965) The Cotton Fiber. In Hamby, D. S. (ed.) *The American cotton handbook: a reference and text for the entire cotton textile industry. Vol 1* (3. ed.). Wiley, pp. 44–81.

Rosa, M. F., Medeiros, E. S., Malmonge, J. A., Gregorski, K. S., Wood, D. F., Mattoso, L. H. C., Glenn, G., Orts, W. J. and Imam, S. H. (2010) Cellulose Nanowhiskers from Coconut Husk Fibers: Effect of Preparation Conditions on Their Thermal and Morphological Behavior. *Carbohydrate Polymers*, 81(1), 83-92. https://doi.org/10.1016/j.carbpol.2010.01.059

Sayeed, M. A., Schumann, M., Wanjura, J., Kelly, B. R., Smith, W., & Hequet, E. F. (2021) Characterizing the total within-sample variation in cotton fiber length using the High Volume Instrument fibrogram. *Textile Research Journal*, 91(1-2), 175-187. https://doi.org/10.1177/0040517520935212

Schwippl, H. (2020) *The Increasing Importance of Recycling in the Staple-Fiber Spinning Process.* Rieter Machine Works Ltd. Available at: https://www.rieter.com/services/expertise/textile-technology [2023-01-30]

SFS 4876. *Tekstiilit. Kuitusisällön ilmoittaminen.* (2000) Suomen Standardisoimisliitto SFS ry.

Spatafora, J. & Schwippl, H. (2020) *The Ideal Rotor Spinning Process for a High Short-Fiber Content.* Available at: https://www.rieter.com/fileadmin/user_upload/services/documents/expertise/textile-technology/rieter-rotor-special-print-process-shortening-3371-v1-94182-en.pdf [31.7.2023]

Sysav (2023) Siptex – textilsortering. Available at: https://www.sysav.se/om-oss/forskning-och-projekt/siptex/#block1 [9.2.2023]

Tamanna, T. A., Belal, S. A., Shibly, M. A. H., & Khan, A. N. (2021) Characterization of a new natural fiber extracted from Corypha taliera fruit. *Scientific reports*, 11(1), 7622. https://doi.org/10.1038/s41598-021-87128-8

Telaketju (2023) Projects. Available at: https://telaketju.turkuamk.fi/en/projects/ [2023-01-30]

Textile Exchange (2021) *Textile Exchange Guide to Recycled Inputs.* https://textileexchange.org/app/uploads/2021/09/GRS-202-V1.0-Textile-Exchange-Guide-to-Recycled-Inputs.pdf [online document] Available at: https://textileexchange.org/knowledge-center/documents/ [9.8.2023]

Textile Exchange (2022) Preferred Fiber & Materials Market Report. [Online] Available at: https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf [6.7.2023]

Textile Learner (2022) Technical Properties of Cotton Fiber [online] Available at: https://textilelearner.net/technical-properties-of-cotton-fiber/ [23.8.2023]

Thibodeaux, D., Senter, H., Knowlton, J. L., McAlister, D., & Cui, X. (2008a) A comparison of methods for measuring the short fiber content of cotton. *Journal of Cotton Science,* 12(3), 298–305. Available at: https://www.cotton.org/journal/2008-12/3/ [Online] [26.7.2023]

Thibodeaux, D., Senter, H., Knowlton, J. L., McAlister, D., & Cui, X. (2008b) The impact of short fiber content on the quality of cotton ring spun yarn. *Journal of Cotton Science,* 12(4), 368–377. Available at: https://www.cotton.org/journal/2008-12/4/ [Online] [26.7.2023]

Trivedi, M., Tallapragada, R. M., Branton, A., Trivedi, D., Nayak, G., Mishra, R. K., & Jana, S. (2015) Spectral and thermal properties of biofield energy treated cotton. *American Journal of Energy Engineering*, 6(3), 86-92. https://doi.org/10.11648/j.ajee.20150306.12

Trzepacz, S., Bekkevold Lingås, D., Asscherickx, L., Peeters, K., van Duijn, H., Akerboom, M. (2023) LCA-based assessment of the management of European used textiles [Online] Available at: https://euric.org/images/Position-papers/lca-based-assessment-of-the-management-of-european-used-textiles_corrected.pdf

Tyagi, G. K. (2010) Yarn structure and properties from different spinning techniques. In Lawrence, C. A. (ed.) *Advances in yarn spinning technology*. Woodhead Publishing, pp. 119-154.

Ütebay, B., Çelik, P., & Çay, A. (2019) Effects of cotton textile waste properties on recycled fibre quality. *Journal of Cleaner Production*, 222, 29-35. https://doi.org/10.1016/j.jclepro.2019.03.033

Ütebay, B., Çelik, P., & Çay, A. (2023) Valorization of fabric wastes through production of recycled cotton yarns by compact ring and open-end rotor spinning. *Journal of Cleaner Production*, 409, 137135. https://doi.org/10.1016/j.jclepro.2023.137135

Vahur, S., Teearu, A., Peets, P., Joosu, L., & Leito, I. (2016) ATR-FT-IR spectral collection of conservation materials in the extended region of 4000-80 cm–1. *Analytical and Bioanalytical Chemistry*, 408(13), 3373-3379. https://doi.org/10.1007/s00216-016-9411-5. [Library] available at: https://spectra.chem.ut.ee/

Valmet (2021) Valmet's technology to first of its kind textile recycling plant. *Valmet,* 12th February 2021 https://www.valmet.com/insights/articles/pulp/chemical-pulping/renewcell-textile-recycling-plant/ [26.1.2023]

Vetenskapsradion Klotet (2023) Textilåtervinning på gott och ont. Sveriges Radio, P1, 25th January 2023. [podcast] Available at: https://sverigesradio.se/avsnitt/textilatervinningens-pris [30.1.2023]

Wang, S., & Salmon, S. (2022) Progress toward Circularity of Polyester and Cotton Textiles. *Sustainable Chemistry*, *3*(3), 376-403. https://doi.org/10.3390/suschem3030024

Wilting, J. & van Duijn, H. (2020) *Clothing labels: Accurate or not?* [Online]. Available at: https://assets.website-files.com/5d26d80e8836af2d12ed1269/5e9feceb7b5b126eb582c1d9_20200420%20-%20Labels%20Check%20-%20report%20EN%20web%20297x210mm.pdf [17.3.2023]

Yasin, S., Massimo, C., Rovero, G., Behary, N., Perwuelz, A., Giraud, S., Migliavacca, G., Chen, G. & Guan, J. (2017) An alternative for the end-of-life phase of flame retardant textile products: Degradation of flame retardant and preliminary settings of energy valorization by gasification. *BioResources*, 12(3), 5196-5211. https://doi.org/10.15376/biores.12.3.5196-5211

Ympäristöministeriö (2022) Kierrätyksestä kiertotalouteen: Valtakunnallinen jätesuunnitelma vuoteen 2027. Ympäristöministeriön julkaisuja 2022:13. Available at: http://urn.fi/URN:ISBN:978-952-361-266-2 [2023-01-19]

Yousef, S., Tatariants, M., Tichonovas, M., Kliucininkas, L., Lukošiūtė, S. I., & Yan, L. (2020) Sustainable green technology for recovery of cotton fibers and polyester from textile waste. *Journal of cleaner production*, 254, 120078. https://doi.org/10.1016/j.jclepro.2020.120078

Yuksekkaya, M. E., Celep, G., Dogan, G., Tercan, M., & Urhan, B. (2016) A comparative study of physical properties of yarns and fabrics produced from virgin and recycled fibers. Journal of Engineered Fibers and Fabrics, 11(2), https://doi.org/10.1177/155892501601100209

Östlund, Å., Wedin, H., Bolin, L., Berlin, J., Jönsson, C., Posner, S., Smuk, L., Eriksson, M. & Sandin, G. (2015) Textilåtervinning Tekniska möjligheter och utmaningar. Stockholm. [Online] Available at: https://www.naturvardsverket.se/om-oss/publikationer/6600/textilatervinning/ [13.1.2023]

APPENDIX A: FIBRE LENGTH RESULTS

The fibre distributions calculated per the number of fibres are presented in this appendix. The number of fibres is based on calculations according to Equations 4.2 and 4.3. The mean length, variance, coefficient of variation and confidence interval are calculated with the whole 1-3 mm group obtaining a length of 2 millimetres, the 4-6 mm group obtaining a length of 5 millimetres, and so on. It is also assumed, that all the fibres are of the same thickness, shape, and linear density.

μ	mean
s^2	variance
σ	standard deviation
c_v	coefficient of variation
CI (α=0.05)	confidence interval
	ALL VALUES ARE IN MILLIMETRES

Table A. 1: REF-CO uncleaned.

μ	15.269364
s^2	54.49379
σ	7.381991
c_v	0.483451
CI (α=0.05)	0.334134

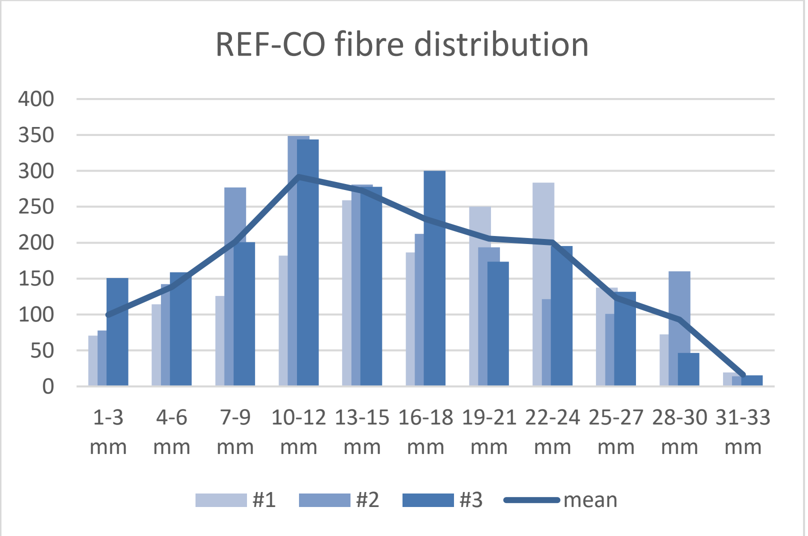


Table A. 2: PRE-KNIT (company) accept.

μ	6.316750
s^2	14.60722
σ	3.821939
c_v	0.605048
CI (α=0.05)	0.133109

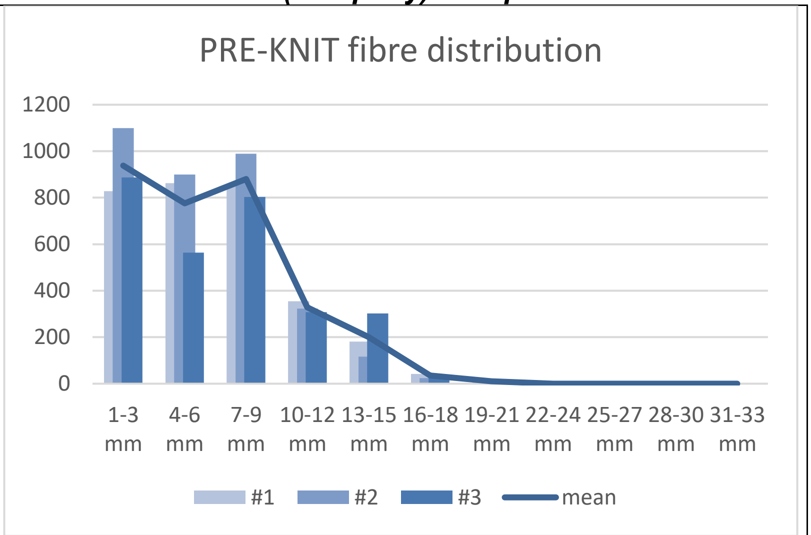


Table A. 3: PRE-WOVEN accept.

μ	8.550438
s^2	23.41784
σ	4.839199
c_v	0.565959
CI (α=0.05)	0.157902

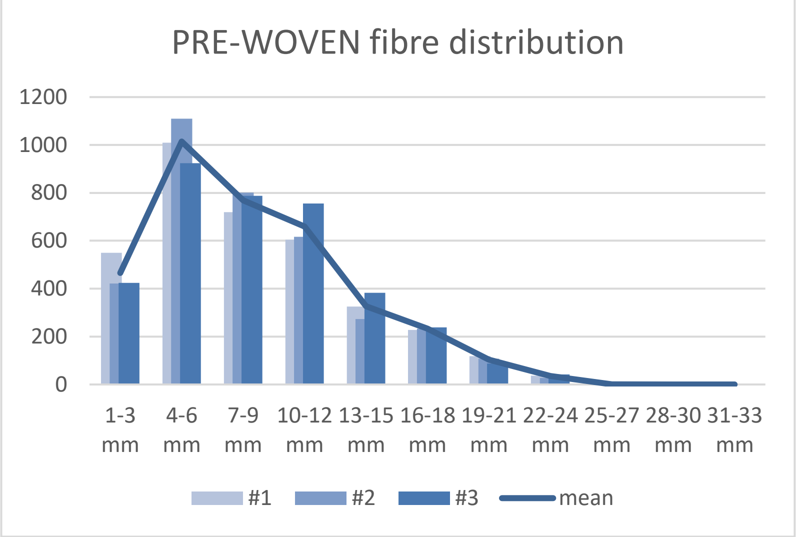


Table A. 4: POST-B2B accept.

μ	8.354007
s^2	22.84382
σ	4.77952
c_v	0.572123
CI (α=0.05)	0.176749

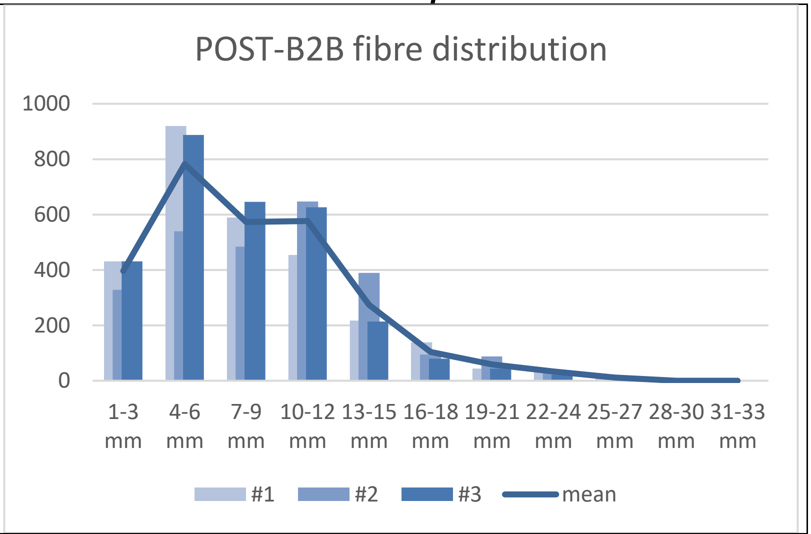


Table A. 5: POST-n accept.

μ	6.976779
s^2	19.36492
σ	4.400559
c_v	0.630744
CI (α=0.05)	0.152588

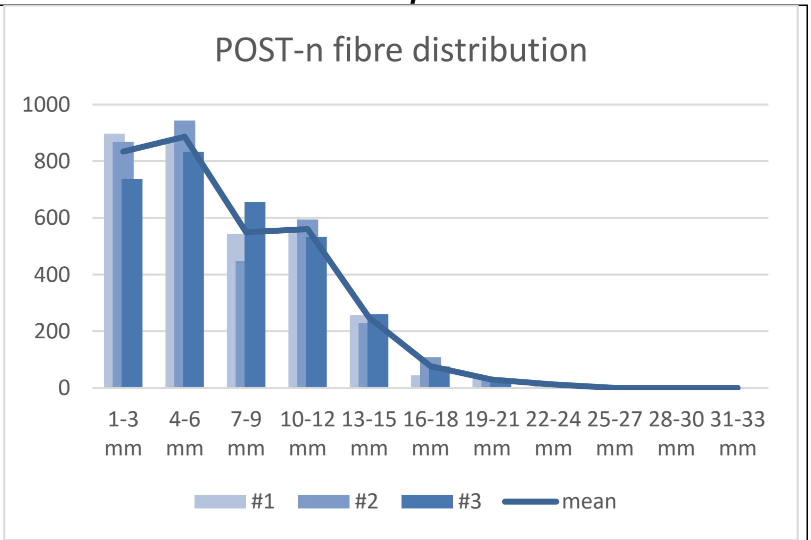


Table A. 6: POST-s accept.

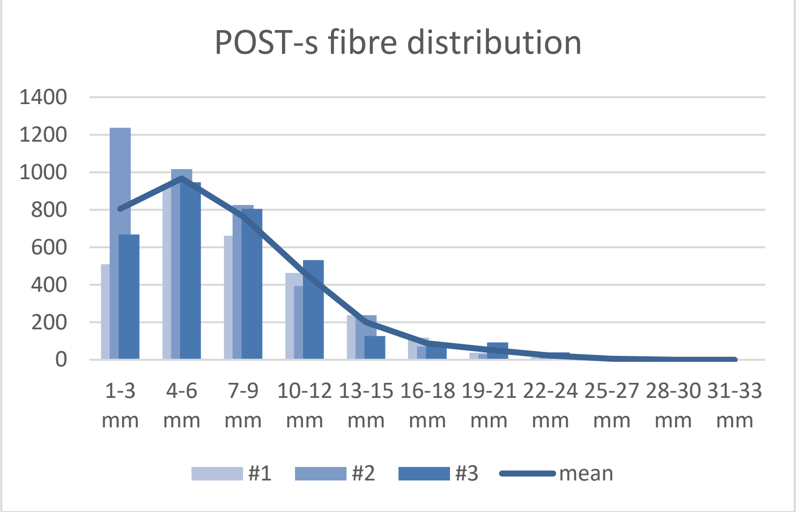
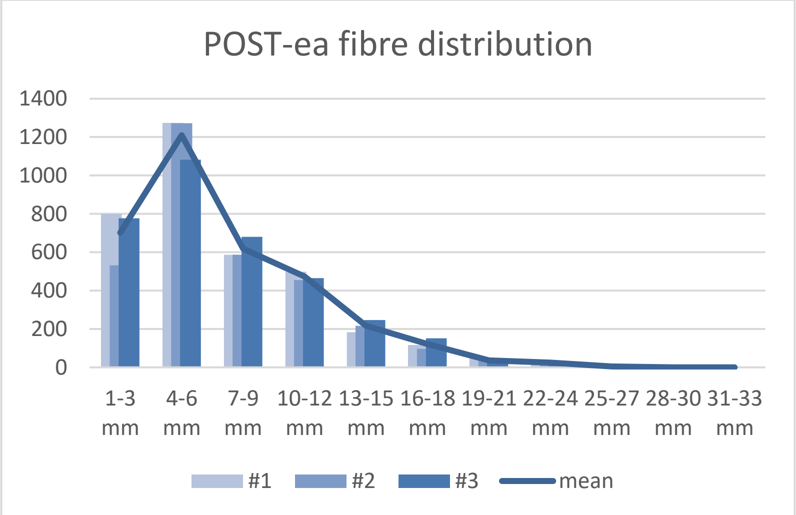
μ	7.023510	
s^2	19.97484	
σ	4.469322	
c_v	0.636337	
CI (α=0.05)	0.151007	

Table A. 7: POST-ea accept.

μ	7.074488	
s^2	19.78593	
σ	4.448138	
c_v	0.628757	
CI (α=0.05)	0.149384	

APPENDIX B: FIBRE TENACITY RESULTS

The 10-mm gauge length results are presented in Figures B.1-B7 and the same results in their respective Tables B.1-B.7. The results for 20-mm gauge length are presented in Figures B.8-B.10 and respective Tables B.8-B.10.

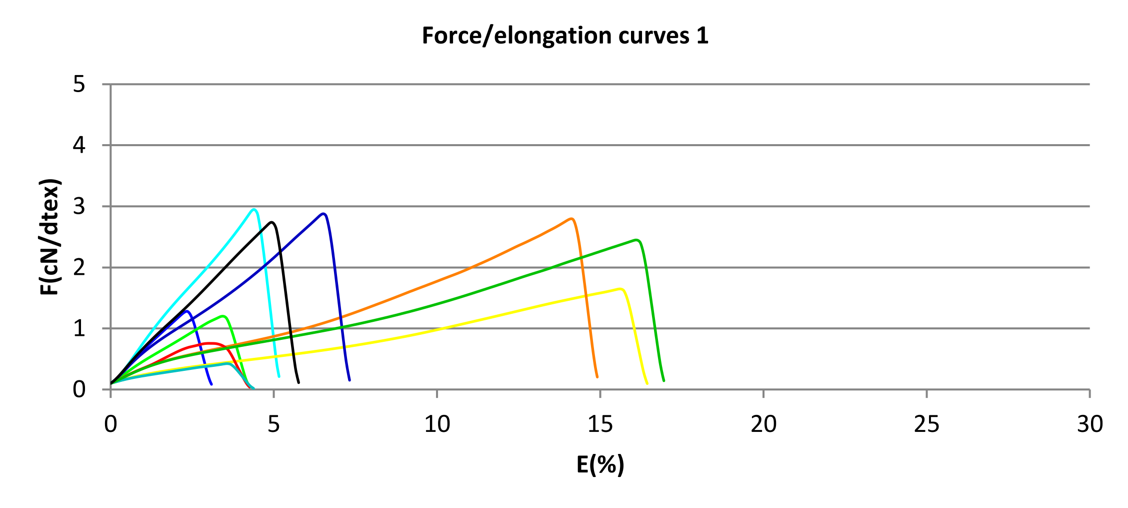


Figure B. 1: REF-CO uncleaned measured with the 10-mm gauge distance.

Table B. 1: The results for individual fibres of REF-CO uncleaned with the 10-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=10) and selected specimens (n=6).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
------------------	1	2.35	2.83	0.04	1.28	2.21	0.71	60.44
------------------	2	4.38	5.83	0.14	2.95	1.98	1.32	77.30
------------------	3	3.43	2.84	0.06	1.20	2.37	1.04	38.97
------------------	4	15.61	3.83	0.31	1.65	2.32	4.73	15.88
------------------	5	14.10	5.77	0.39	2.80	2.06	4.27	32.50
------------------	6	3.00	1.91	0.04	0.76	2.52	0.91	27.60
------------------	7	6.52	5.08	0.17	2.88	1.77	1.97	55.70
------------------	8	3.58	0.98	0.03	0.42	2.32	1.09	15.38
------------------	9	16.12	4.69	0.39	2.45	1.92	4.88	26.17
------------------	10	4.92	6.31	0.17	2.74	2.30	1.49	63.18
Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)		
	n	10	6	10	6	10	6	
	x	7.40	4.10	1.91	1.97	2.18	2.19	
	s	5.57	1.50	0.96	0.99	0.24	0.28	
	c_v (%)	75.31	36.68	50.20	50.40	10.89	12.62	
	Q(95 %)	3.99	1.58	0.69	1.04	0.17	0.29	
	min	2.35	2.35	0.42	0.76	1.77	1.77	
	max	16.12	6.52	2.95	2.95	2.52	2.52	

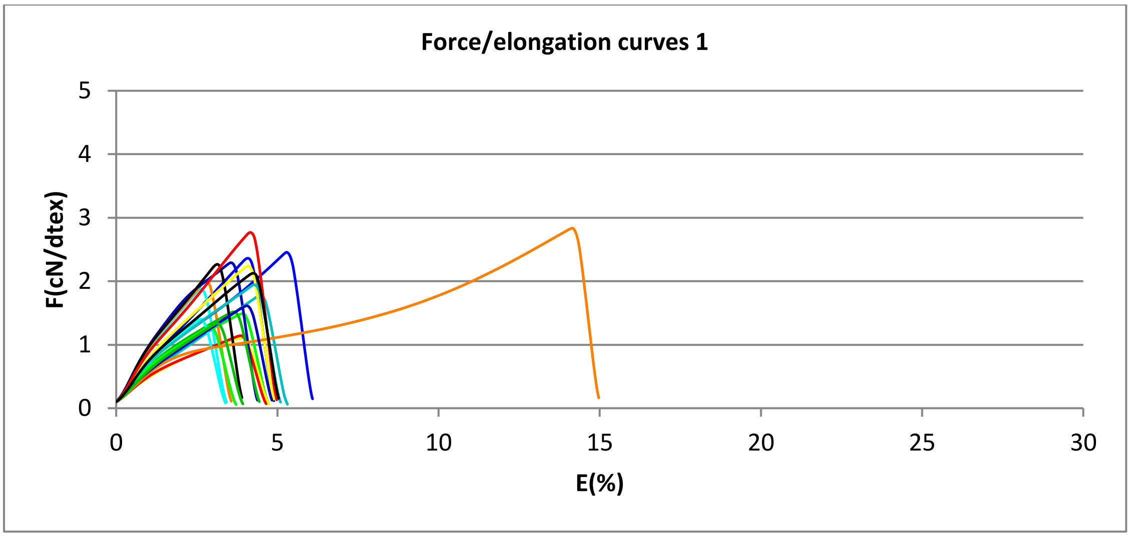


Figure B. 2: PRE-KNIT accept measured with the 10-mm gauge distance.

Table B. 2: The results for individual fibres of PRE-KNIT accept with the 10-mm gauge distance. The value marked in red indicates deviation with a c_v > 50 % and is thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20) and selected specimens (n=19).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
	1	5.28	5.29	0.16	2.46	2.15	1.59	71.27
	2	2.64	2.65	0.04	1.40	1.89	0.80	67.36
	3	2.92	2.35	0.04	1.29	1.82	0.88	62.84
	4	4.11	4.72	0.11	2.25	2.10	1.24	78.43
	5	14.16	4.94	0.36	2.84	1.74	4.28	50.14
	6	4.18	4.84	0.11	2.77	1.75	1.26	90.47
	7	4.05	3.55	0.09	1.62	2.20	1.23	52.97
	8	4.27	3.47	0.09	1.95	1.79	1.29	70.84
	9	3.14	4.00	0.08	1.34	2.99	0.95	55.10
	10	4.26	5.55	0.14	2.13	2.61	1.29	74.50
	11	4.10	5.02	0.11	2.36	2.12	1.24	69.17
	12	2.64	4.23	0.07	1.89	2.24	0.80	91.89
	13	3.91	3.22	0.08	1.49	2.16	1.18	57.62
	14	3.92	2.77	0.07	1.11	2.50	1.18	42.46
	15	2.79	3.78	0.06	2.00	1.88	0.84	99.00
	16	3.86	3.13	0.08	1.14	2.74	1.17	44.62
	17	3.55	4.75	0.10	2.29	2.07	1.07	102.25
	18	4.47	4.25	0.11	1.78	2.39	1.35	52.11
	19	3.63	3.59	0.08	1.52	2.37	1.10	61.57
	20	3.12	3.94	0.07	2.27	1.74	0.94	102.82

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	19	20	19	20	19
	x	4.25	3.73	1.89	1.84	2.16	2.18
	s	2.43	0.70	0.52	0.48	0.35	0.35
	c_v (%)	57.19	18.82	27.54	26.30	16.36	15.97
	Q(95 %)	1.14	0.34	0.24	0.23	0.17	0.17
	min	2.64	2.64	1.11	1.11	1.74	1.74
	max	14.16	5.28	2.84	2.77	2.99	2.99

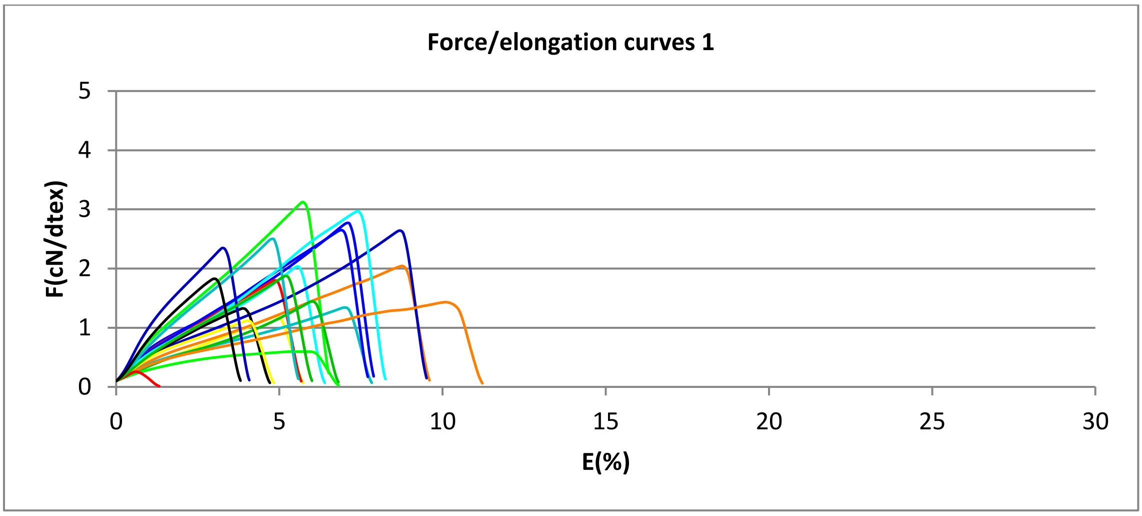


Figure B. 3: PRE-WOVEN accept measured with the 10-mm gauge distance.

Table B. 3: The results for individual fibres of PRE-WOVEN accept with the 10-mm gauge distance. There are no values resulting in c_v > 50 % for elongation, tenacity, or linear density. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
-----------------	1	6.89	4.26	0.16	2.65	1.61	2.08	55.43
-----------------	2	7.41	5.87	0.23	2.97	1.97	2.24	52.06
-----------------	3	5.54	1.40	0.06	0.60	2.34	1.68	22.61
-----------------	4	4.01	2.02	0.05	1.12	1.81	1.21	42.21
-----------------	5	10.11	2.35	0.15	1.43	1.64	3.06	30.62
-----------------	6	0.62	0.55	0.00	0.26	2.15	0.19	30.60
-----------------	7	3.25	4.05	0.08	2.35	1.72	0.98	106.55
-----------------	8	4.79	4.05	0.11	2.50	1.62	1.45	67.00
-----------------	9	5.22	2.96	0.09	1.87	1.58	1.58	46.19
-----------------	10	3.02	3.19	0.06	1.83	1.74	0.91	82.66
-----------------	11	7.10	5.69	0.22	2.77	2.05	2.15	61.05
-----------------	12	5.56	4.76	0.14	2.03	2.34	1.68	47.60
-----------------	13	5.70	5.62	0.17	3.12	1.80	1.72	76.18
-----------------	14	4.93	2.82	0.08	1.19	2.37	1.49	32.22
-----------------	15	8.76	4.75	0.23	2.05	2.32	2.65	34.97
-----------------	16	4.88	3.37	0.10	1.80	1.87	1.47	55.17
-----------------	17	8.68	6.01	0.27	2.64	2.27	2.62	44.54
-----------------	18	7.00	2.55	0.10	1.34	1.90	2.12	31.72
-----------------	19	5.99	3.36	0.11	1.45	2.32	1.82	31.02
-----------------	20	3.88	3.15	0.08	1.33	2.37	1.17	47.26

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	[same]	20	[same]	20	[same]
	x	5.67		1.87		1.99	
	s	2.22		0.78		0.30	
	c_v (%)	39.11		42.05		14.88	
	Q(95 %)	1.04		0.37		0.14	
	min	0.62		0.26		1.58	
	max	10.11		3.12		2.37	

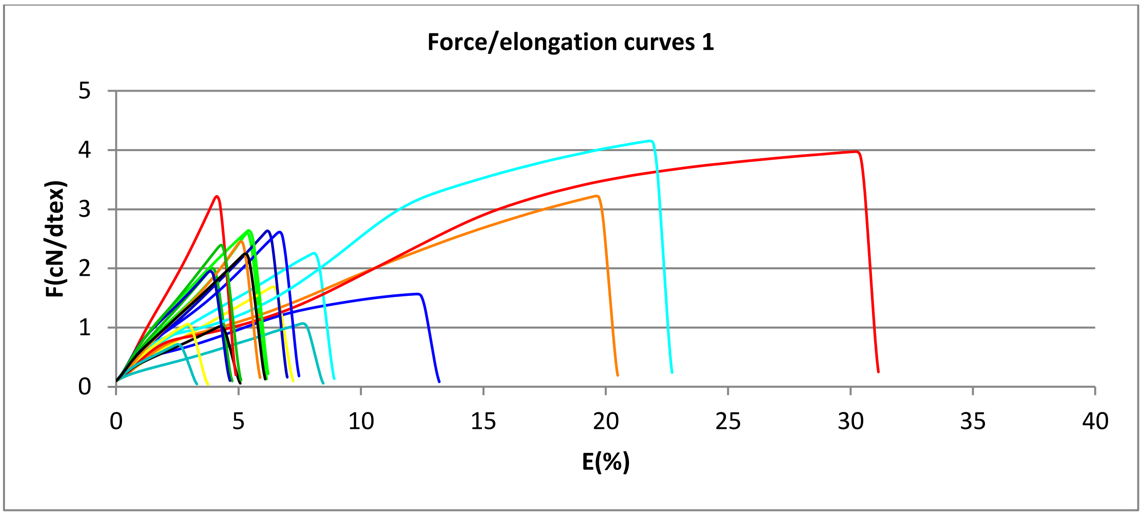


Figure B. 4: POST-B2B accept measured with the 10-mm gauge distance.

Table B. 4: The results for individual fibres of POST-B2B accept with the 10-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20) and selected specimens (n=17).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
----------------	1	12.28	3.66	0.31	1.57	2.33	3.71	46.97
----------------	2	8.09	4.26	0.20	2.26	1.88	2.44	46.81
----------------	3	5.37	5.49	0.15	2.59	2.12	1.62	59.74
----------------	4	6.41	4.64	0.17	1.69	2.74	1.94	30.40
----------------	5	19.63	8.69	0.99	3.22	2.70	5.96	36.19
----------------	6	30.21	6.72	1.32	3.97	1.69	9.14	39.27
----------------	7	6.16	4.79	0.16	2.63	1.82	1.86	49.74
----------------	8	7.62	2.54	0.11	1.07	2.38	2.31	20.96
----------------	9	3.94	4.91	0.11	2.00	2.45	1.19	61.75
----------------	10	4.29	2.51	0.07	1.02	2.46	1.29	35.44
----------------	11	6.69	5.57	0.20	2.61	2.13	2.02	59.14
----------------	12	21.82	9.87	1.33	4.15	2.38	6.60	49.07
----------------	13	5.40	5.77	0.18	2.64	2.18	1.63	72.62
----------------	14	2.95	2.73	0.05	1.06	2.58	0.89	44.92
----------------	15	5.10	5.40	0.14	2.45	2.20	1.54	58.86
----------------	16	4.11	7.16	0.15	3.22	2.22	1.24	90.27
----------------	17	3.84	3.75	0.08	1.95	1.92	1.16	73.20
----------------	18	2.52	1.66	0.03	0.72	2.32	0.76	36.88
----------------	19	4.31	5.92	0.14	2.39	2.47	1.30	70.83
----------------	20	5.26	4.33	0.13	2.25	1.93	1.59	56.37

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	17	20	17	20	17
	x	8.30	5.55	2.27	2.01	2.25	2.24
	s	7.27	2.31	0.94	0.71	0.29	0.26
	c_v (%)	87.63	41.65	41.20	35.54	12.96	11.59
	Q(95 %)	3.40	1.19	0.44	0.37	0.14	0.13
	min	2.52	2.52	0.72	0.72	1.69	1.82
	max	30.21	12.28	4.15	3.22	2.74	2.74

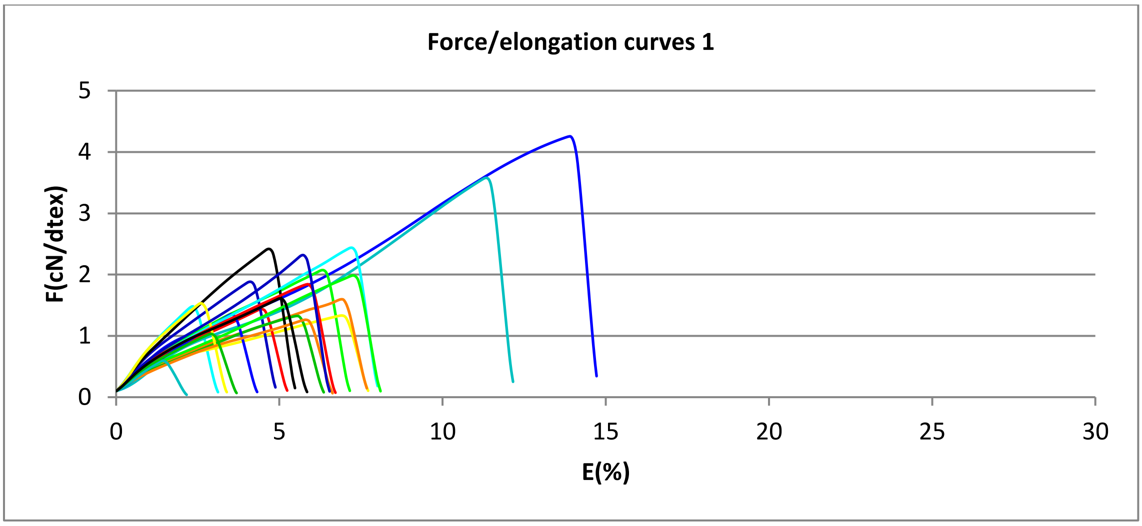


Figure B. 5: POST-n accept measured with the 10-mm gauge distance.

Table B. 5: The results for individual fibres of POST-n accept with the 10-mm gauge distance. The value marked in red indicates deviation with a c_v > 50 % and is thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20) and selected specimens (n=19).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
-----------------	1	13.89	7.59	0.57	4.25	1.78	4.21	57.18
-----------------	2	2.35	2.64	0.04	1.48	1.78	0.71	78.58
-----------------	3	6.34	4.01	0.15	2.07	1.94	1.91	56.17
-----------------	4	6.90	3.05	0.14	1.33	2.29	2.09	55.43
-----------------	5	6.92	4.21	0.18	1.60	2.64	2.09	36.00
-----------------	6	4.44	2.97	0.08	1.44	2.07	1.34	50.15
-----------------	7	4.11	3.33	0.08	1.88	1.77	1.24	68.72
-----------------	8	11.35	5.98	0.33	3.58	1.67	3.44	42.85
-----------------	9	5.56	3.13	0.11	1.32	2.36	1.68	38.65
-----------------	10	4.68	5.75	0.16	2.42	2.38	1.41	71.74
-----------------	11	3.55	3.24	0.07	1.35	2.39	1.07	41.50
-----------------	12	7.19	6.15	0.25	2.44	2.52	2.18	52.39
-----------------	13	7.26	4.88	0.20	1.99	2.46	2.19	45.08
-----------------	14	2.61	3.39	0.06	1.53	2.21	0.79	80.91
-----------------	15	5.79	3.02	0.11	1.26	2.40	1.75	34.44
-----------------	16	5.88	3.24	0.12	1.84	1.76	1.78	54.08
-----------------	17	5.73	4.27	0.13	2.32	1.84	1.73	58.57
-----------------	18	1.42	1.71	0.02	0.60	2.86	0.43	39.85
-----------------	19	2.91	2.31	0.04	1.03	2.24	0.88	46.49
-----------------	20	5.03	4.70	0.15	1.61	2.92	1.52	51.48

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	19	20	19	20	19
	x	5.70	5.26	1.87	1.74	2.21	2.24
	s	2.94	2.28	0.85	0.65	0.38	0.37
	c_v (%)	51.60	43.29	45.33	37.37	16.99	16.64
	Q(95 %)	1.38	1.10	0.40	0.31	0.18	0.18
	min	1.42	1.42	0.60	0.60	1.67	1.67
	max	13.89	11.35	4.25	3.58	2.92	2.92

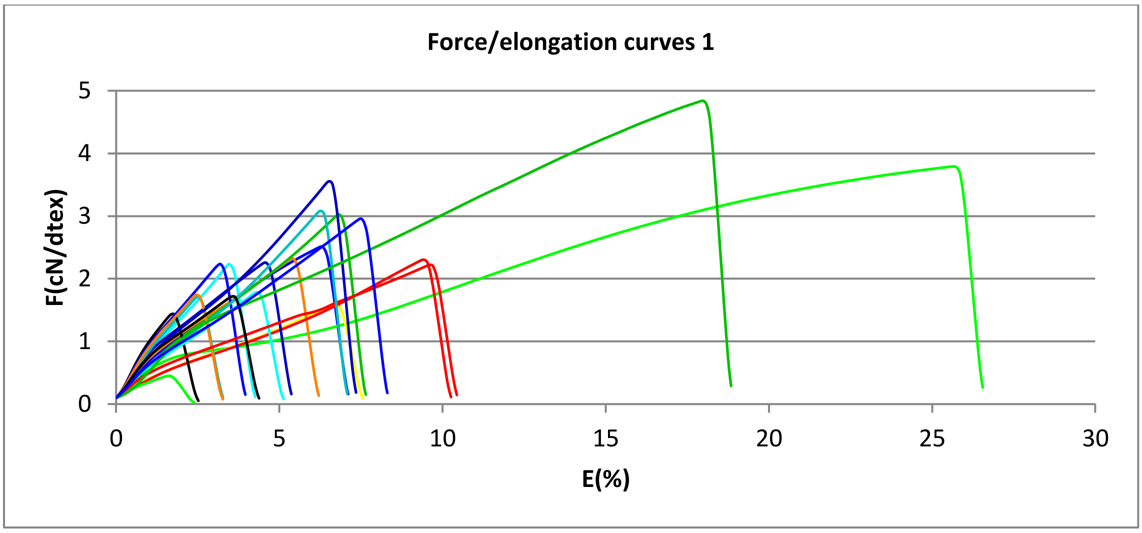


Figure B. 6: POST-s accept measured with the 10-mm gauge distance.

Table B. 6: The results for individual fibres of POST-s accept with the 10-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20) and selected specimens (n=18).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
	1	3.18	4.16	0.08	2.24	1.86	0.96	97.49
	2	4.30	4.18	0.10	1.78	2.35	1.30	57.39
	3	1.62	1.06	0.01	0.45	2.35	0.49	29.70
	4	2.47	4.20	0.06	1.74	2.41	0.74	92.68
	5	9.61	4.19	0.23	2.22	1.88	2.90	45.25
	6	6.56	7.86	0.27	3.56	2.21	1.98	74.33
	7	6.29	6.88	0.22	3.08	2.23	1.90	59.50
	8	17.97	11.62	1.20	4.84	2.40	5.46	59.71
	9	3.57	3.87	0.09	1.72	2.25	1.08	76.99
	10	7.49	6.36	0.26	2.96	2.15	2.26	61.03
	11	6.28	3.91	0.15	2.51	1.55	1.90	67.80
	12	3.44	5.72	0.11	2.23	2.57	1.04	81.44
	13	25.66	9.12	1.39	3.79	2.41	7.76	47.97
	14	6.73	3.14	0.12	1.59	1.98	2.04	31.89
	15	5.42	5.09	0.16	2.32	2.19	1.64	72.81
	16	9.43	5.01	0.25	2.30	2.17	2.85	30.84
	17	4.55	4.91	0.13	2.26	2.17	1.36	82.87
	18	2.49	3.58	0.05	1.71	2.09	0.75	85.30
	19	6.82	7.38	0.27	3.03	2.44	2.06	58.47
	20	1.76	2.57	0.03	1.44	1.78	0.53	105.75

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	18	20	18	20	18
	x	6.78	5.11	2.39	2.18	2.17	2.15
	s	5.78	2.45	0.96	0.72	0.25	0.25
	c_v (%)	85.18	47.97	40.35	33.19	11.66	11.85
	Q(95 %)	2.70	1.22	0.45	0.36	0.12	0.13
	min	1.62	1.62	0.45	0.45	1.55	1.55
	max	25.66	9.61	4.84	3.56	2.57	2.57

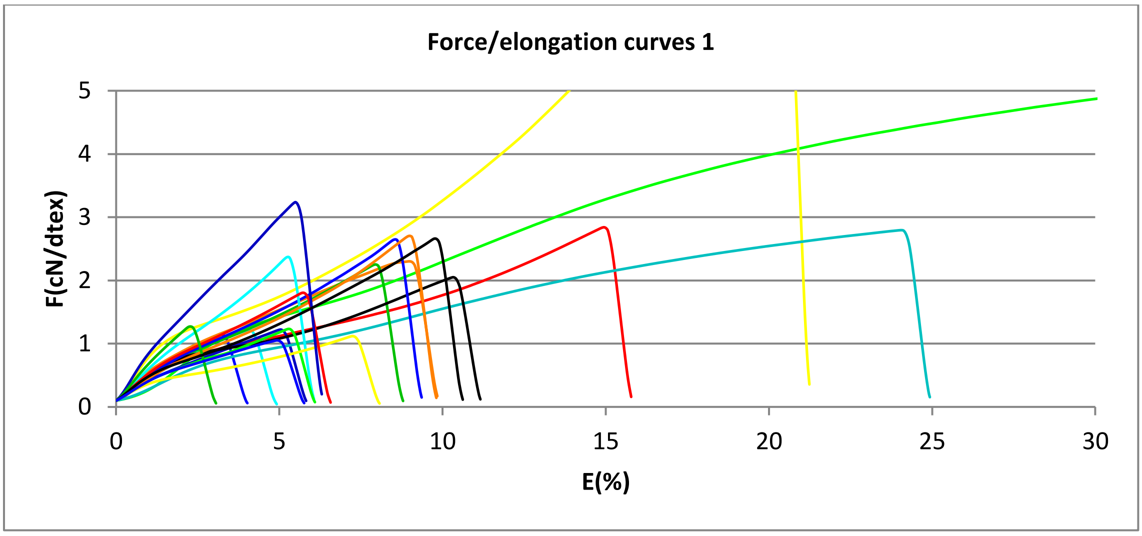


Figure B. 7: POST-ea accept measured with the 10-mm gauge distance.

Table B. 7: The results for individual fibres of POST-ea accept with the 10-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=20) and selected specimens (n=17).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
	1	8.54	6.41	0.29	2.65	2.42	2.59	42.66
	2	5.26	5.39	0.15	2.37	2.27	1.59	56.06
	3	5.30	2.88	0.09	1.23	2.33	1.60	35.41
	4	7.24	2.67	0.12	1.12	2.38	2.19	30.43
	5	8.98	6.30	0.29	2.71	2.33	2.72	39.84
	6	5.73	3.44	0.12	1.81	1.91	1.73	46.90
	7	5.49	7.60	0.23	3.24	2.35	1.66	85.87
	8	2.26	2.09	0.03	1.27	1.64	0.68	64.92
	9	9.79	5.05	0.26	2.66	1.90	2.96	42.75
	10	4.94	2.46	0.08	1.05	2.34	1.49	33.20
	11	3.23	2.75	0.05	1.14	2.41	0.98	45.13
	12	4.08	2.96	0.08	1.22	2.44	1.23	40.58
	13	35.36	12.21	2.81	5.20	2.35	10.82	42.35
	14	20.36	19.86	1.85	8.40	2.36	6.15	79.61
	15	8.99	4.39	0.24	2.30	1.90	2.71	52.09
	16	14.94	4.74	0.37	2.84	1.67	4.52	38.08
	17	5.04	2.55	0.08	1.22	2.08	1.52	35.99
	18	24.04	7.58	1.14	2.80	2.71	7.37	25.76
	19	7.96	4.27	0.19	2.25	1.90	2.40	47.30
	20	10.33	6.10	0.36	2.05	2.97	3.13	44.55

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	20	17	20	17	20	17
	x	9.89	6.95	2.48	1.95	2.23	2.19
	s	8.15	3.12	1.72	0.73	0.33	0.34
	c_v (%)	82.38	44.98	69.27	37.67	14.94	15.41
	Q(95 %)	3.81	1.61	0.80	0.38	0.16	0.17
	min	2.26	2.26	1.05	1.05	1.64	1.64
	max	35.36	14.94	8.40	3.24	2.97	2.97

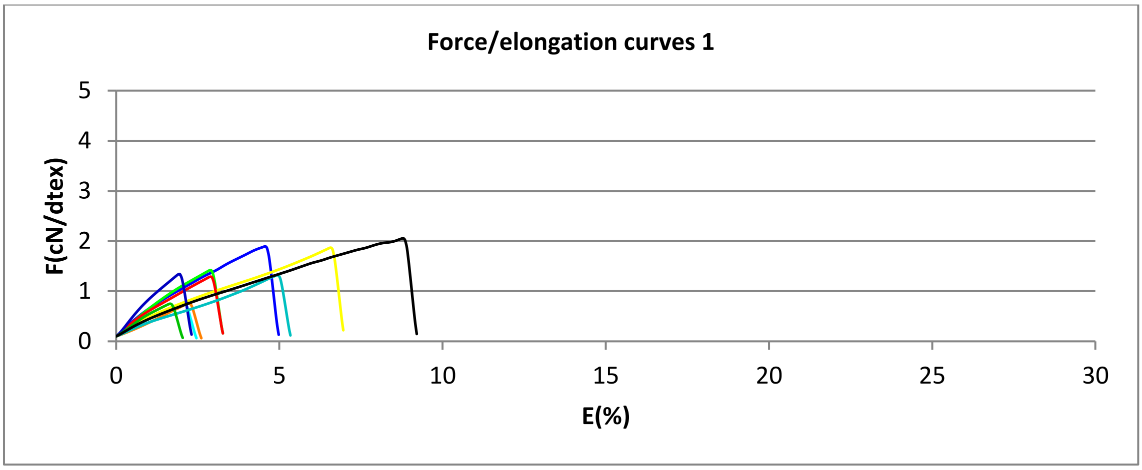


Figure B. 8: REF-CO uncleaned measured with the 20-mm gauge distance.

Table B. 8: The results for individual fibres of REF-CO uncleaned with the 20-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=10) and selected specimens (n=8).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
-----------------	1	4.56	2.16	0.12	1.89	1.14	2.75	61.95
-----------------	2	2.06	1.76	0.05	0.76	2.32	1.25	36.17
-----------------	3	2.89	2.73	0.09	1.42	1.92	1.74	60.40
-----------------	4	6.57	3.73	0.28	1.87	2.00	3.97	42.83
-----------------	5	2.22	1.55	0.04	0.76	2.03	1.34	32.90
-----------------	6	2.89	1.45	0.05	1.29	1.12	1.74	59.24
-----------------	7	1.94	1.79	0.04	1.34	1.33	1.17	83.66
-----------------	8	4.94	1.98	0.11	1.32	1.50	2.98	31.33
-----------------	9	1.67	1.26	0.03	0.75	1.68	1.01	49.32
-----------------	10	8.79	3.50	0.36	2.06	1.70	5.30	38.41

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	10	8	10	8	10	8
	x	3.85	2.90	1.35	1.19	1.67	1.63
	s	2.35	1.23	0.49	0.41	0.40	0.43
	c_v (%)	60.93	42.34	36.07	34.11	23.92	26.66
	Q(95 %)	1.68	1.03	0.35	0.34	0.29	0.36
	min	1.67	1.67	0.75	0.75	1.12	1.12
	max	8.79	4.94	2.06	1.89	2.32	2.32

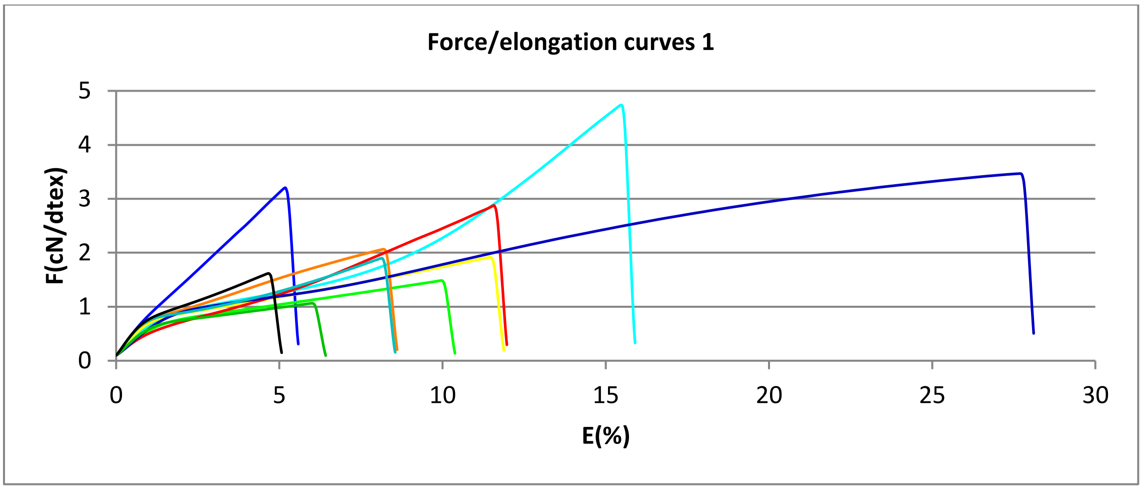


Figure B. 9: POST-B2B accept measured with the 20-mm gauge distance.

Table B. 9: The results for individual fibres of POST-B2B accept with the 20-mm gauge distance. The value marked in red indicates deviation with a c_v > 50 % and is thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=10) and selected specimens (n=9).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
------------------	1	5.18	4.93	0.28	3.21	1.54	3,12	86,45
------------------	2	15.48	6.42	0.87	4.74	1.36	9,32	63,56
------------------	3	9.97	2.25	0.31	1.49	1.51	6,01	53,32
------------------	4	11.46	2.27	0.34	1.92	1.19	6,90	73,19
------------------	5	8.20	2.97	0.31	2.07	1.44	4,94	84,28
------------------	6	11.58	5.94	0.71	2.88	2.07	6,97	47,70
------------------	7	27.69	12.13	4.27	3.47	3.50	16,72	53,57
------------------	8	8.13	2.85	0.29	1.90	1.50	4,90	84,93
------------------	9	6.00	1.82	0.16	1.07	1.71	3,62	57,93
------------------	10	4.66	2.35	0.14	1.62	1.46	2,81	86,77

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	10	9	10	9	10	9
	x	10.84	8.96	2.43	2.32	1.73	1.53
	s	6.79	3.53	1.12	1.12	0.66	0.25
	c_v (%)	62.68	39.34	46.04	48.49	38.52	16.08
	Q(95 %)	4.86	2.71	0.80	0.86	0.48	0.19
	min	4.66	4.66	1.07	1.07	1.19	1.19
	max	27.69	15.48	4.74	4.74	3.50	2.07

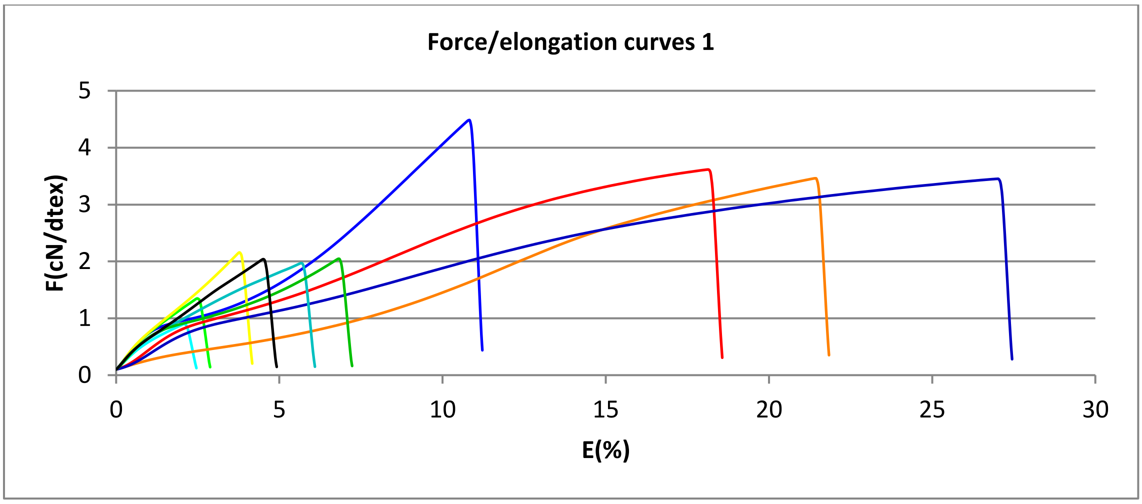


Figure B. 10: POST-s accept measured with the 20-mm gauge distance.

Table B. 10: The results for individual fibres of POST-s accept with the 20-mm gauge distance. The values marked in red indicate deviation with a c_v > 50 % and are thus removed from the calculations of "selected specimens" as described in chapter 5.3. Below a data analysis of elongation, tenacity, and linear density with all specimens (n=10) and selected specimens (n=6).

Individual values		E_{max}	F_{max}	Work TB	Tenacity	Lin.Den.	Time TB	Ini.Mod
Colour	No	%	cN	cN*cm	cN/dtex	dtex	sec	cN/dtex
						1.30		
----------------	1	10.82	5.89	0.59	4.49	1.31	6.51	75.28
----------------	2	2.10	1.83	0.05	0.90	2.03	1.27	57.60
----------------	3	2.49	2.45	0.08	1.35	1.81	1.50	77.10
----------------	4	3.78	3.83	0.16	2.16	1.77	2.28	78.37
----------------	5	21.42	11.13	2.40	3.46	3.22	12.97	24.40
----------------	6	18.14	7.87	1.71	3.62	2.18	10.98	44.00
----------------	7	27.02	8.95	3.12	3.45	2.59	16.44	36.95
----------------	8	5.68	3.53	0.24	1.97	1.79	3.42	68.80
----------------	9	6.83	2.98	0.23	2.05	1.45	4.11	65.24
----------------	10	4.52	3.46	0.18	2.04	1.70	2.72	68.64

Data analysis		Elongation (%)		Tenacity (cN/dtex)		Linear density (dtex)	
	n	10	6	10	6	10	6
	x	10.28	4.23	2.55	1.74	1.99	1.76
	s	8.83	1.83	1.14	0.50	0.56	0.19
	c_v (%)	85.95	43.15	44.72	28.86	28.35	10.68
	Q(95 %)	6.32	1.92	0.82	0.53	0.40	0.20
	min	2.10	2.10	0.90	0.90	1.31	1.45
	max	27.02	6.83	4.49	2.16	3.22	2.03

APPENDIX C: SEM RESULTS

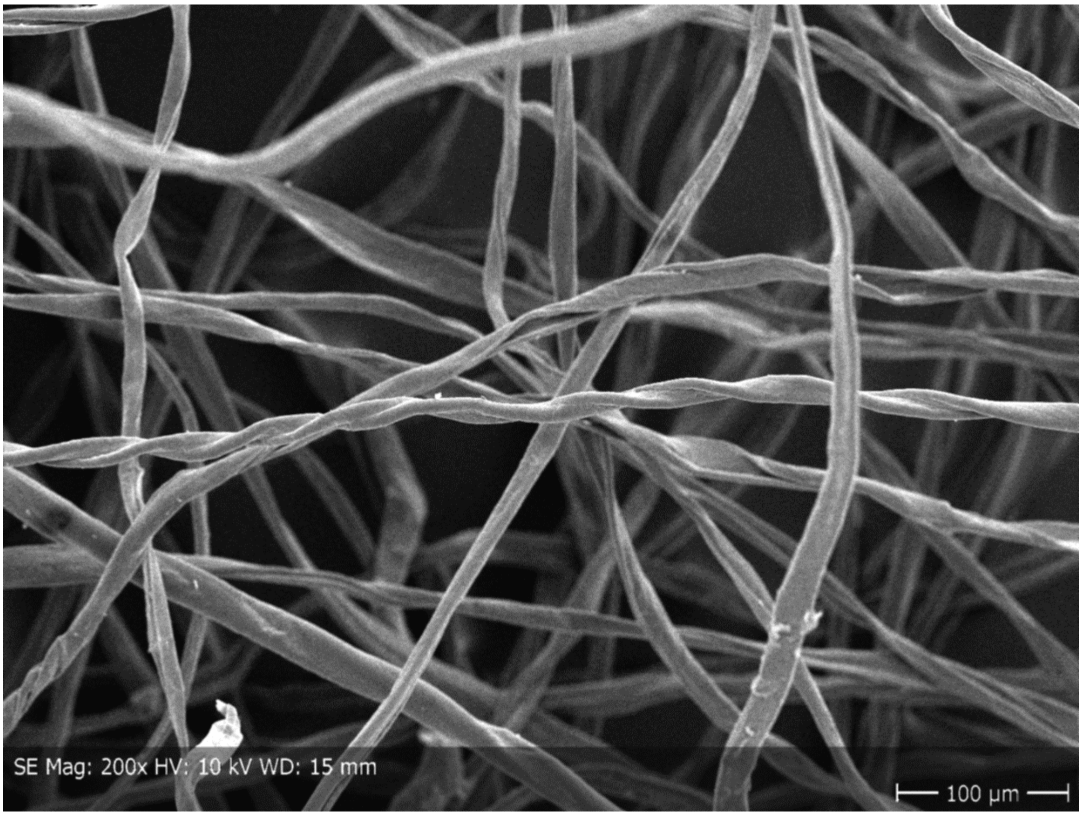


Figure C. 1: REF-CO accept.

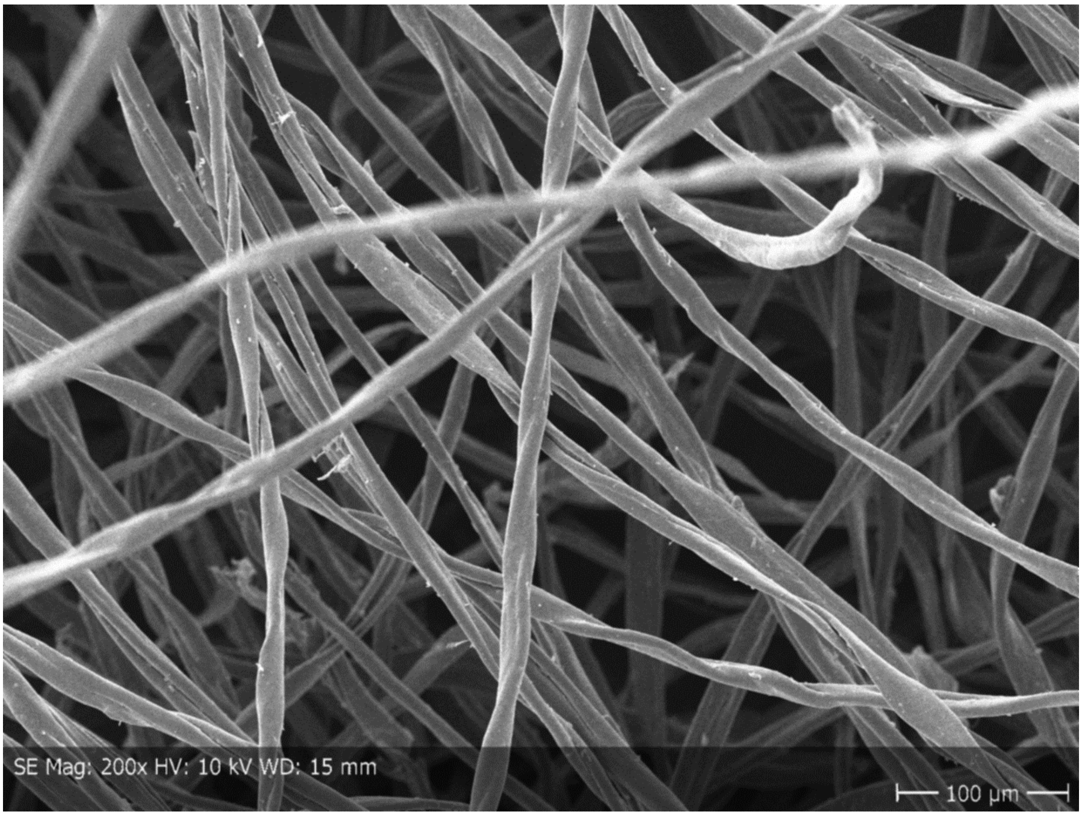


Figure C. 2: PRE-KNIT company accept.

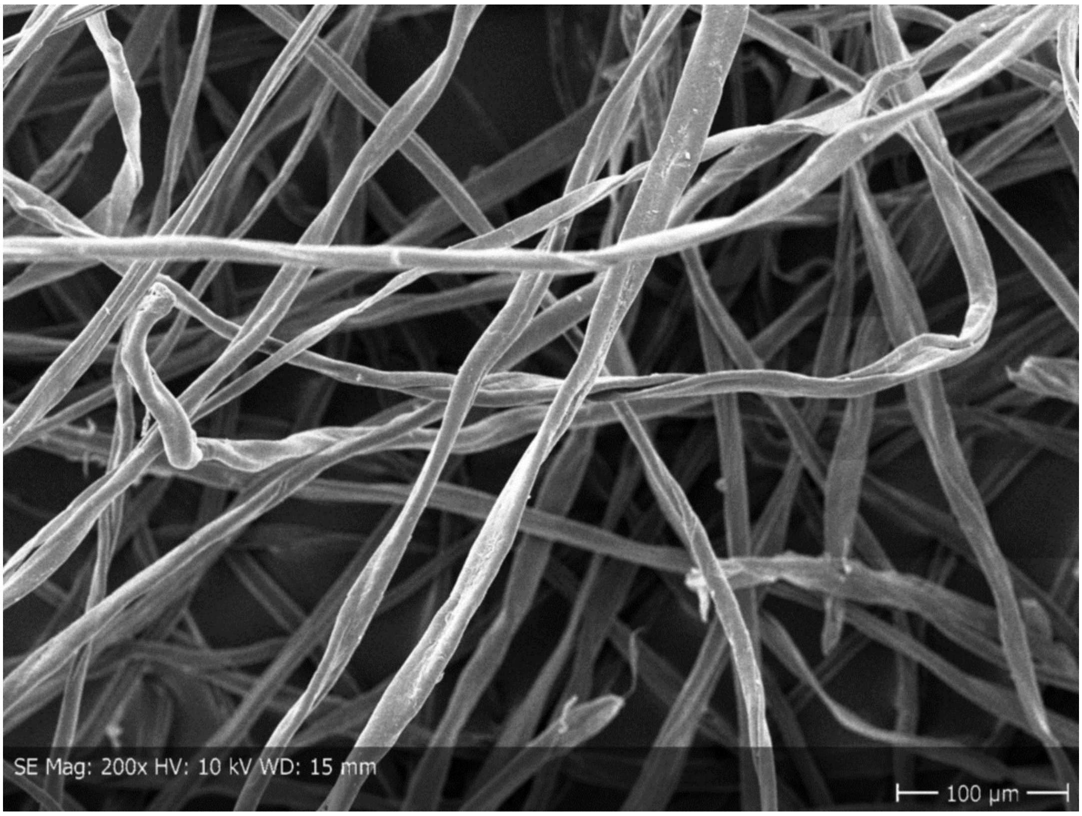


Figure C. 3: PRE-WOVEN accept.

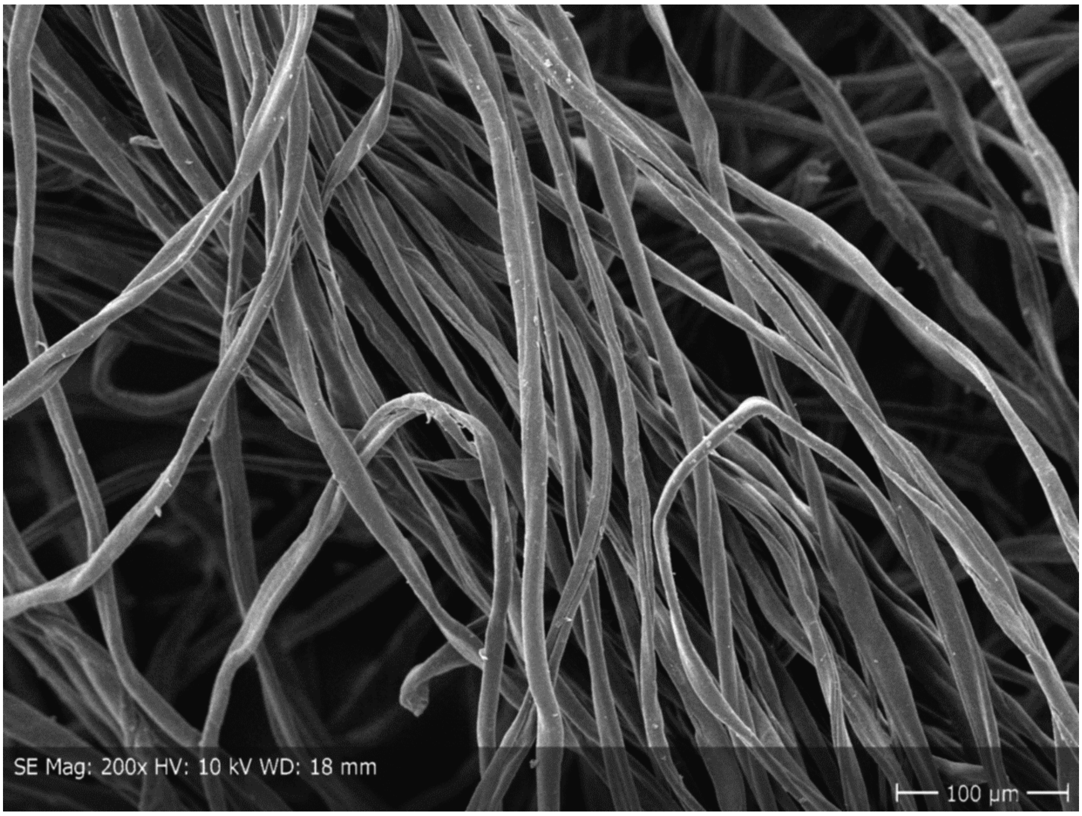


Figure C. 4: PRE-WOVEN uncleaned. WD:15 mm and not 18 mm as printed on the image.

Figure C. 5: POST-B2B accept.

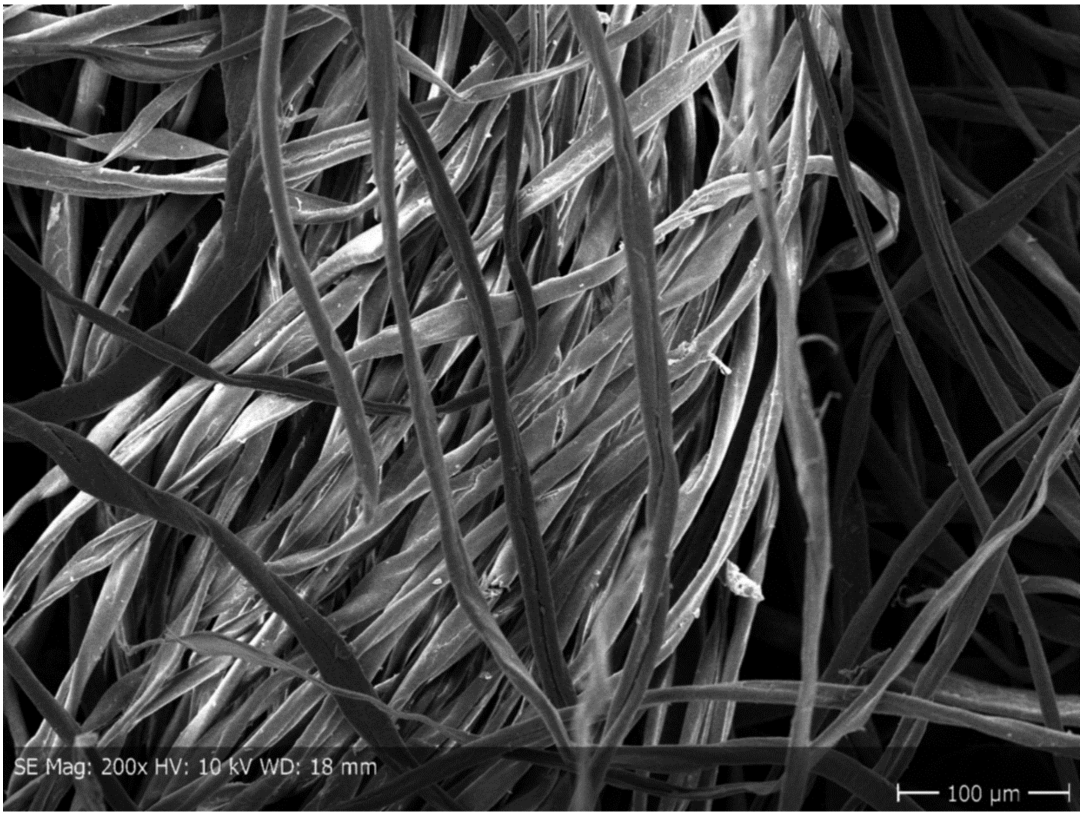


Figure C. 6: POST-B2B uncleaned. WD:15 mm and not 18 mm as printed on the image.

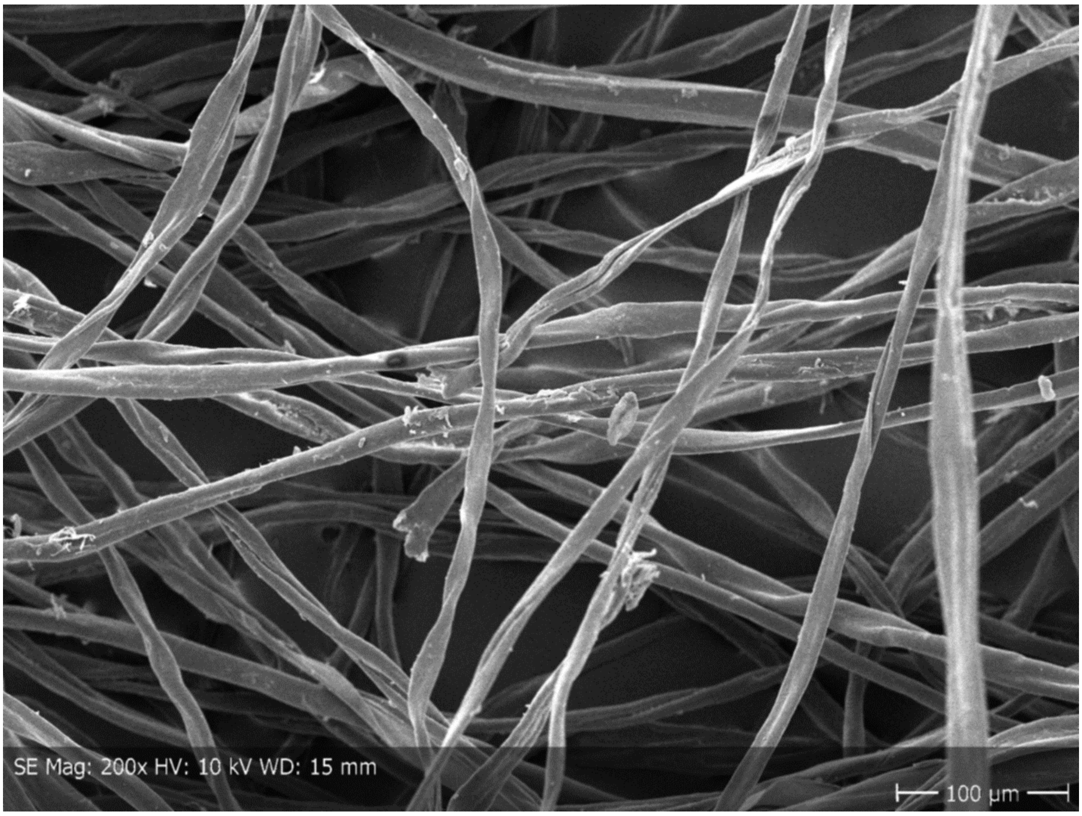


Figure C. 7: POST-n accept.

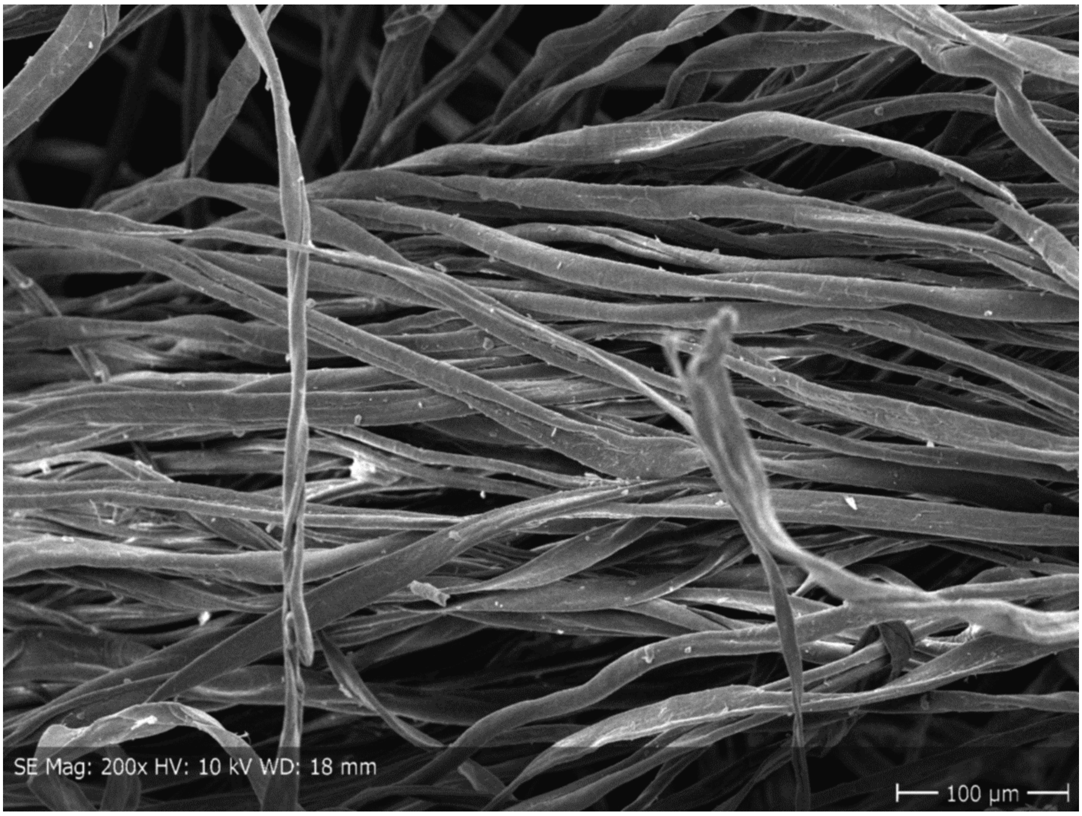


Figure C. 8: POST-n uncleaned. WD:15 mm and not 18 mm as printed on the image.

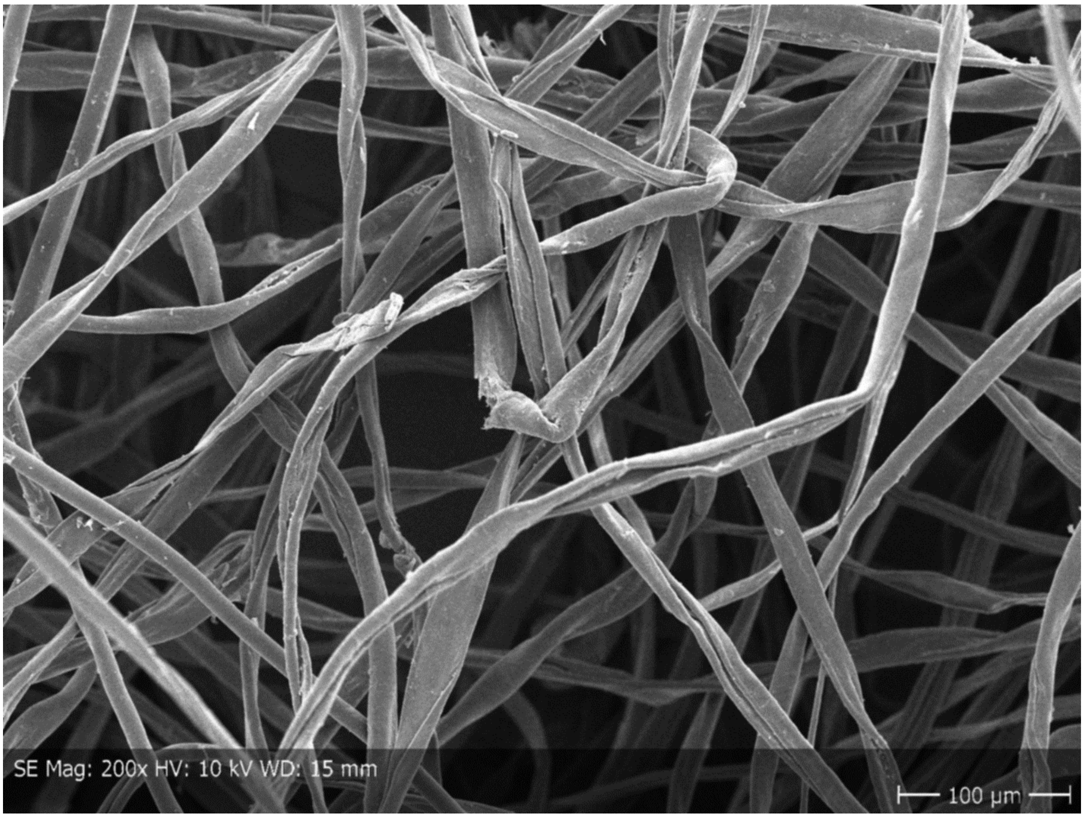


Figure C. 9: POST-s accept.

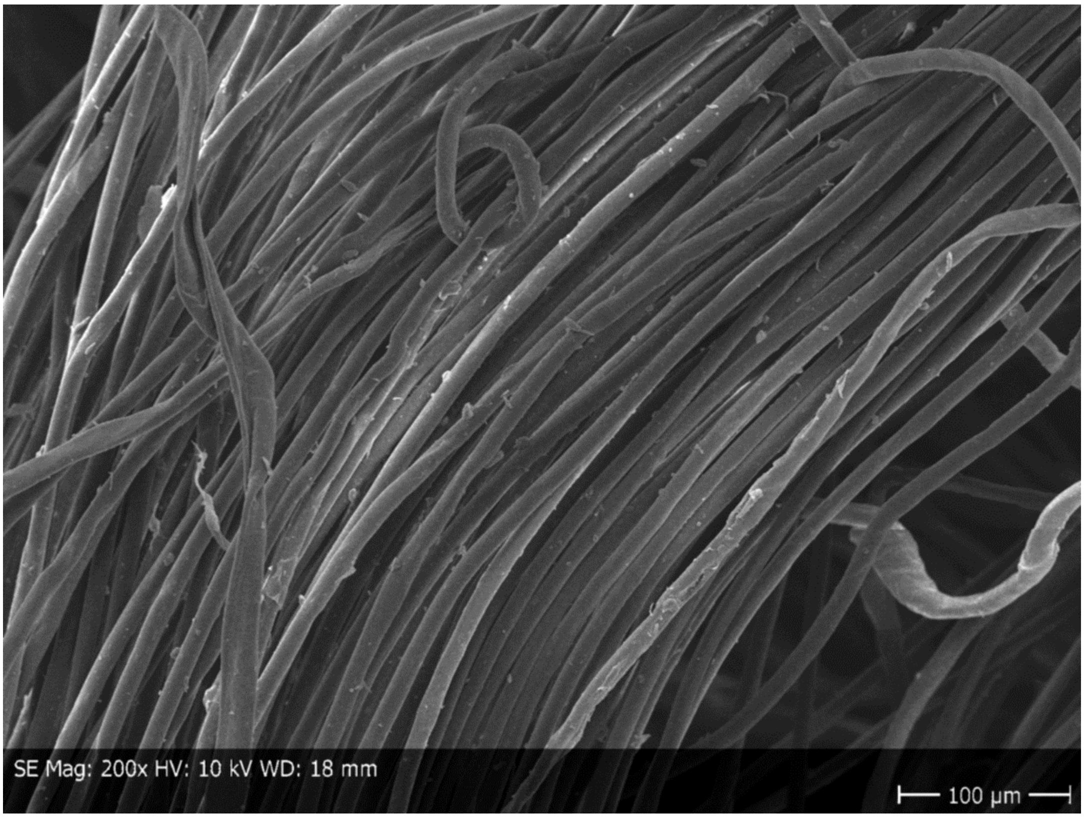


Figure C. 10: POST-s uncleaned. WD:15 mm and not 18 mm as printed on the image.

Figure C. 11: POST-ea accept.

Figure C. 12: POST-ea uncleaned.

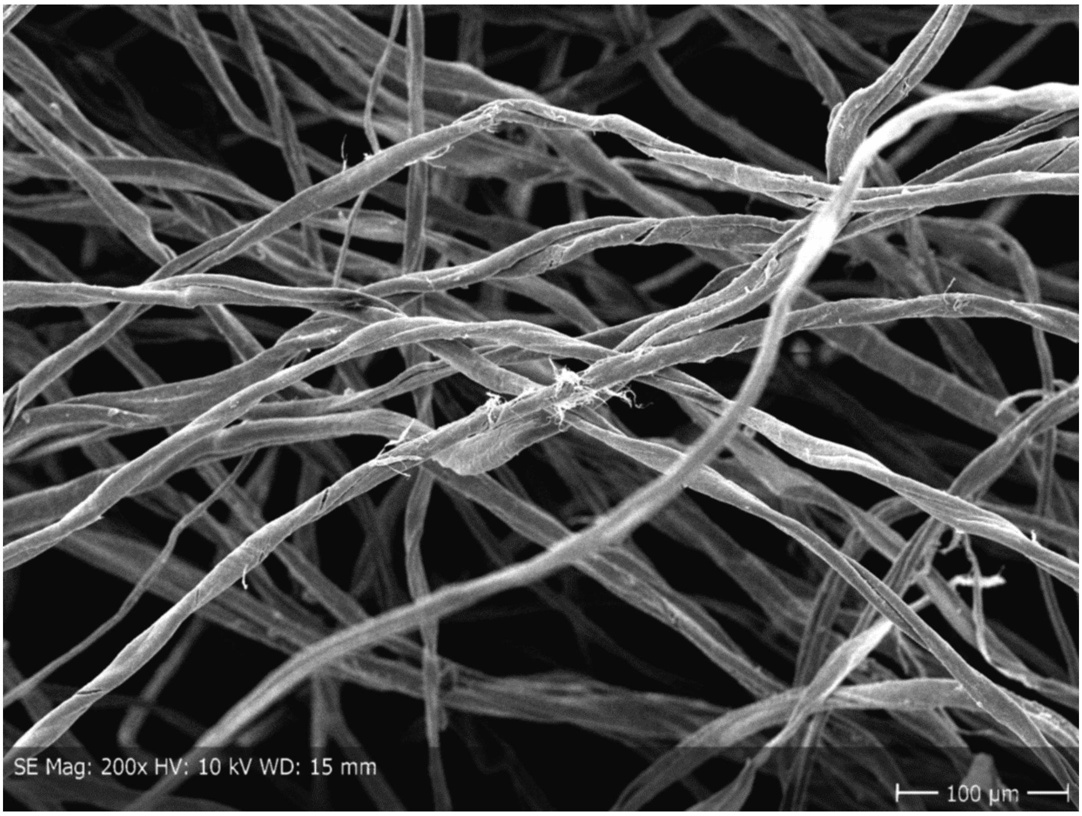


Figure C. 13: The bedsheet pictured in Figure 5.15 (left).

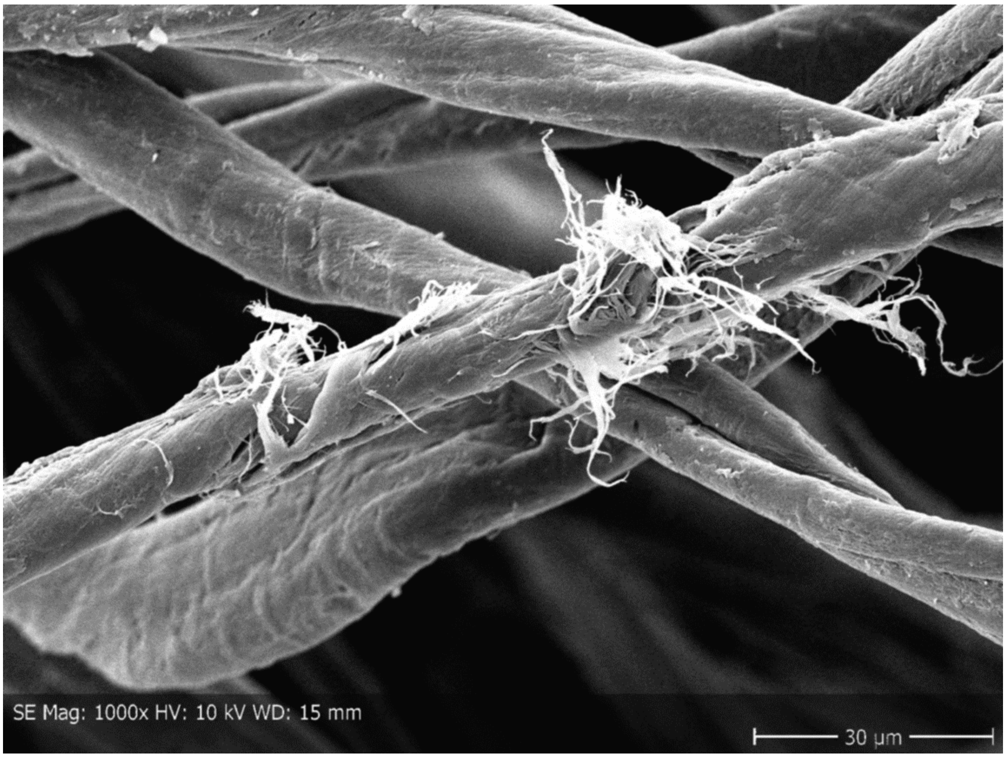


Figure C. 14: The bedsheet pictured in Figure 5.15 (right).

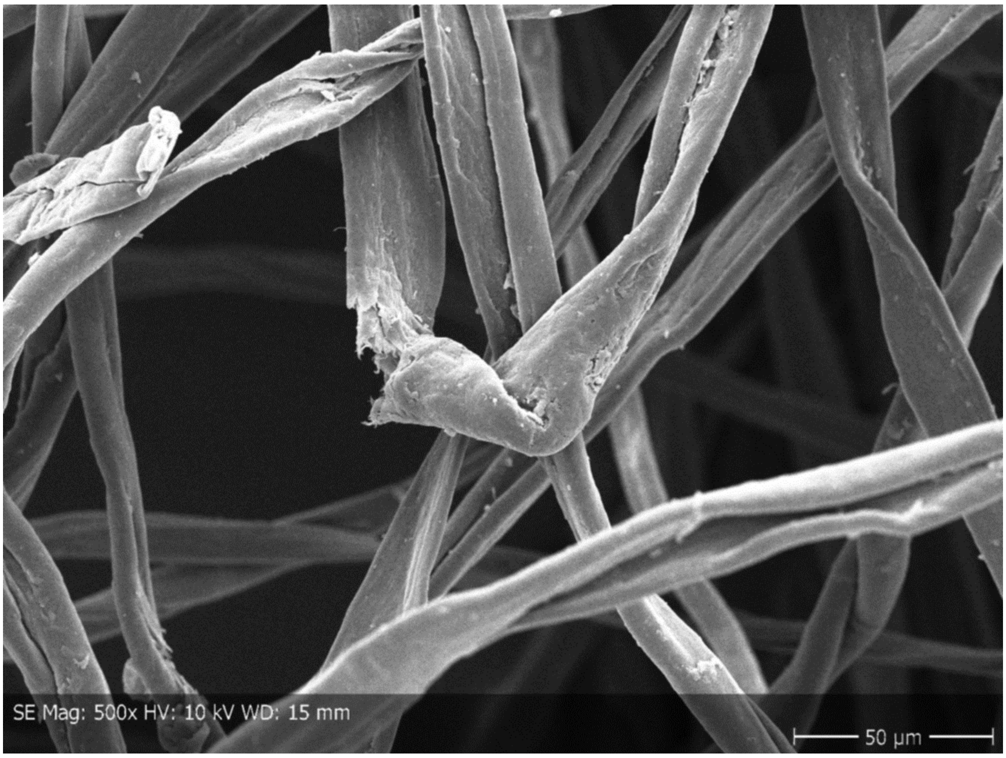


Figure C. 15: POST-s accept pictured in Figure 5.16 (left).

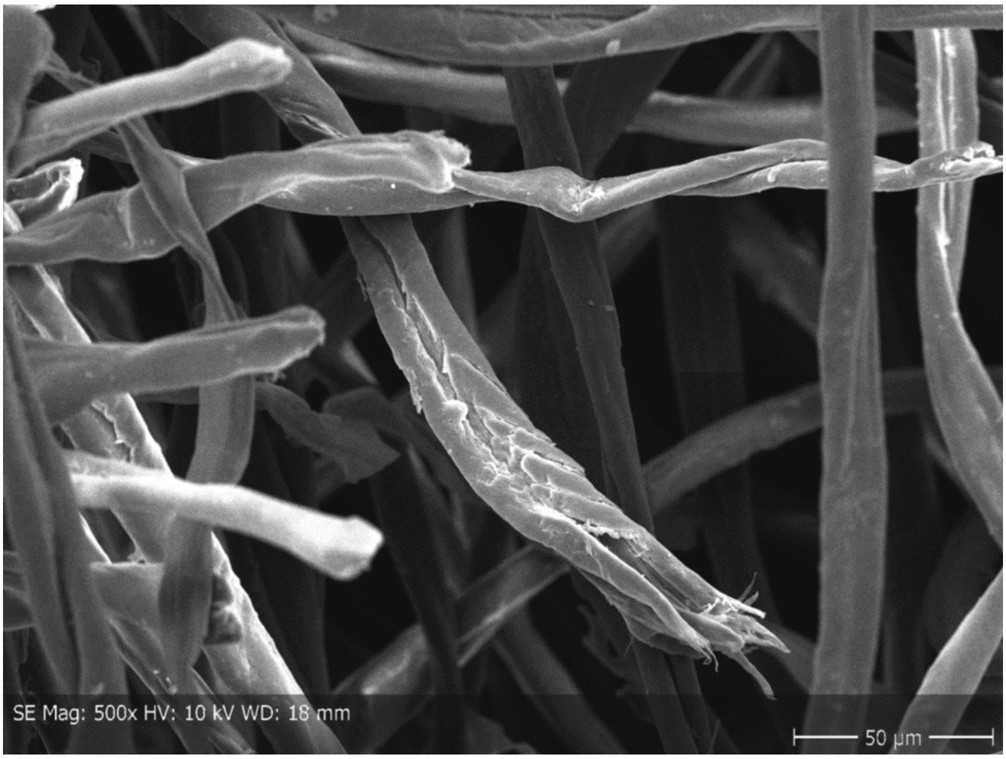


Figure C. 16: POST-B2B uncleaned pictured in Figure 5.16 (right). WD:15 mm and not 18 mm as printed on the image.

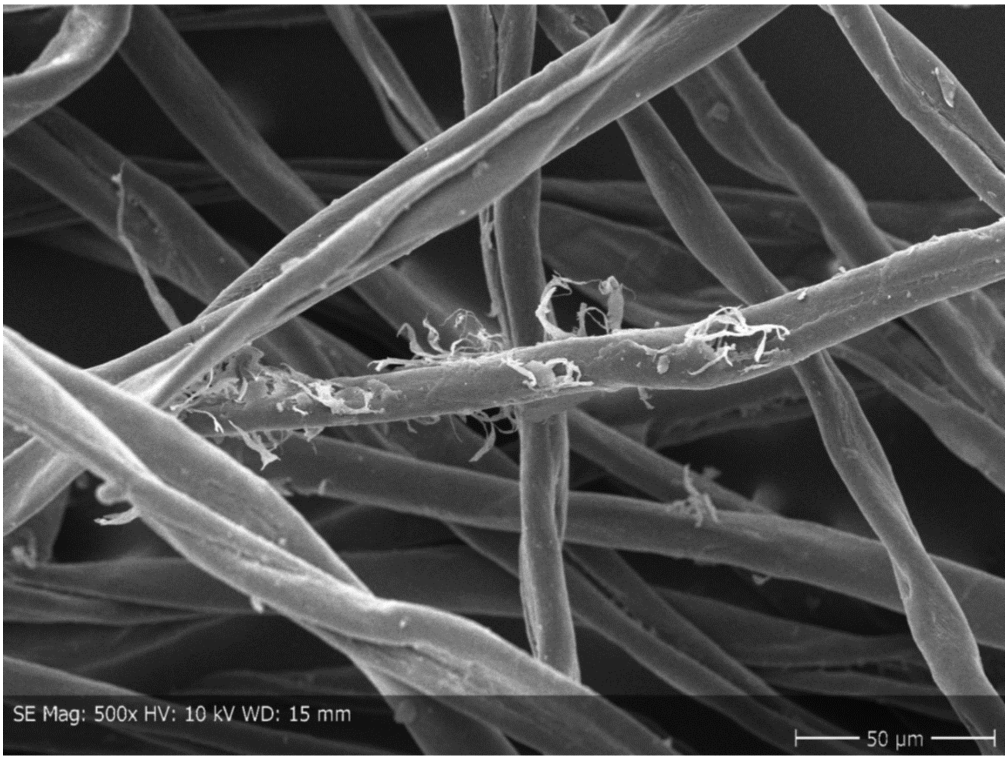


Figure C. 17: POST-n accept pictured in Figure 5.17 (left).

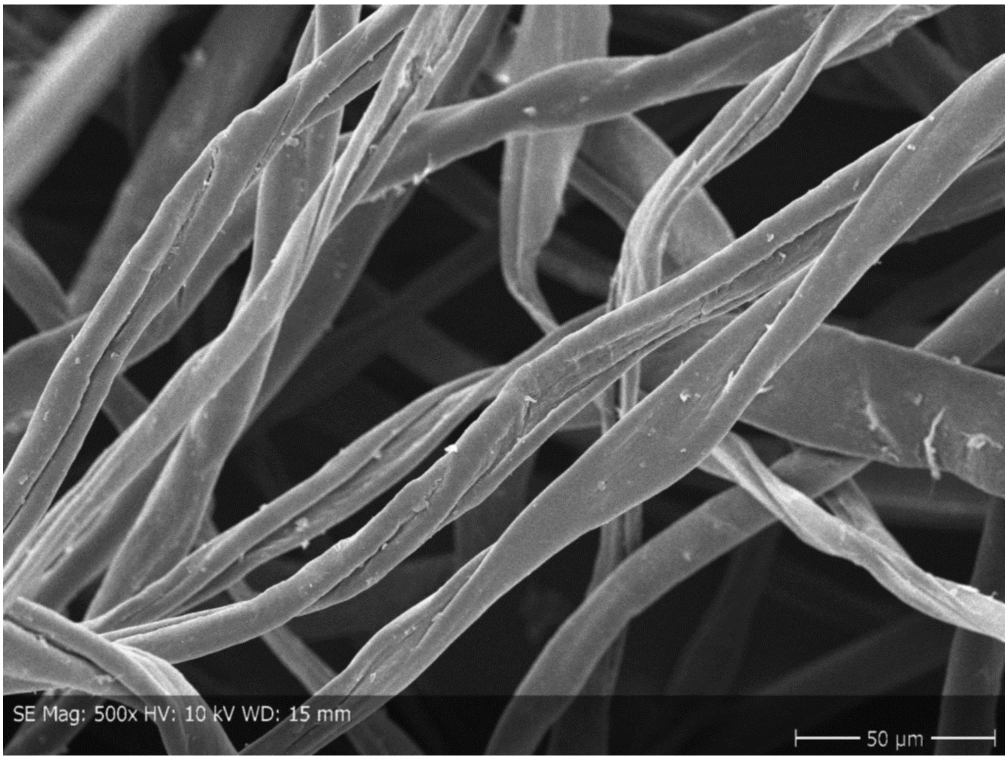


Figure C. 18: PRE-KNIT company accept pictured in Figure 5.17 (right).

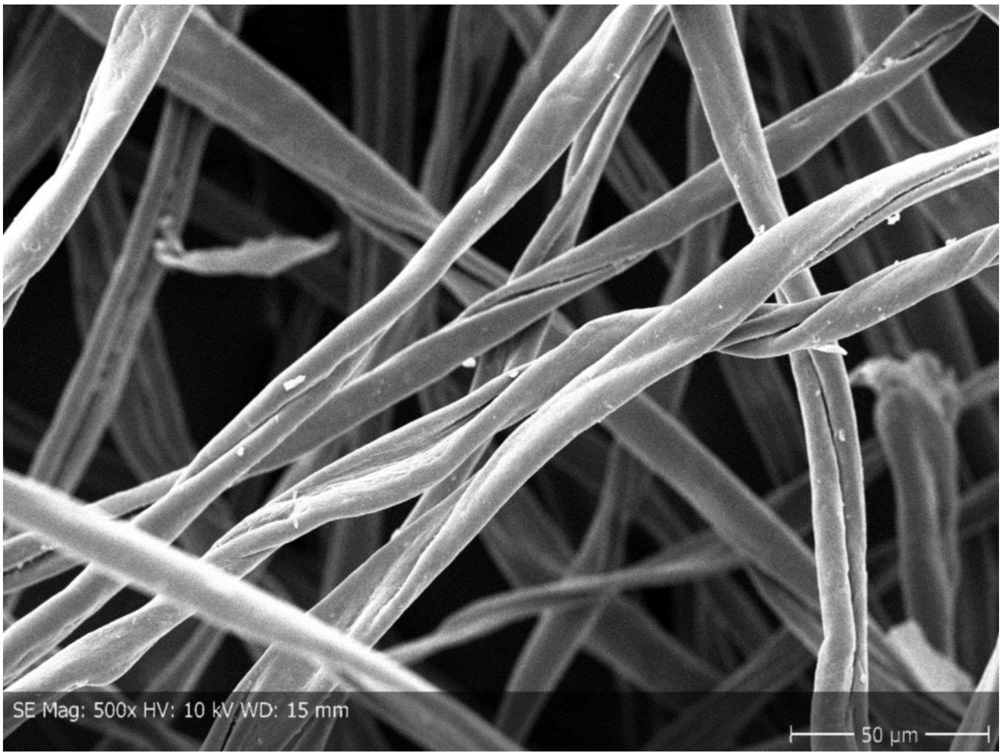


Figure C. 19: PRE-WOVEN accept pictured in Figure 5.18a.

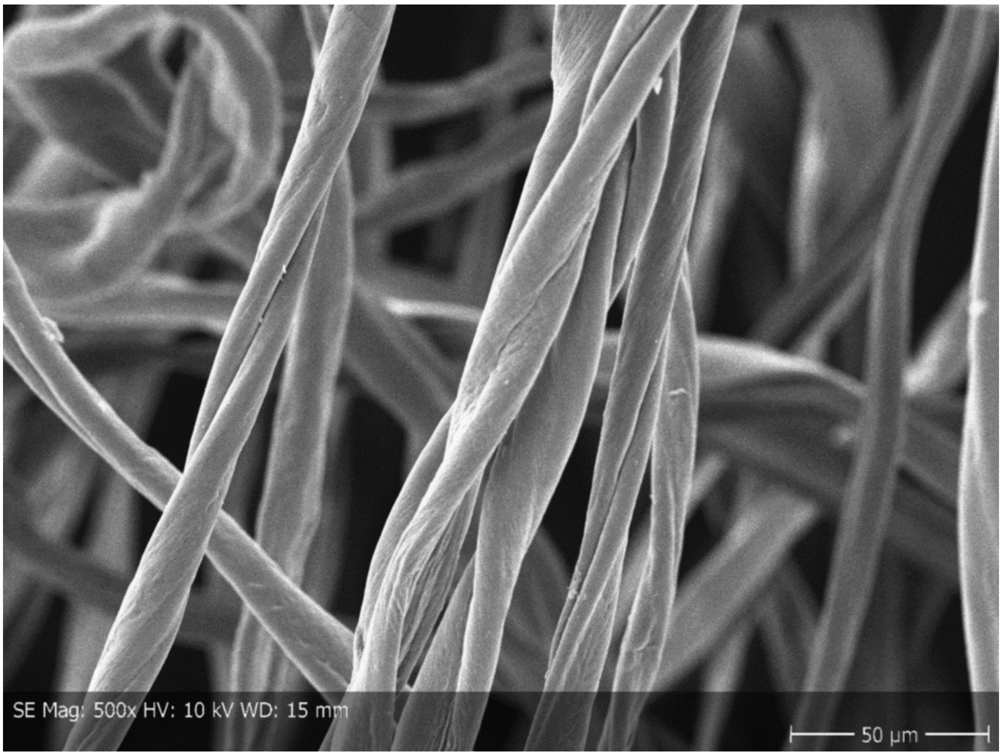


Figure C. 20: REF-CO accept pictured in Figure 5.18b.

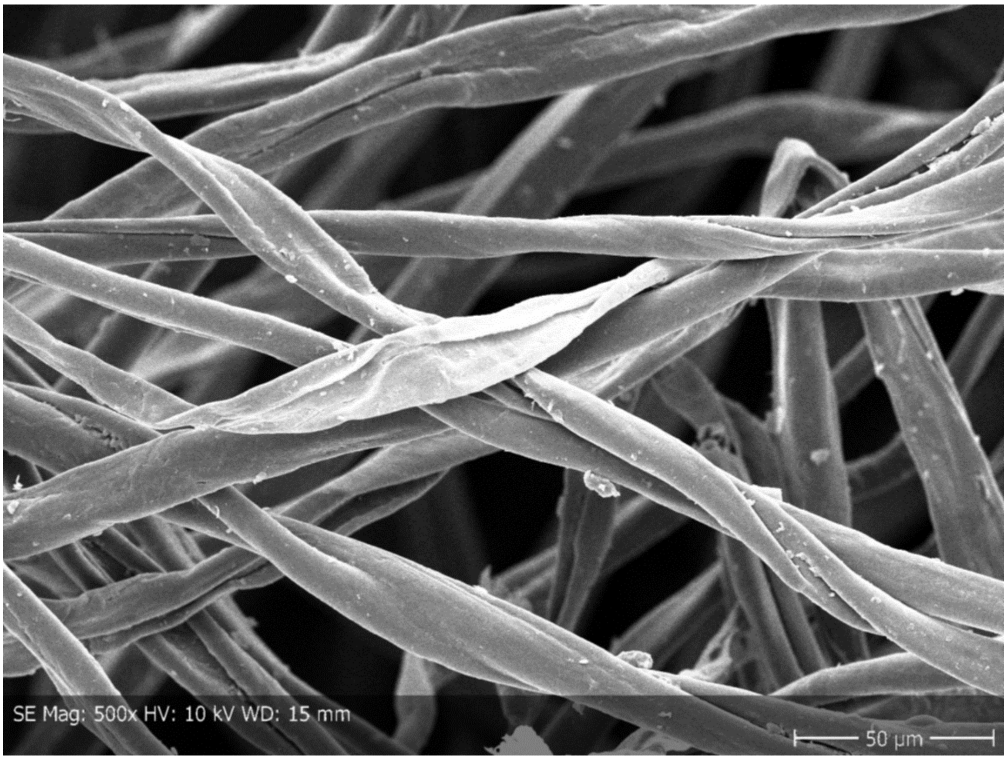


Figure C. 21: POST-ea accept pictured in Figure 5.18c.

Figure C. 22: POST-n accept pictured in Figure 5.18d.

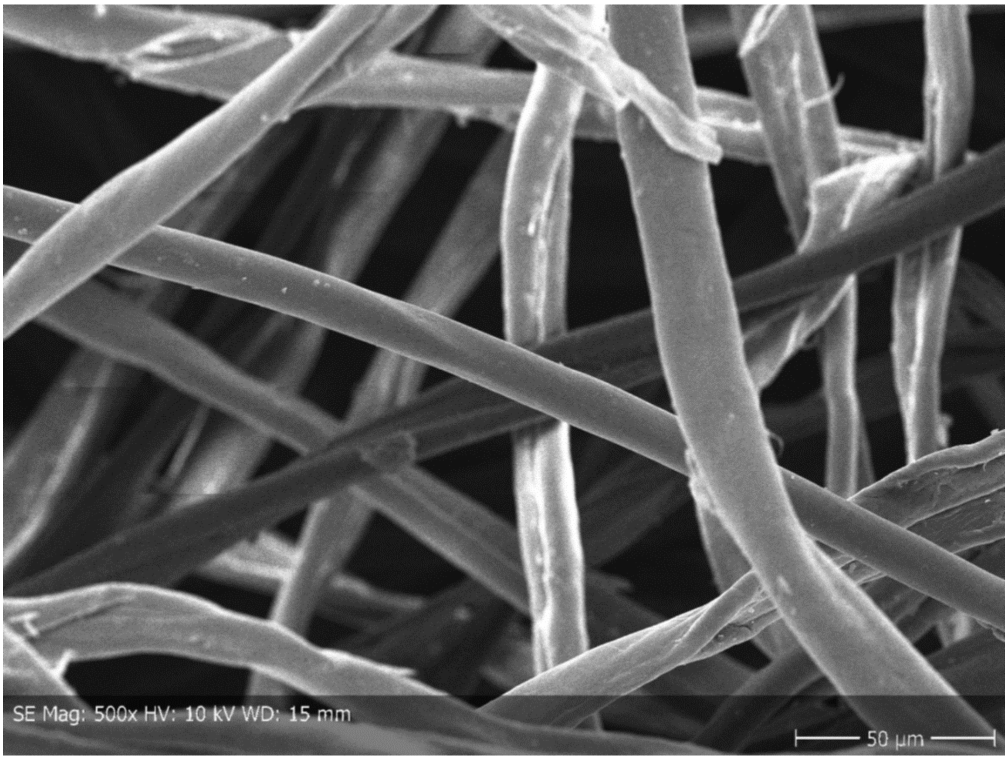


Figure C. 23: POST-s accept pictured in Figure 5.22 (left).

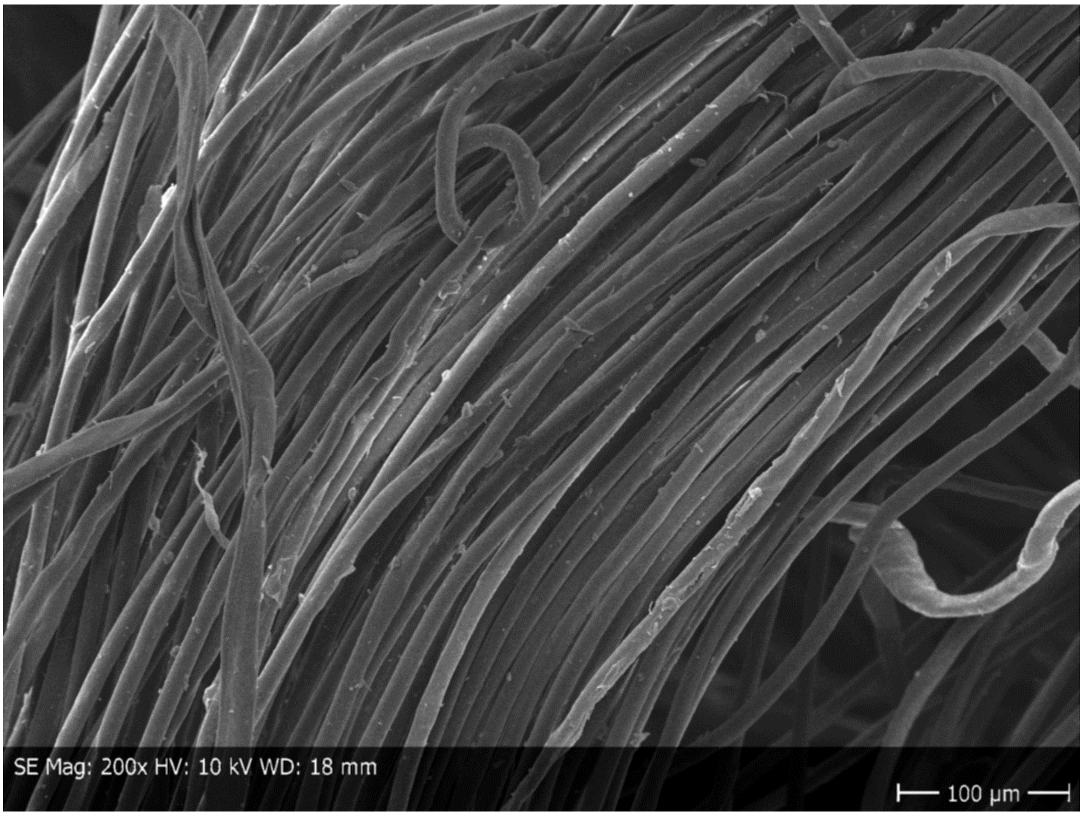


Figure C. 24: POST-s uncleaned pictured in Figure 5.22 (centre). WD:15 mm and not 18 mm as printed on the image

Figure C. 25: POST-ea uncleaned pictured in Figure 5.22 (right).

APPENDIX D: DSC RESULTS

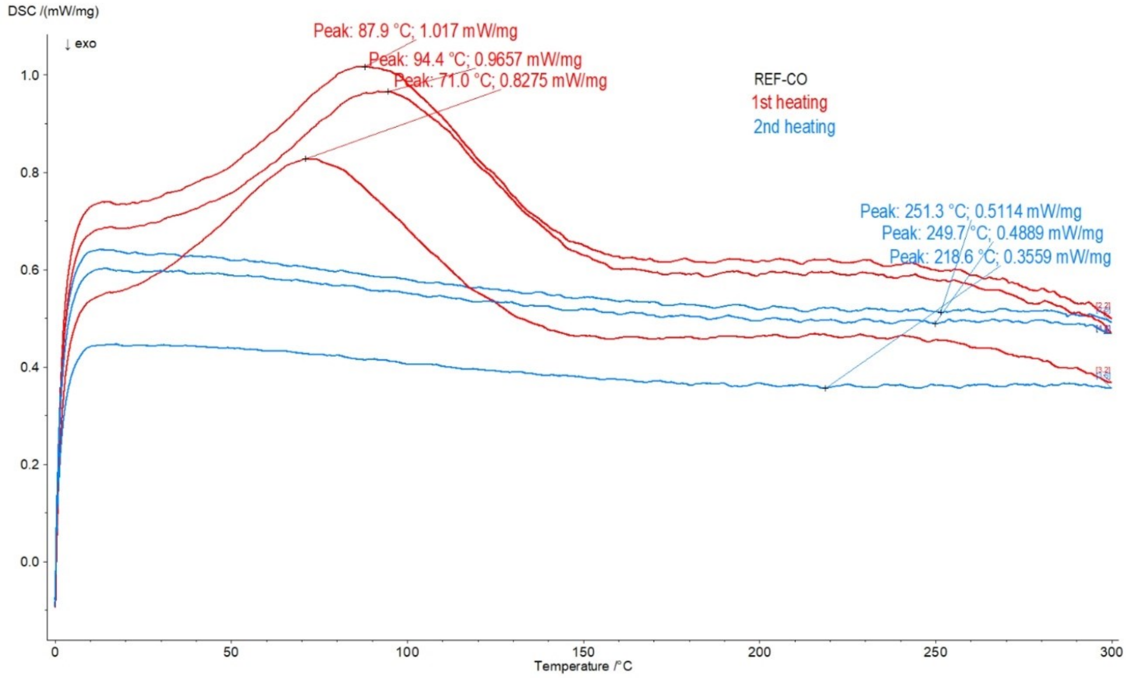


Figure D. 1: DSC curves for REF-CO accept. The peaks are detected with the help of NETZSCH software.

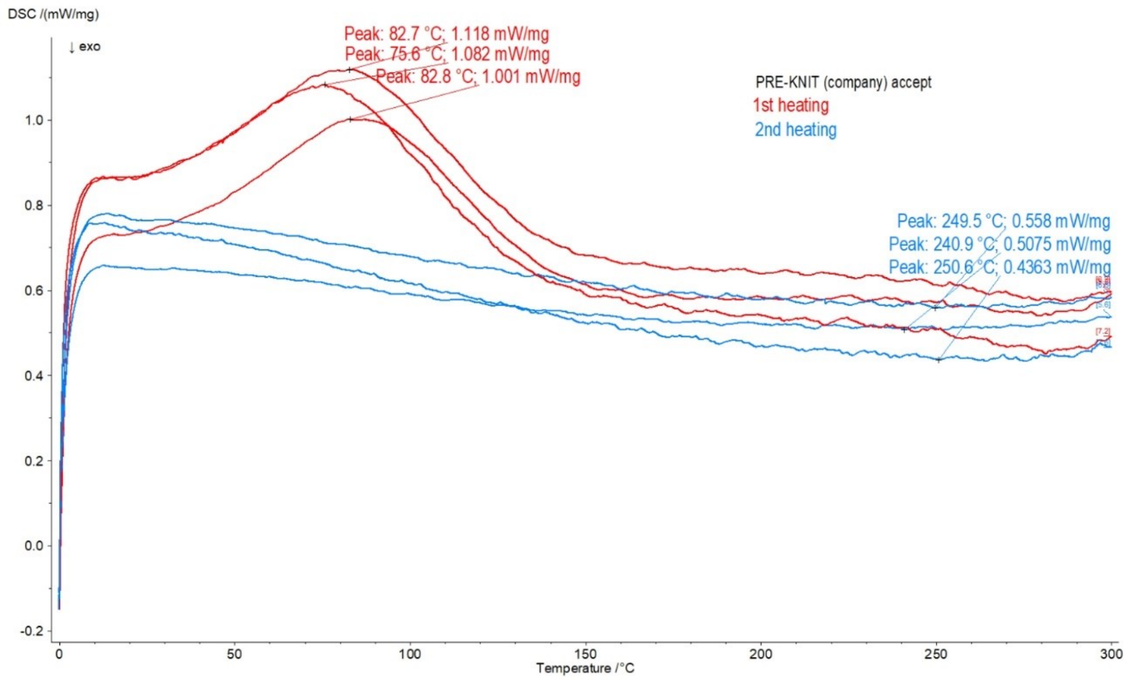


Figure D. 2: DSC curves for PRE-KNIT (company) accept. The peaks are detected with the help of NETZSCH software.

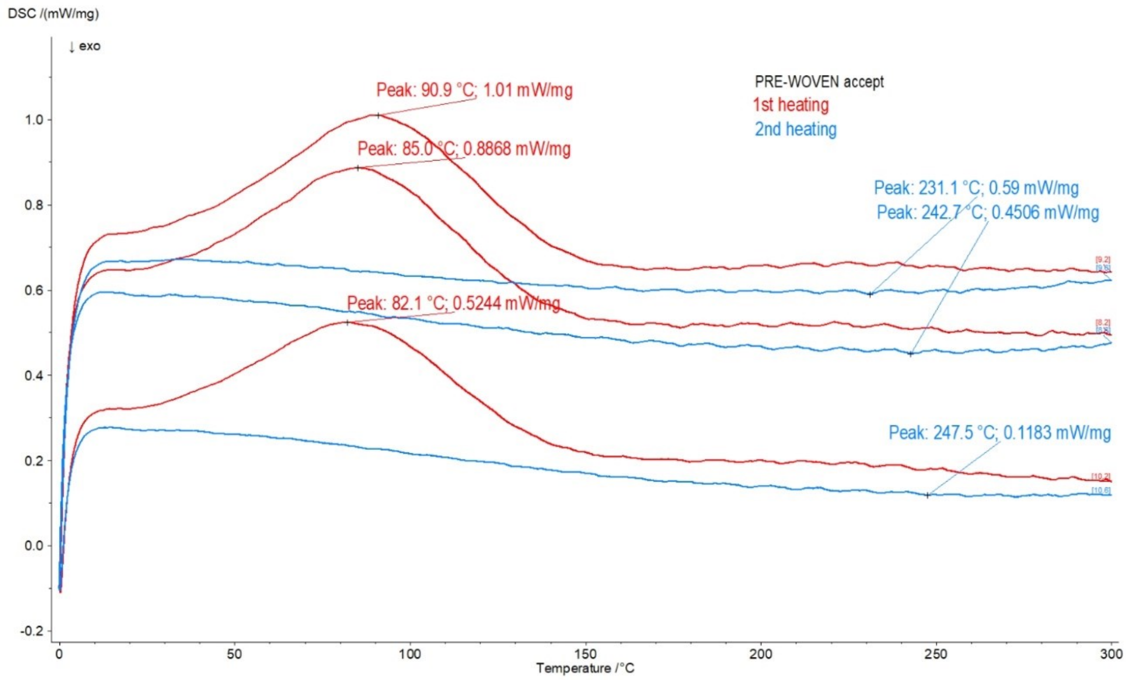


Figure D. 3: DSC curves for PRE-WOVEN accept. The peaks are detected with the help of NETZSCH software.

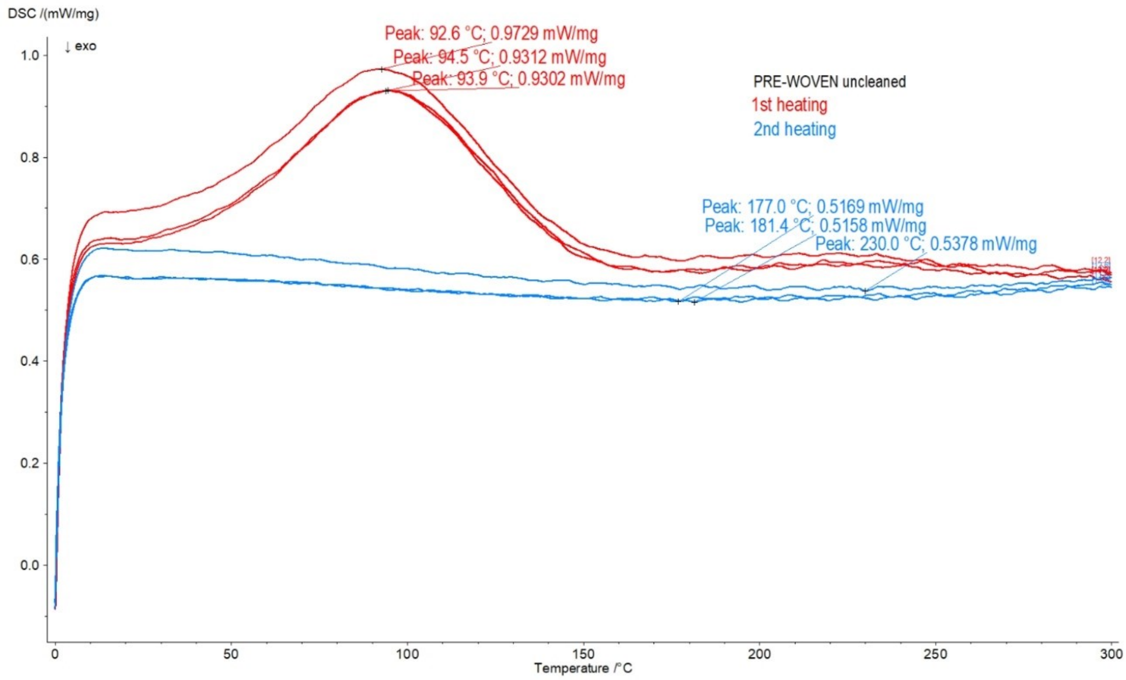


Figure D. 4: DSC curves for PRE-WOVEN uncleaned. The peaks are detected with the help of NETZSCH software.

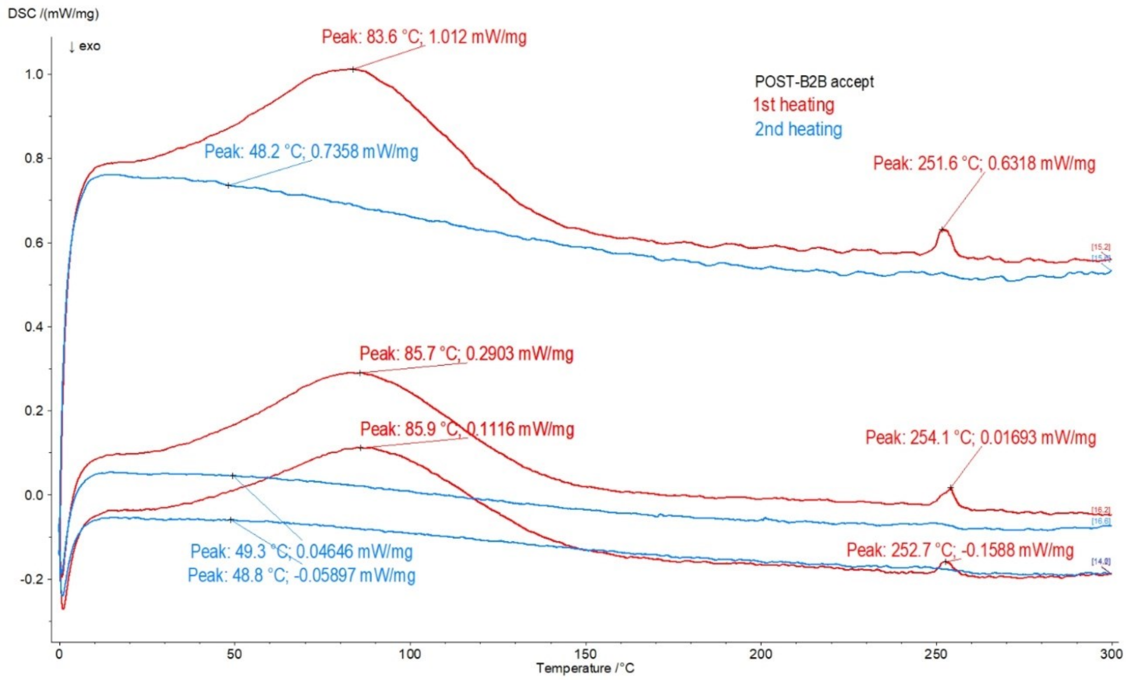


Figure D. 5: DSC curves for POST-B2B accept. The peaks are detected with the help of NETZSCH software.

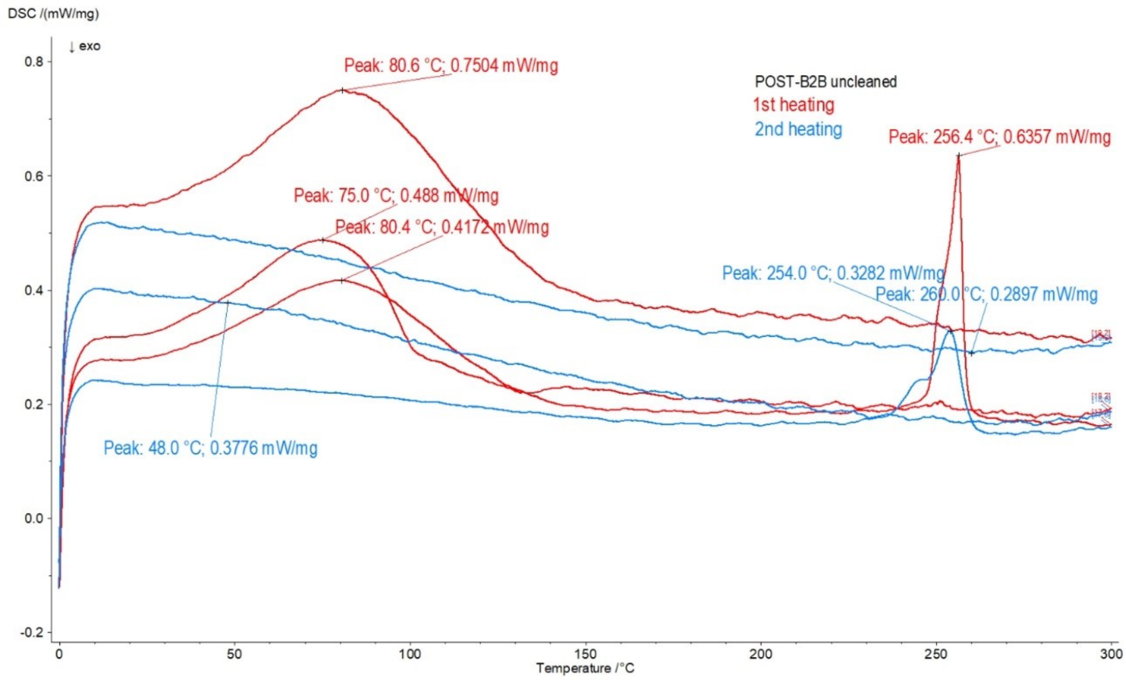


Figure D. 6: DSC curves for POST-B2B uncleaned. The peaks are detected with the help of NETZSCH software.

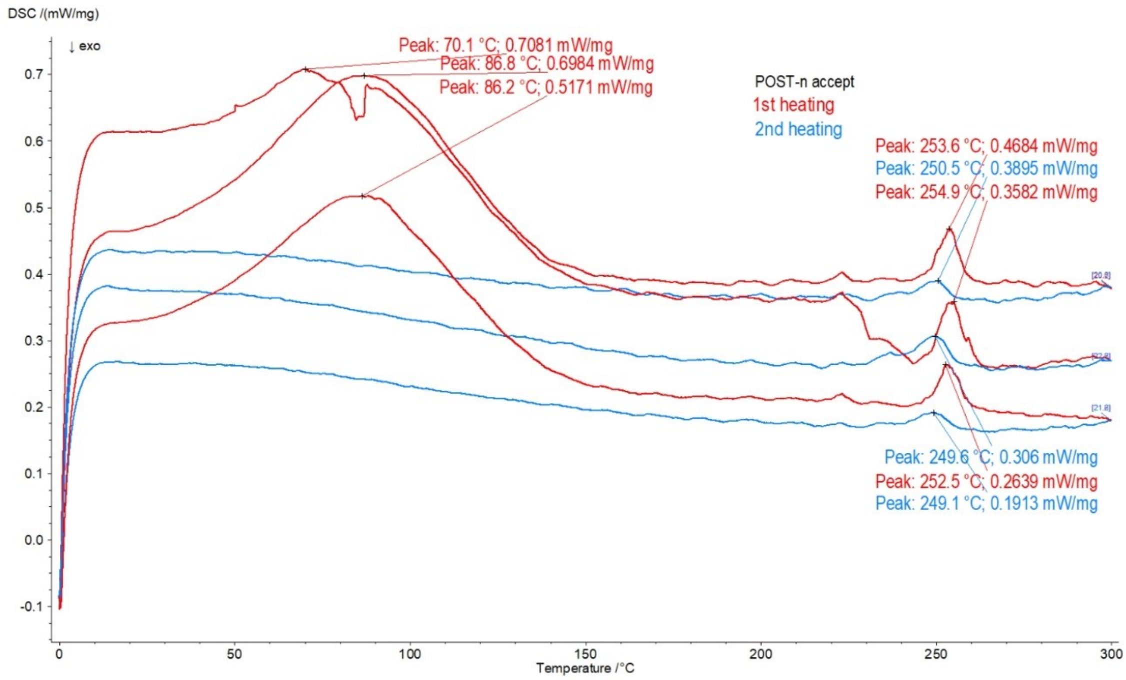


Figure D. 7: DSC curves for POST-n accept. The peaks are detected with the help of NETZSCH software.

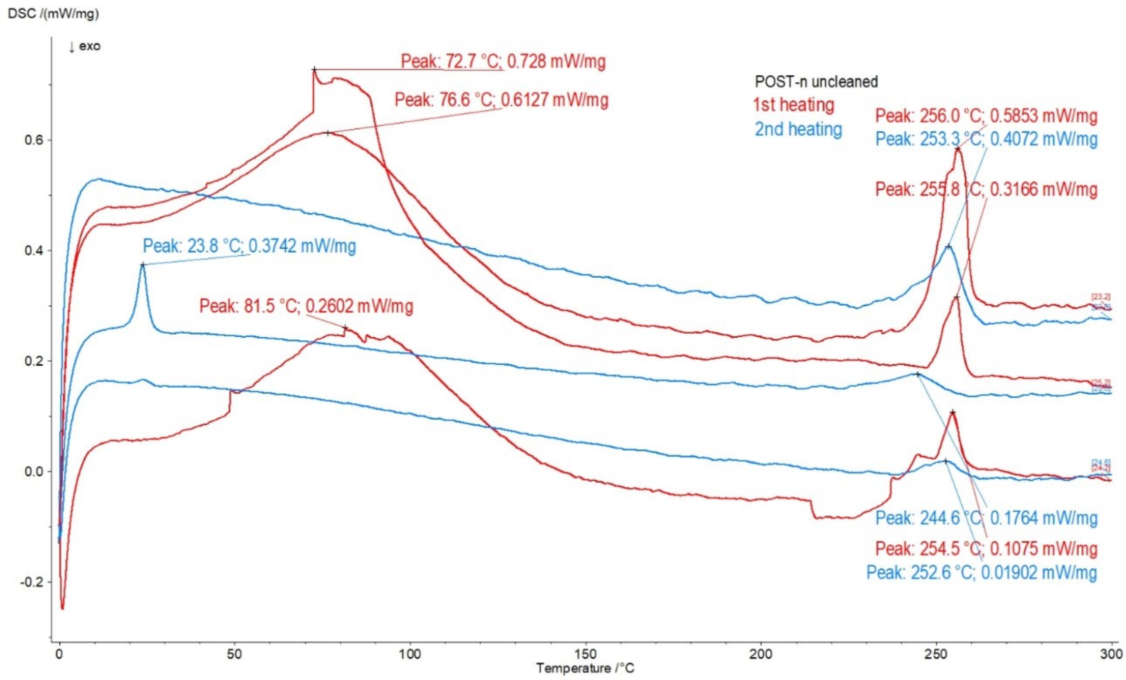


Figure D. 8: DSC curves for POST-n uncleaned. The peaks are detected with the help of NE-TZSCH software.

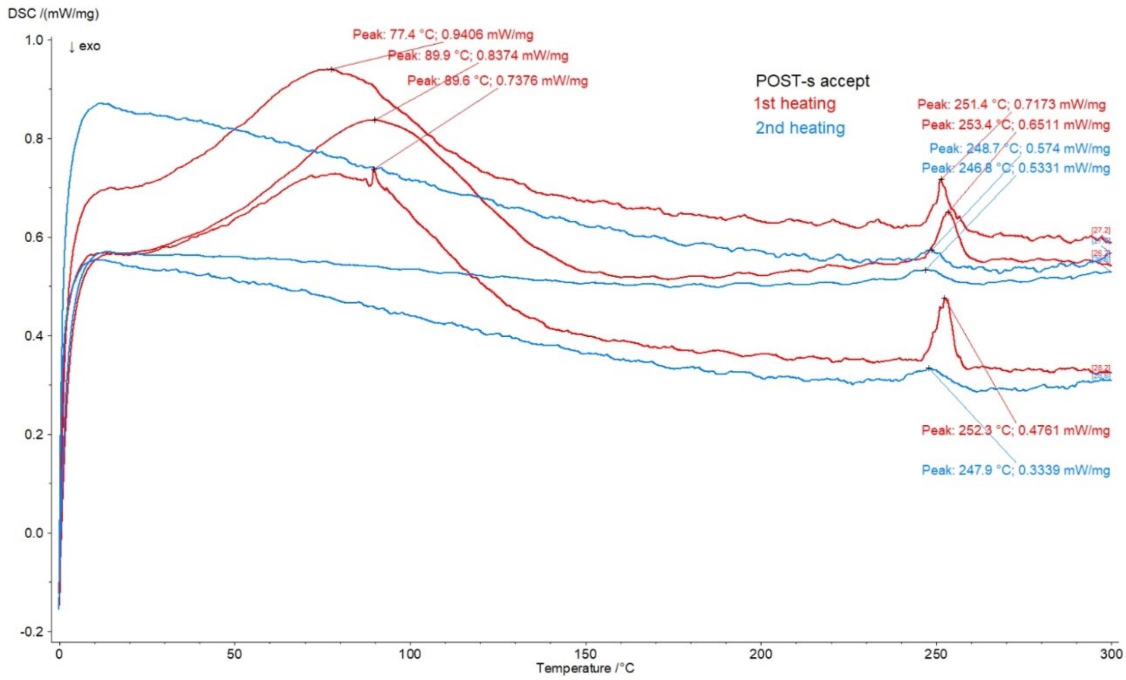


Figure D. 9: DSC curves for POST-s accept. The peaks are detected with the help of NE-TZSCH software.

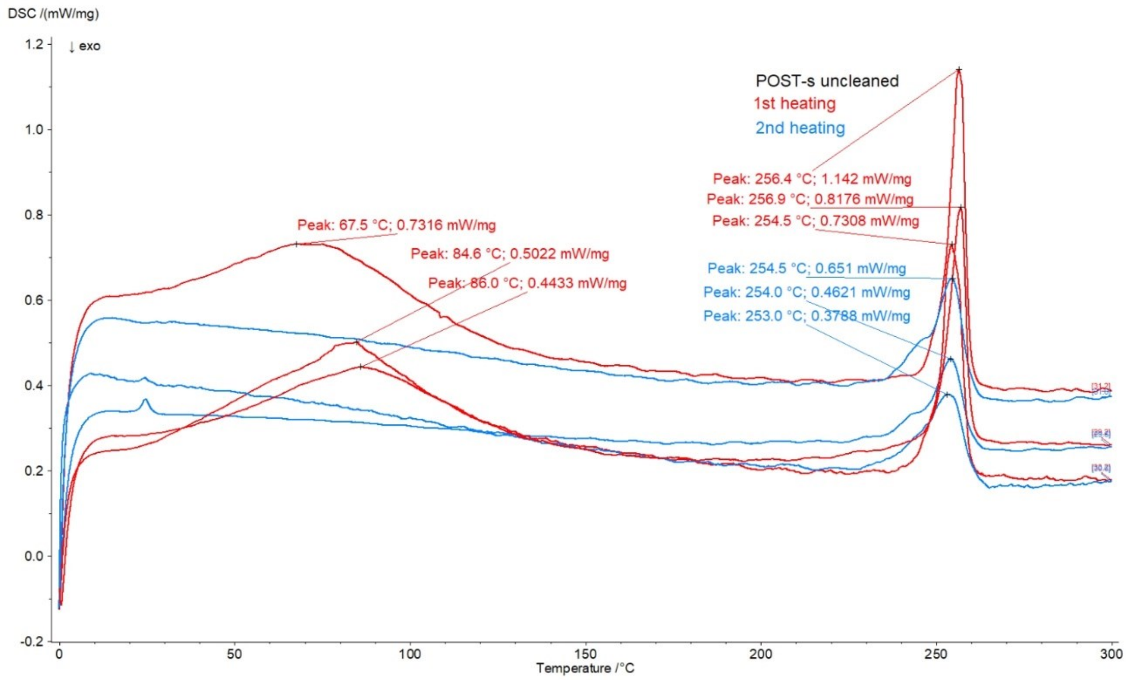


Figure D. 10: DSC curves for POST-s uncleaned. The peaks are detected with the help of NE-TZSCH software.

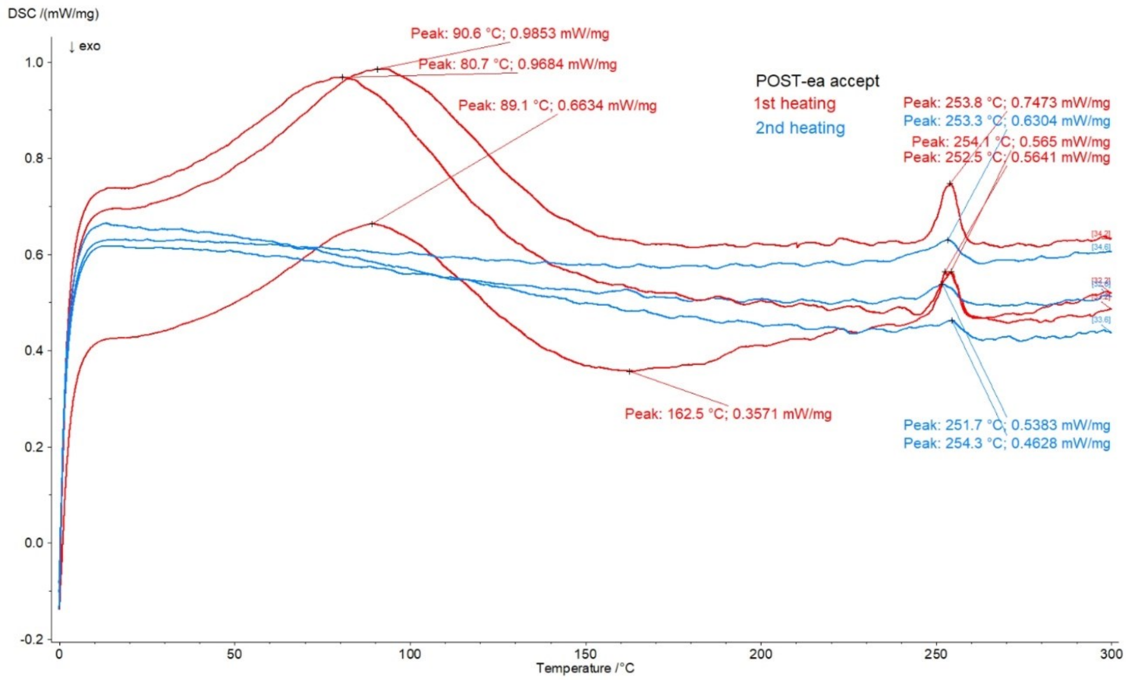


Figure D. 11: DSC curves for POST-ea accept. The peaks are detected with the help of NE-TZSCH software.

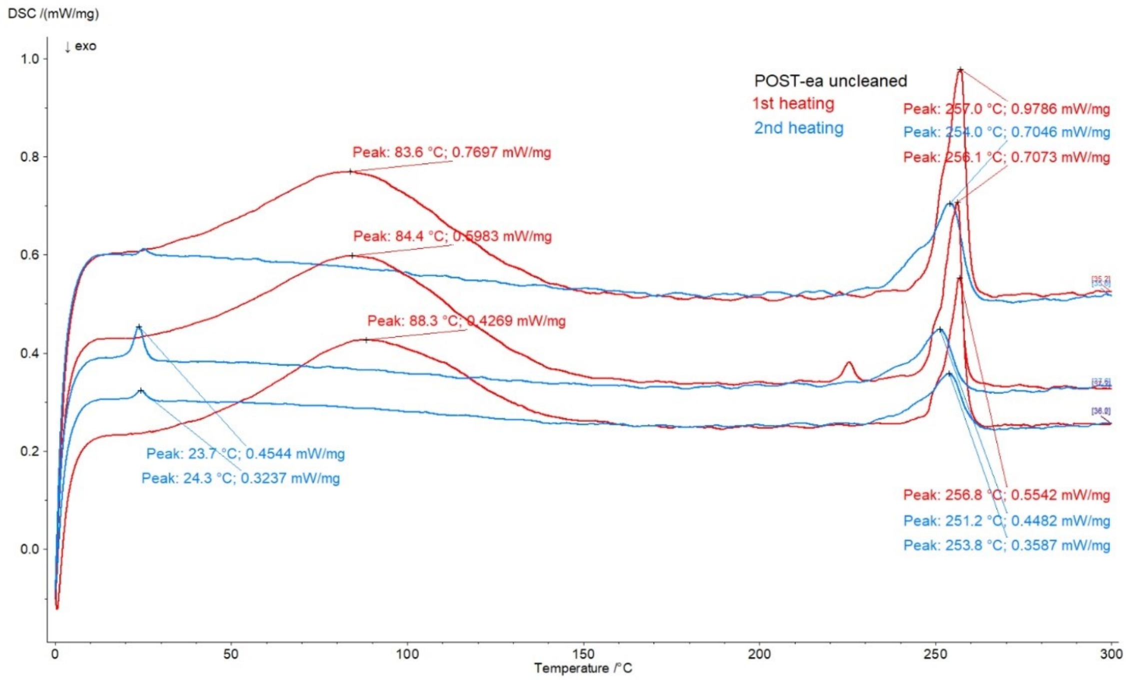


Figure D. 12: DSC curves for POST-ea uncleaned. The peaks are detected with the help of NE-TZSCH software

APPENDIX E: FT-IR RESULTS

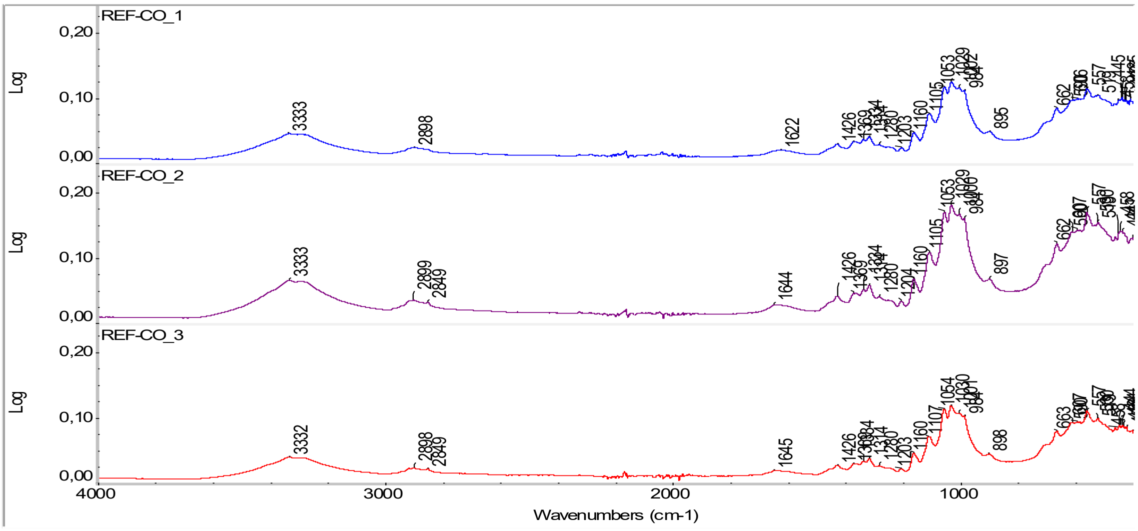


Figure E. 1: FT-IR spectra for REF-CO accept.

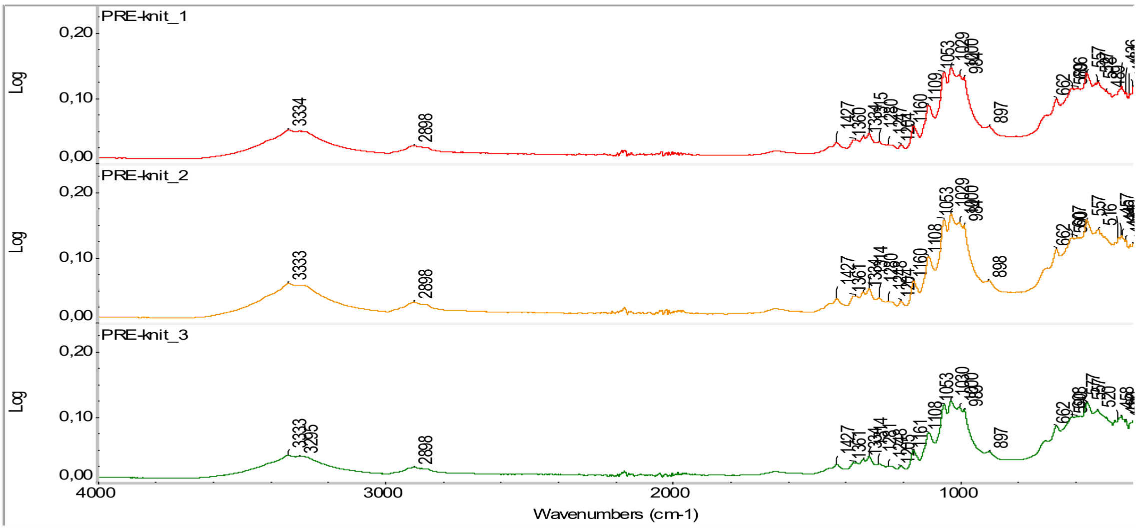


Figure E. 2: FT-IR spectra for PRE-KNIT (company) accept.

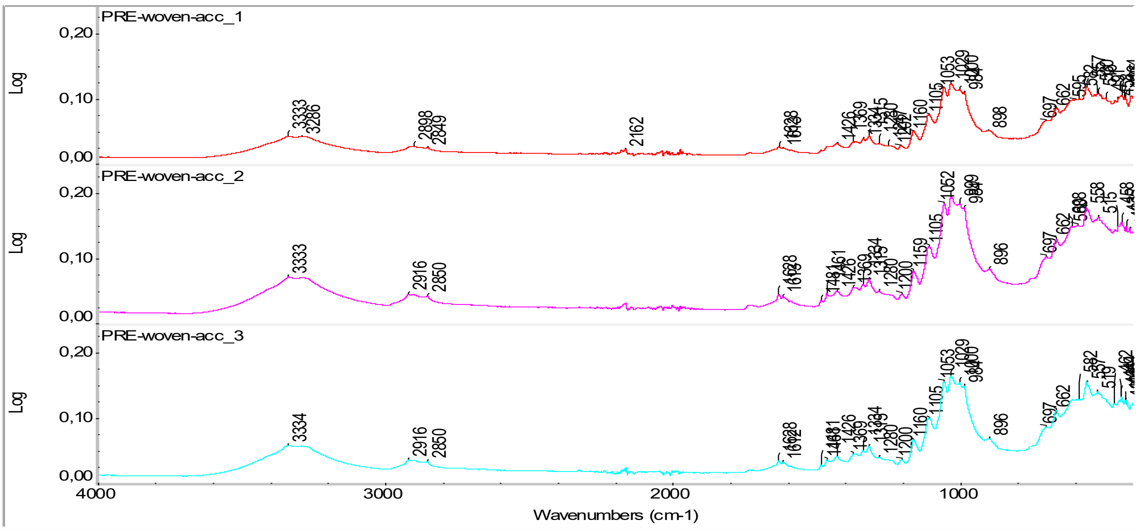


Figure E. 3: FT-IR spectra for PRE-WOVEN accept.

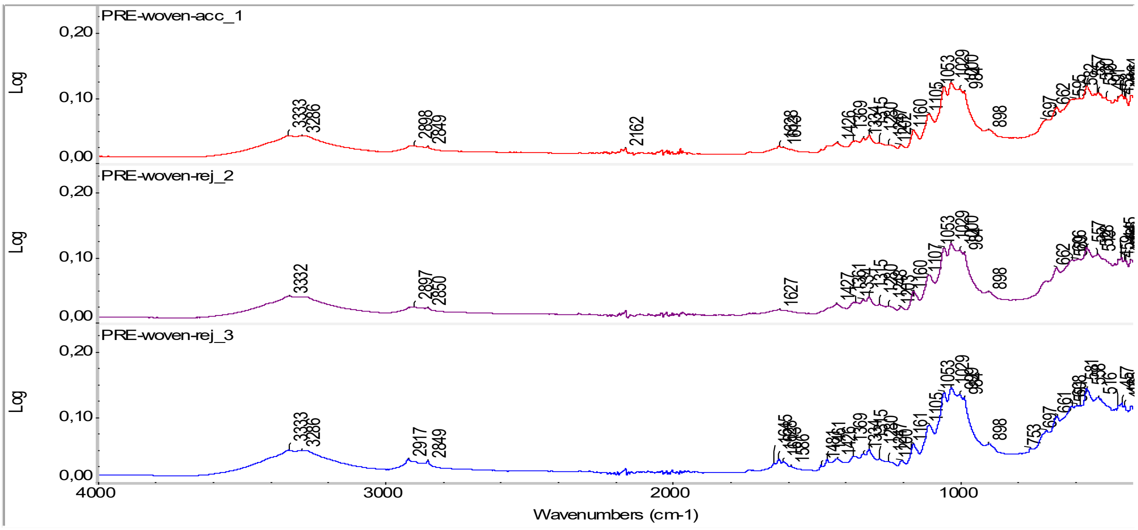


Figure E. 4: FT-IR spectra for PRE-WOVEN reject.

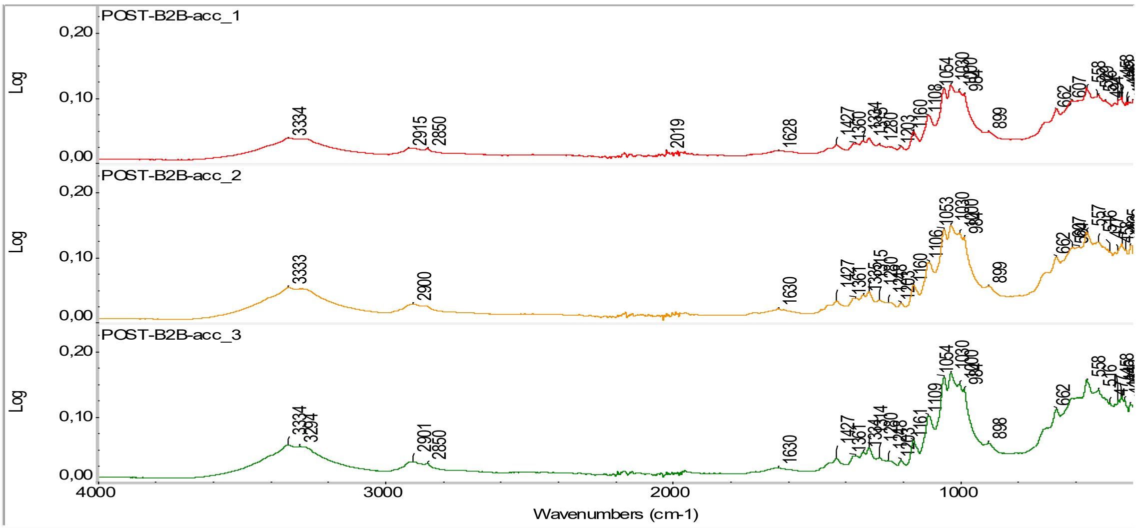


Figure E. 5: FT-IR spectra for POST-B2B accept.

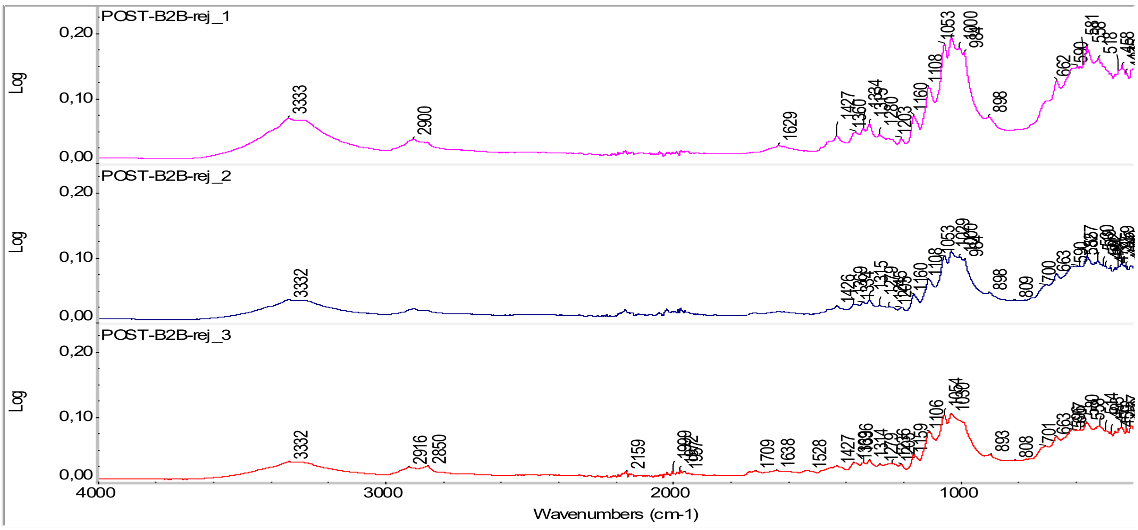


Figure E. 6: FT-IR spectra for POST-B2B reject.

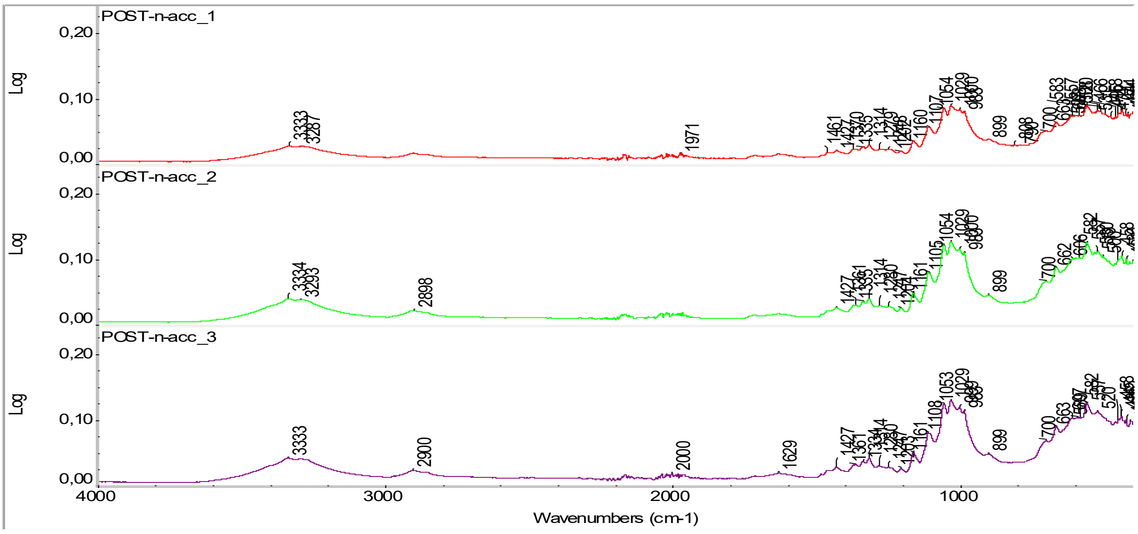


Figure E. 7: FT-IR spectra for POST-n accept.

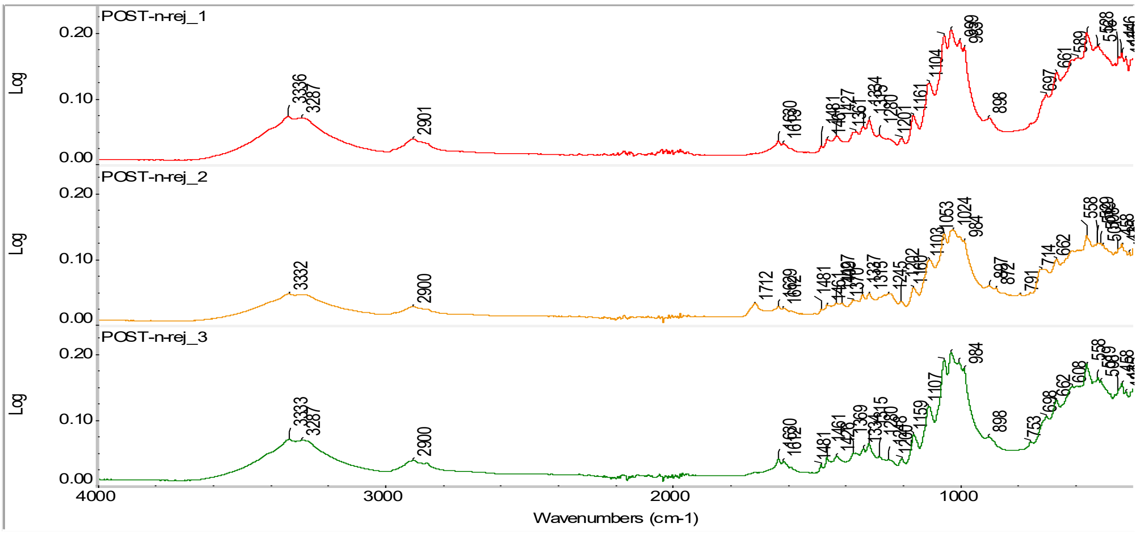


Figure E. 8: FT-IR spectra for POST-n reject.

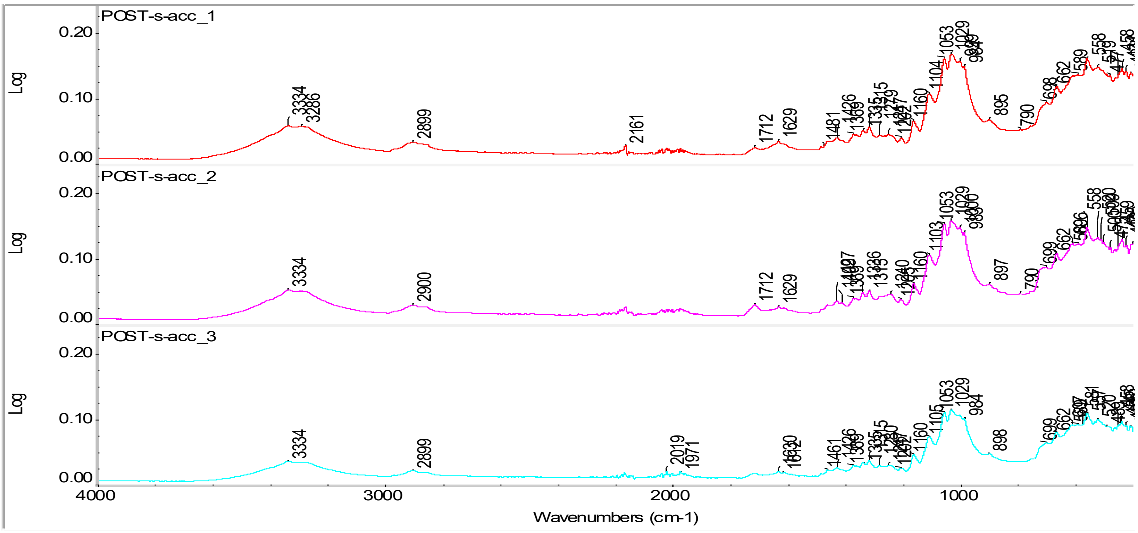


Figure E. 9: FT-IR spectra for POST-s accept.

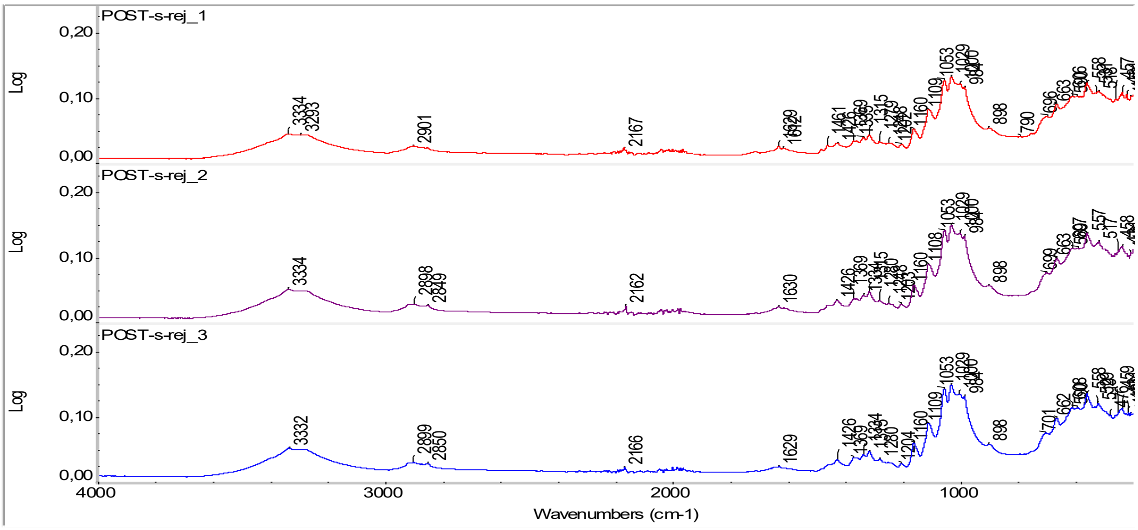


Figure E. 10: FT-IR spectra for POST-s reject.

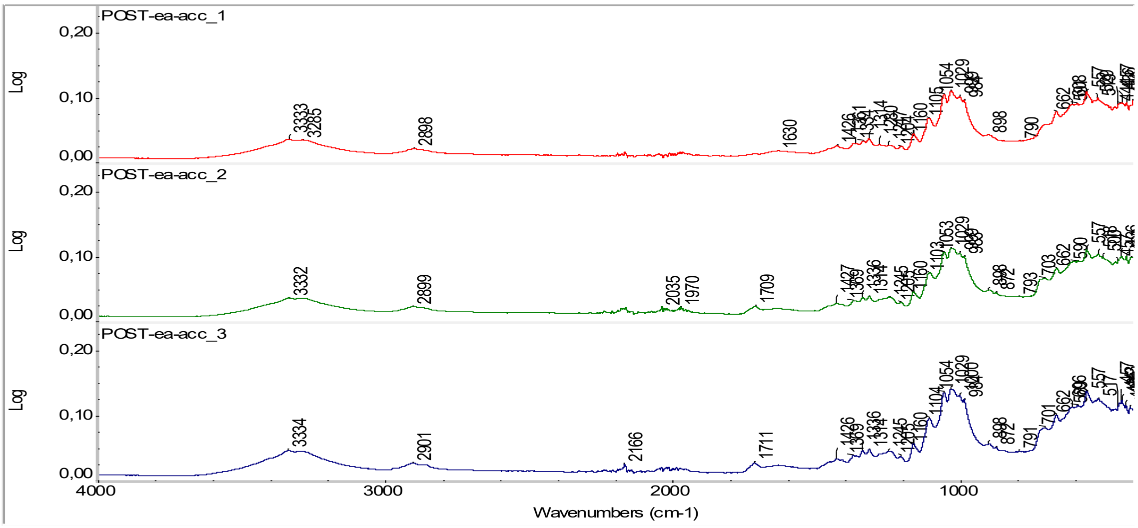


Figure E. 11: FT-IR spectra for POST-ea accept.

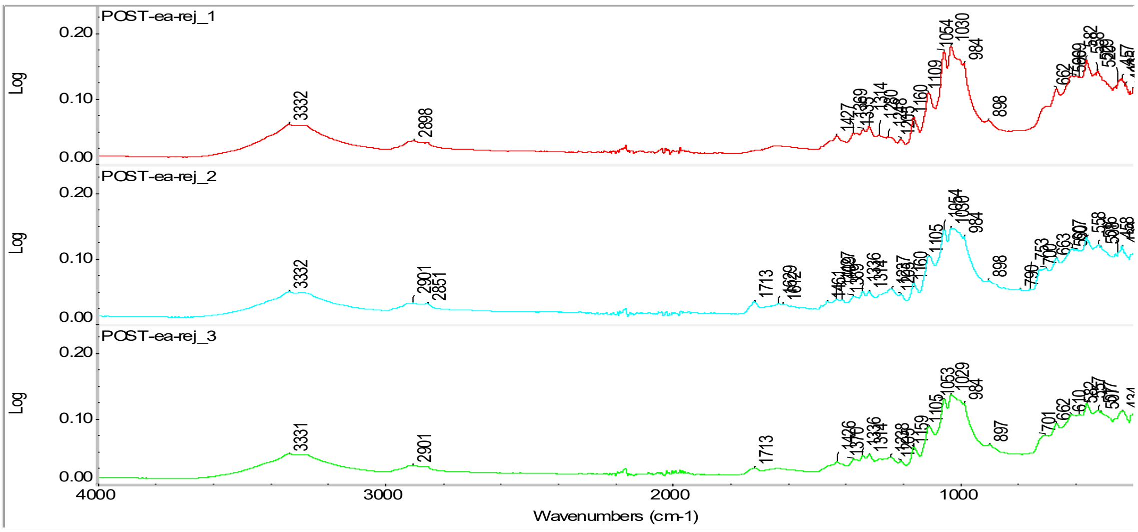


Figure E. 12: FT-IR spectra for POST-ea reject.