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Ring spinning of recycled cotton fibers blended with natural fibers

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SAXION

Ring spinning of recycled cotton fibers blended with natural fibers

Master Thesis

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Preface

This thesis is written as part of the masters program Innovative Textile Development of Saxion University of Applied Sciences, Enschede, the Netherlands. The thesis research is executed and written over the period of five months from September 2018 to January 2019. The thesis was written in collaboration with the Swedish School of Textiles in Borås, Sweden.

I would like to thank all the people at the Swedish School of Textiles for an educative time. I would like to thank Anders Persson and Nawar Kadi for their help with the research and a special thanks to Katarina Lindström Ramamoorthy for all her help and support during my time in Sweden. I would also like to thank Pramod Agrawal from the Saxion University of Applied Sciences for his help and feedback.

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Abstract

The fast fashion industry leads to high consumption and waste generation. To reduce the waste, recycling plays an important part. With mechanical recycling the textiles are shredded into fibers for reuse. The downside of mechanical recycling is that the harsh process decreases the fiber length, which influences the quality of the eventual yarn. At the Swedish School of Textiles, previous research showed that the fiber length loss during shredding could be decreased by pre-treatment of the textile. A lubricant pre-treatment reduced friction in the process which made the shredding process gentler and longer fibers was obtained. The research at hand focuses on the possibility to ring spin the untreated and treated mechanically recycled cotton fibers.

The untreated and treated recycled cotton fibers were blended with virgin cotton, flax and hemp fibers. The yarn prototypes were evaluated on mechanical properties, tensile strength, elongation, twist number and a visual analysis was performed. To evaluate the yarns in a fabric, plain weft knit textiles were produced with the spun yarns. The knitted fabrics were tested on their mechanical properties, tensile strength, elongation, abrasion and pilling resistance as well as flexibility.

After optimizing the ring spinning process for short staple fibers, a spinnable blend was achieved with 60% untreated or treated recycled cotton fibers. However it was not possible to spin this with 40% hemp or flax fibers, in all yarns at least 10% virgin cotton need to be added for spinnability. During the spinning it was noticed that the spinnability of the treated recycled cotton fibers compared to the untreated recycled cotton fibers was equally. There was also no significant difference between the tensile strength of the yarns spun with untreated and treated recycled cotton fiber. The twist number of the yarns was very high, which was necessary to be able to create the yarns. Based on these evaluations, the following best performing yarns were selected for the fabric prototyping:

- 60% untreated recycled cotton, 30% medium cotton, 10% flax;
- 60% treated recycled cotton, 30% medium cotton, 10% flax;
- 60% treated recycled cotton, 40% medium cotton.

The test result of the fabric prototypes showed that the abrasion and pilling resistance of the fabrics were high, which made the fabric suitable for upholstery purposes.

This research shows that friction and rigidity are the main factors that influence the spinnability of the recycled fibers. The blend also influences the spinnability of the recycled cotton fibers. By adding virgin cotton the recycled cotton fibers became more spinnable and by adding flax fibers the yarn gives a higher tensile strength.

1 Introduction

1.1 Company Overview

The Swedish School of Textiles is part of the University of Borås, with several bachelor as well as post graduate programs. The programs are divided into three textile areas: design, engineering and management. There are different areas in which research is done at this university, mostly the focus lies on sustainability and contributing to a better world.

1.2 Problem Analysis

The world population is growing and this has consequences for the environment. People have become used to the 'making, using, disposing' principle, (Stahel, 2016) and the fast fashion industry contributes to this. The fast fashion industry leads to a high level of consumption and waste generation. Around 90.4 million tons of textile fibers were produced in 2014 and this number is expected to grow 3.7% every year. At some point all these fibers turn into waste (Pensupa, et al., 2017). Several industries, including the textile industry, use non-regenerative resources that, eventually, will not be available anymore. For this reason, it is important that products and materials that are currently used can be recycled and made into new products. By implementing this, none or less virgin material is needed for the production of new textile products (Wang, 2006). Recycling of textile waste involves breaking down the textile products and using components for producing new products (Wang, 2006). Nowadays, it is still preferred to use virgin natural and man-made fibers. This is due to the possible poor quality of recycled fibers and fabrics and the obtained, often negative, perception consumers have of recycled fibers (Fletcher, 2008).

The Swedish School of Textiles is dealing with this problem by improving the quality of mechanically recycled fibers, in particular for polyester and cotton fibers. This research is done together with Swerea IVF, a Swedish research institute. The quality of a fabric is highly influenced by the length of the fibers. At the Swedish School of Textiles, a shredding process is developed that obtains longer fibers after shredding by using a treatment. It was possible to spin a yarn out of these fibers using rotor spinning (Sjöblom, 2018). Still, it is also desirable to be able to spin the yarns through ring spinning because, the ring spinning process is most commonly used and produces stronger yarns with a softer hand, compared to rotor spinning (Ahmed, Syduzzaman, Mahmud, & Rahman, 2015). Various research has been done on the rotor spinning of recycled cotton fibers (Yuksekkaya, Celep, Dogan, Tercan, & Urhan, 2016; Halimi, Jaouadi, Hassen, & Sakli, 2008; Wanassi, Azzouz, & Hassen, 2016). However, little information is available on the ring spinning of recycled cotton fibers. Therefore, this research will focus on producing yarns with the recycled cotton fibers using the ring spinning process. It is desirable to use as much recycled cotton fiber as possible, but it is likely that the recycled cotton fibers need to be blended with virgin fibers to be spinnable. The blending fibers should be natural materials with a low environmental impact according to the MADE BY benchmark. Additionally, little information is available on producing a fabric with yarns containing recycled fibers. Therefore this research will also include the production of a fabric with the yarn prototypes.

1.2.1 Field of research (scope)

The previous research done at the Swedish School of Textiles focuses on the recycling of polyester fibers, cotton fibers and polyester cotton blends. This research will only focus on the processing of the recycled cotton fibers. A particular end application for the ring spun yarn produced in this research was not specified by the university. Therefore, it was decided that a benchmark would be set using virgin cotton fibers and achievable requirements will be set for the prototypes containing recycled cotton fibers. The yarns will be knitted into a fabric to see the reproducibility of the yarns. After creating the yarns and fabrics it will be decided for which sector(s) the yarns would be applicable according to its properties.

1.3 Research Questions

How can a yarn be created with the ring spinning method, containing the maximum amount of mechanically recycled cotton fibers, blended with natural fibers, while achieving the minimum required mechanical properties?

Sub-questions

- What are the parameters that influence the spinnability of the recycled cotton fibers?
- What are the mechanical properties of the yarn prototypes?
- How can fabric be produced with the yarn prototypes?
- What are the mechanical properties of the fabric prototypes?
- How can the newly produced yarn be implemented in the textile industry?

1.4 Literature review

This literature will give preparatory information about textile recycling and the different methods to recycle textiles. This will be followed by information about the ring spinning process and aspects that influence the properties of the yarn. In the final paragraph information is given about the selection of fibers for blending.

1.4.1 Textile recycling

Generally when hearing about recycled textiles this is immediately considered a sustainable alternative, however not in all cases this is true. The yarn prototypes produced in this research were analyzed on their sustainability, regarding the production process and the materials used. A review study about the environmental impact of textile recycling was analyzed. The publications reviewed by Sandin and Peters (2018) support the statement that compared to incineration and disposing to landfills, the recycling of textiles commonly reduces the impact it has on the environment. This is however dependent on each specific situation. In general the environmental impact shredding the material in to fibers has is lower than the environmental impact for disposing to landfills and incineration (Esteve-Turrillas & de la Guardia, 2017). It can be beneficial for textile companies to recycle their waste. It will reduce the costs that are spend on waste processing the recycled materials could be sold or used for own purposes. Furthermore, it contributes to a positive image perceived by the society. Textiles are nearly 100% recyclable, but due to the low quality of the recycled textiles, compared to the virgin textiles, there is not always a purpose for these recycled textiles (Hawley, 2014). Textile waste can be recycled in different ways, including extrusion, chemical and mechanical methods (Bartl, Hackl, Mihalyi, Wistuba, & Marini, 2005).

Extrusion: thermo-mechanical recycling

Extrusion concerns the melting of thermoplastic waste, to obtain pellets. The most common used method is extruding the pellets directly into fibers, but the pellets can also be saved for later use (Patel, Patel, & Sinha, 2010). The following extrusion steps can be differentiated: cutting, compacting/drying or drying and feeding to extruder (Altun & Ulcay, 2004). This method is only suitable for synthetic fibers such as polyester, and can only be used if the material is a mono material (Horrocks, 1996).

Chemical recycling

Chemical recycling involves a transformation of the polymer chain, also called depolymerization. The polymer is degraded into monomer units or oligomers (Sinha, Patel, & Patel, 2010). In chemical fiber-to-fiber recycling, changes on the molecular level are made to textile fibers through chemical processing to form recycled fibers (Palme, Peterson, De la Motte, Theliander, & Brelid, 2017). First, the waste is collected, sorted and then subjected to a mechanical shredding process before depolymerization (Wang, 2010).

Mechanical recycling

Mechanical recycling is done by unraveling discarded textile into patches (Modint B.V., 2010). The fibers pass through a drum rotating surface several times to obtain fibers (Fletcher, 2008). To enhance the quality of the fibers the short fibers should be eliminated, furthermore should the fibers be cleaned and blended with virgin fibers, if needed (Oakdene Hollins Ltd., 2009). The length of the fibers is an essential parameter in yarn spinning, which may be significantly reduced by the mechanical treatment to obtain fibers from fabrics. Therefore, it is common practice to mix recycled fibers with virgin fibers in order to obtain a higher quality yarn (Gulich, 2006). However, for most fibers, mechanical recycling leads to recycled fibers of inferior quality (Watson, Elander, Gylling, Andersson, & Heikkila, 2017). A large part of the textile waste, that is mechanically recycled, is used for manufacturing nonwoven products. Spinning new yarns from a recycled fiber is much more complicated than using it for a non-woven application (Modint B.V., 2010)

At the Swedish School of Textiles research is done to obtain longer cotton fibers after shredding. This is important for increasing the quality and spinnability of mechanically recycled fibers. This is done by treating the fabrics before shredding. The cotton is treated with two treatments polyethene glycol (PEG) 4000 and glycerol. These are both considered environmentally friendly chemicals. PEG 4000 can be used in the textile industry as lubricant, softener, antistatic agent and conditioning agent. Glycerol can be used in the textile industry as lubricant, softener, sizing agent and finishing agent. These were added to reduce the inter-fiber friction (Sjöblom, 2018). With a high friction between the fibers a strong opening force is required during shredding. By reducing the inter-fiber friction less force is needed to open the fibers less damage is done to the fibers and longer fibers can be obtained (Namuga, 2017). The glycerol treatments turned out not to be effective in contrast to the PEG 4000 treatment. By treating the cotton with 0.29 w% PEG 4000 the fibers were almost 50% longer compared to the fibers of the untreated cotton. Additionally, it was possible to spin a yarn, using rotor spinning, of 100% recycled cotton which was stronger than the 100% recycled cotton yarn from the untreated fabric (Sjöblom, 2018).

Recycled yarn

To produce yarns out of recycled fibers rotor spinning is most often used (Vadicherla & Saravanan, 2017). In a few cases friction spinning is used. Usually coarse yarns are produced with recycled fibers.

Some research was done on the influences of the percentage of recycled fiber content in a yarn by Vadicherla and Saravanan (2017). This concerned recycled polyester fiber blended with virgin cotton fibers. This research used ring spinning to produce the yarns with three linear densities; 23.6, 29.5 and 39.4 tex. The fiber length of the cotton used was 27.1 mm and the recycled polyester had a fiber length of 34.2 mm. An increase in the percentage of recycled polyester content equaled an increase in the tensile strength and elongation. A higher recycled polyester content also made for a more even yarn (Vadicherla & Saravanan, 2017).

In the research of Wanassi, Azzouz & Hassen (2016) rotor spun yarns were produced with 50% recycled cotton and 50% virgin cotton, in three linear densities; 60,40 and 30 tex. It was noticed that the produced yarn had lower tensile properties and a lower hairiness and evenness than a 100% virgin cotton yarn. When it comes to costs, the produced yarn would reduce the manufacturing costs by 33.5% compared to 100% virgin cotton yarns (Wanassi, Azzouz, & Hassen, 2016).

Halimi, Hassen, Azzouz & Sakli (2007) did research on influence of cotton waste and rotor spinning parameters on the yarn. This research concluded that the percentage of waste influences the quality of the yarn. However, up to 25% of waste fibers did not influence the quality of the yarn. The selection of parameters for the rotor spinning process also influences the yarn quality strongly (Halmi, Hassen, Azzouz, & Sakli, 2007).

In the research of Merati and Okamura (2004) a friction spun, 30 tex, yarn is produced containing different recycled fibers. This research showed that when 100% recycled fibers were used or only two components, recycled fibers and cotton, the 30 tex yarns were weak or difficult to spin. A three component yarn was produced with a filament core, recycled fibers as the middle layer and virgin fibers as the outer layer. This yarn was stronger and had a more even appearance as the other yarns (Merati & Okamura, 2004).

Rotor spinning was used to produce yarns with recycled fibers in the research of Telli and Babaarslan (2017). In this research yarn from recycled PET bottles and recycled cotton fibers were produced. The yarn with 25% recycled cotton and 75% recycled PET had the best results. The fiber length of the recycled PET fiber was 38 mm and for the recycled cotton the length was 25.5 mm (Telli & Babaarslan, 2017).

The research of Halimi, Hassen and Sakli (2008) produced rotor spun yarns with recycled cotton fibers. It showed that a yarn could be produced containing between 15 and 25% recycled cotton fiber without influencing the yarn quality. The research highlights the importance of evaluating the quality of the waste before using it for further purposes (Halimi, Hassen, & Sakli, 2008).

1.4.2 Ring Spinning

As mentioned previously most spinning with recycled cotton fibers is done via rotor spinning. However, friction spinning and ring spinning are methods that can also be used for the spinning of recycled fibers. Rotor spinning is a fast and often used method to produce yarns but produces a yarn that gives a harsh feel to the fabric (Tyagi, 2010). Rotor spinning is cheaper than ring spinning and processes a more even yarn, even though the strength of rotor spun yarn is lower than ring spun yarns. Furthermore, a wider range of different yarn counts can be produced with a ring spinning machine compared to rotor spinning (Ahmed, Syduzzaman, Mahmud, & Rahman, 2015). Additionally rotor spun fibers have a poor orientation, as well as friction spun yarns. Friction spun yarns are generally not as strong as ring spun yarns, but the yarn appearance of friction yarns is very good. Ring spinning can contribute to a stronger yarn and, is the most often used method for cotton yarn spinning. The fiber orientation of ring spun yarns is good, which helps with the spinning of short staple fibers (Tyagi, 2010).

On the other hand, the mean fiber length distribution necessary for ring spinning is higher than for rotor spinning (Ahmed, Syduzzaman, Mahmud, & Rahman, 2015). Several steps are needed prior to the ring spinning. First the fibers go through an opening step. In this step the bales containing the fibers are reduced into smaller fiber pieces while removing dirt and other impurities. In this process step the fibers can be blended with different fibers. Following, the loose fibers go through a carding machine, to produce a web. The fibers in the web will then become more parallel during drawing and a sliver or a roving is produced. This step is followed by ring spinning where the sliver or roving is stretched and twisted into a yarn. This can be done using a z-twist, which is more commonly used, or an s-twist (Alagirusamy & Das, 2015).

To be able to produce a yarn in a ring spinning machine a sliver or roving is supplied to the ring spinning machine. To obtain the right amount of fiber for the desired thickness of the yarn a roller drafting system is used. During this process the fiber strand becomes thinner, how much thinner is defined by the amount of draft used. A higher draft equals a thinner fiber strand and thus a thinner yarn. Subsequently twist needs to be added to the fiber strand to produce a yarn. A bobbin is placed on the rotating spindle of the machine, the yarn will be collected on this bobbin. The yarn from the bobbin will go under the traveler, which is placed over the ring as shown in Figure 1. Following, the yarn goes through a guide eye and is connected to the fiber strand at the front roller of the drafting system (Rengasamy, 2010).

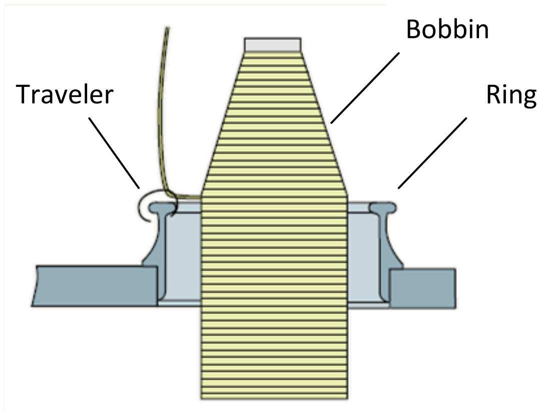

Figure 1. Cone, ring and traveler
Note. Adapted from "Volume 4 – Ring Spinning" by W. Klein and H. Stalder. 2016, *The Rieter Manual of Spinning*, p. 26.

The traveler rotates around the ring, adding the twist to the yarn (Rengasamy, 2010). The rotating bobbin makes the traveler move around the ring and, as the bobbin moves faster than the traveler, the yarn is wrapped around the bobbin simultaneously. Additionally, the ring also moves up and down the bobbin to spread the yarn over the entire bobbin (Lord, 2003).

At the front roller where the fibers are shaped into a yarn there is a spinning triangle. The width and the length of this triangle influence the quality of the yarn. Most of the yarn breakage happens at this point. A high twist usually leads to a short spinning triangle as shown in Figure 2 and a low twist results in a long spinning triangle (Klein & Stalder, 2016).

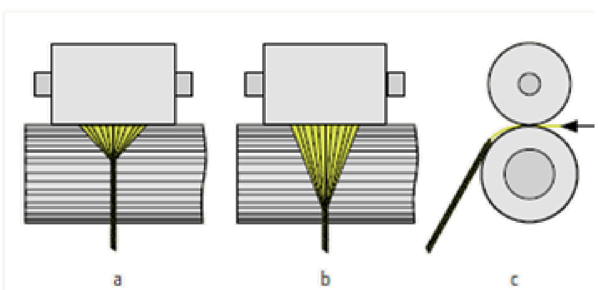

Figure 2. Spinning triangle, short (a), long (b) and side view (c)
Note. Reprinted from "Volume 4 – Ring Spinning" by W. Klein and H. Stalder. 2016, *The Rieter Manual of Spinning*, p. 20.

During spinning, the yarn is leaving the front roller going through the traveler, obtaining a balloon around the bobbin. This balloon is usually guided by a balloon control ring. The size of the balloon is hugely dependent on the yarn tension, as well as the mass of the traveler used. When the mass is too low the balloon becomes too big, and the other way around (Klein & Stalder, 2016). The shape of the traveler also influences the properties of the yarn. The different shapes can be found in Figure 3. When the balloon is not sufficient it can collapse, this usually happens when the neck of the balloon touches the top of the bobbin and causes the yarn to break. This can be prevented by selecting the right mass of the traveler and reducing the spindle speed, but this influences the productivity of the spinning (Rengasamy, 2010).

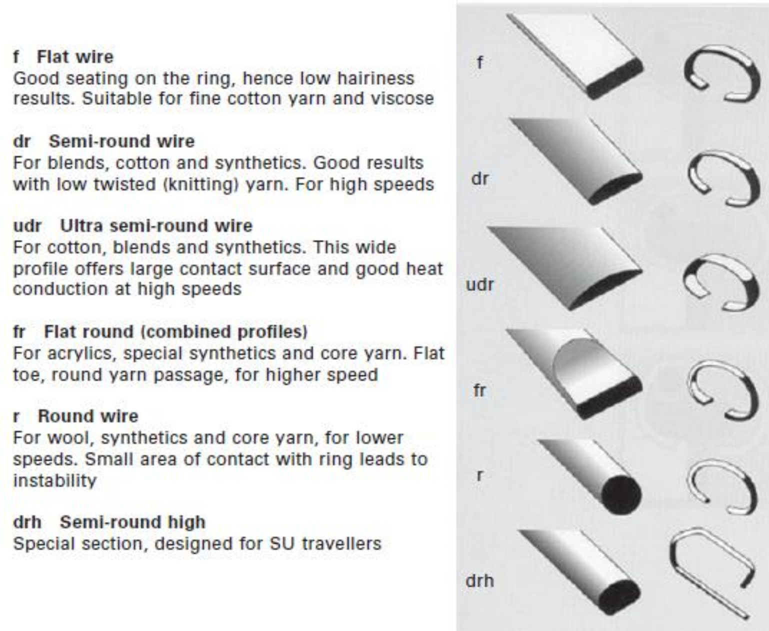

Figure 3. Cross-section of travelers
Note. Reprinted from "Fundamental principles of ring spinning of yarn" by R.S. Rengsamy. 2010, *Woodhead Publishing Limited*, p. 57. Copyright 2010 by Woodhead Publishing Limited.

Ring spinning of short staple fibers

Drafting system

In general, for the ring spinning of short staple fibers two rollers are used and one apron. This is called a double apron drafting system and can be seen in Figure 4. For short staple fiber spinning usually a long bottom apron and a short top apron is used as illustrated in Figure 5. The aprons are usually made of a synthetic material. During the drafting, the problem that occurs with a high percentage of short fibers in the sliver is that the amount of fibers passing through the drafting system is uneven. The fibers are uncontrollably pulled out from the rollers or the apron, which creates an uneven stream of fibers and thus an uneven spinning triangle. This also causes yarn breakage when there are too little fibers to make a yarn (Rengasamy, 2010).

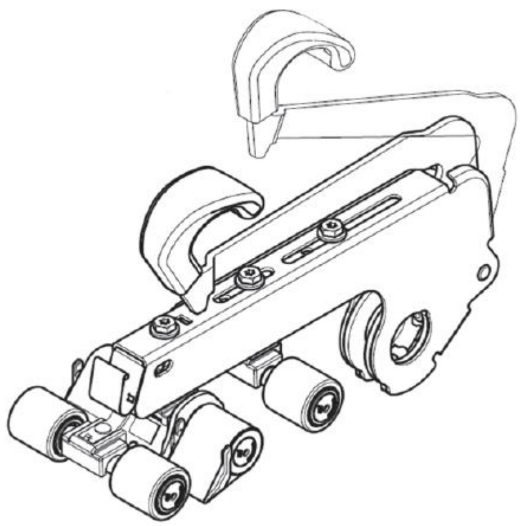

Figure 4. Double apron drafting system

Note. Reprinted from “Fundamental principles of ring spinning of yarn” by R.S. Rengsamy. 2010, *Woodhead Publishing Limited*, p. 51. Copyright 2010 by Woodhead Publishing Limited.

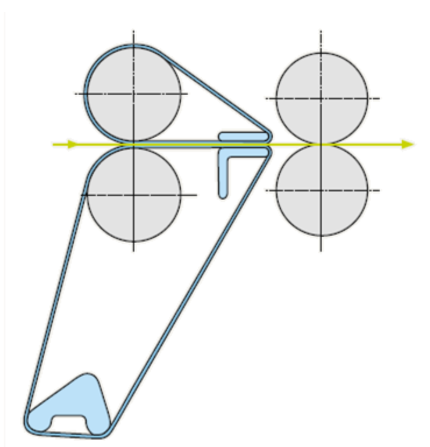

Figure 5. Apron system with long bottom apron
Note. Reprinted from “Volume 4 – Ring Spinning” by W. Klein and H. Stalder. 2016, *The Rieter Manual of Spinning*, p. 20. Copyright 2016 by Rieter Machine Works Ltd.

To prevent the fibers from leaving the apron too soon the pressure of the top apron on the bottom apron should be adjusted. This can be done by changing the spacer clips used on top apron system as shown in Figure 6. Finding the right spacer clip to use for a specific yarn is done by practice, to see which spacer clip contributes to the right yarn count and rigidity of the yarn (Rengasamy, 2010).

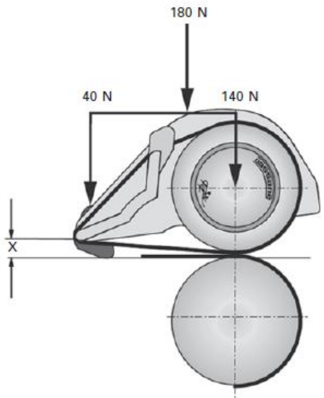

Figure 6. Spacer clips on the drafting system
Note. Reprinted from "Fundamental principles of ring spinning of yarn" by R.S. Rengsamy. 2010, *Woodhead Publishing Limited*, p. 52. Copyright 2010 by Woodhead Publishing Limited.

The front and back roller that are used in the double apron drafting system are usually made of synthetic material and can vary in hardness. With a softer roller the area of contact with the fibers is increased and also the contact between the fibers. This provides a better grip on the fibers while spinning and is therefore suitable for short staple fiber spinning (Rengasamy, 2010; Klein & Stalder, 2016).

Traveler
The traveler of the ring spinning process travels around the ring to create twist in the fiber strand while winding the yarn onto the bobbin. The diameter and shape of the traveler may vary, depending on the yarn density (Lord, 2003; Rengasamy, 2010). The traveler weight influences the yarn tension, which determines the size of the balloon. Additionally the traveler weight and shape influence the hairiness of the yarn. The traveler weight should around be 2.6 mg/tex (Lord, 2003).

1.4.3 Aspects to influence yarn properties

There are different aspects that influence the properties of a yarn during spinning. In this paragraph these influences will be discussed. First the influences of the fibers will be discussed, followed by the influences of the spinning process.

Fibers

Fiber fineness
The first aspect that influences the properties of a yarn is the fineness of the fibers that used during spinning. When many fibers are present in the cross-sectional area of a yarn they contribute to a higher strength of the yarn. According to Klein the following aspects are influenced by fiber fineness:

- "yarn strength;
- yarn evenness;
- yarn fullness;
- drape of the fabric;
- luster;

- handle;
- productivity of the process" (Klein, 2016, p. 13).

The fiber fineness also influences the rigidity of the fibers. As a lower fineness equals a more rigid fiber. The fineness of fibers can be defined by the correlation between the weight and the length of the fiber. The following, Equation 1 is applicable (Klein, 2016):

$$\boldsymbol{tex} = \frac{\boldsymbol{mass\ (gram)}}{\boldsymbol{km}} \tag{1}$$

There also is a fineness scale for cotton fibers in specific, for this the Micronaire (Mic) value is used. To convert the text number to the Mic value of a fiber the conversion in Equation 2 can be used (Montalvo, 2005; Klein, 2016).

$$\boldsymbol{Mic} = \ \boldsymbol{tex} \div \mathbf{0.0394} \tag{2}$$

The fineness scale can be seen in Table 1:

Table 1
Fiber fineness scale cotton

Mic Value	**Fineness**
up to 3.1	very fine
3.1-3.9	fine
4.0-4.9	medium (premium range)
5.0-5.9	slightly coarse
above 6	coarse

Note. Reprinted from "Volume 1 – Technology of Short-staple Spinning" by W. Klein. 2016, *The Rieter Manual of Spinning*, p. 13. Copyright 2016 by Rieter Machine Works Ltd.

Fiber maturity

This aspect is only relevant for cotton fibers. Cotton fibers consist of lumen and cell walls. The thickness of the cell wall defines the maturity index. The growth of the cell walls is influenced by the environment. If the growing conditions are positive the cotton will have a thick cell wall and is called mature. In the opposite case the fibers weaker, and are called immature (Wakelyn, et al., 2007; Klein, The Rieter Manual of Spinning, 2016). The fiber maturity is defined by the wall area (Aw) in ratio to the total fiber area. When a fiber has matured too much, the fibers can become stiff which is an undesired result (Morton & Hearle, 2008)

Fiber length

The length of the fibers is an essential parameter in yarn spinning (Gulich, 2006). The fiber length influences several aspects during spinning, as mentioned by Klein, such as:

- "yarn strength;
- yarn evenness;
- handle of the product;
- luster of the product;
- yarn hairiness;
- productivity" (Klein, The Rieter Manual of Spinning, 2016, p. 14).

Fibers up to a length between 12 and 15 mm do not contribute much to the strength of a yarn, only the fullness. Some of these fibers might even get lost during processing. Fibers longer than 12-15 mm contribute to a stronger yarn (Klein, The Rieter Manual of Spinning, 2016; Wakelyn, et al., 2007). The length of cotton fibers and the fineness of the fibers are related to one another. In general, the longer the cotton fibers, the finer these fibers are (Morton & Hearle, 2008).

Fiber strength

Fibers with low strength cannot be used in textile applications. The minimum strength requirement for textile fibers is 6 cN/tex. When spun into a yarn the minimum strength requirement for a yarn is 3 cN/tex. For cotton fibers the breaking strength is between 15-40 cN/tex. The strength of cotton fibers is also dependent on the moisture content, as cotton fibers get stronger while containing more moisture (Klein, The Rieter Manual of Spinning, 2016). The strength of the fibers used for spinning is most important in defining the strength of a ring spun yarn (Simpson & Murray, 1978)

Fiber friction

The friction between fibers can be described as the resistance when the fibers slide against each other (El Mogahzy, Broughton, & Wang, 1994). The fiber friction is dependent on the morphology of the fibers that are used like, the linear density length, crimp, cross-sectional shape and the structure of the surface of the fiber. These characteristics can be modified by the use of treatments on the fibers. Additionally, the fiber friction influences the spinnability coherently with the static electrical properties and the hygroscopic nature of the fiber (Kothari & Das, 2008; Gupta, 2008). When the fiber friction is too low it can cause slippage of the fibers during drafting which causes uncontrolled movement of the fibers. Though, a fiber friction that is too high is also not beneficial as this may cause difficulties for the separation of the fiber during opening or carding (Gupta, 2008).

Process influences

Blending

Blending fibers is used for many reasons; to add characteristics of other fibers to the yarn, to lower the costs and to improve the process ability of the fibers. Blending can happen at different stages of the spinning process. During opening the fibers can be blended, this is called flock blending. The advantage of this is a good cross-sectional blend. Another option is to do fiber blending, where the fibers are blended during carding. This method helps distributing the fibers and creating an intimate blend. The next option is to use sliver blending. With this method the slivers are combined during drawing. Finally, two yarns can also be blended; this is a non-intimate blend (Klein, The Rieter Manual of Spinning, 2016; Lam, Zhang, Guo, Ho, & Li, 2017).

Twist

The twist in a yarn is important because it creates the friction between the fibers that keeps the yarn together. With short fibers there is usually less friction between the fibers, by increasing the twist more friction is obtained (Behery, 2010). It is possible to produce a yarn in two twist directions, with an S- or a Z-twist. When using short staple yarns, it is more common to use a Z-twist (Klein, The Rieter Manual of Spinning, 2016).

Draft

To obtain the correct number of fibers before twisting the yarn roller drafting is used. For the spinning of cotton fibers, the break draft usually varies between 1.1 and 1.5 break draft and between 6 and 30 for the main draft (Rengasamy, 2010). The break draft is usually not adjusted because it is mostly used to prepare the fibers for the main draft. By increasing the main draft, the fiber fineness will increase as well as the parallelization of the fibers (Klein, The Rieter Manual of Spinning, 2016).

1.4.4 Fiber selection

The produced yarn should contain the highest amount of recycled cotton fiber as possible, but can be blended with other fibers to improve the spinnability of the fiber. When selecting the fibers to blend with the recycled cotton several aspects were taken into account. A trend in the current society is the use of natural materials. Conscious customers tend to be more interested in buying products of a natural origin (Dawson, 2011; Muzyczek, 2012). Therefore, it is chosen to use natural fibers to blend with the recycled cotton fiber. Furthermore, the environmental impact of the fibers is considered while selecting. For this selection the MADE BY benchmark was used to evaluate the fibers. This benchmark evaluates six parameters. It takes into account the impact of these parameters while producing the fibers until spinning. So, it does not involve the spinning and the steps that follow after this. The parameters are:

- green house gases;
- human toxicity;
- eco-toxicity;
- energy input;
- water input and land use (MADE-BY, 2013).

Within the timeframe of this research it was decided to use three different fibers to blend with the recycled cotton fibers. Looking at the fibers from Class A, as shown in Figure 7, organic flax, organic hemp and recycled wool would be suitable to blend with the recycled cotton fibers. Eventhough, it is not desirable to add more recycled fibers to the recycled cotton so recycled wool will not be used. Flax and Hemp were selected for blending with the recycled cotton fibers. In Class B there are some natural fiber that can be used for blending. It was decided to add organic cotton to the selection as it is desirable for possible closed loop recycling to have a mono material (Brouwer, 2017; Wang, 2006)

MADE-BY ENVIRONMENTAL BENCHMARK FOR FIBRES www.made-by.org

CLASS A	CLASS B	CLASS C	CLASS D	CLASS E	UNCLASSIFIED
Mechanically Recycled Nylon	Chemically Recycled Nylon	Conventional Flax (Linen)	Modal® (Lenzing Viscose Product)	Bamboo Viscose	Acetate
Mechanically Recycled Polyester	Chemically Recycled Polyester	Conventional Hemp	Poly-acrylic	Conventional Cotton	Alpaca Wool
Organic Flax (Linen)	CRAiLAR® Flax	PLA	Virgin Polyester	Generic Viscose	Cashmere Wool
Organic Hemp	In Conversion Cotton	Ramie		Rayon	Leather
Recycled Cotton	Monocel® (Bamboo Lyocell Product)			Spandex (Elastane)	Mohair Wool
Recycled Wool	Organic Cotton			Virgin Nylon	Natural Bamboo
	TENCEL® (Lenzing Lyocell Product)			Wool	Organic Wool
					Silk

More Sustainable → Less Sustainable

Figure 7. MADE-BY Environmental Benchmark

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Flax

Flax fibers are bast fibers and can reach very high lengths, up to 1 meter. To obtain flax fibers the flax stems first have to undergo the retting process that helps to remove the bast later on in the process. After retting the stems are dried followed by a mechanical process that removes the bast. Afterwards the flax fibers are combed to increase the softness of the fiber. Prior to spinning flax fibers need to be degummed, which means the removal of the gummy substance that keeps the fibers together. On average the fiber length of flax fibers is 20 mm and the fiber fineness is around 20 µm this can be seen in Table 2. Overall flax is known for its high strength, but flax is not very extensible (Mather & Wardman, 2015). The spinning of flax fibers can be difficult due to their irregular nature. The fibers are heterogeneous when it comes to the length as well as the fineness of the fibers (Kozlowski, Mackiewicz-Talarczyk, & Allam, 2012). Additionally, flax fibers have a weak fiber adhesion which can make the spinning difficult (Jos Vanneste nv, 2018). Flax fibers can be cottonized, which means that the flax fiber is made shorter and finer, more similar to cotton. Cottonization can be done by different methods, with chemical or enzyme treatments, ultrasound or with the steam explosion method (Muzyczek, 2012). Flax fibers require relatively little chemicals while growing. (Sevajee & Edyvean, 2007). The direct water use of flax fibers is also low; this leads to a smaller impact on the environment. Furthermore, it is possible to grow flax fibers in Europe which gives companies in Europe the opportunity to produce locally (Turunen & van der Werf, 2008). The bending rigidity of flax fibers is higher than for cotton fibers. This is due to the cross-section shape. The cross-section shape of cotton fibers is flat while the shape of flax fibers is more circular. Additionally, the bending rigidity of flax fibers is higher due to the higher linear density of the fibers. This makes it relatively difficult to spin and blend flax fibers (Harwood, McCormick, Waldron, & Bonadei, 2008).

Hemp

Hemp fibers are also bast fibers and the fibers are obtained from the stem of the hemp plant. To obtain these fibers the same retting process is used as for flax. Hemp is generally known for being strong and durable. The general properties of hemp can be found in Table 2. Similar to flax fibers, hemp fibers are not very extensible. Additionally, hemp fibers also have a poor elastic recovery, the fibers can be harsh and brittle which can make it difficult to spin these fibers. Within the hemp fibers is usually a big variety in length, which influences the average length of the hemp fiber in Table 2. However for spinning only the longer hemp fibers are used as fibers shorter than 15 mm do not contribute to the strength of the yarn (Mather & Wardman, 2015; Horne, 2012). Hemp fibers can also be obtained as a cottonized fiber. The processes to do this are similar to the cottonization of flax fibers. Cottonized hemp fibers are easier to blend with cotton fibers (Muzyczek, 2012). Hemp fibers require even fewer chemicals while growing, but use slightly more water than flax. Furthermore, it is also possible to grow hemp fibers in Europe (Turunen & van der Werf, 2008). Similar to flax fibers, hemp fibers are rather rigid and brittle. Hemp also has a nearly circular cross-section and a low fineness which makes it a rigid fiber; this makes the hemp fibers difficult to spin (Jinqiu & Jianchun, 2009)

Cotton

Cotton is a seed fiber, and can vary strongly in length, with fibers of 9mm up to a length of 60 mm for high quality cotton as shown in Table 2. The fineness of cotton fibers can also vary between averages of 10 to 20 µm. Cotton fibers are fairly strong but have a good abrasion resistance. Wet cotton fibers can get up to 20% stronger (Mather & Wardman, 2015). For the production of regular cotton lots of pesticides and other chemicals are used. The difference with organic cotton is that this is grown without the use of fertilizers and synthetically compounded chemicals (Murugesh Babu, Selvadass, & Somashekar, 2013).

Table 2

Fiber properties hemp, flax and cotton

	Hemp	**Flax**	**Cotton**
Fiber length	Average 15 mm*	Average 20 mm*	High quality 25-60 mm American Upland cottons 13-33 mm Indian and Asiatic cottons 9-25 mm
Fineness	20 µm	20 µm	10 - 20 µm
Tenacity	53-62cN tex^{-1}	55 cN tex^{-1}	15-40 cN tex^{-1}
Elongation at break	1.5%	1.8%	5-10%
Elastic recovery	Poor	Recovers almost completely	Fairly inelastic
Resilience	Good	Good	Low
Moisture regain	12%	12%	7-8%

Note. Adapted from *The Chemistry of Textile Fiber* (p 45,53,55) by R.R. Mather and R.H. Wardman, 2015, Cambridge: The Royal Society of Chemistry. Copyright 2015 by Royal Society of Chemistry.

* Different lengths were found in literature as the length varies depending on the production process. Both fibers can be found with higher lengths.

2 Methodology

This chapter starts with some general information about the methodology that is used for this research. This is followed by a more detailed description of the used methodology. In the detailed description the methodology of the preliminary study is discussed. This is followed by the yarn prototyping and the yarn prototype testing. Then the fabric prototyping, fabric prototype testing and finally the implementation of the prototypes are discussed.

Lamb & Kallal design process model is used as a framework to guide this research (1992), as can be seen in Figure 8. The research is divided in two rounds of the Lamb & Kallal model. The first round concerns the creation of yarns and the second round concern the creation of fabrics. An experimental breakdown structure is created to visualize the steps and can be seen in Figure 9.

In the first *problem identification* phase the problem will be defined and analyzed. Based on literature, requirements will be set for the yarns as well as the fabrics. This phase is followed by the *preliminary ideas* where based on literature research experiments will be done on the different variations that can be made for the yarn prototypes. These variations concern the percentage of blend, type of blend (flax, hemp or virgin cotton), yarn count, method to produce blend and type of twist. Following in the d*esign refinement* phase the most suitable variations are selected that will be used to produce prototypes. In the *prototype development* phase the different yarn prototypes are actually created. These prototypes are evaluated in the *evaluation* phase. The prototypes are tested according to the list of demands that was stated in the beginning of the research.

With the test results the research will go back to the second *problem identification* phase. Here the prototypes will be evaluated on the test results, and compared to the list of demands. The most suitable yarn prototypes will be selected. In the *preliminary ideas* phase research is done on the different methods to produce a fabric from the yarn prototypes. Following the most suitable methods will be selected in the *design refinement* phase. The fabric prototypes are created in the *prototype development* phase and will be evaluated in the *evaluation* phase. The evaluating will be done by testing the fabrics and analyzing the prototypes according to the list of demands. For the implementation of the prototypes a research will be done on the possible applications for the most suitable prototypes.

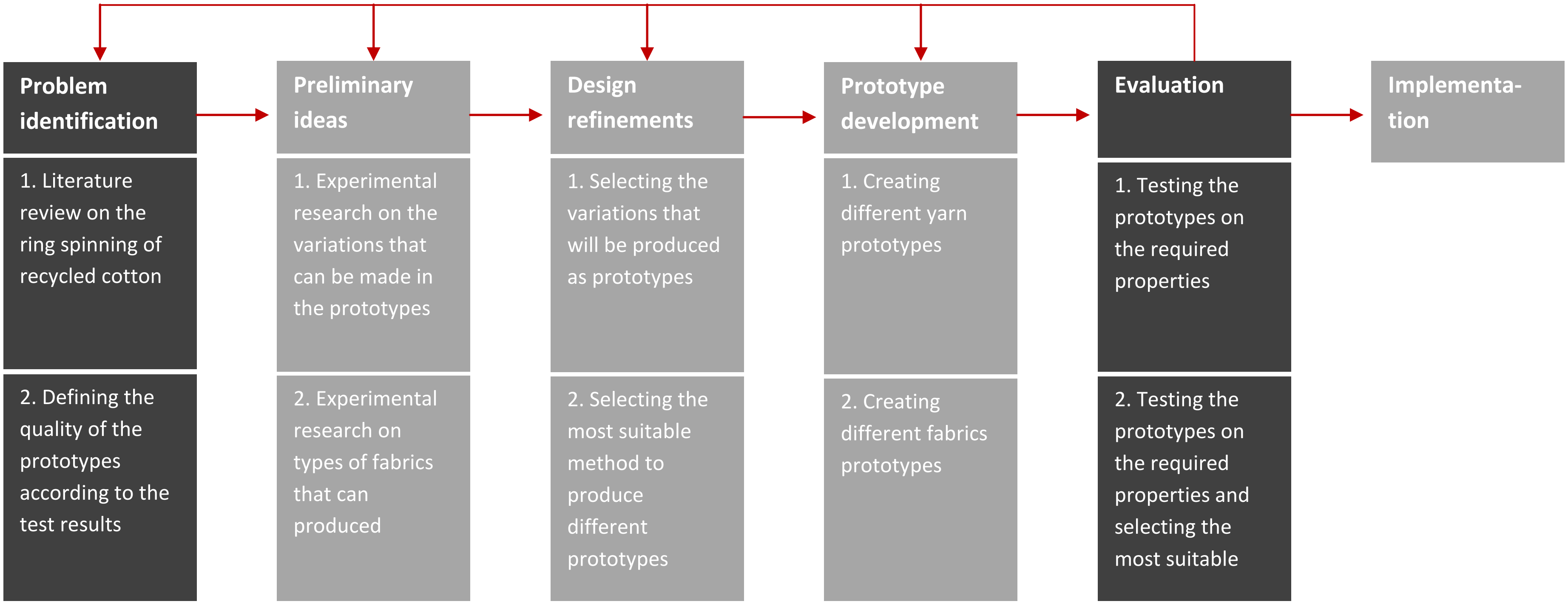

Figure 8. Framework for Apparel Design by Lamb & Kallal.
Note Adapted from “A conceptual framework for apparel design” by J.M. Lamb and M.J. Kallal, 1992, *Clothing and Textile Research Journal,* 10(2), 42-47

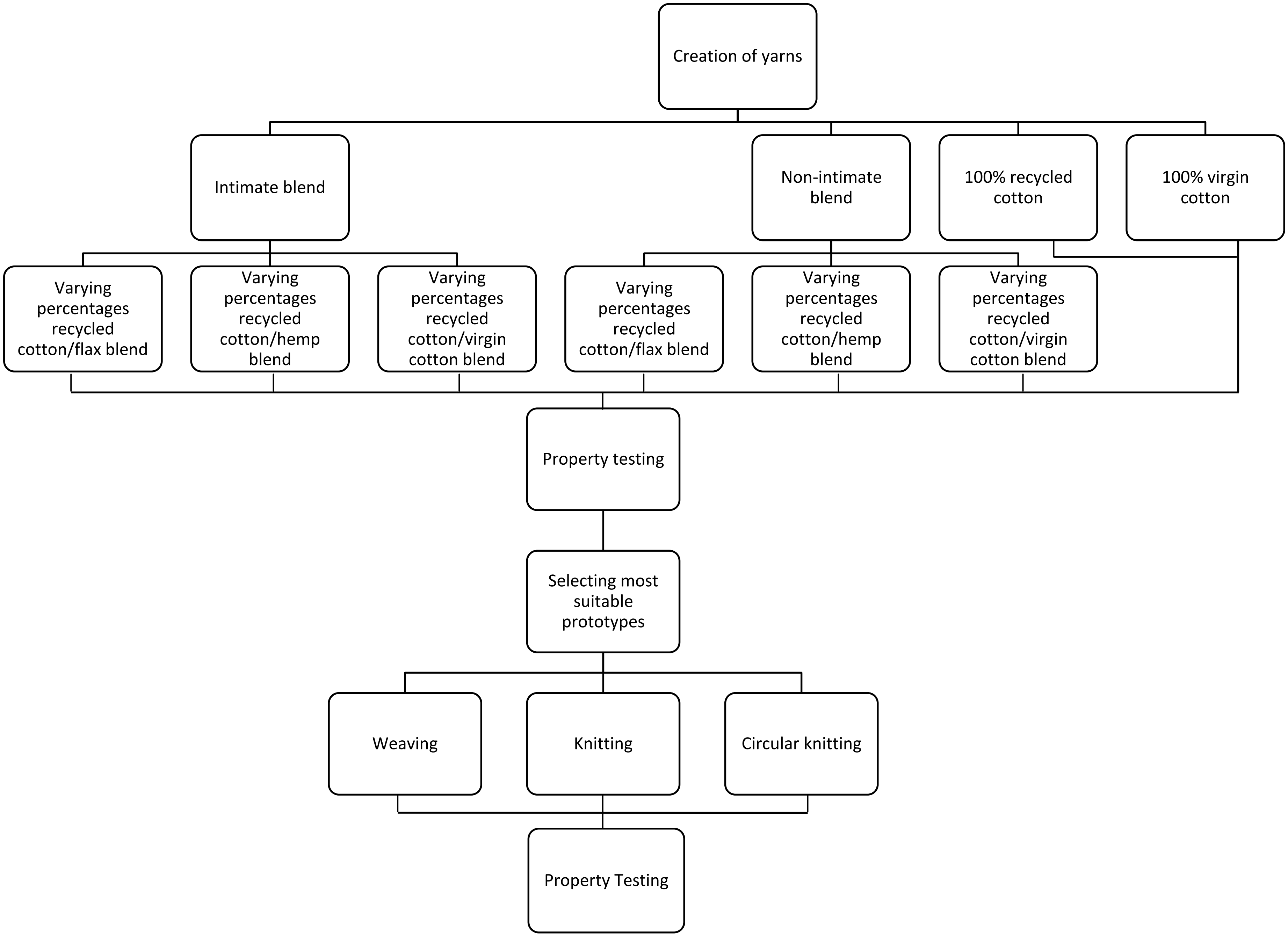

Figure 9. Experimental breakdown structure developed for this research

3 Materials and methods

3.1 Materials

During this research different fibers were used. In this chapter the fibers that were used will be specified. The first cotton mentioned in Table 3 will be referred to as ‘short cotton fiber’ and the second as the ‘medium cotton fiber’. All the fiber lengths are averages as the length varies within the fibers. It can be seen that these lengths differ from the average lengths mentioned in Table 2. This is because the lengths can vary per harvest, these are the lengths of the fibers used within this research.

Table 3
List of materials

Fiber	Fiber length	Note
Cotton, short	18 mm	
Cotton, medium	26 mm	
Recycled cotton untreated	9.1 mm	
Recycled cotton treated	13.4 mm	Treated with 0.29 % wof PEG 4000
Hemp	37 mm	Cottonized
Flax	22 mm	Cottonized

Both cotton fibers were already available at the university. The recycled fibers used in this research were produced during a previous research by T. Sjöblom (Sjöblom, 2018). To obtain the recycled fibers a plain woven fabric was used, from pre-consumer waste. The hemp fibers were provided by IKEA and the flax fibers were provided by Jos Vanneste nv.

3.2 Attainability properties

The minimum attainability for the properties of the yarn should state:

- type of blend;
- minimum strength requirement;
- which tex numbers should be produced;
- twist factor.

It was decided to produce a yarn that is suitable for knitting purposes. The strength requirements for weaving yarns are higher and therefore more difficult to reach when using short fibers in a yarn (Behery, 2010). The twist factor is something that highly influences the properties of a yarn. It is desirable to reach the optimum twist for a yarn. To calculate the yarn twist the English twist factor is used, as this factor also considers the relation between the yarn count and the twist. A fine yarn requires a higher twist than a coarse yarn does. The formula is as follows in Equation 3 (Furter & Meier, 2009):

$$\alpha e = turns\ per\ inch \div \sqrt{Ne} \quad (3)$$

A high twist is desirable because this causes more friction between the fibers and especially with short fibers this helps keeping the fibers together. The highest twist factor for knitted yarns is 3.9, it was decided to make this number the desirable twist factor for the yarn because it has the highest twist factor in the range for knitting yarns as can be seen in Table 4 (Furter & Meier, 2009).

Table 4
Twist factor

Twist factor αe	Application range	Characteristics
2.5 – 3.9	Knitting yarns	Soft twist
3 – 4.3	Weft yarns	Normal twist
3.7 – 4.5	Warp yarns, soft	Hard twist
4.3 – 4.6	Warp yarns, normal	Hard twist
4.6 – 5.4	Warp yarn, hard	Hard twist
6.3 – 8.9	Crepe yarns	Special twist

Note. Adapted from "Measurement and significance of yarn twist" by R. Furter and S. Meier. 2009. Copyright 2009 by Uster Technologies AG.

Yarns will be produced with three different linear densities (tex) to be able to determine at which tex the yarn properties are the best. It was decided to produce a yarn of 20 tex, 50 tex and 80 tex. To calculate the necessary turns per meter the tex numbers first had to be converted to Ne values. When the αe value is 3.9 the formula to calculate the turns per inch will be as follows in Equation 4 (Furter & Meier, 2009):

$$\boldsymbol{turns\ per\ inch} = \mathbf{3.9} \times \sqrt{\boldsymbol{Ne}} \tag{4}$$

Converting the turns per inch to twist per meter it is divided by 0.0254 (Furter & Meier, 2009). The calculation can differ when producing a blended yarn with different fiber fineness (Xie, Gordon, Long, & Miao, 2017). As mentioned in Table 2 the used fibers have almost the same fineness so the same calculation was used.

3.3 Preliminary study

To define accurate process settings a preliminary study was executed with the short cotton fibers. The detailed information on the fibers that were used in the pre-study can be found in the Materials chapter. The settings were defined based on the literature study. Additionally the best method for blending was identified using the virgin cotton fibers.

Before the yarn can be spun a sliver needs to be produced. This is done according to the opening, carding and drawing steps which are explained in detail below. All steps were performed in the same room with a relative humidity of 63% and a temperature of average 21 degrees Celsius. The fibers were, for at least 24 hours, left in this room before using.

3.3.1 Opening

Opening of the fibers was done with the LAROCHE opener. The fibers were placed in the opener and the attached Canvac EAN C140 vacuum was turned on to collect the opened fibers. The opening process prepares the fibers for carding, but when the opening is too harsh this can cause an increase of neps and possibly damage the fibers (Alagirusamy, 2013). To prevent the fibers from getting damaged the opening process was only done once.

3.3.2 Carding

The opened fibers went to the carding process. For carding the Mesdan Lab 337A laboratory carding machine was used. 15 grams of the opened fibers were placed on the belt of the carding machine. The fibers were equally spread out with a distance of 5 cm from the edges of the belt. The carding was done twice. After the first carding the web is folded in four layers and the web is placed at the belt at the beginning of the machine rotated 90°, so the fibers are carded in the other direction.

3.3.3 Drawing

To produce a sliver from the web the Mesdan 3371 Stiro-roving lab machine was used. The web was folded into four layers, over the length of the web, and fed into the drawing machine; this was done three times to obtain a sliver that is suitable for spinning. The draw frame contains four sets of rollers that perform the pre-draft and the main draft. The draft is determined by the sprockets size that influences the speed of the rollers. As it was not possible to produce a roving, the sliver was used for spinning.

3.3.4 Ring spinning

Ring spinning was done with the Mesdan Ring Lab 3108A. Spinning was done at the lowest speed of approximately 5461 rotations per minute, and 6.5 meter per minute. In the paragraph Attainability properties yarn, the different tex that are produced were decided, these tex are 20 tex, 50 tex and 80 tex. For the 50 tex and 80 tex yarns produced with the virgin fibers the full web was used. For the 20 tex yarn the web was cut in half folded in half and drawn three times. This gives a thinner sliver, which makes creating a thinner yarn easier. During the spinning different variations were made to find the optimum settings to produce the yarns. These variations were regarding:

- number of drafting systems;
- type of rollers;
- traveler weight;
- spacer clips;
- total draft ratio;
- draft ratio;
- twist number.

Temperature and moisture help fixating the dimensions of cotton fibers (Möller & Popescu, 2012). To fixate the yarn twist after spinning a microwave is used. First the cone with the yarn was placed in a water bath for 2 minutes. Afterward the cone was placed in the microwave at 450 Watt until dry, approximately 2 minutes. In between the yarn should be checked so it does not get too hot.

3.3.5 Blending

To define the most suitable method for blending the short cotton fibers were blended with flax and hemp fibers. This is based on the results found in the Fibers paragraph. Four different methods for blending were tried based on the literature results of the Process influences paragraph. The hemp and flax fibers were blended in 10% with 90% short cotton fibers.

First the fibers were blended during opening. This was done by weighing the fibers before opening. As a total of 15 grams was needed for carding; 13.5 grams of short cotton fibers was used, and 1.5 grams of either hemp or flax fibers. The hemp or flax fibers and the short cotton fibers were inserted in the opening machine at the same time, and blended that way. After opening the blended fibers were weighted.

To blend during carding, again the fibers were weighted before and 13.5 grams of short cotton fibers was used and 1.5 grams of either hemp or flax fibers. The fibers were manually spread on the belt before carding. After carding the weight of the web was measured.

To blend the fibers during drawing or spinning first a web needs to be produced of the different fibers separately. To blend during drawing the slivers should be placed together at the drawing frame in the correct distribution of 10%. To blend during spinning a sliver is spun around a previously spun yarn. First a yarn should be produced of 100% short cotton fibers, following the sliver of the hemp or flax fibers will be spun around the cotton yarn. In this case, it is not possible to create a yarn blended with only 10% hemp or flax. Therefore the blend will be 50% hemp or flax and 50% short cotton fiber.

To determine whether the fibers are blended evenly the hemp and flax fibers were dyed a blue color. This was done with reactive dyes in the AHIBA lab dye machine. Six tubes of were used with three tubes for hemp and three tubes for the flax fibers. The recipe as shown in Table 5 was used for dyeing. The dyeing bath was topped off with water to 2100 ml. The dyeing temperature was 60 °C and the dyeing was ready 45 minutes after reaching this temperature. After dyeing the fibers were washed with hot water and detergent and rinsed with cold water.

Table 5
Dyeing recipe

	Quantity (gram)
Flax fibers	42
Hemp fibers	42
Dye stuff	0.7
Common salt	140
Soda ash	56

Based on the results of the preliminary study the settings for the yarn prototyping with the recycled cotton fibers were defined.

3.4 Yarn prototyping

Based on the previous results, a new experimental breakdown structure was created. This can be found in Figure 10. The yarn prototyping started by using the untreated recycled cotton fibers. This was done to be able to define the difference between the untreated and treated recycled cotton fibers when used in a yarn, and to see if the treatment used on the treated fibers influences the ring spinning process. The yarns containing the untreated recycled cotton fiber and treated recycled cotton fibers were produced in different blends. The prototyping started with producing a yarn of 100% untreated or treated recycled cotton fibers and when this was not possible 10% of different fibers were added. This was either medium cotton, hemp or flax fibers. Every time it was not possible to produce a yarn the blend went up 10% until a percentage was reached that was spinnable. The results from the preliminary study in the Ring spinning paragraph showed that it was very difficult to produce a yarn of 20 tex, therefore it was decided to only produce the yarn containing the recycled fibers in 50 tex and 80 tex.

The yarns were spun using one drafting system, the soft front roller, the yellow spacer clips and the EM1, 200 mg dr traveler as shown in Figure 3 in the Ring Spinning paragraph. The spinning was still done at the same speed as mentioned before. The optimal settings concerning draft and twist were defined while spinning.

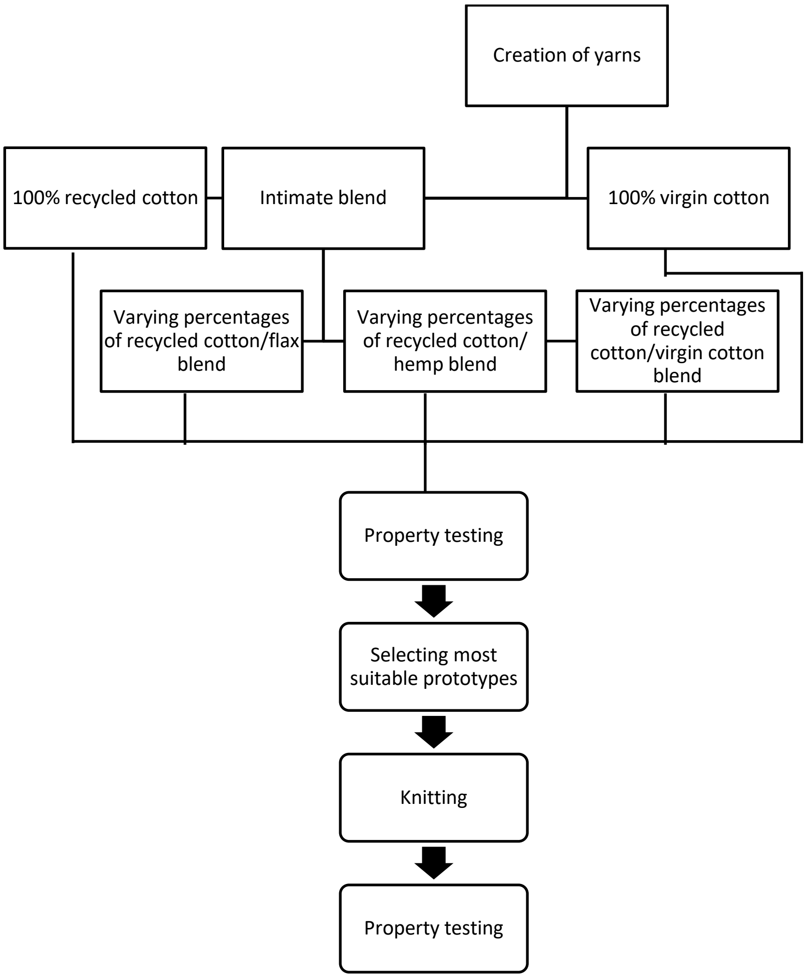

Figure 10. Adjusted experimental breakdown structure

3.5 Yarn prototype evaluation

To determine the properties of the produced yarns, tests were performed. The first test was the measurement of the tex. This was done with a hand drive wrap reel. The weight of 10 meter yarn was taken and measured, this was done twice, and the average was used and converted to tex.

3.5.1 Twist measurement

The applied twist of the yarn was measured, with the Mesdan Twist Lab 2531 C according to the ISO 2061:2015 standard. Looking at the standard the specimen length of single spun, cotton yarns should be between 10 and 25 mm, for bast fibers this is between 100 and 250 mm. As the yarns consist mostly out of cotton materials it was decided to use a specimen length of 50mm. The number of specimens that should be tested is for single spun yarns 50. The available amount of yarn was limited therefore it was decided to take half of the number of specimens, so 25. As the Z-twist was used to spin the yarns, the setting Z-twist was used to untwist the yarns, along with Mode A was used, as this is the suitable method for single spun yarns. A pre-tensioning weight of 30 cN was used.

3.5.2 Tensile strength and elongation

Subsequently, the tear strength and elongation of the yarns was measured with the Mesdan Tensolab 2512 according to ISO 2062:2009. This test method measures the tensile strength and the elongation simultaneously. Specimens of 250 mm were used. According to the standard 50 specimens should be taken from ten packages. As, in this case there is only one package and the amount of yarn is limited it was decided to use ten specimens. The results of the tensile test were analyzed using ANOVA in excel to define whether the results were significant or not. ANOVA is a method to analyze the variance between the mean of the samples. It can define whether the differences within the groups and between the groups are significant. An alpha of 0.05 was used, which means that if the p-value was less than 0.05 the result was considered significant.

The twist and the tensile testing were both performed in the same room, with an average temperature of 21^{o}C and 63% relative humidity according to ISO 139:2005. The temperature and humidity could not be adjusted. The specimens were kept in this room for at least 24 hours before testing.

The results of the tensile strength test and the twist measurement were compared to each other. This was done by creating a scatter plot in excel along with a residual plot. As the tex values for the yarns were slightly different the twist factor was used. For the scatter plot a linear regression line was added and the correlation was calculated with the r value. The r value is between -1 and 1 where -1 means there is a negative correlation and 1 means there is a positive correlation. A value of 0 means there is no correlation.

3.5.3 Visual analysis

The yarns were visually analyzed using the ASTM D2255 test method. Here the yarns are evaluated on their appearance and evenness. They are rated from Grade A to Grade D, where A is a uniform yarn and D is the least uniform yarn. The yarns were wrapped around a black paper of 8 cm by 9 cm.

3.6 Fabric prototyping

Shown from the results in the Attainability properties yarn paragraph it was most suitable to make knitted fabric prototypes with the yarn prototypes. This was done on the Universal Transrapid H flat bed knitting machine, with a gauge of 12. A stitch length of 10 was used, samples were made in a plain weft knit with 52 needles and with 108 needles.

3.7 Fabric prototype evaluation

The fabric prototypes will be evaluated on different mechanical properties. All tests were executed in the same room, with an average temperature of 21^{o}C and 63% relative humidity, according to ISO 139:2005. The specimens were kept in this room for at least 24 hours before testing.

3.7.1 Tensile strength and elongation

For tensile testing of the fabrics, ISO 13934-1:2013 was used. This was done with the Mesdan Tensolab 2512. According to the standard at least 5 specimens should have been tested of each prototype. There was not enough material to do this, so two specimens of 200 mm by 50 mm were tested.

3.7.2 Abrasion and pilling resistance

To test the abrasion and pilling resistance the Martindale testing machine was used from SDL Atlas. According to ISO 12947-2-2016 for the abrasion resistance and ISO 12945-2:2000 for the pilling. According to the standard for both tests 3 samples were required. This was however not possible due to the limited amount of material available. For the abrasion resistance two samples were tested of a diameter of 38mm. For the pilling one sample was tested with a diameter of 150 mm. The abrasion test was run until one yarn in each specimen broke. The weight of the specimen was measured before the test and after the test, to calculate the weight loss. The specimens of the abrasion resistance were tested for 7000 cycles, with stages in between to assess the pilling. The fabrics were graded according to a standardized grading system in compliance with ISO 12945-2: 2000.

3.7.3 Flexibility

To test the flexibility of the fabrics the Shirley stiffness test was executed according to ASTM D1388. For each prototype two specimens were tested with the size of 200 mm by 25 mm. According to the standard it was required to test 4 samples, but this was not possible. The two specimens were tested five times each, on the Shirley stiffness tester and the average was used as the result.

3.8 Implementation of the prototypes

The method to produce the yarn prototypes will be analyzed on its applicability for the industry. To do this an 80 tex, 100% cotton yarn, industrially produced, was tested on some properties to compare to the yarn and fabric prototypes. The yarn was tested on twist and tensile strength based on the same methods as previously mentioned. For the twist 25 measurements were done and for the tensile strength ten measurements were done. The yarn was knitted into a fabric with the same method as the fabric prototypes. This fabric was tested on the tensile strength and abrasion resistance according to the same methods as mentioned before. For the tensile strength five specimens were used and for the abrasion resistance two specimens. The results were compared to the results of the yarn and fabric prototypes.

4 Result and discussion

4.1 Attainability properties

4.1.1 Attainability properties yarn

The results of the calculation of Equation 3, concerning the three selected densities are shown in Table 6.

Table 6

Twist per meter

Tex	Ne	Turns per inch	Twist per meter
80	7.38	10.59	417
50	11.81	13.40	528
20	29.53	21.19	834

To sum up the requirements of the yarn prototypes are as follows:

- blending with hemp, flax or cotton fibers, or a combination of those;
- tear strength should be at least 3 cN/tex, according to literature in the Fibers section;
- the tex of the yarn prototypes should be 20, 50 or 80;
- the twist factor should be 3.9 αe.

4.1.2 Attainability properties fabric

As mentioned previously, it was decided to produce a knitted fabric with the yarn prototypes. The gauge of the knitting machine that can be used is dependent on the linear density of the yarn. A basic fabric will be produced so this should be done by a plain weft knit. The requirements of the fabric are not specified as there is no defined end use of the fabric. The fabric however, will be tested on certain qualities and these are ranked according to their importance:

- tensile strength;
- abrasion;
- pilling;
- flexibility;
- elongation.

4.2 Preliminary study

First the yarn prototypes with the virgin cotton were produced. A few trial runs were done to obtain the right settings to obtain the three different tex yarns.

4.2.1 Carding

It was noticed that during carding the web and the fibers would stick to the rollers. This can be due to a low humidity (Alagirusamy, 2013). The humidity in the carding room was 63% but an even higher humidity might be better. Another reason for this can be the neps in the web that would stick to the rollers. The neps would then stick to the fibers of the web and therefore make the web stick to the roller. A different reason for the fibers sticking to the rollers is the presence of honeydew on the cotton fibers. Honeydew causes the fibers to stick to each other but also to the machines (Hequet & Abidi, 2005; Lawrence, 2007).

4.2.2 Drawing

During the first drawing trials it was noticed that the sliver was very uneven, because the drawing was too high. To obtain a more gentle drawing the sprockets and the chains were changed for the largest once available, this can be seen in Appendix I. With larger sprockets the drawing speed is less, and thus a gentler drawing.

4.2.3 Blending

The four different methods, discussed in the Blending paragraph were tested to blend the short cotton fiber with the flax or hemp fibers. The first method that was used was blending during opening. It was possible to blend the fibers during opening, but it is difficult to control the blending percentage, as well as the evenness of the blend. The second method was blending during carding. It was possible to blend the fibers during carding and the blend seemed even. The only problem is that fibers get lost in the machine during carding so the exact percentage of the blend is not controllable. After this the third and fourth method were tried, to do this a web needed to be produced from the hemp or the flax fibers. As mentioned in the fiber selection paragraph, the fiber adhesion of flax fibers is poor, and hemp has similar fiber properties. Therefore, it was not possible to obtain a web out of only hemp or flax fibers, as the fibers would not stick together to form a web. Therefore, the third and fourth methods for blending were not possible to use.

It was decided to use the blending method, during carding, because this is more controllable than blending during opening. To confirm the evenness of the blend the hemp and flax fibers were dyed in a blue color. Following a web was made according to the regular steps. After the first carding it was noticed that the blue fibers were positioned in the web in lines, as shown in Figure 11a. After the second carding the blue fibers were evenly spread among the web as shown in Figure 11b.

(a) After first carding (b) After second carding

Figure 11. Carded web results of the evenness of the blend

4.2.4 Ring spinning

To find the best settings for spinning several variations were tested regarding the following aspects:

- number of drafting systems;
- type of rollers;
- traveler mass;
- spacer clips;
- total draft ratio;
- draft ratio;
- twist number.

It is possible to spin with two aprons and three rollers, or one apron and two rollers. According to the literature in paragraph Ring spinning of short staple fibers it is best to only have one apron and two rollers. To make sure this is correct both variations were tested. When using the double aprons the draft was so high that the amount of fibers left at the last roller was too little to spin a yarn. Therefore, it was decided to only use one apron and two rollers. When looking at the type of rollers there were two rollers available.

The hardness of the rollers is expressed in Shore. The rollers were available in 83° and 72° Shore. Both rollers are considered medium hard rollers, but a higher Shore equals a harder roller (Klein & Stalder, 2016). It was noticed that with the softer roller the fibers would stick less to the roller. Additionally, it seemed that the fibers were also more centered as also predicted in literature.

The mass of the traveler that is used is dependent on the tex of the yarn that is produced. The guideline is 2.6 mg/tex in the case of a 20 tex yarn the traveler weight is 52 mg, for 50 tex the mass is 130 mg and in the case of the 80 tex yarn the traveler mass should be 208 mg. As these exact masses are not available, for the 20 tex yarn the utilized traveler mass was 50 mg, for the 50 tex yarn a traveler with the mass of 125 mg is used and for the 80 tex yarn 200 mg. While creating the yarns different masses were tested as well. As confirmed by the literature in Ring Spinning, the balloon size changes and the mass based on the calculations turned out to be the best. Based on the literature in Ring spinning of short staple fibers the traveler shape was selected. For all travelers used, the shape of the traveler was dr, as shown in Figure 3, because this is suitable for cotton blends and knitting yarns.

Break draft and main draft

When varying in the draft settings it was noticed that the changes made in the break draft settings were very small. The main purpose of the break draft is to keep tension on the fibers so no big adjustments were made. The main draft influences the thickness of the yarn and therefore many variations were tried to obtain the target linear density for the yarns. It is desirable to have a low twist to obtain the right twist angle for knitting yarns. However, this is more complicated with short fibers as they require higher twist to increase the friction between the fibers. Trying to keep the twist as low as possible the following settings, as shown in Table 7, were successful to produce the different blends with the different tex. It should be kept in mind that the twist set in the machine might not be the same as the actual applied twist. During spinning it was noticed that is was very difficult to obtain yarns with exactly the same tex. Therefore, it was defined that the tex should be within a range of 6 tex, so 3 tex more or less than the set tex.

Table 7

Spinning parameter settings of the yarns produced in preliminary study

Composition	Tex	Draft	Twist per meter
100% short cotton	80	29.8	505
90% short cotton 10% hemp	80	31.5	505
90% short cotton 10% flax	78	31	506
100% short cotton	49	44	680
90% short cotton 10% hemp	52	47	680
90% short cotton 10% flax	52	44	681
100% short cotton	18	59	1255
90% short cotton 10% hemp	18	58	1309
90% short cotton 10% flax	22	58	1230

During spinning it was noticed that is was very difficult to obtain a yarn of 20 Tex with the short cotton fibers. This is because of the fiber friction which is low between short fibers and the short fibers have fewer inter-fiber contact points and thus also a lower degree of entanglement. A yarn of 20 Tex has a low linear density and thus only few fibers in linear cross-section, which makes it difficult to spin a yarn. Therefore, it was decided to only produce a yarn of 50 Tex and 80 Tex with the untreated or treated recycled cotton fibers.

4.3 Yarn Prototyping

Based on the results of the previous paragraph, the settings for the ring spinning with untreated or treated recycled cotton fibers were defined. The prototyping started with the creation of yarns with the untreated recycled cotton fibers. The first thing that was noticed was that more fibers got lost in the machine during carding compared to the short cotton fibers. When 15 grams of fibers was put in the carding machine the web that came out was an average of 10 grams, this equals a loss of one third of the fibers. This weight of the web was too little so it was decided to use 20 grams of fibers as input. The carded web should be between 13.5 grams and 14 grams. When the web weighted more than this; fibers were cut off on the side to obtain the correct weight. While doing this the rest of the web was not touched to prevent damaging the web. This was done to obtain evenness within the slivers used for the research. During the drawing it was noticed, when drawing three times the sliver was too weak to use for spinning as it would break in many places. Therefore, it was decided to draw the sliver twice instead of three times.

The ring spinning started with a yarn of 100% untreated recycled fibers, it was noticed that because of the short fibers it was not possible to spin this sliver. Another reason for this could be the rigidity of the recycled cotton fibers. During the recycling process the cotton fibers undergo hornification. This means that the crystallinity of the cotton fibers increases, which causes a higher rigidity. This is due to the collapse of the pores during the drying process, as recycled fibers undergo many laundering and drying steps (Palme A. , 2017). As shown in the literature in the Ring spinning of short staple fibers paragraph, the fibers were pulled between the apron and the front roller. To make the spinning triangle as even as possible the front roller was placed closer to the drafting apron. Before, the distance between the apron and the roller was 15 mm and after 9 mm. This distance was used during the production of all yarn prototypes. The stream of fibers in the spinning triangle seemed more even after this.

The experiments continued with blending of the untreated recycled fibers with virgin cotton, hemp and flax. First adding 10%, followed by 20%, until it was possible to spin a yarn. When reaching a blend of 60% untreated recycled fibers and 40% cotton fiber it was possible to produce a yarn. The same was done for the treated recycled cotton fibers and also at 60% recycled cotton fiber content and 40% cotton it was possible to spin a yarn. As the goals was to achieve a yarn with the highest recycled content as possible it was decided to not try to blend with less than 60% untreated or treated recycled cotton fibers. It was possible to spin yarns in different blends, but it was not possible to spin a yarn with only 60% untreated or treated recycled fibers and 40% hemp or flax fibers. This was due to the low friction properties and high rigidity of the hemp and flax fibers but also of the recycled cotton fibers. It was necessary to add virgin cotton fibers to increase the friction between the fibers and add a flexible fiber between the rigidity of the recycled cotton fibers and flax or hemp fibers. All the prototype trials can be found in Appendix II with the comment if the trial failed or passed. It was not possible to produce a yarn of 50 Tex. A thinner yarn requires a higher draft, but for the 80 Tex yarns the highest draft possible was used and the twist was also relatively high. As the twist was high it was not possible to obtain the *α*e of 3.9 so it was decided to try and keep the twist as low as possible. In Table 8 the compositions of the produced yarns can be found, along with the machine settings and the linear density of the sliver in ktex. For some of the yarns only one tex measurement could be done due to limited amount of yarn. This was often due to difficulties during spinning, e.g. yarn breakage or balloon collapse. Benchmarks in the same compositions were produced to compare the yarn prototypes with. This was done using the short cotton fibers.

Table 8

Settings yarn prototypes

Compositions	**Draft**	**Twist setting**	**Ktex Sliver**	**Tex**	**Average Tex (+/- 3)**
60% short cotton 40% medium cotton	37	650	3.07	79 79	79
60% short cotton 30% medium cotton 10% hemp	38	660	3.1	81 76	78.5
60% short cotton 30% medium cotton 10% flax	38	650	3.05	82 83	82.5
60% short cotton 20% medium cotton 20% hemp	37	650	3.05	81 73	77
60% short cotton 20% medium cotton 20% flax	36,5	655	3.06	76 78	77
60% short cotton 10% medium cotton 30% flax	35	630	3.08	83	83
60% untreated recycled cotton 40% medium cotton	52	855	4.29	83	83
60% untreated recycled cotton 30% medium cotton 10% hemp	51.6	837	4.33	78 85	81.5
60% untreated recycled cotton 30% medium cotton 10% flax	50.1	830	4.43	78 84	81
60% untreated recycled cotton 20% medium cotton 20% hemp	51.5	855	4.21	82 74	78
60% untreated recycled cotton 20% medium cotton 20% flax	51.5	845	4.34	83 71	77
60% treated recycled cotton 40% medium cotton	51	810	4.58	84 77	80.5
60% treated recycled cotton 30% medium cotton 10% hemp	51	825	4.34	83 75	79
60% treated recycled cotton 30% medium cotton 10% flax	51.5	835	4.51	79 87	83
60% treated recycled cotton 20% medium cotton 20% hemp	45	805	4.59	84 80	82
60% treated recycled cotton 20% medium cotton 20% flax	51.5	820	4.55	77 85	81
60% treated recycled cotton 10% medium cotton 30% flax	45	805	4.35	100	100

When looking at the spinnability of the untreated recycled cotton fibers and the treated recycled cotton fibers, not a big difference was noticed. This is interesting because the treated recycled cotton fibers are longer than the untreated recycled cotton fibers. According to the literature research longer fibers usually equal a better spinnability. However, the treatment used to obtain longer recycled fibers reduces the friction between the fibers. The treatment, and thus the lower friction could influence the spinnability of the treated recycled cotton fibers.

Additionally it was noticed that adding the virgin cotton fibers help increasing the spinnability of the recycled cotton fibers. Adding only flax or hemp fibers does not increase the spinnability but when also adding virgin cotton fibers the blends became spinnable.

4.4 Yarn prototype evaluation

As mentioned in the methodology, the yarns were tested on their twist, tensile strength and elongation.

4.4.1 Twist measurement

On average the difference between the twist set on the machine and the actual twist is 75 turns per meter. When looking at the twist factor in Table 9, the yarns containing the recycled cotton fibers all have a very hard twist, this is necessary to obtain the needed amount of friction between the fibers.

Table 9

Results from twist testing, standard deviation shown between brackets

Composition	**Twist setting**	**Actual twist**	**Twist factor** (αe)
60% short cotton 40% medium cotton	650	574 (70.2)	5.3
60% short cotton 30% medium cotton 10% hemp	660	583 (80.5)	5.4
60% short cotton 30% medium cotton 10% flax	650	591 (72.3)	5.7
60% short cotton 20% medium cotton 20% hemp	650	556 (75.4)	5.1
60% short cotton 20% medium cotton 20% flax	655	555 (78.5)	5.1
60% short cotton 10% medium cotton 30% flax	630	610 (95.6)	5.8
60% untreated recycled cotton 40% medium cotton	855	785 (87.6)	7.5
60% untreated recycled cotton 30% medium cotton 10% hemp	837	747 (96.6)	7.1
60% untreated recycled cotton 30% medium cotton 10% flax	830	758 (96.4)	7.1
60% untreated recycled cotton 20% medium cotton 20% hemp	855	780 (104.2)	7.2
60% untreated recycled cotton 20% medium cotton 20% flax	845	752 (96.9)	6.9
60% treated recycled cotton 40% medium cotton	810	759 (163)	7.1
60% treated recycled cotton 30% medium cotton 10% hemp	825	772 (106.2)	7.2
60% treated recycled cotton 30% medium cotton 10% flax	835	754(89.3)	7.2
60% treated recycled cotton 20% medium cotton 20% hemp	805	760 (125)	7.2
60% treated recycled cotton 20% medium cotton 20% flax	820	764 (84.4)	7.2
60% treated recycled cotton 10% medium cotton 30% flax	805	645 (123.4)	6.7

4.4.2 Tensile strength

The tensile test results are visualized in a graph based on the cN/tex, visible in Figure 12. It can be seen that the strength of the yarns containing the recycled fiber is much lower compared to the short cotton fiber. The results of the treated recycled cotton fibers are slightly higher than the untreated recycled fiber, even though the yarn containing 60% untreated recycled cotton fiber, 30% medium cotton and 10% flax has the highest tensile strength. All yarns meet the minimum strength requirement of 3 cN/tex.

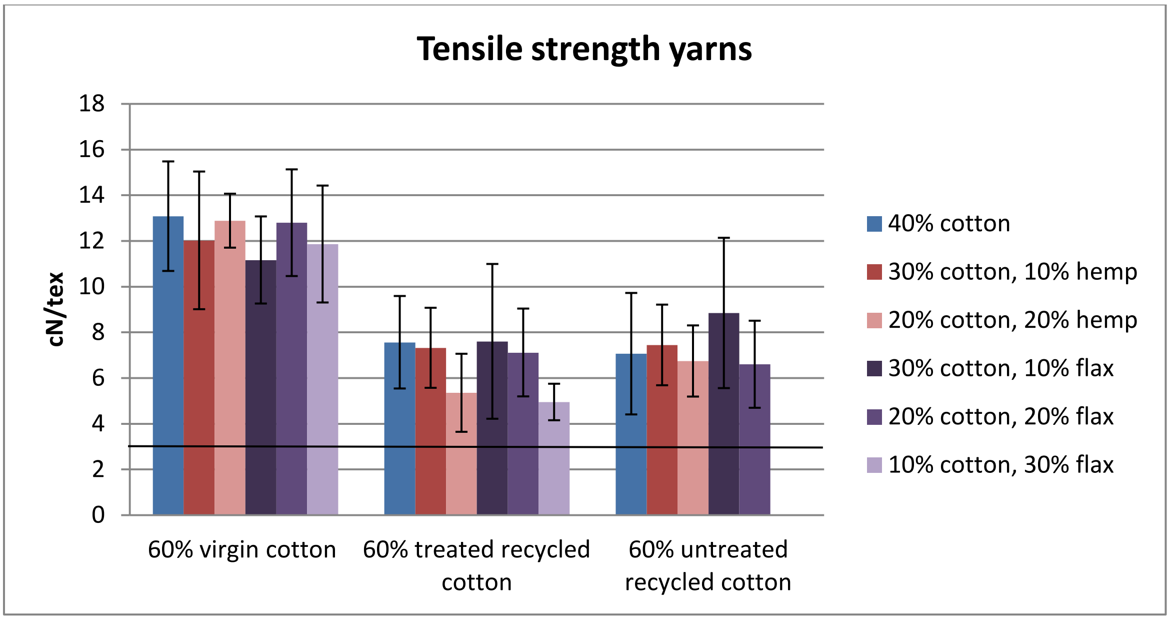

Figure 12. Results tensile strength yarns with error bars for standard deviation, line for minimum requirement of 3 cN/tex

It is noticeable that in the blend with the virgin cotton the blend with 30% medium cotton 10% flax has the lowest results, but in the other two cases it has the highest results. The blends with hemp have a lower tensile strength than the blends with flax. This can be due to the high length of the hemp fiber as the difference between the length of the hemp fiber and the recycled cotton fibers is very high as can be seen in Figure 3. The difference between the flax fibers and the recycled cotton fibers is a bit lower which can be the reason it is easier to spin and creates a stronger yarn.

It can also be noticed in the figure that there are big variations within the standard deviations, and the error bars are relatively big. This is due to the high irregularities within the yarn. As some parts of the yarns are thicker and stronger and some parts are much thinner and weaker. The tensile test results within one yarn prototype varied a lot which makes the error bars big.

The results were analyzed with ANOVA in several ways, the complete analysis can be found in Appendix III. The results of the yarns with 30% flax were not considered in these analyses because it was not possible to produce this yarn with the untreated recycled cotton. The first analysis was done with all the yarns. From this analysis it showed that the differences between the yarns containing the virgin cotton and the untreated or treated recycled cotton are significant. However when excluding the virgin cotton the results are not significantly different between the untreated and the treated recycled cotton yarns. This means that it cannot be confirmed nor denied that either the treated or the untreated recycled fibers have a better result on the yarn tenacity.

The blend containing flax fibers were compared together to see if the percentage of flax fibers significantly influences the tensile strength. This was also done for the hemp fibers. The different percentages were also compared so the yarns containing 20% flax were compared to the yarns containing 20% hemp. This was done for all percentages. None of these results were significant. This means that it cannot be said that one of the compositions affects the tenacity more than the others. Furthermore there is no interaction between the two groups, which means that the different compositions do not influences the effect of the virgin cotton fibers and the untreated or treated recycled cotton fibers on the yarn tenacity.

As mentioned previously ring spun yarns usually have a higher tenacity than rotor spun yarns. When comparing these results to rotor spun yarn produced by Sjöblom, it can be noticed that most ring spun yarns containing treated recycled cotton are stronger than the rotor spun yarn created by Sjöblom with the treated recycled cotton fibers. The rotor spun yarn with the treated recycled cotton fibers had an average strength of 6.3 cN/tex. The yarn produced with the untreated recycled cotton had an average strength of 7.4 cN/tex, which is higher than most ring spun yarns produced with the untreated recycled cotton fibers (Sjöblom, 2018). Though, it should be considered that the ring spun yarns were blended and have a different composition than the rotor spun yarns, which were made of 100% recycled fibers. This makes it difficult to compare the results. It can be noticed that in both cases the yarns containing the untreated recycled cotton fibers have a higher tensile strength than the yarns containing the treated recycled cotton fibers, before washing.

The amount of twist of the yarn was compared to the tensile strength to see if there is a correlation between these values. Two scatter plots were made, one containing all the yarn prototypes, and one only containing the yarn prototypes with the recycled cotton fibers. For both analyses a residual plot was made as well, these are visible in Appendix IV. When looking at the scatter plot of all the yarn prototypes in Figure 13, it can be seen that the linear tenacity is negative. This would suggest that with an increase of twist per meter the cN/tex decreases. The r value shows a strong negative correlation. This is due to the big difference of twist and tensile strength between the yarns containing recycled fibers and the yarns containing only virgin fibers. The yarns containing only virgin fibers have a lower twist factor and a higher tensile strength.

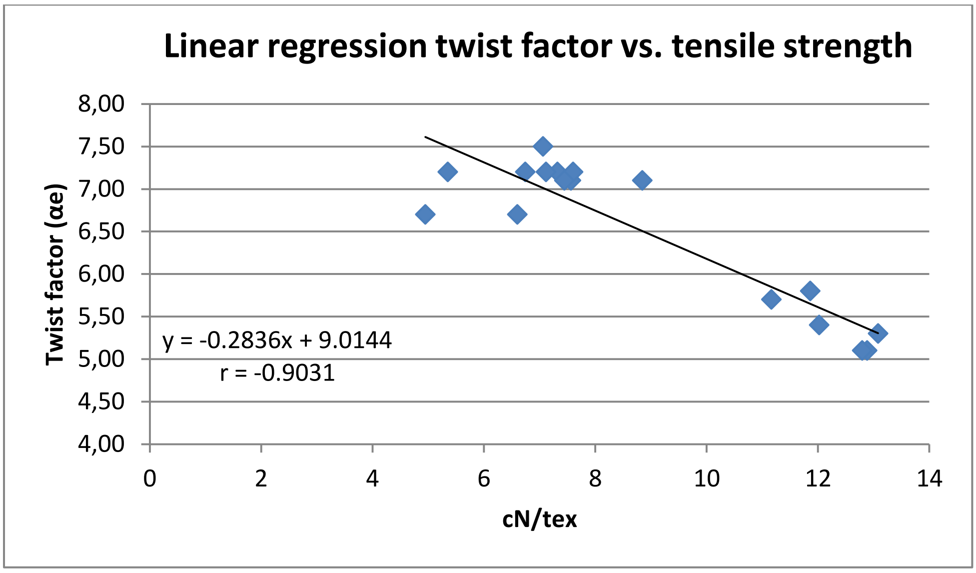

Figure 13. Linear regression twist vs. tensile strength for all yarns

When comparing the results for only the yarns containing the recycled fibers in Figure 14, the yarn containing 60% treated recycled cotton, 10% medium cotton, 30% flax was excluded. In Appendix V the linear regression figure including this yarn can be found. This yarn varied much from the other results and influenced the linear regression therefore it was excluded. The r value is nearly zero, which indicated that there is no correlation between the two factors.

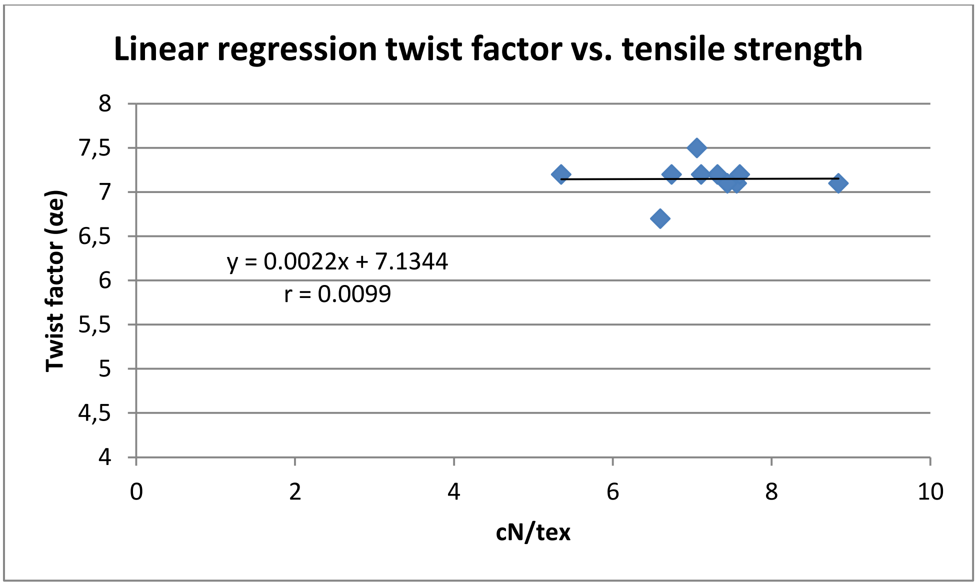

Figure 14. Linear regression twist vs. tensile strength for yarns containing recycled cotton fibers

Washing

To see if the treatment influences the tensile strength of the yarns a test was done with the best performing yarns according to the tensile strength. The yarns were washed with regular detergent. After washing the yarns were rinsed and air dried. Following 10 specimens of each yarn was tested with the same method as in the previous tensile test. When looking at the results in Figure 15 it can be seen that there is no increase in the tensile strength for the washed yarns. The results are not significant, based on the ANOVA analysis. These results can be seen in Appendix VI. In the figure below it can be seen that there is a big difference in the tensile strength for the washed and unwashed yarns with the untreated recycled cotton fiber. As the yarns are very uneven it can be that the washing test was done with a weaker part of the yarn. From these results it does not seem like washing the treatment away increases the tensile strength of the yarn. However, when looking at the results from Sjöblom, washing the rotor spun yarn does influence the tensile strength of the rotor spun yarns. The difference of the tensile strength of the treated yarn, before and after washing, is significant according to Sjöblom (2018). The different results could be because caused by the different composition of the yarns created in this research compared to the research of Sjöblom.

In this figure the error bars are also large with big variations, the reason for this is the same as previously mentioned. Due to the big variations of linear density and tensile strength within the yarns.

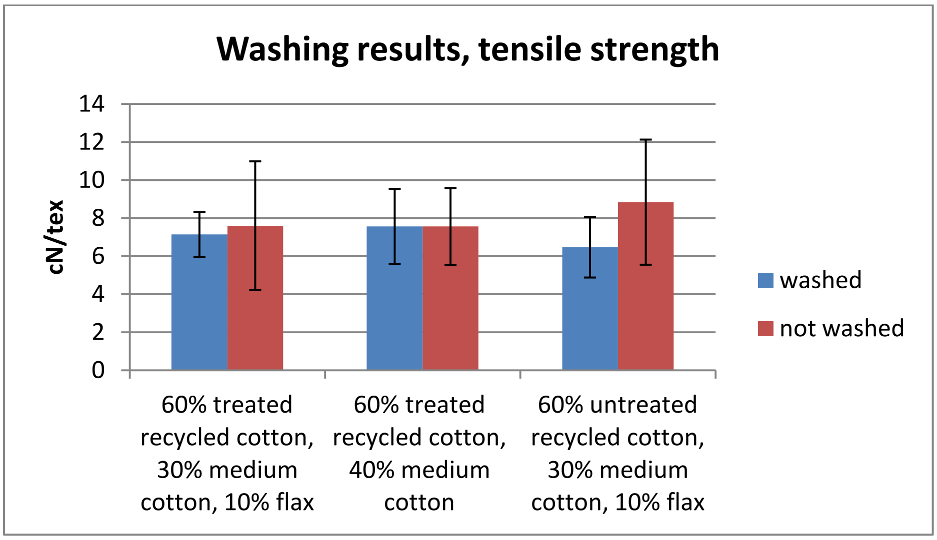

Figure 15. Tensile strength yarns before and after washing with error bars for standard deviation

4.4.3 Elongation

When looking at the Elongation results of the yarn prototypes, in Figure 16, it can be noticed that all the yarns containing the virgin cotton have a higher elongation % compared to the yarns containing the recycled cotton fibers. Analyzing these results with ANOVA this difference is significant. However, when comparing the difference between the treated recycled cotton and the untreated recycled cotton the results are not significant. So it cannot be said if either the treated recycled cotton or the untreated recycled cotton influences the elongation more. When looking at the different blends there is a significant difference between these results. This means that the type of blend influences the percentage of elongation. According to the ANOVA analysis there is no correlation between the type of blend and the type of cotton used (virgin or recycled). The complete ANOVA analysis can be found in Appendix VII.

The elongation test was done simultaneously with the tensile test. The error bars are similar to the error bars of the tensile strength. Again, the large error bars are due to the uneven yarns. A low tensile strength of the yarn was equal to a lower elongation.

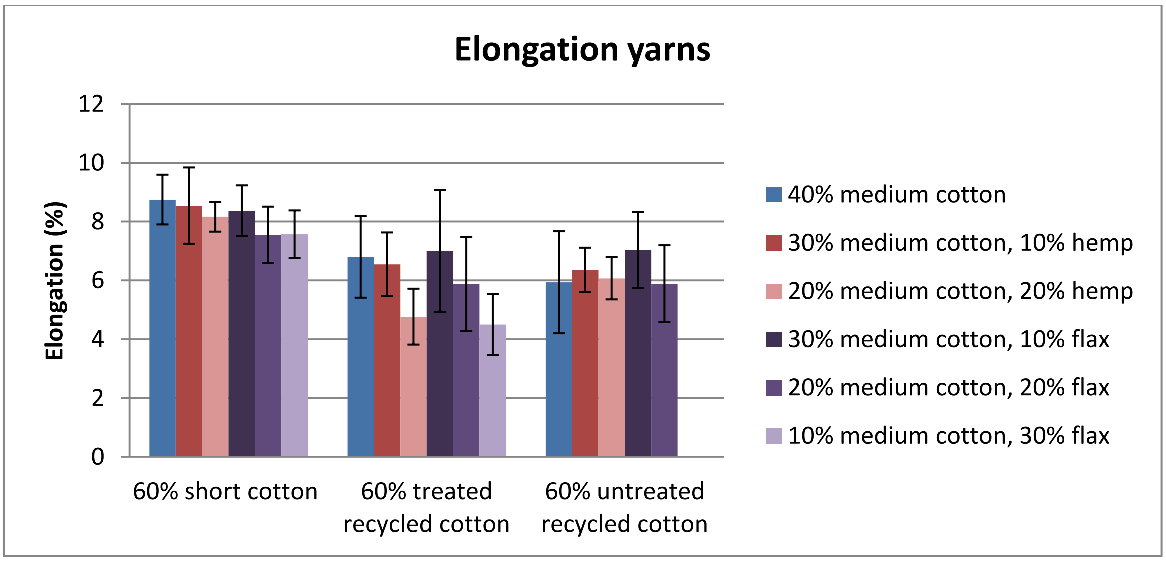

Figure 16. Results elongation yarns with error bars for standard deviation

4.4.4 Visual analysis

When comparing the different yarns visually, it was noticed that the yarns containing the untreated or treated recycled fibers were judged a grade lower than the yarns containing only the short cotton fibers. The short cotton fibers were longer and easier to spin, which created a more even yarn. It also seemed that the yarns containing hemp fibers were more uneven than the yarns containing flax fibers. This could be due to the high length of the hemp fibers, which makes them more likely to stick out of the yarn. The yarns and the grading per yarn are presented in Appendix VIII.

Based on these results, with the tensile strength as most important characteristic, the following yarns were selected for knitting:

- 60% untreated recycled cotton, 30% medium cotton, 10% flax;
- 60% treated recycled cotton, 30% medium cotton, 10% flax;
- 60% treated recycled cotton, 40% medium cotton.

4.5 Fabric prototyping

During the first trials to knit fabrics the yarn kept breaking after a few laps on the knitting machine. To solve this problems wax was applied to the yarns. This was done with a Simet SE 6 electronic winder. The waxing was done twice to assure the presence of wax on the yarns. After doing this it was possible to knit the fabrics, however there were still some problems occurring. This was often due to the unevenness of the yarn or the high twist, which caused the yarn to break. When looking at the produced fabrics it was also noticed that the fabrics are uneven. Some parts have a more open structure than other parts, which is due to the varying thicknesses within the yarn, as can be seen in Figure 17.

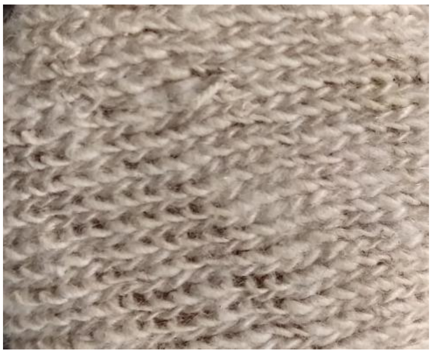

Figure 17. Fabric structure

4.6 Fabric prototype evaluation

4.6.1 Tensile strength

The results of the tensile test can be seen below in Figure 18; these visualize the average results of the two tests performed for each different blend. The results are not significant. Based on the average the knitted fabric containing the untreated recycled cotton fiber and 10% flax has the highest strength. This seems plausible as this yarn also had the highest strength in the tensile test.

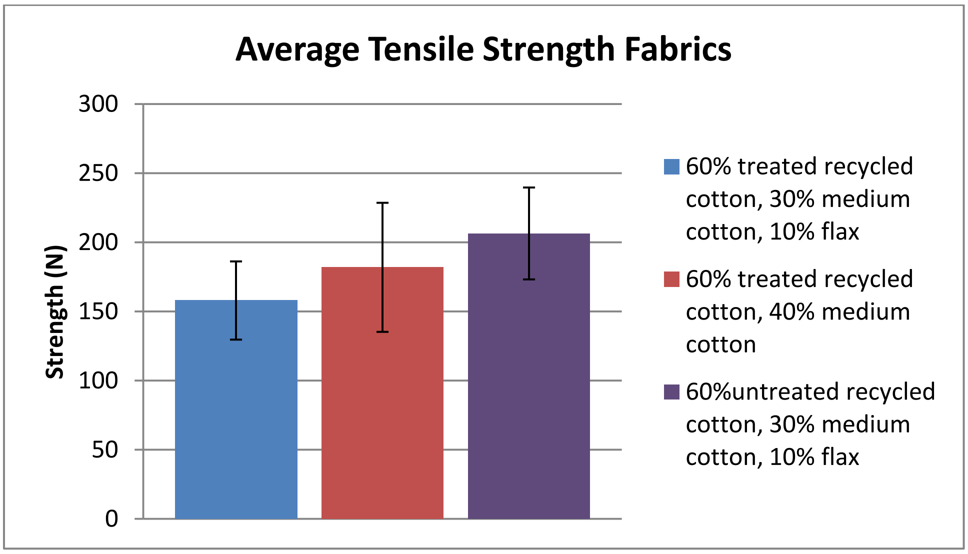

Figure 18. Results tensile strength fabrics with error bars for standard deviation

4.6.2 Abrasion resistance

The abrasion resistance measurement should be executed until breakage of one of the yarns in the fabric. The first yarns broke at 35.000 cycles, which is a high abrasion resistance, especially for a fabric containing a high percentage of short fibers. As shown in Table 10 it can be seen that the weight loss is lowest for the fabric containing 60% treated recycled cotton, 40% medium cotton. This could indicate that a higher percentage of cotton fibers blended with the untreated or treated recycled cotton fibers results in a higher abrasion resistance.

Table 10
Results abrasion resistance fabric

	Yarn break (cycles)	Weight specimen before test (gram)	Weight specimen after yarn break (gram)	Weight loss
60% treated recycled cotton,	35.000	0.45	0.39	13.4%
30% medium cotton, 10% flax	40.000	0.36	0.30	15.8%
60% treated recycled cotton,	40.000	0.51	0.43	9.6%
40% medium cotton	35.000	0.53	0.48	9.3%
60% untreated recycled cotton,	35.000	0.44	0.38	13.3%
30% medium cotton, 10% flax	40.000	0.48	0.43	10.4%

It should be noted that the fabrics were not washed after knitting, this means that the wax is still on the yarns and this could have influenced the results of the abrasion test. To see if this is the case another set of specimens was tested, but this time after washing. As visible in Table 11, the results are similar to the unwashed specimen. However, the weight loss is less after washing.

Table 11
Results abrasion resistance fabric after washing

	Yarn break (cycles)	Weight specimen before test (gram)	Weight specimen after yarn break (gram	Weight loss
60% treated recycled cotton,	40.000	0.49	0.45	8.2%
30% medium cotton, 10% flax	35.000	0.47	0.43	8.5%
60% treated recycled cotton,	40.000	0.52	0.49	5.8%
40% medium cotton	40.000	0.42	0.39	7.2%
60% untreated recycled cotton,	35.000	0.41	0.38	7.3%
30% medium cotton, 10% flax	35.000	0.42	0.37	11.9%

4.6.3 Pilling

When looking at the pilling results the fabrics show a hardly any pilling, but the fabrics got a bit more hairy. Based on the scales the fabrics were judged as follows:

- 60% treated recycled cotton, 30% medium cotton, 10% flax 3-4
- 60% treated recycled cotton, 40% medium cotton 4-5
- 60% untreated recycled cotton, 30% medium cotton, 10% flax 3-4

The before and after pictures of the fabric prototypes for the pilling test can be seen in Appendix IV.

4.6.4 Flexibility

From the results of Shirley stiffness test, the fabric containing 60% untreated recycled cotton, 30% cotton and 10% flax is the most flexible as shown in Figure 19. The difference is however very little compared to the other two fabrics. It was difficult to measure the flexibility of the knitted fabrics, because the edges of the fabric would curl even after ironing. This influenced the measurement because the fabric could not be measured flat.

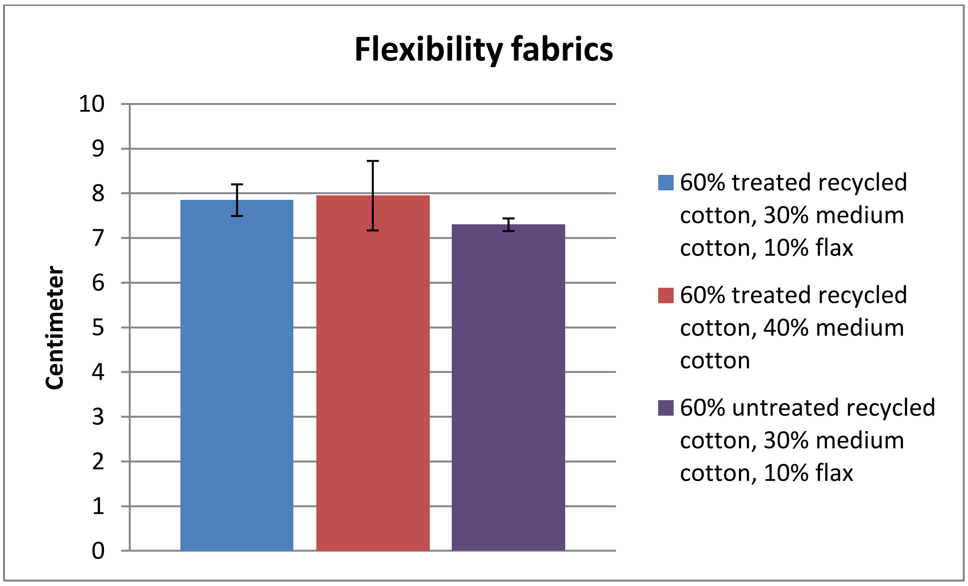

Figure 19. Results flexibility test fabrics with error bars for standard deviation

4.6.5 Elongation

The results of both of the fabrics containing the treated recycled cotton were almost the same as shown in Table 12. The elongation of the fabric containing the untreated recycled fibers was the highest.

Table 12

Results elongation fabrics standard deviation between brackets

	Elongation
60% treated recycled cotton, 30% medium cotton, 10% flax	44.9% (0.6)
60% treated recycled cotton, 40% medium cotton	45% (11.9)
60% untreated recycled cotton, 30% medium cotton, 10% flax	52.4% (3.5)

4.7 Implementation of the prototypes

In general the production speed of ring spinning is relatively low when compared to other spinning processes. However, a production speed of 6.5 meters per minute, as used in this research is very low even for ring spinning (Ahmed, Syduzzaman, Mahmud, & Rahman, 2015).

There are some aspects about the industrial process that could benefit the quality of the yarn prototypes. Different factors in the industrial process are more constant compared to the lab process. This concerns for example the shifting of the web and the sliver. In the lab the web has to be carried to the drawing machine and from the drawing machine to the ring spinning machine. While doing this the fibers are touched and possibly rearranged, this could influence the spinnability. The benefit of the industrial process is that the fibers are barely touched, especially in between the different process steps.

When looking at the possible application of the yarns, the properties were taken into account. The fabrics are relatively stiff, and as the fabrics have a high abrasion resistance they might be suitable for upholstery fabrics. As mentioned before, the current trend in society is that customers are more interested in products from natural origin. This is also in regards to the looks of fabrics, it embraces the natural look and its imperfections (Dawson, 2011; Muzyczek, 2012). This is a perfect fit with the yarn prototypes as they are irregular and have a rustic feel to them.

The mechanical properties of the yarn prototypes were compared to the mechanical properties of an industrial 100% virgin cotton yarn. The average twist of the industrial 100% virgin cotton yarn is 383 twists per meter, which is equal to a twist factor of *α*e 3.6. The standard deviation for this yarn is 34, which is much lower than for the yarn prototypes. This shows that the industrial yarn is more even when it comes to the twist. For knitting this twist factor is suitable, whereas the twist factor of the yarn prototypes is too high for knitting purposes.

The average tensile strength of the industrial 100% virgin cotton yarn is 14.74 cN/tex. When comparing this to the tensile strength of the yarn prototypes in Table 13, it can be seen that the industrial 100% virgin cotton yarn is slightly stronger than the yarn prototypes containing only short virgin cotton. It is however approximately twice as strong as the yarn prototypes containing the recycled cotton fibers.

Table 13

Tensile strength yarn prototypes cN/tex

	40% medium cotton	**30% medium cotton, 10% hemp**	**30% medium cotton, 10% flax**	**20% medium cotton, 20% hemp**	**20% medium cotton, 20% flax**	**10% medium cotton, 30% flax**
60% short cotton	13,08 cN/tex	12,02 cN/tex	11,16 cN/tex	12,88 cN/tex	12,79 cN/tex	11.86 cN/tex
60% treated recycled cotton	7,56 cN/tex	7,32 cN/tex	7,6 cN/tex	5,35 cN/tex	7,11 cN/tex	4.95 cN/tex
60% untreated recycled cotton	7,06 cN/tex	7,44 cN/tex	8,84 cN/tex	6,74 cN/tex	6,6 cN/tex	

The fabric prototypes were also compared to a knitted fabric produced with the industrial 100% cotton yarn. When looking at the results of the tensile strength measurement in Table 14, it can be seen that the industrial 100% virgin cotton fabric is approximately twice as strong as the fabrics containing the recycled fibers. This coheres with the tensile strength results of the yarns.

Table 14

Tensile strength comparison fabrics with standard deviation between brackets

Compositions	Tensile strength (N)
60% treated recycled cotton, 30% medium cotton, 10% flax	158 (28.3)
60% treated recycled cotton, 40% medium cotton	182 (46.7)
60% untreated recycled cotton, 30% medium cotton, 10% flax	206.5 (33.2)
100% cotton	374.8 (73.5)

When looking at the abrasion resistance of the fabrics it can be seen that the yarn breaks quicker, than for the fabrics containing the recycled fibers, which broke between 35.000 and 40.000 cycles. The results of the fabrics containing the recycled fibers are visible in Table 10 and Table 11, shown previously. The results of the abrasion resistance of the industrial 100% virgin cotton yarn can be seen below in Table 15. The weight loss of the industrial 100% virgin cotton yarn is much lower. This can be due to the fewer cycles or because the yarn contains longer fibers and will therefore not lose the fibers as easily.

Table 15

Results abrasion resistance industrial 100% cotton yarn

	Yarn break (cycles)	Weight specimen before test (gram)	Weight specimen after yarn break (gram)	Weight loss
100% cotton	20.000	0.36	0.35	2.78 %
	25.000	0.39	0.37	5.13 %

The knitted fabric created with the 100% virgin cotton yarn was only slightly more flexible than the fabrics created with the recycled fibers. The thickness of the yarns and the waxing that is done prior to knitting could influence the flexibility of the fabric.

4.7.1 Sustainability analysis

When looking at the sustainability of a product, several aspects should be considered. To evaluate the sustainability of the created prototypes, the use of recycled cotton fiber was analyzed on its sustainability in comparison to a virgin cotton fiber. The carbon footprint of the textile supply chain is high, to reduce this recycling is a good solution. According to the research of Muthu, Li, Hu and Ze (2012) when mechanical recycling is adapted throughout the entire supply chain the carbon footprint of the textile supply chain can be reduced. When it comes to the different recycling methods, mechanical recycling uses the least energy compared to extrusion and chemical recycling (Pesnel & Perwuelz, 2011)

According to the research of Spathas (2017), recycled cotton fibers use eight times less water and 18% less greenhouse gasses than virgin cotton fibers. However, the quality of the yarns containing recycled cotton fibers is lower and therefore the durability of the product is lower (Spathas, 2017).

Miljögiraff (2016) performed a life cycle assessment (LCA) of mechanically recycled cotton. In this research the LCA of recycled cotton fiber was compared to two different LCA's of virgin cotton fibers. The comparison was made for 1000 kg of cotton fiber. The LCA of the recycled cotton fibers include the following steps; collection, sorting and shredding of the textile waste. The LCA of the virgin cotton fibers asses the cotton fiber ready for spinning. It can be seen in *Figure 20* that impact of the recycled cotton fibers is lower compared to both of the virgin fibers (Miljögiraff, 2016).

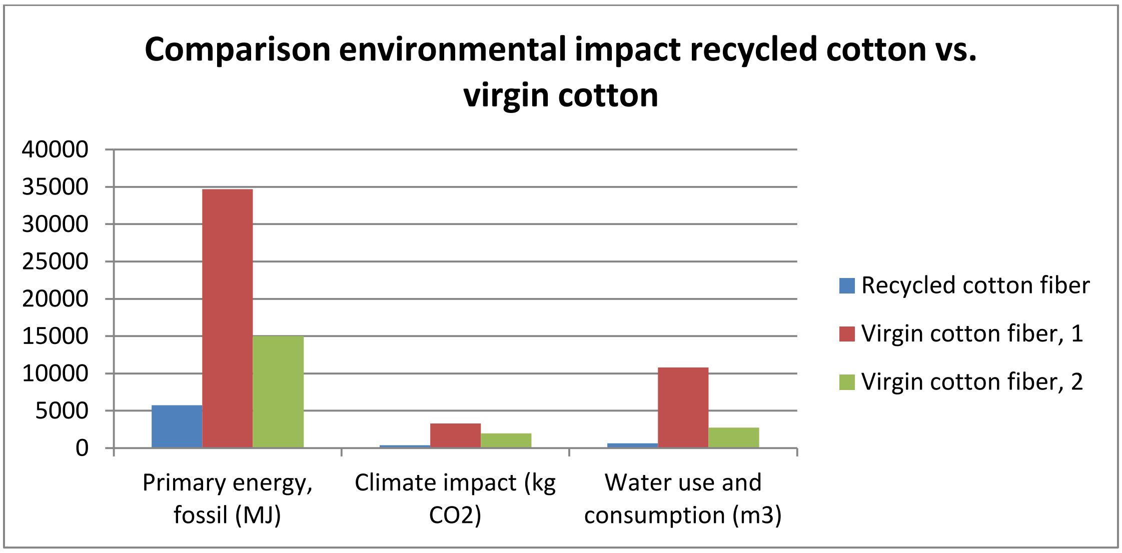

Figure 20. Comparison of the environmental impact of recycled cotton vs. virgin cotton
Note. Adapted from "LCA of recycling cotton" by Miljögiraff. 2016, p. 2. Copyright 2016 by Miljögiraff.

When looking at the environmental impact of a product, it is always better to have as few steps as possible in the supply chain, and add as little treatments or finishes as possible. For this reason, it would be better to use the untreated recycled cotton fiber instead of the treated recycled cotton fiber.

4.7.2 Drivers

What are the drivers that make business decide to use (partially) recycled yarns? First of all there is pressure from the European Union (EU), as well as local governments. The EU is funding projects, that should lead to a circular economy, in which recycling play an important role, through their Horizon 2020 program. Alongside the EU is coming up with legislations regarding recycling and the use of landfill, but also within the different European countries legislations are made. For example the national government in the Netherlands has signed a 'raw materials agreement' with business communities. In this agreement it is pointed out that by 2030, the use of primary raw materials in the industrial production processes must be reduced by 50 percent. On the longer run, by 2050, the Netherlands should be fully circular on reusable raw materials (De Rijksoverheid, 2017).

Another driver is the society, as consumers become more aware of the environmental impact of the products that they purchase. The demand from the society for more sustainable alternatives is growing (Worrell & Reuter, 2014).

The industry itself is also a driver, with the still increasing consumption of society it is important to become more efficient with the resources. One of the ways to do this is by recycling of resources into products (Worrell & Reuter, 2014). Another reason is that the costs of disposing to landfills will continue to increase (Hawley, 2009).

There are also economical drivers to increase recycling of textiles. Textile recycling is often done locally to keep transportation costs to a minimum. Compared to most of the textile industry, the recycling businesses remain in western countries instead of moving to low wage countries. By implementing more recycling into the textile supply chain new opportunities for recycling business are provided, and new jobs are created (Cuc, Iordanescu, Girneata, & Irinel, 2015).

5 Conclusions

To answer the main research question; it can be concluded that it is possible to ring spin the recycled cotton fibers, independent of pre-treatment. Based on the methods used for this research the highest spinnable percentage of recycled content in the yarn was 60%. The best mechanical properties were obtained in the following blends:

- 60% untreated recycled cotton, 30% medium cotton, 10% flax
- 60% treated recycled cotton, 30% medium cotton, 10% flax
- 60% treated recycled cotton, 40% medium cotton

The main factor that influences the spinnability of the recycled fibers was the friction between the fibers and the rigidity of the fibers. As noticed from the results it can be assumed that the fiber friction and rigidity play a bigger role in the spinnability of fibers than the fiber length. There was no big difference noticed between the yarns obtained from the untreated and the treated recycled cotton fibers. This seems to be due to the treatment, which influences the friction between the recycled cotton fibers in the ring spinning process. In this case the treated recycled cotton fiber was longer than the untreated recycled cotton fiber but as the treatment affected the friction and rigidity of the treated recycled cotton fiber, this negatively influenced the spinnability.

Furthermore, the blend influences the spinnability of the recycled cotton fibers. By adding medium virgin cotton the fibers become more spinnable and by adding flax fibers the yarn had a higher tensile strength. Neither the hemp or flax fibers significantly benefit to the spinnability of the recycled cotton fibers. However the yarns containing the flax fibers were easier to spin than the yarns containing the hemp fibers. The flax fibers are slightly shorter than the medium virgin cotton fibers that were added. This made the blend more spinnable, as the difference between the fiber lengths was not as big. The hemp fibers have a high rigidity and a big difference of the fiber length between hemp fibers and recycled fibers. This made the hemp fibers more difficult to spin.

When flax or hemp fibers were used in the yarn it was always necessary to add virgin cotton fibers as well, due to rigidity of recycled cotton, hemp and flax fibers. It was not possible to obtain a web out of only recycled fibers and hemp or flax. This can be due to the inter fiber friction, but also due to the rigidity of the recycled cotton fibers as well as the hemp and flax fibers. By adding the virgin cotton fibers there was more friction between the fibers, as well as a connection between the rigid recycled cotton fibers and the rigid hemp or flax fibers.

Additionally, the twist plays an important role in the spinnability of the fibers. A high twist creates a higher friction between the fibers and thus a stronger and more spinnable yarn. Without the high twist the yarn is very weak and keeps breaking during spinning. The twist factors used for regular yarns are therefore not applicable to yarns containing recycled fibers. According to the results of the yarns containing the recycled cotton, there was no correlation between the twist factor and the tensile strength of the yarns. Some other parameters that influence the spinnability are drawing ratio, drafting system the ring and spacer clips.

The visual analysis showed that the yarns were uneven. This resulted in big varieties in the tensile strength and in the twist. Additionally, in the fabric prototypes it was seen that the yarn varies in thickness throughout the fabric. The mechanical properties of the yarn prototypes do meet the set requirements at the beginning of the research. Only the applied twist of the yarn was much higher than the set requirement for virgin fibers.

For the fabric prototyping, it was not possible to use the yarn on the circular knitting machine, as the linear density of the yarn was too high. This limited the options to the hand knitting machine. After waxing the yarns it was possible to produce a knitted fabric with the yarn prototypes.

The tensile strength of the fabric prototypes was relatively low, with big varieties due to the unevenness of the yarn. On the other hand, the abrasion resistance was relatively high which could make the yarns suitable as upholstery fabric. Creating the yarns in an industrial setting can be an advantage for the quality as the production process is more stable. However the production speed is generally much higher in the industrial process which might not be possible with the yarns containing the recycled cotton fibers.

6 Recommendations for future research

In this research only limited tests were done with the washing of the produced yarns. As this did not show any particular results more tests should be done. More yarns should be washed to see if washing away the pre-treatment influences the tensile strength of the yarn and if it influences the properties of the other fibers blended with the recycled cotton. Additionally, some tests should be done with washing the recycled cotton fibers prior to spinning, to study the effect of pre-treatment on the spinnability of the recycled cotton fibers.

From this research it was noticed that the humidity influences the process-ability of the recycled cotton fibers. It is recommended to do more research on the influences of the humidity and determining the optimal humidity for the spinning process of recycled cotton fibers.

It is also recommended to study the effect of different finishing materials on the yarns to improve their properties. For example a softener to give the fabric a soft hand rather than the stiff hand it currently has. Research can also be done on pre-treating the fibers to make them more spinnable. This pre-treatment should adjust the inter-fiber friction and reduce the rigidity of the recycled cotton fibers, flax and hemp fibers.

If the spinnability of the recycled fibers can be improved by pre-treatment, it should be tested if it is possible to produce thinner yarns. Thinner yarns can used for more different purposes than a thick yarn, and is more commonly produced in the yarn spinning industry. Additionally, a research for the improvement of the evenness of yarn by improvement of the sliver quality needs to be done. When thinner and more even yarns can be produced with the recycled cotton fibers trials should upscale on industrial size to validate these results.

In this research the yarns were used to produce knitted fabrics. However, as the twist factor of the yarns is very high the yarn is more suitable for weaving applications. It should be tested if it is possible to weave the yarns as they are.

During this research no reason was found for the high abrasion properties of the yarn prototypes. It is recommended to do more research, to determine the cause of the high abrasion resistance.

7 Research reflection

This chapter will give a reflection of the execution of the research. The used methods will be discussed and the reliability of the research will be examined. There will also be looked at the results and if they answer the research questions.

Using the Lamb and Kallal method used for this research was a suitable method, the framework helped guiding the research through the different phases necessary to produce and evaluate the prototypes.

With the knowledge I had in the beginning of the research these questions were suitable to answer the main question. Looking back on the research I did not expect the untreated recycled cotton fiber to perform as well as the treated recycled cotton fibers. If I had known this in the beginning of the research I would have added a question that focused more on the influence of the treatment on the spinnability of the fibers.

As ring spinning is a specialized task it took me quite some time to get used to the ring spinning machine as well as the carding and drawing machine. This was time that could not directly be put into the results of the research. However, the obtained results provide useful information for future research. They provide insight in the complications of short fiber ring spinning. Additionally the results give an overview of how, and it what blends these fibers can be spun into a yarn with the ring spinning process.

The planning made for this research was accurate and everything intended to do in the beginning of the research was done. There was even room to do some additional test, for example the dyeing of the fibers and the washing of the yarn.

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I. Appendix: Draw frame

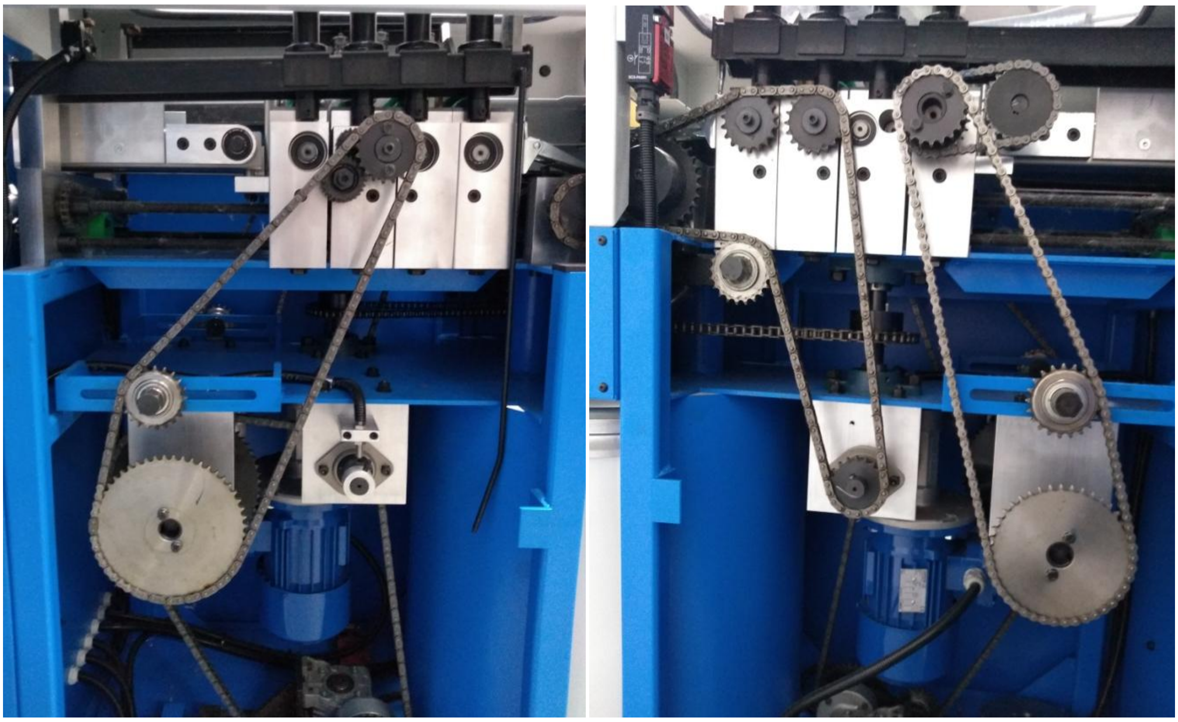


Figure 21. Sprockets draw frame

II. Appendix: Fail or pass yarn prototyping

Table 16

Fail or pass yarn prototyping

Composition	Fail or Pass
100% untreated recycled cotton	Fail
90% untreated recycled cotton, 10% medium cotton	Fail
90% untreated recycled cotton, 10% hemp	Fail
90% untreated recycled cotton, 10% flax	Fail
80% untreated recycled cotton, 20% medium cotton	Fail
80% untreated recycled cotton, 20% hemp	Fail
80% untreated recycled cotton, 20% flax	Fail
70% untreated recycled cotton, 30% medium cotton	Fail
70% untreated recycled cotton, 30% hemp	Fail
70% untreated recycled cotton, 30% flax	Fail
60% untreated recycled cotton, 40% medium cotton	Pass
60% untreated recycled cotton, 40% hemp	Fail
60% untreated recycled cotton, 40% flax	Fail
60% untreated recycled cotton, 30% medium cotton, 10% hemp	Pass
60% untreated recycled cotton, 30% medium cotton, 10% flax	Pass
60% untreated recycled cotton, 20% medium cotton, 20% hemp	Pass
60% untreated recycled cotton, 20% medium cotton, 20% hemp	Pass
60% untreated recycled cotton, 10% medium cotton, 30% hemp	Fail
60% untreated recycled cotton, 10% medium cotton, 30% flax	Fail
100% treated recycled cotton	Fail
90% treated recycled cotton, 10% medium cotton	Fail
90% treated recycled cotton, 10% hemp	Fail
90% treated recycled cotton, 10% flax	Fail
80% treated recycled cotton, 20% medium cotton	Fail
80% treated recycled cotton, 20% hemp	Fail
80% treated recycled cotton, 20% flax	Fail
70% treated recycled cotton, 30% medium cotton	Fail
70% treated recycled cotton, 30% hemp	Fail
70% treated recycled cotton, 30% flax	Fail
60% treated recycled cotton, 40% medium cotton	Pass
60% treated recycled cotton, 40% hemp	Fail
60% treated recycled cotton, 40% flax	Fail
60% treated recycled cotton, 30% medium cotton, 10% hemp	Pass
60% treated recycled cotton, 30% medium cotton, 10% flax	Pass
60% treated recycled cotton, 20% medium cotton, 20% hemp	Pass
60% treated recycled cotton, 20% medium cotton, 20% hemp	Pass
60% treated recycled cotton, 10% medium cotton, 30% hemp	Fail
60% treated recycled cotton, 10% medium cotton, 30% flax	Pass

III. Appendix: ANOVA analysis tensile strength

Summary	40% cotto	10% hemp	10% flax	20% hemp	20% flax	Total
Virgin						
Count	10	10	10	10	10	50
Sum	130,7848	120,2038	111,6242	128,8182	127,9351	619,3661
Average	13,07848	12,02038	11,16242	12,88182	12,79351	12,38732
Variance	5,744193	9,074326	3,631056	1,393169	5,44924	5,160208
Treated						
Count	10	10	10	10	10	50
Sum	75,62733	73,20253	76,01205	53,5122	71,14815	349,5023
Average	7,562733	7,320253	7,601205	5,35122	7,114815	6,990045
Variance	4,096406	3,068029	11,46696	2,917602	3,690225	5,352477
Untreated						
Count	10	10	10	10	10	50
Sum	70,61446	74,44872	88,44156	67,42331	66	366,928
Average	7,061446	7,444872	8,844156	6,742331	6,6	7,338561
Variance	7,063481	3,110784	10,8125	2,422581	3,628553	5,630609
Total						
Count	30	30	30	30	30	
Sum	277,0266	267,8551	276,0778	249,7537	265,0832	
Average	9,23422	8,928502	9,202595	8,325123	8,836107	
Variance	12,93339	9,681093	10,29425	13,16304	12,10871	

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	912,3676	2	456,1838	88,21498	3,13E-25	3,063204
Columns	16,15512	4	4,03878	0,781003	0,539398	2,438739
Interaction	76,74435	8	9,593044	1,855064	0,072188	2,007635
Within	698,122	135	5,171274			
Total	1703,389	149				

Figure 22. ANOVA tensile strength all yarn prototypes

Summary	40% cotto	10% hemp	10% flax	20% hemp	20% flax	Total
Treated						
Count	10	10	10	10	10	50
Sum	75,62733	73,20253	76,01205	53,5122	71,14815	349,5022523
Average	7,562733	7,320253	7,601205	5,35122	7,114815	6,990045046
Variance	4,096406	3,068029	11,46696	2,917602	3,690225	5,352477488
Untreated						
Count	10	10	10	10	10	50
Sum	70,61446	74,44872	88,44156	67,42331	66	366,9280471
Average	7,061446	7,444872	8,844156	6,742331	6,6	7,338560942
Variance	7,063481	3,110784	10,8125	2,422581	3,628553	5,63060922
Total						
Count	20	20	20	20	20	
Sum	146,2418	147,6512	164,4536	120,9355	137,1481	
Average	7,312089	7,382562	8,22268	6,046775	6,857407	
Variance	5,352391	2,930893	10,95999	3,038821	3,536535	

ANOVA

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	3,036583	1	3,036583	0,580863	0,447967	3,946875558
Columns	50,65387	4	12,66347	2,422373	0,053948	2,472927039
Interaction	17,02328	4	4,255819	0,814088	0,519446	2,472927039
Within	470,4941	90	5,227712			
Total	541,2078	99				

Figure 23. ANOVA tensile strength yarns recycled cotton fibers

IV. Appendix: Residual plots twist vs. tensile strength

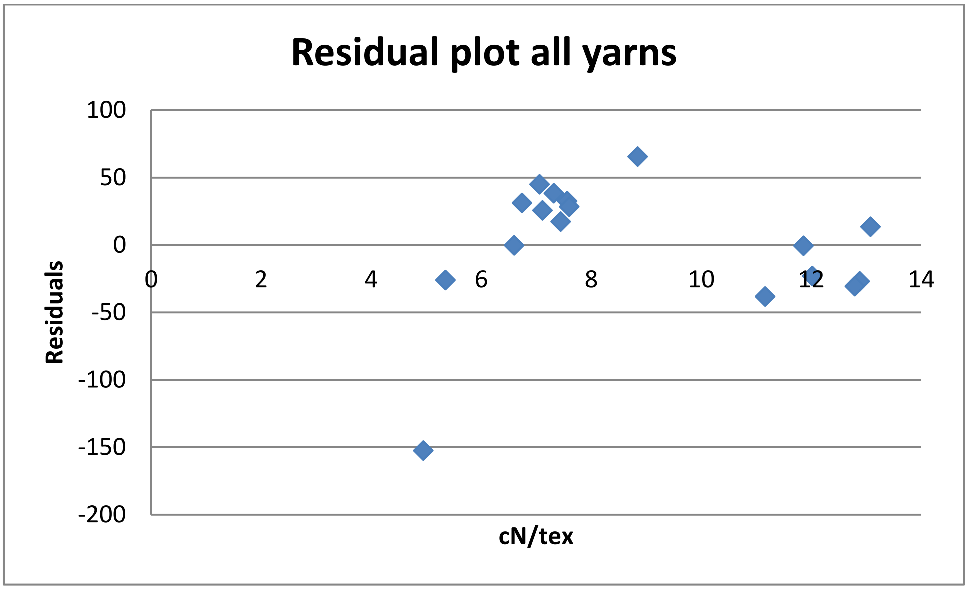


Figure 24. Residual plot twist vs. tensile strength all yarns

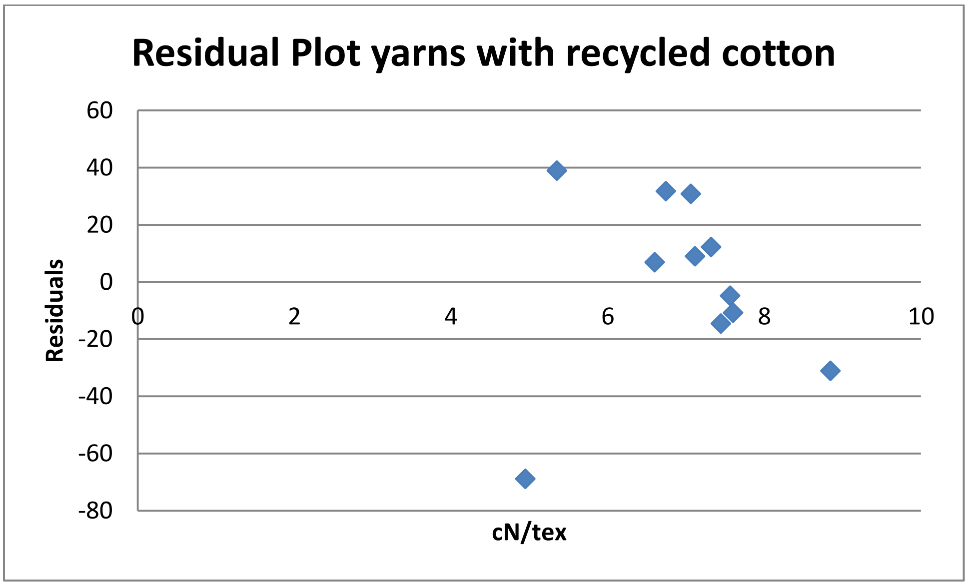


Figure 25. Residual plot twist vs. tensile strength yarns with recycled cotton fibers

V. Appendix: Linear regression twist factor vs. tensile strength

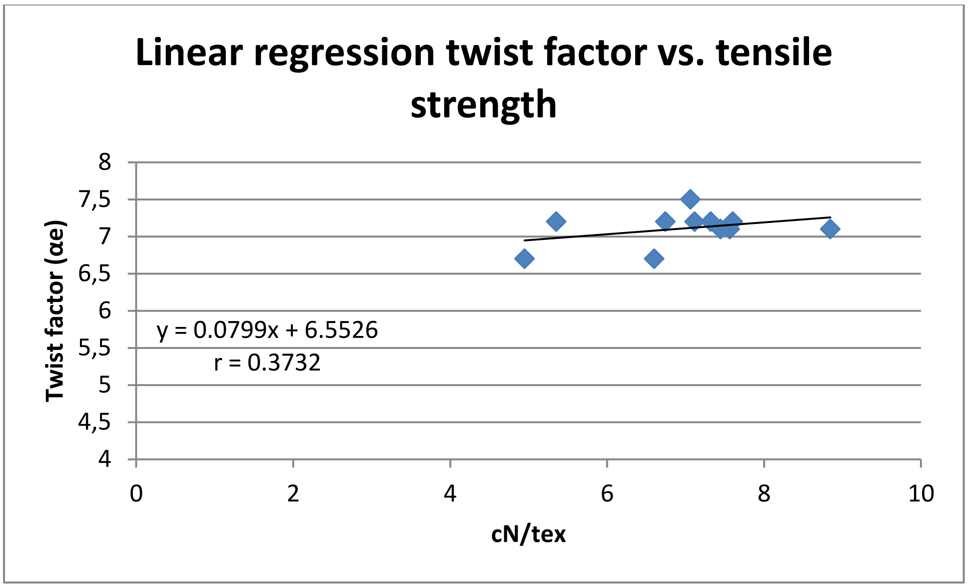


Figure 26. Linear regression twist factor vs. tensile strength including 60% treated recycled cotton, 10% medium cotton, 30% flax yarn

VI. Appendix: ANOVA washed yarns

Summary	treated 10	treated 40	untreated	Totaal		
washed						
Count	10	10	10	30		
Sum	71,42169	75,68944	64,75309	211,8642		
Average	7,142169	7,568944	6,475309	7,06214		
Variance	1,415293	3,906367	2,540509	2,64951		
not washed						
Count	10	10	10	30		
Sum	76,01205	75,62733	88,44156	240,0809		
Average	7,601205	7,562733	8,844156	8,002698		
Variance	11,46696	4,096407	10,8125	8,552103		
Total						
Count	20	20	20			
Sum	147,4337	151,3168	153,1946			
Average	7,371687	7,565839	7,659732			
Variance	6,15757	3,790798	7,801805			
ANOVA						
Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	13,26972	1	13,26972	2,325435	0,13311	4,019541
Columns	0,863208	2	0,431604	0,075636	0,927252	3,168246
Interaction	15,84123	2	7,920613	1,388037	0,258325	3,168246
Within	308,1423	54	5,70634			
Total	338,1165	59				

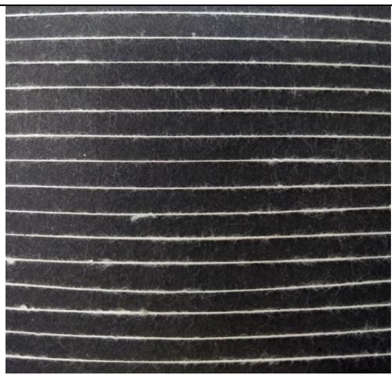
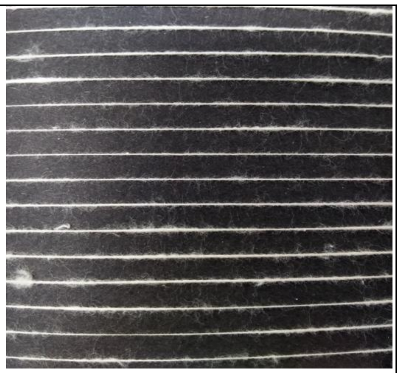
Figure 27. ANOVA washed yarns

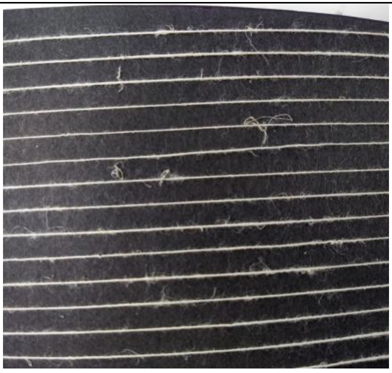
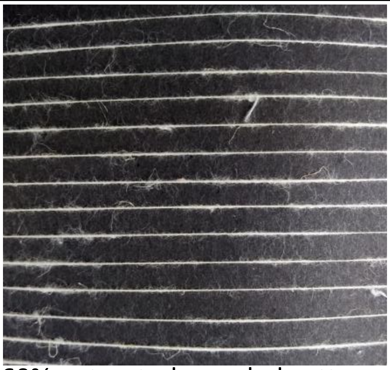
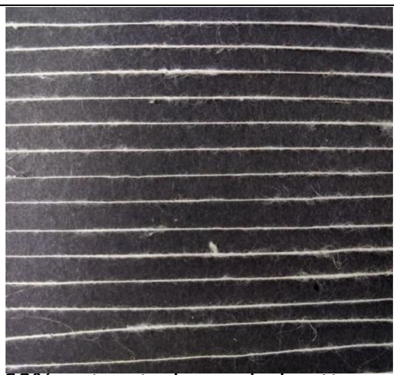
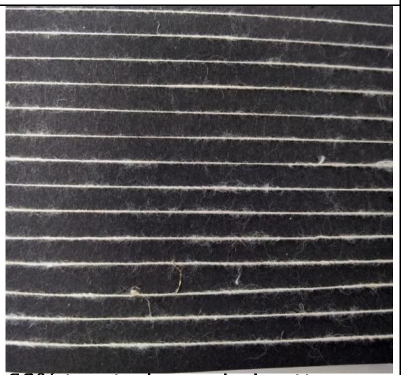
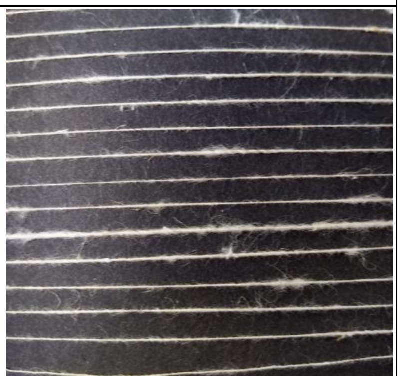
VII. Appendix: ANOVA elongation yarns

Sumary	40% cotto	10% hemp	10% flax	20% hemp	20% flax	Total
Virgin						
Count	10	10	10	10	10	50
Sum	87,48	85,428	83,691	81,637	75,5	413,736
Average	8,748	8,5428	8,3691	8,1637	7,55	8,27472
Variance	0,716745	1,680591	0,740617	0,256574	0,916064	0,963642
Treated						
Count	10	10	10	10	10	50
Sum	67,989	65,441	69,933	47,668	58,701	309,732
Average	6,7989	6,5441	6,9933	4,7668	5,8701	6,19464
Variance	1,925057	1,177084	4,306259	0,903163	2,560254	2,664041
Untreated						
Count	10	10	10	10	10	50
Sum	59,344	63,531	70,359	60,728	58,843	312,805
Average	5,9344	6,3531	7,0359	6,0728	5,8843	6,2561
Variance	3,009356	0,574374	1,66222	0,518332	1,71211	1,555423
Total						
Count	30	30	30	30	30	
Sum	214,813	214,4	223,983	190,033	193,044	
Average	7,160433	7,146667	7,4661	6,334433	6,4348	
Variance	3,186302	2,079609	2,504209	2,545657	2,253515	
Variantie-analyse						
Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	140,0889	2	70,04447	46,36905	4,68E-16	3,063204
Columns	29,55167	4	7,387918	4,890761	0,001029	2,438739
Interaction	20,49131	8	2,561414	1,695642	0,104848	2,007635
Within	203,9292	135	1,510587			
Total	394,0611	149				

Figure 28. ANOVA elongation yarns

VIII. Appendix: Visual analysis

 60% virgin cotton, 40% cotton B	 60% untreated recycled cotton, 40% cotton C	 60% treated recycled cotton, 40% cotton D
 60% virgin cotton, 30% cotton, 10% hemp C	 60% untreated recycled cotton, 30% cotton, 10% hemp D	 60% treated recycled cotton, 30% cotton, 10% hemp D
 60% virgin cotton, 30% cotton, 10% flax C	 60% untreated recycled cotton, 30% cotton, 10% flax D	 60% treated recycled cotton, 30% cotton, 10% flax D

 60% virgin cotton, 20% cotton, 20% hemp C	 60% untreated recycled cotton, 20% cotton, 20% hemp D	 60% treated recycled cotton, 20% cotton, 20% hemp D
 60% virgin cotton, 20% cotton, 20% flax B	 60% untreated recycled cotton, 20% cotton, 20% flax C	 60% treated recycled cotton, 20% cotton, 20% flax C
 60% virgin cotton, 10% cotton, 30% flax B		 60% treated recycled cotton, 10% cotton, 30% flax D

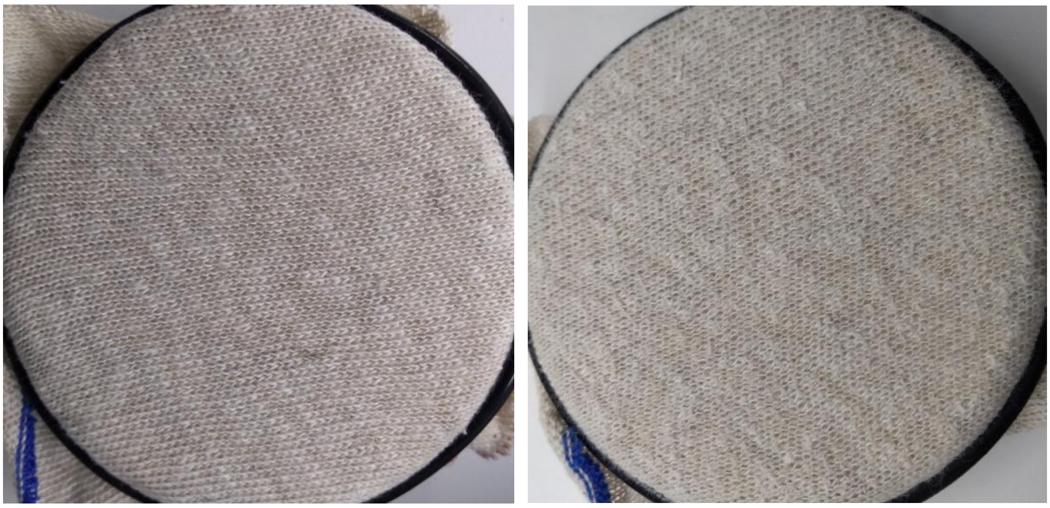
IX. Appendix: Results pilling resistance

a) before test b) after test

Figure 29. Pilling results 60% treated recycled cotton, 30% cotton, 10% flax

a) before test b) after test

Figure 30. Pilling results 60% treated recycled cotton, 40% cotton



a) before test b) after test

Figure 31. Pilling results 60% untreated recycled cotton, 30% cotton, 10% flax