TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology of Wood, Plastics and Textiles

APPLICATION OF CIRCULAR ECONOMY PRINCIPLES IN LINGERIE PRODUCTION

RINGMAJANDUSE PÕHIMÕTETE RAKENDAMINE ALUSPESU TOOTMISEL

MASTER THESIS

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Tallinn 2021

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THESIS TASK

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Study programme, KVEM12/18 – Technology of Wood, Plastics and Textiles

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Thesis topic:

(in English) *Application of circular economy principles in lingerie production*

(in Estonian) Ringmajanduse põhimõtete rakendamine aluspesu tootmisel

Thesis main objectives:

1. To study the basic aspects of the circular economy, with the main focus on materials, and applying these principles in the production of lingerie
2. To research more sustainable lingerie fabrics as alternatives to widely used conventional fabrics
3. Test the quality and performance of conventional and alternative materials according to different standards, compare and analyse the results
4. To facilitate product recyclability at the end of its life through product design

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Testing fabric selection and acquisition	15.03.21
2.	Main theory part completed	20.03.21
3.	Material tests completed	20.04.21
4.	Accessories and trimmings acquisition	22.04.21
5.	Design and processing technology decided	28.04.21
6.	Patterns completed	01.05.21
7.	Products finished	05.05.21
8.	Master thesis completed	24.05.21

Language: English **Deadline for submission of thesis:** "24" May 2021a

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CONTENTS

1 INTRODUCTION

The lingerie industry is part of the textile and fashion industry and has come a long way from being just an undergarment to a fashion statement. Lingerie industry has gone hand in hand with a technological and industrial revolution that has brought many additional scientific impetuses to its products, but also a linear supply chain model. Most manufacturers follow a "take-make-dispose" model without acknowledging that resources are not limitless. To reduce the negative environmental impact of the lingerie industry, it is essential for brands and manufacturers to focus on the transition to a circular system. Unlike the linear system, the circular economy focuses on making, using, and returning / recovering products. To ensure that products are suitable for the circular economy, they need to be designed for circularity from the very beginning.

Circular economy can be defined as an economic system of closed loops based on principles of designing out waste and pollution and keep raw materials, components, and products inside the circle as long as possible. Although the concept of the circular economy has been in use for a long time, implementing its principles is not an easy task for a deep-rooted and non-transparent textile industry. The challenges cover both social and economic areas. As part of the textile and fashion industry, the lingerie industry is also facing major difficulties in circular development but seems to be falling behind in outer garments. Partly due to the relatively small share in the clothing industry and partly due to the complex nature of the products, which cannot be easily recycled or reused.

The aim of this thesis is to study the application of circular economy principles in the production of lingerie. First objective to achieve this aim is to research more sustainable lingerie fabrics as an alternative to widely used conventional fabrics such as polyester, polyamide, and viscose. To perform this task, five different fabrics, either chemically or mechanically recycled, were tested in parallel with conventional lingerie fabrics to determine whether the properties and performance of the recycled fabrics are comparable to virgin fibres. Second objective of this thesis is to facilitate the recyclability of the lingerie set at the end of its life. To accomplish this task, the lingerie set is designed using mono materials and as few accessories and trimmings as possible, and the patterns are created in a way to maximize fabric consumption.

This thesis consists of a theoretical and a practical part. The theoretical part provides an overview of the lingerie industry, the main materials used and their properties, the environmental impact of the industry and future trends. It also introduces the principles of circular economy and discusses the challenges of implementing them in the lingerie industry, how to overcome these difficulties and what would be the alternative materials to the conventional ones. The theoretical part also tries to find solutions on how to design for circularity and what recycling methods to use for leftovers and discarded products.

In the practical part, there are two main parts. The first part focuses on testing, evaluation of the test results, and comparison of alternative and conventional materials. The second part is dedicated to product development that considers the concept of circular design, it includes the choice of materials, patterns and sewing technologies, and price calculations.

The discussion chapter at the end of the thesis analyses the overall performance of alternative fabrics and the problems encountered in testing and product development. The chapter also includes a flow chart of materials to illustrate the circular concept of a developed lingerie set. To demonstrate the competitiveness of the products developed in this dissertation, they are compared with similar products currently available.

2 CONCEPT OF CIRCULAR ECONOMY

A circular economy is an economic system of closed loops based on principles of designing out waste and pollution and keep raw materials, components, and products inside the circle as long as possible. Hundreds of different definitions are used in the circular economy and different aspects of the term are emphasized in different fields. [1]

There are three main principles of circular economy by The Ellen MacArthur Foundation. Those three principles are based on recognizing the importance of the economy, which needs to work effectively at every scale. [2]

The first principle is "design out waste and pollution" which strives to eliminate negative impacts of economic activity that cause damage to the environment and human health. It includes the pollution of air, land and water and release of greenhouse gases and toxic substances. [2]

The second principle is "keep products and materials in use". Products and components are designed for durability, reuse, remanufacturing and recycling to keep them circulating. Circular system that encouraging the use of bio-based materials as they cycle between economy and natural systems. [2]

The third principle is "regenerate natural systems". Renewable resources should be used instead of non-renewable ones, while also preserving and enhancing them. [2]

The transition from a linear to a circular economy should not be seen as more efficient waste management but should go beyond that and represent a fundamental paradigm shift that waste does not exist. In circular economy waste is perceived as valuable resource or waste is simply eliminated by designing products that can circulate in closed-loop cycles, illustrated in Figure below (Figure 2.1). [3]

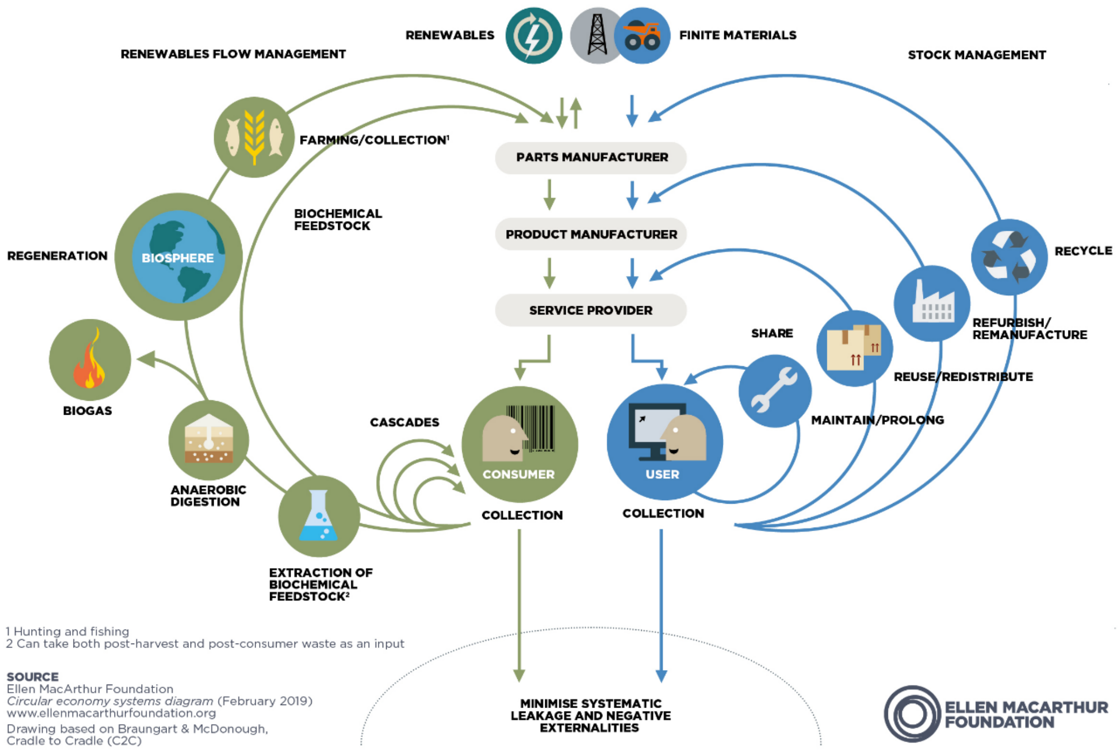


Figure 2.1. Circular economy systems diagram [4]

Two metabolisms are differentiated – biological and technical metabolism. Biologically based materials are designed in such way that these can go back into the system by composting and anaerobic digestion to nourish living systems. Technical metabolism is a closed loop system in which technical materials circulate in a closed loop system as valuable inputs. Both, biological and technical metabolism have many inner circles and the tighter the circle the less product needs to be changed. [3]

2.1 Prolonging the life of the product

Prolonging the life of a product means that it circulates within the system inside the inner circles and requires little or no change. Therefore, the inner circles of the circular economy scheme are the most powerful. It is also beneficial for the economy, as there are lower financial costs associated with the inner circle.

There are several approaches to keep products circulating within the smaller circles, and the following sections explain some of the most common ones.

Sharing platforms - this approach evolves several business models such as sharing, swapping, gifting, lending, or bartering of recourses. It is more popular amongst the younger generations, who have adopted this model due to lower prices and greater convenience. [5]

Product life extension – this business model extends product life and a useful life cycle, earning income from it, not from volume. This can be done either by selling reused products, using exchange or repurchase models, or companies can extend the life of a product by providing repair or maintenance services or guidance to customers on how to maintain items. [6]

Product as a service – this approach transforms the customer from being the owner of the product into the user of the product. This model is most relevant for products with high operating costs or expensiveness and long payback periods make it unappealing for the customer to own the product. Such a model could be preferred for short or infrequent use of the product, or for lack of space. [5]

2.2 Recycling

Recycling waste materials is a good way to save valuable resources that are going to landfills or incineration plants. Materials can be recycled in two ways:

1. Mechanically - which is categorized as a secondary recycling approach [7].
2. Chemically - which is categorized as a tertiary recycling approach [7].

2.2.1 Mechanical recycling

Today, mechanical recycling is the main method of recycling, it is cheaper, it takes less energy, it does not require big investments and it can be done on a small scale. For example, plastic bottles and fishing nets can be mechanically recycled into fibres. First, the source material is collected, chopped into small flakes, melted, and extruded into filament fibres. There is a slight difference in quality between recycled and virgin polyester / polyamide fibres, and each time the material is recycled, the properties of the material decrease. [7]

Pre- and post-consumer textile waste can also be mechanically recycled into new fibres and fabrics. The process involves cutting the textiles into smaller pieces, passing through a rotating drum that results in the textile fibres. The length, fineness, strength, polymer, and colour properties of the recycled fibre determine the quality of the fibre and what would be the most suitable new final product. Usually, the pre-consumer phase leftovers provide higher quality recycled fibres. The highest quality recycled fibres can be respun into yarns that are used to make woven or knitted fabrics for the use in clothing, bed linens and upholstery. Medium grade fibres can also be used to make fabrics, but they are used in end products such as napkins and fillings. Lower quality fibres are used for reinforcement in other constructions, non-woven fabrics, carpets, shoe linings, car sound and heat insulation, home insulation, toy fasteners and other end products. [7]

For example, the Finnish company Pure Waste started mechanical processing of fabrics and production of fabric from the obtained fibres already in 2013. The raw material is obtained from the pre-consumer cotton waste, which are sorted by colour (this determines the colour of the finished product) and converted back into fabric by mechanical processing (Figure 2.2.1.1). The resulting fibres are mixed with recycled polyester or viscose and spun into yarn. [8]

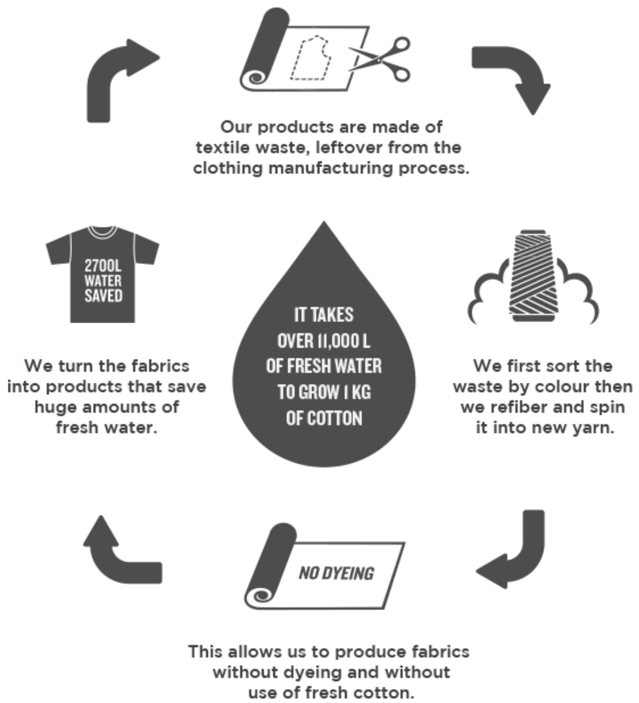


Figure 2.2.1.1. Pure Waste production chain [8]

2.2.2 Chemical recycling

This is another recycling method, where polymeric waste is converted back into basic chemical constituents, monomers, or fuels. Both natural and man-made fibres can be chemically recycled. The method requires the breakdown of synthetic fibres for polymerization. The process begins with the collection of waste (polyethylene terephthalate bottles, fabric scraps, clothes, etc.), which is then crushed into small pieces to form chips. The chips are decomposed, and then repolymerized and spun into new filament fibres. The advantages of chemical recycling are the same quality as virgin fibres, and the recycling of fibre blends commonly used in the lingerie industry has proven successful. [7]

Commonly used fibre blend polyester-cotton is chemically recycled using a selective degeneration method. The method uses n-methylmorpholine-N-Oxide, which dissolves cellulose. The dissolved cellulose and polyester are separated by filtration and the polyester is respun into a fibre, the dissolved cellulose can be used in the production of regenerated cellulosic fibres. [7]

Another commonly used fibre blend in lingerie industry is polyamide-elastane. Although there are methods for separating elastane from polyamide by dissolving it, the solvent N-dimethylformamide used for that is expensive and there are environmental concerns with its use. Several studies and pilot projects have been carried out to find more sustainable separation methods, but none of them is yet commercially available. [7] One promising method for selectively dissolving polyamide without damaging the elastane (or other fibres such as wool, cotton, etc.) is to use a mixture of water, ethanol, and calcium chloride as the solvent. [9]

In recent years there is big interest to use cellulosic fibres for chemical recycling. For example, Austrian company Lenzing has developed a lyocell production process using REFIBRA technology. REFIBRA™ technology involves the conversion of post-production cotton residues into cotton pulp, which is added to the wood pulp. TENCEL™ lyocell fibres are obtained from the combined raw material (Figure 2.2.2.1). [10]

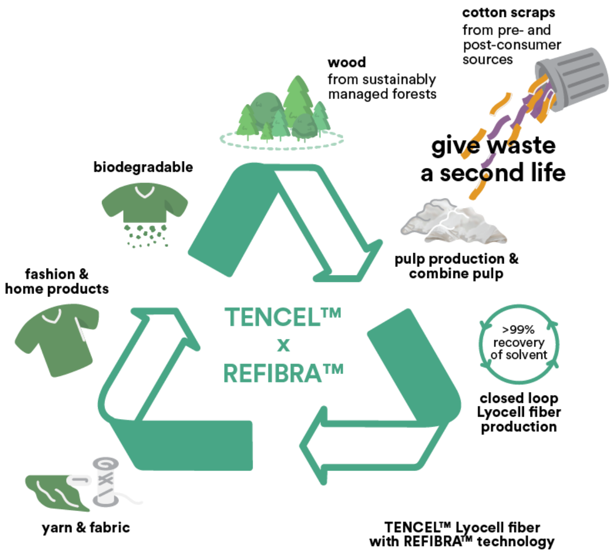


Figure 2.2.2.1. TENCEL ™ lyocell production chain using REFIBRA ™ technology [10]

2.3 Composting

Materials made of natural fibres, such as cotton, silk, etc., as well as materials made of regenerated cellulose fibres, such as lyocell, are biodegradable and compostable. This means that microorganisms convert these materials into organic matter. The difference between biodegradable and compostable materials is that biodegradable materials degrade into few natural elements, while only one organic material remains, called humus, from the compostable material [11]. The degradation process can take place either with oxygen, called aerobic digestion, or without oxygen - anaerobic digestion [12].

Although materials named above are biodegradable and compostable, under the wrong condition (for examples dumped in landfills) these materials start to decompose anaerobically in an oxygen-free environment. Anaerobic digestion produces a number of bio-products including methane. [13]

To achieve toxin-free biodegradation, at least 99% of the product must be biodegradable and all non-degradable parts, such as accessories, buttons, trims, must be removed before the process begins. Also, fabrics and other materials used in garment must be free from toxic matters, such as AZO dyes. An oxygen-rich environment is necessary for decomposition, and breaking clothes into smaller pieces can reduce composting time. The addition of earthworms to the composting environment also helps to speed up the process, as worms are considered to be very efficient for the treatment of organic waste. [14]

3 OVERVIEW OF THE LINGERIE INDUSTRY

3.1 History of lingerie and future trends

Centuries ago, underwear was designed to cover intimate body parts, protect valuable outerwear from body secretion, and add an extra layer of insulation. The underwear patterns were simple, and the well-fitting undergarments were not a major concern. Men usually wore loincloths or shorts, and women wore long underskirts and bands around their chest. The materials used were mainly undyed linen, cotton, sometimes silk or leather. [15]

Underwear remained functional and practical for a long time. It was not until the 16th century that women's underwear gained an erotic meaning thanks to an iconic fashion item - a corset. It became a device used to narrow the waist and draw attention to the breasts and hips. It was a complex underwear consisting of bones (real whale bones were used in the early days), fabric and ribbons. As the corset was designed to be worn tightly against the body, it also required more intricate patterns. [16]

Underwear, as we know it today, began to take shape in the 20th century. New man-made materials such as viscose and polyamide were introduced, and in 1913 a modern bra was invented. Patterns and sewing technologies became more sophisticated and the list of materials used in the lingerie industry grew rapidly. [17]

In 2018, the global lingerie market size was valued at USD 29.9 billion [18]. The choice of underwear is huge - different styles, colours, materials, functions, etc. Various materials are used in one product and the designs are much more complex than they were decades ago. While centuries ago, underwear had only three main functions, today underwear can have many different functions and purposes.

As for future trends, lingerie styles have been shifted away from the bust-emphasizing bra styles that became popular in the 1990s to reflect the demand for comfort and functionality from modern consumers. Predictions of future trends show fluctuations in push-up bras and a downward trend and the emergence of a triangular bralettes, which are also a most invested bra types across UK and USA. [19]

Another growing trend is the "nude-line" lingerie in a wider range of colours. The "nude" tone of the underwear has meant light beige fabrics for many years and has been designed for light-skinned wearers. There are now several lingerie brands that offer women and men lingerie in a variety of nude tones to suit different skin colours (Figure 3.1.1). [19]

The diversity of lingerie and the inclusion of sizes and genders continue to be important, especially as younger generations are demanding a reassessment of the industry's traditionally sexualized images (Figure 3.1.1). [19]

Figure 3.1.1. From the left: Nubian Skin nude shades [20], Les Girls Les Boys unapologetic modernity [21]

As in other sectors of the textile and clothing industry, the environmental impact of lingerie has been examined, in particular due to its low cost, excessive use of dyes and the use of petroleum-based fabrics. Sustainability remains crucial due to the growing pressure from younger consumers, who tend to be more vocal on these issues. [19]

As functionality and comfort are increasingly important in lingerie, it is important that the materials used in the products help to achieve these goals. As a result, many innovative and high-tech materials become an integral part of the lingerie industry.

3.2 Materials used in lingerie industry

Nowadays, when lingerie has more and more purposes, different materials with different properties and functions are also needed. New technologies enable better quality materials, which also changes the requirements for materials and products. Knowledges about harmful substances has improved the safety of materials and there are many standards regulating the amount of chemicals in fabrics used in the underwear industry. As sustainability is an inevitable path, there is a growing interest in green materials and sustainable production methods.

Many different fabrics, laces, trimming and accessories are used in the lingerie production. For example, some bras may consist of about 20 different materials (including different fabrics, accessories, trimmings etc.) All these components and materials have a role to play in making underwear comfortable as well as functional.

3.2.1 Fabrics

Many different fabrics are used in the production of lingerie, which differ in composition, construction, properties, processing methods, etc. The choice of fabric depends mainly on the properties and functions of the product - whether it must be flowing (nightgowns) or shaping (trimming underwear), go unnoticed (seamless underwear) or be attractive (bedroom underwear), etc.

Knitted fabrics – there are two main types of knitted fabrics – warp-knit and weft knit (Figure 3.2.1.1). The main characteristics of knitted fabrics used in the lingerie production are stretchiness due to their construction, smoothness, and light to medium weight. The composition can vary from natural fibres (mainly cotton but also silk, hemp, and linen) to the man-made ones (regenerated fibres such as viscose, modal, and synthetic fibres such as polyester and polyamide). Elastane is often added to the fabric composition to make the knitted fabric even more stretchy. [22]

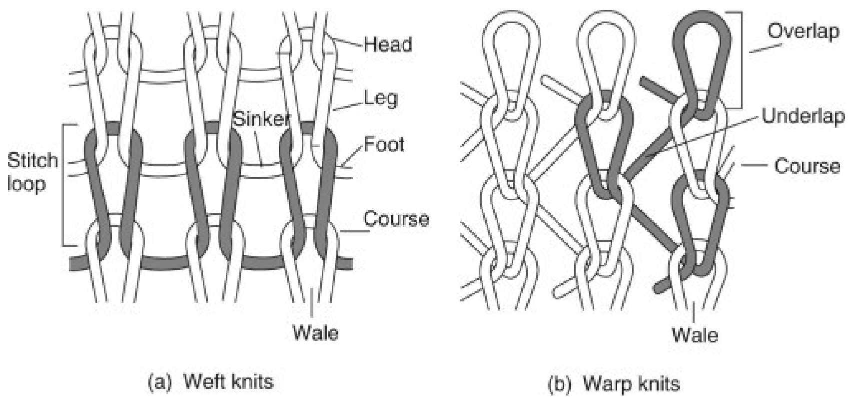


Figure 3.2.1.1. Two main types of knitted fabrics [22]

Mesh (stretchy) – is a warp knit fabric which main characteristics are light weight, permeable texture, and stretchiness in all directions. The difference from other warp knitted fabrics is that it is loosely woven, resulting in thousands of tiny holes in the fabric. The mesh is made mainly of synthetic fibres such as polyester and polyamide. The mesh composition may also contain elastane to increase elasticity. [23]

Net (stiff) - it is a wide range of fabrics in which the yarns are knotted, knitted, looped, or twisted at intersections. The result is a fabric formed with many open spaces. The main feature of the net is its rigidity and permeable structure. The net fabric may be made of silk, polyester, polyamide, viscose, or acetate. Tulle is the most widely used net fabric in the production of lingerie and can be made from a variety of fibres, including silk, viscose, polyamide, and polyester. [24]

Woven fabrics – these types of fabrics are not too common in the lingerie industry due to their stiffness. In some cases, they are still used, for example, to create a special look or design. The composition can vary from natural fibres to chemical ones and the manufacturing process depends on the construction of the fabric.

3.2.2 Lace

Lace is probably the most iconic material of lingerie due to its luxurious appearance and wide range of uses. It is a delicate fabric made of yarn or thread in an open mesh-like pattern. Lace can be made by hand, but nowadays lace is created by machines. [25]

There are several types of lace and one way to classify them is according to their manufacture. Table 3.2.2.1 gives and overview of different types of laces used in lingerie industry.

Table 3.2.2.1. Different laces used in the lingerie production

	Raschel lace	Leaver's lace	Embellished laces	Schiffli embroidery	Guipure lace
Photo					
Machinery used	Jacquard apparatus	Leaver machine	Processed either by machine or by hand	Schiffli machine	Chemical dissolving of tulle
Properties	Cheap and easy to manufacture	Delicate, finest lace	Time consuming and expensive	Complex and beautiful designs	Time consuming and resource intensive, expensive

In addition to different types of laces, these can be found in completely different shapes and forms - with different widths and different edges, all of which have a huge impact on the use of lace. There are lace fabrics without finished edges and they are used like ordinary woven or knitted fabrics. Lace trims, which are thin strips of lace, used to finish the edges. Both flounce and gallon laces have scalloped edges, the difference being that both sides of a gallon lace are scalloped-shaped, the flounce lace has one scallop and the other a flat edge. [25]

3.2.3 Moulded cups and foam

Moulded cups and foam are used as lining in bras, swimwear, and corsets. These materials give a firm shape and add support.

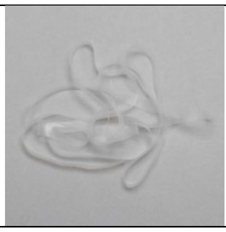
Moulded cups – retain their shape due to the moulding technology, which is very complex and time-consuming process. Synthetic fibres are used to make moulded cups. The cups can be of different shapes and thicknesses, and gel can be inserted to add push-up effect. [26] The advantage of moulded cups over foam-sewn cups is a seamless piece, the shape of which follows the shape of the breast.

Foam – the lingerie industry uses laminated polyurethane to make foam. Its thickness and the material used to laminate the foam varies. The fabric used for lamination is usually knitted fabric made of natural or synthetic fibres. The advantage over moulded cups is that foam is cheaper and allows to create a desired shape.

3.2.4 Elastic bands

The elastic band is a narrow fabric that stretches mainly due to its composition. Polyester, polyamide, or cotton fibres are wrapped around rubber or spandex cores and then woven, knitted, or braided into an elastic band. Elastic bands help to hold lingerie more tightly against the body and add support (for example, by adding an elastic band under the bust). Elastic bands can be classified according to their structure and fibre content: braided elastic, knitted elastic, woven elastic and transparent polyurethane bands. The most commonly used elastic bands for underwear are shown in the table below (Table 3.2.4.1). [27]

Table 3.2.4.1. Elastic bands used in the lingerie production

	Knitted elastic band	Transparent elastic band	Fold-over elastic band	Lingerie elastic band
Photo				
Composition	Elastane / polyamide or polyester	Polyurethane	Elastane / polyamide or polyester	Elastane / polyamide or polyester
Properties	Soft, retains its width when stretched, easy to manufacture	Stretches three to four times its length with complete recovery to its original size and shape	Indentation in the middle of the elastic band	Decorative edge, soft body side

3.2.5 Accessories

Accessories are a group of materials widely used in the manufacture of lingerie, especially in bras. Accessories have many different applications and purposes. They can be used to add support, keep a certain shape, for decorative purposes, to connect parts of underwear, etc.

Underwire – is a semi-circular wire used at the bottom of the bra cups to shape and hold the cup and support the breast. The underwire can be made of metal or moulded plastic. In the bra industry, three types of metal wires are commonly used: iron, stainless steel, titanium-nickel alloy. There are also plastic underwires made of polyvinyl chloride or polyethylene. They are softer and lighter than metal and adjust to the body, but do not offer the same support and rigidity as metal underwires. [26]

Shoulder straps – these are tightly woven elastic bands with a certain thickness and little elasticity compared to other elastic bands. Shoulder straps are an important part of bras because they help keep the bra on our body and add support. Bra straps are usually made of polyamide because it is a strong fibre. [28]

Buckle, ring, and slide - these three accessories above are usually connected to the bra's shoulder strap. They may vary in shape, size, and material. The ring, slider and buckle may be made of metal, polyamide-coated metal, alloys, electro-plated metal, and plastic.

Hook and eye – also called the back buckle and is used as a closure and adjust the tightness of the bra or bodice. Different widths are available, but single and triple row hooks the most common. For bras with a longer bodice or corset, a hook tape is used, which can be cut to the required length. The back buckle consists a metal hook and eye, and the fabric, which usually consists of four layers – front fabric, a stabilizer, interlining and back fabric. The most commonly used material for the fabric parts is polyamide. [26]

Boning – is a thin bone that has a certain toughness and strength. It is used along the edge of the seam between the side cradle and wing, to prevent the wing from curling. If bra has a longer bodice, then boning can be used underneath of the bust as well. The ends of the bone are rounded to avoid breakage of the fabric material and poking out. They come in different shapes, lengths and thicknesses depending on a purpose. Main materials used for boning are polyester, polyamide, and steel. [29]

Casing - is a tubular casing sewn to bra into which underwire or boning is inserted. It consists of three layers: brushed tricot, a stabilizer, and a woven fabric. It is made mainly of polyamide or polyester and can be finished in many ways. [26]

Ornaments – these are accessories that are added for beauty. They come in many different sizes, shapes, colours, and materials. The main materials used are plastic and metal.

Bows – added for beauty reasons and also to cover some seams. The bows are made of ribbons that are made of polyester or polyamide, with different widths, colours and finishes. Satin, velvet, grosgrain, transparent and tulle ribbon are most commonly used in underwear production.

3.3 Important properties of the fabrics used in lingerie industry

One of the biggest challenges in creating a perfect lingerie set is choosing the right fabric. It usually depends on the function of the underwear - whether it needs to shape the body or just feel comfortable against the skin, whether it needs to absorb moisture or dry quickly, etc.

To determine the fabric properties and performance, different fabric testing methods are used. Textile testing is the key to measure product quality and evaluating fabric performance. The performance of a fabric is determined by its chemical and physical structure. Textile tests are used to assess whether a fabric meets the requirements set out in a specified standard. Due to different end uses, fabrics have different performance requirements. Testing can be done at various stages of production, starting with fibres, yarns, fabrics and finally products. [30]

All tests must be performed in a well-organized manner and therefore various methods and procedures are standardized. Standards are provided by many different national and international organizations.

The following sections provide an overview of the main desired properties of lingerie fabrics and the test methods used to determine these properties.

3.3.1 Elasticity

Elasticity is a property of a material to stretch and return to its original shape after stretching or compression [31]. The elongation of the fabric may be due to the fibre content, when elastic fibres such as elastane or natural rubber are added to a fabric composition, or the way the fabric is constructed. This is an important feature, as lingerie is in most cases designed to fit snugly against the body without restricting body movement. Stretchability becomes less important when we talk about flowing garments such as nightgowns, bathrobes, etc. For some materials, elasticity can also be an undesirable property, such as a bra frame, which must be firm and rigid.

Methods used to determine the elasticity of fabrics are based on stretching, releasing, and repeating the piece of fabric. Measured values include elongation at maximum force, permanent deformation of the specimens and recovery.

3.3.2 Light weight

The weight of the fabric can be expressed as area density and is calculated as mass per unit area (g/m^2). The mass per unit area indicates the thickness of the material, the thicker it is, the greater the mass per unit area. The weight of the fabric depends on its fibre composition and/or its construction. For the lingerie products, lighter materials are preferred, it adds comfort and goes unnoticed under outerwear. Thinner and lighter weight fabrics also tend to dry faster, adding even more comfort. According to K. L. Hatch's book "Textile Science", fabrics can be classified as follows [32]:

- very light <34 g/m^2
- light 35-102 g/m^2
- medium 103-237 g/m^2

- heavy >237 g/m^2
- very heavy

To determine fabric weight, the fabric pieces with an agreed measurements and area are weighted and weight expressed as mass per unit area.

3.3.3 Softness and smoothness

Softness and smoothness can be measured by physically touching the fabric and describing its feeling against the body. The softness and smoothness are due to the fibres used in the fabric or the special treatment of the fabric. This is an important feature of underwear, as the fabric is against the skin and must feel comfortable and pleasant to the wearer.

In addition to the subjective approach, smoothness and softness can also be physically measured and quantified. Softness is often called the opposite of stiffness, which can be measured by bending length. Softness also opposes to firmness and hardness, which are measured by the thickness tests and the ease of yielding to pressure test, respectively. [33]

3.3.4 Absorbency

Absorbency is the property of a material to absorb moisture from the environment [31]. The absorbed liquid may be in the capillary spaces between the fibres or inside of the fibres. The absorbency is affected by fibre composition, thread twists, density of the thread, and fabric finishing and/or treatment. [34]

Absorbency also can affect other fabric properties such as skin comfort, accumulation of static electricity, shrinkage, stain removal and wrinkle recovery. [31] The downside of fabrics with high hygroscopic properties is that once the fabric has absorbed moisture, it tends to retain moisture and the fabric dries slowly.

The absorption can be tested by various standard methods and which one is chosen depends on the fabric and the intended use. The values measured include of how quickly the fabric absorbs a certain amount of fluid and/or how much fluid the fabric can absorb [34].

3.3.5 Short dry time

Most quick-drying fabrics are made of synthetic fibres such as polyester and polyamide. As the polyester yarn cannot retain water molecules, the drying time of the polyester fabric is also much shorter. [35] Short dry time is an important feature, especially for fabrics used in sportswear, because moist and wet fabric can cause discomfort and increases the weight of the garment. The main mechanism by how garment dries is evaporation [36].

To test the drying time, the fabrics must first be moistened or wettened and then left to dry. The values measured are the length of time required to dry a known mass of moisture from a textile fabric (drying rate) and time for which 100 % of applied water loss occurs (drying time) [37].

3.3.6 Abrasion resistance

Abrasion is the ability of the fabric to resist surface wear, rubbing, chafing caused by contact with another material [31]. This is an important feature of underwear, as underwear is constantly in contact with outerwear, which causes abrasion. It is therefore essential that the fabrics used in the lingerie industry be abrasion resistant to retain their appearance.

To determine fabrics abrasion resistance, abrasion and pilling testers are used. The test method is based on the friction of the sample against abrasive materials and the amount of abrasion or pilling is compared to standard parameters. Pilling is a phenomenon where entangled fibres stay on a fabric surface during abrasion and wear. Pilling formation can be divided into four stages: fuzz formation, entanglement, growth and wear-off. The pilling and fuzzing are referred as an unwanted property that can affect the aesthetics of the fabric and unacceptance by customers. [31]

3.3.7 Colour fastness

Colour fastness is a textile property that characterizes material's colour's resistance to fading or running under the influence of water / laundering, perspiration, rubbing, sun, light, atmosphere, or other environmental conditions [38]. It is especially important that the underwear has good colour fastness to abrasion, laundering and sweating, as these are the main factors that cause the underwear to fade or stain the outer garments.

Several test methods and standards have been developed to assess colour fastness in different categories mentioned above. The main purpose of the test is to evaluate the fading of the fabric and / or the staining of the standard fabric or abrasive used during the test.

Colour fastness to perspiration is the ability not to fade or stain when the fabric is perspired. Lingerie products are constantly exposed to sweat secreted by the skin, which can cause the transfer of dyes to the skin, so it is important to test the colour fastness of lingerie products for perspiration. [39] The ions in perspiration react with the ionic bonds of fabric dyes and can affect their colour fastness. Some respond more to acidic sweating, while others respond to alkaline sweating. [40]

3.3.8 Air permeability

Air permeability is the velocity of the air flow passing perpendicularly through the fabric [41]. Good air permeability allows free movement of air and adds comfort to the wearer. In contrast to some functional textile products, such as tents, industrial filters, sails, etc., air permeability is a desirable property of lingerie products [42].

Air permeability is related to porous structure of the fabric, but it is also affected by many other properties such as fibre structure and yarn properties, mass per unit area, fabric treatments, and environmental conditions. For example, knitted fabrics, that are also widely used in the lingerie industry, have a higher air permeability than woven fabrics due to their structure [42].

An air permeability tester, which measures the flow of air through a fabric, is typically used to test air permeability. Depending on the fabric and its purpose, different pressure drops are used.

3.3.9 Free from toxic chemicals

About 8,000 synthetic chemicals are used to produce textiles, including pesticides, heavy metals, hormone-altering chemicals, dyes, and cleaning solvents [43]. Chemicals used offer certain advantages, such as simplifying production processes and give the final product a specific function or desired look. However, these chemicals also can pose a threat to both the environment and human health.

Several textile certifications programs have been set up to control the presence of harmful chemicals in textiles. These include the specific certification of textiles to comply with chemical limits. Most well-known certifications include REACH (certificate for various product categories, including textiles), Oeko-Tex and asthma and allergy friendly. [44]

The pH of fabrics and garments can be greatly affected by scouring, bleaching, after-treatment, or final washing. Fabrics in direct contact with the skin, such as those used in lingerie, have a stricter pH requirement than, for example, outerwear. Too low or too high pH can cause skin irritation or other skin problems. Neutral pH is 7, values below 7 indicate acidic levels, and values above 7 indicate alkaline levels. [45] According to the Oeko-tex standard, fabrics in direct contact with the skin can have a pH between 4.0 and 7.5 [46].

3.4 Construction of lingerie

The most common lingerie products are bras and panties. Lingerie, especially bra, is a complex product group in terms of patterns, consisting of different parts, each with a specific purpose to perform. There are many different types of bras and their names may differ within different brands. Some of the well-known types of bras are push-up bra, underwire bra, triangle bra, balconette, plunge bra, wireless bra, full cup bra, t-shirt bra, sports bra, corset bra, bandeau bra etc. (Appendix 1).

The construction of different types of bras can vary greatly, as does the number of pattern pieces and materials. For example, in terms of the number of pattern pieces, the most complicated bras are underwire and corset bras. They can consist of more than 20 different pattern pieces (Figure 3.4.1).

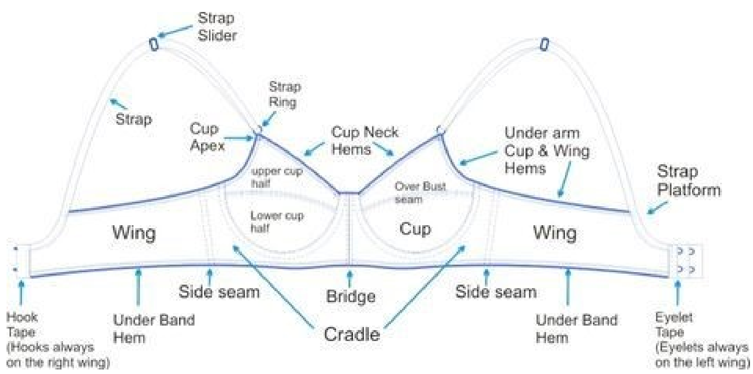


Figure 3.4.1. The parts of the underwire bra [47]

Triangle bras, on the other hand, are much simpler, sometimes consisting of only one pattern piece (Figure 3.4.2).

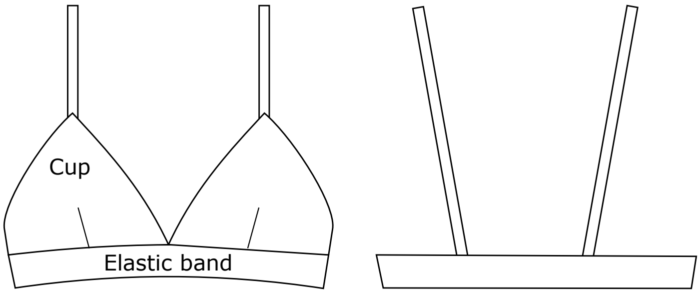


Figure 3.4.2. The parts of triangle bra

There are also many different styles of panties, for example, hipsters, high-waist panties, thongs, strings, cheekies, etc. (Appendix 1).

In terms of sewing patterns of underpants they do not vary that much between different styles. The pattern block usually consists of three main parts: front, back, gusset, which is usually doubled for hygienic reasons (Figure 3.4.3).

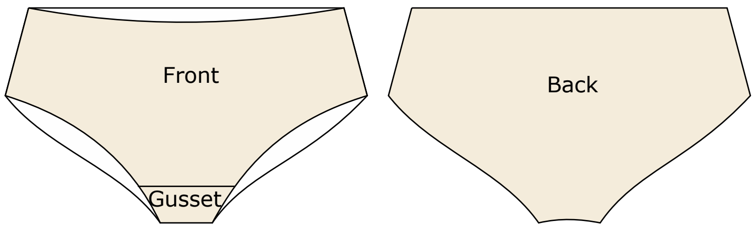


Figure 3.4.3. The parts of panties

3.5 Patternmaking of lingerie

Garment patterns are often described as emblems of the highest skill in the art of forming a model. Patternmaking requires high skills, practical knowledge of cutting and the art of modelling. Creating bra patterns is even more complex and requires a higher level of expertise and understanding of body anthropometry, movements, and fabric properties. Bra needs to fit perfectly, be comfortable, allow free body movements and be aesthetically pleasing. To achieve all this, several patternmaking methods are used to ensure high accuracy and perfect fit. [48]

There are three main methods to create lingerie patterns: constructing a flat 2D pattern on paper or using CAD, 3D modelling the fabric directly on the mannequin, and tracing pattern from the sample [48]. The method used depends on many factors, such as the complexity of the pattern, the materials used, the design of the product, the expertise of the pattern maker, etc.

As in other sections of the apparel industry, different styles of lingerie are being developed, modifying the basic pattern block. This saves time and ensures the same well-known fit between different collections. Therefore, it is especially important that the basic pattern block is well constructed and satisfying costumer needs.

3.6 Manufacturing process

After the design, fabric selection and patternmaking phase, the production process begins. It starts with depositing the fabric on the cutting table. Due to the high content of elastane, the fabric must be "relaxed" to prevent it from shrinking later. Cutting is usually done with a dye cutter or band knife or, for larger volumes, with a computer-controlled knife cutting machine. Since the pattern pieces for lingerie products are relatively small, extremely high accuracy is required in cutting phase. [49]

After cutting, the same size pieces are bundled and sent to the sewing department. Bundling requires great precision, because pieces of different sizes look quite similar and therefore it is easy to make mistakes when bundling them. [49]

Not only the sewing equipment but also the operator's skills are critical for efficient handling of small parts [49]. The main machines used to assemble lingerie products include:

Single needle lockstitch – to ensure strength and stability. Lockstitch is used more in bras than in panties because certain parts of bras need high stability and strength.

Double needle lockstitch – used to sew an underwire casing and casing for the bonings. This allows two parallel seams, saving time and ensuring even seam lines.

Zig-zag lockstitch – to provide stretch and to create a unique look. Zigzag machines can perform different stitch types, such as commonly used standard zigzag, 2-step zigzag, and 3-step zigzag, and not so often used scallop and blind stitch.

Overlock machine – to give finished edge and to prevent fraying. It also provides stretchy seam that is crucial for some seams in lingerie products.

Cover stitch machine – from above it looks like double needle lockstitch and from the below as a overlock. It is used for finishing edges and sewing elastic bands on a fabric as it allows for a stretchy seam.

Chain stitch machine – to joining the parts but compared with the lockstitch it allows flexibility and stretchiness yet being solid.

Bartack machine – is done on areas which require extra strength. It is used to seal underwire casings, bone channels and joining shoulder strap with the bra cup. It looks like an extremely tight zigzag stitch.

4 CHALLENGES OF IMPLEMENTING THE CIRCULAR ECONOMY IN LINGERIE PRODUCTION

The lingerie industry is one of the sectors of the clothing and textile industry, facing the same environmental problems as elsewhere in this industry. The main problems are CO_2 emissions, huge freshwater consumption, usage of hazardous substances and massive waste generation.

The underwear industry mainly uses synthetic fibres, which cause CO_2 emissions, ocean micro-pollution and the use of hazardous chemicals in the production of synthetic fibres. In addition, synthetic fibres are not biodegradable and must be properly recycled to return to the cycle. This is a complex process due to a number of factors discussed in Chapter 2.1.

Cotton, which is also widely used in lingerie industry, requires large amounts of water to produce, uses fertilizers and pesticides and ultimately leads to soil depletion. Although cotton itself is biodegradable, elastane is usually added to cotton fabrics used in the lingerie industry to make it stretchier. However, this results in a mixture of non-biodegradable fibres, which is also difficult to recycle properly.

Due to the relatively small share of the clothing industry and the complex nature of the products, the lingerie industry seems to fall behind in the implementation of the circular economy in outer garments. Main challenges include complex design and the use of fibre blends, which is why recycling of used lingerie products is difficult, and they usually end up in a landfill or incineration plant, instead of recycling facilities or donation points. In addition, underwear has a relatively short lifespan due to frequent washing; elastane fibre added to the fabric composition reduces the tensile strength of the fabric and elastane fibres are also sensitive to heat and chlorine. And last but not least lingerie products have very limited aftermarket.

4.1 Various components

Lingerie is a complex group of garments to recycle since it consists many different materials within a product. There are different types of fabrics used in a product combined with elastic bands, accessories, and other trimmings. For example, bras may contain 20 different material and components. All those materials need different recycling methods which means they need to be separated before material is directed to a recycling facility.

Manual separation of clothing is currently the most widely used to disassemble products. This process is very time consuming and prone to mistakes. Furthermore, this type of processes is usually done in developing countries where wages are low and working conditions bad. It is also prone to child labour and so-called modern slavery.

The most effective solution would be to design homogeneous products. This means that all materials are made of the same fibre composition, including sewing thread and other trimmings. However, when it comes to underwear, this approach is quite difficult to achieve due to the different applications of different materials.

4.2 Fibre blends

In the lingerie industry, the most common fabric blends are either natural fibres mixed with man-made fibres or man-made fibres mixed with other man-made fibres. In most cases elastane is added to a fabric composition to increase stretchiness which is one of the most important characteristics of lingerie products. Although fabric blends give fabrics desired properties it also makes the recycling process more complicated.

The best solution would be to avoid the use of fabric blends and to use mono materials instead. It will simplify recycling process by making it less energy and time consuming and ensure that recycled materials are free from the impurities.

Despite the benefits of using mono materials, elastane fibres play an important role in the manufacture of underwear and in most cases are incorporated into lingerie fabrics. One option would be to recycle fabric blends by shredding them mechanically and use recycled fibres as insulation panels, paddings, or industrial wipes. The drawbacks of mechanical recycling are that fibres get down-cycled instead of up-cycled and elastane can cause problems during mechanical processing.

In order to obtain fibres of a higher grade and to allow fibre-to-fibre processing, three main steps should be followed. First, fibre content needs to be detected which can be done using NIRS (Near Infrared Spectroscopy). Low percentage of elastane fibres may cause misrecognition since it overlaps with the main material spectrum [50]. A study conducted with six elastane-containing cotton samples (2-5% elastane in cotton) indicated that only two out of six samples showed elastane content [50].

After the fibre content is detected, fibres from different origin need to be separated. Removal of elastane from blends using more sustainable solvents and keeping the other fibres intact is a major challenge [51]. Sections below describe two sustainable fibre separation methods used for polycotton blends.

Hydrothermal process is developed to fully separate and recycle cotton and polyester blends. It is sustainable by means of using only heat, water, and 5% of biodegradable chemical to separate the fibres. Hydrothermal reaction is catalysed by an organic acid, is biodegradable and not polluting the environment. [52]

Another sustainable separation method is the use of enzymes to break down the fabric into various fibres. During the biological recycling process the cotton fibres are degraded efficiently into glycose and highly pure polyester fibre are re-spun into a fibre. [53]

Finally, separated fibres can be properly mechanically or chemically recycled. These two methods are discussed in more detail in paragraph six.

4.3 Pre-consumer waste

As in the rest of the clothing industry, pre-consumer leftovers are generated at different production stages of the underwear industry.

One group of leftovers are the roll-ends. Fabrics and laces are typically bought either by the rolls or rounded quantities. For example, if the total need for lace per collection is 2800 meters, it is usually rounded to 3000 meters at the request of the lace manufacturer. It means that 200 meters of lace is already labelled as a waste. Roll-ends can also occur due to miscalculation of material consumption. As the roll-ends are in large pieces they can be used for making new products.

Other group of pre-consumer leftovers are cut-offs or scraps. These are fabric pieces that are too small to use for a new product and usually be discarded. Lingerie manufacturing is creating big quantities of that kind of leftovers. In Figure 4.3.1, there are two images of lingerie layouts. First image is showing underpants layout, where fabric utilization is only 65,56% and image on the right is illustrating a layout scheme for bra cup where lace band utilization is slightly over 50%. The average fabric utilization of lingerie is only 70-75% and even lower for lace bands, averaging 50-60%. Due to the small and irregular shape of the remaining pieces, it is difficult to upcycle them or find other use for them. Therefore, to prevent this waste from ending up in landfills or incineration plants, it should be recycled and returned to the system.

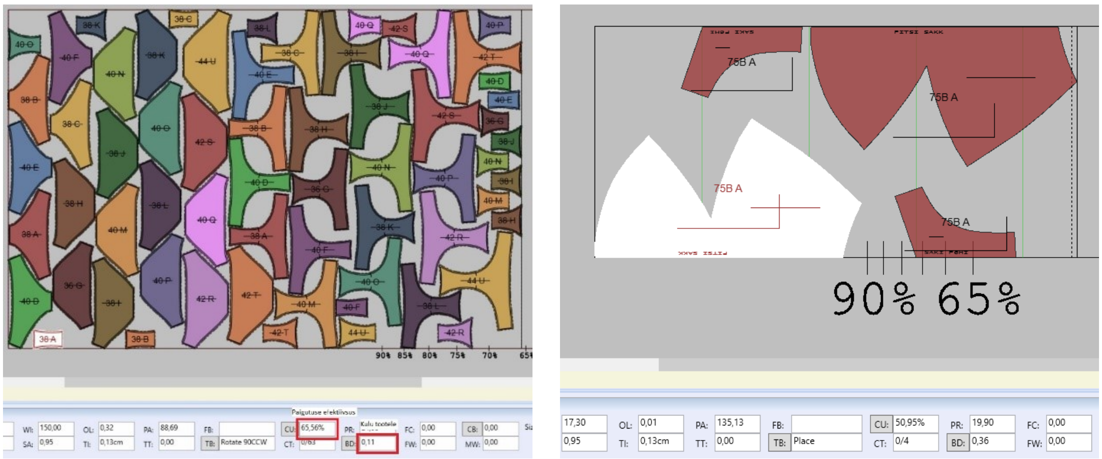


Figure 4.3.1. Underpants and bra layout schemes showing utilization and consumption per item.

Third group of pre-consumer leftovers is spoilage. A material defect makes it impossible to use it for products and is usually thrown away.

The last group of pre-consumer waste is overproduction and defected items. Large companies, which produce huge quantities, usually order more goods than are actually needed to fulfil the orders. This is to prevent a shortage in the event of defects in the fabric or garment. In addition, garment defects may occur during sewing or finishing processes or due to fabric / material defects. In many cases, repairing defected items is too time consuming and will be discarded.

4.4 Aftermarket for lingerie

Due to issues related with hygiene and relatively short lifespan of lingerie, the aftermarket for lingerie products is quite limited. Underwear is prone to pilling, abrasion, stretching out etc. and since elastane fibres (which is often added to the fabric composition) have a short lifespan, the lingerie products lose their appearance quite fast. This results in large amounts of post-consumer leftovers that cannot be reused or repaired and need to be properly recycled to close the loop.

It is possible to sell more valuable and desired brands or luxury lingerie, but it is not a big trend. Some facilities, such as homeless shelters, domestic violence shelters and refugee resettlement homes, also accept donations, but the items must be clean and in good condition.

5 OVERCOMING CHALLENGES

Although there are many challenges in implementing the concept of a circular economy in lingerie production, systematic thinking, innovation, and technological development are the keywords that will help overcome the difficulties.

This chapter will examine the material innovations, new thinking of patternmaking and sewing technologies and the platforms helping lingerie industry to become more circular.

5.1 Choice of sustainable materials

The choice of materials plays a major role in both the lingerie industry and the circular economy. The biggest challenge in replacing conventional materials with alternatives is how to provide sustainable materials without compromising the quality and essential properties of lingerie.

The fabrics used to make lingerie mainly comprise synthetic materials such as polyester, polyamide and elastane or fabrics from cellulose fibres such as cotton and viscose. Synthetic fibres have many of the essential properties for lingerie, such as elasticity, relatively light weight, short drying time, and smoothness. However, polyester, polyamide and elastane are made from non-renewable resources, they are responsible for microplastic pollution in the ocean, waste generation and huge energy consumption. Cotton and viscose fabrics have good breathability and absorbency, but cotton production also requires large amounts of water, fertilizers and pesticides and viscose production is related to high usage of toxic chemicals.

5.1.1 Alternative fabric options

There are various options for more sustainable fabrics to use as an alternative to conventional ones. Table below (Table 5.1.1.1) will give a short overview of those options and what are the advantages and disadvantages of using these fabrics.

Table 5.1.1.1. Alternative fabric options

Type of fibre	Advantages	Disadvantages
Chemically recycled fibres	-Reduces waste -Reduces water usage -Reduces CO_2 emissions	-Energy intensive -Using harmful chemicals -Difficult to use with fabric blends -Requires separation of the components before recycling
Mechanically recycled fibres	-Reduces waste -Reduces water usage -Reduces CO_2 emissions	-Energy intensive -Decreased value of the fibre -Requires separation of the components before recycling
Organic cotton	-No use of pesticide or fertilizers -Better soil conditions than conventional cotton growing -Decompose relatively fast -Made of renewable resources -Do not cause microplastic pollution -Lower energy consumption -Naturally breathable	-Usage of prime arable land -More expensive than synthetic fibres -Longer production times than conventional cotton -Poorer mechanical properties than conventional cotton -Extensive usage of water
Hemp	-Uses 50% less water than cotton -Does not require pesticides or herbicides to grow -Durable, has anti-bacterial properties and offers UV-protection -Made of renewable resources	-Has to blended with other fibres -Limited design options
Regenerated cellulose fibres: lyocell	-Biodegradable -Made of renewable resources -Uses non-toxic solvent	-Extensive water usage
Regenerated protein fibres	-Silky -Biodegradable -Uses leftovers/waste to n create an additional value	-Low tensile strength -Has to be blended with other fibres

5.1.2 Alternatives to elastane

Elastane is widely used fibre in clothing. The properties such as elasticity, lightweight, resistance to pilling etc. makes it highly desirable for activewear and lingerie industry. But there are many environmental issues related to this iconic fibre as well. That is why it is important to find alternatives that are more sustainable without compromising the quality and characteristics of the fibre.

On the below there are some of the alternatives in form of fibres that could replace elastane or at least allowing to decrease its manufacturing quantities.

Bio-derived elastane - it can be used with cotton and viscose staple fibres for wide variety of apparel fabrics and garments [54]. Spandex fibres come from a renewable butanediol raw material source that is made from dextrose derived from corn. The quality of bio-derived spandex fibres is same as the oil-based spandex because the molecule is the same, just from different source. Using bio-derived spandex in the fabrics makes no difference to the final product, since it has good knitting, dying, and finishing performance. [55]

Natural rubber - is derived from natural sources – from the plants. There are different species that produce rubber like substance, as a by-product of the cell metabolism. Most rubber-containing plants grow in tropical areas and only commercially sourced rubber comes from the *Hevea brasiliensis* tree that grows in Central and South America. The tree contains rubber in a form of latex. [56]

Since synthetic rubber created to mimic properties of natural rubber the characteristics are quite similar. Natural rubber has high tensile strength and it is resistant to the chipping, cutting and tearing. The other advantages include biodegradability and that it is sourced from renewable resources. The disadvantage of natural rubber is that it does not withstand damage from the UV-light, heat and ozone in the air too good. [57]

Recycled spandex - is using spandex leftovers from manufactures. It has claimed that recycled spandex has identical functionality with the virgin one. The manufacturing process includes collecting the leftover material, then shredding and drying it, dissolving the shredded mass. After that aging, filtering, and degassing and finally, yarn spinning. [58]

Naturally stretchy cotton - team of Australian scientists has been working to develop a cotton yarn that has some of the properties as synthetic fibres have – one of them is stretchiness. [59]

5.1.3 Sustainable innovations in bra cups

Moulded cups and foam are used in bras, swimwear, and corsetry as a lining. These materials will give a firm shape and add a support. Usually, synthetic fibres like polyurethane are used to make a foam, or for example polyethersulfone (PES) for moulded cups. Foams or conventional cups made of polyurethane are covered with a fabric made of different materials, it means that it needs to be separated before recycling it. Alternatives are spacer bra cups that are using fibrefill materials made solely out of synthetic materials such as polyester (Figure 5.1.3.1). These are created by connecting two knitted fabrics with a spacer yarn, which gives the fabric a three-dimensional look. The advantage compared with PU foams is that their porous structure adds air permeability, they have better elasticity and compression resistance. Since they do not need lamination is saves production times and makes recycling procedure easier. [26]

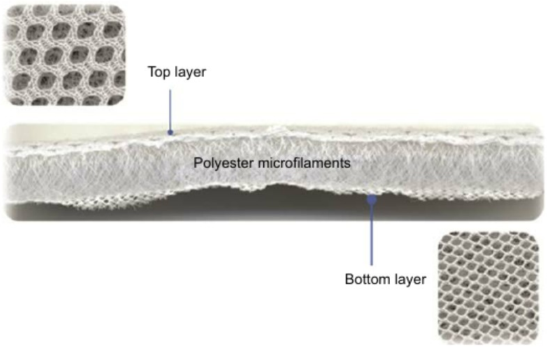


Figure 5.1.3.1. Cross-sectional view of a spacer fabric [26]

5.1.4 Sustainable thread selection

Although threads make up only a small part of the total product, they still play an important role in the garment circularity. Threads can make disassemble process easier, be biodegradable, or be made from recycled materials. All this helps to promote the circular economy.

Biodegradable threads are available in cotton, silk, viscose, or PLA. Due to the stretchy materials used in lingerie, viscose threads with an elasticity of more than 100% are the best choice. A company called Johann Müller AG produces cradle-to-cradle certified Tencel™ sewing thread, which is available in many different sizes, including #120, which is suitable for sewing lingerie [60].

Threads from recycled material are also gaining popularity. They are usually made of recycled PET bottles and have same properties as polyester thread made of virgin material. [61]

5.2 Circular approach in patternmaking and technology

The circular approach must start at the beginning of product creation. This means that the decisions made at the design stage also affect the end-of-life phase of the product in terms of recyclability, reusability, biodegradability, etc.

5.2.1 Patterns with minimal waste

As mentioned in paragraph 3.3, a lot of pre-consumer waste is generated during the cutting phase. One solution to reduce fabric waste is to create zero-waste patterns. One way to achieve 100% fabric utilization is to eliminate fabric scraps by incorporating all the fabric to a product (Figure 5.2.1.1). Although it is extremely difficult to achieve 100% fabric utilization with every product and in every size, it could still be the goal to pursue.

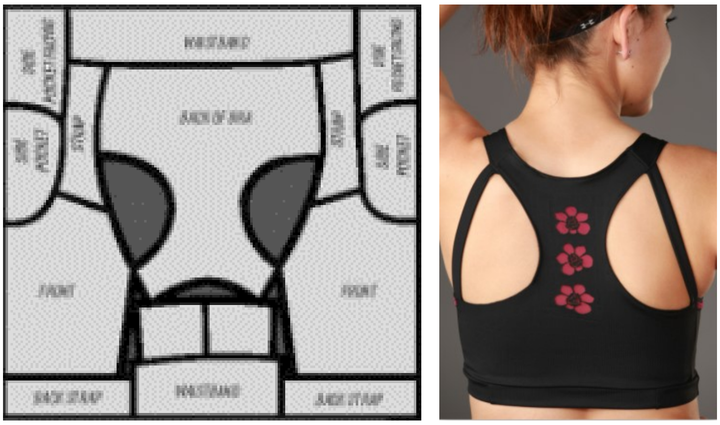


Figure 5.2.1.1. Minimal waste sports bra by Morgan Manuel [62]

Another way to minimize the fabric waste is to find use for the pieces of fabric between the patterns. For example, they could be used to make bow for accessorizing (Figure 5.2.1.2). The patterns for bows could already be placed in the layout markers together with the basic pattern pieces. This solution reduces waste and adds value to otherwise discarded fabrics.

Figure 4.2.1.2. Agent Provacature underwire bra using tulle pieces for accessorizing [63]

5.2.2 Increasing the efficiency of layout markers

Bras consist of many small irregularly shaped pattern pieces that can help to create an effective marker, as small parts are easy to adjust on the marker. To increase fabric utilization even more the multiple sizes and / or styles can be added on a one marker.

The pattern maker must consider that smaller pieces give a better utilization rate and large irregular shapes should be avoided if possible.

The same logic applies to panties - the smaller the pieces and the more they can be placed on one layout drawing, the higher the fabric utilization rate. For example, it would be possible to design panties that contain just one pattern piece, such a design would allow for fewer seams, which would reduce manufacturing time and costs. However, creating such a pattern causes a very high fabric consumption and a large amount of waste due to empty spaces between the pattern pieces.

5.2.3 Seamless and sew-free technologies

One way to reduce fabric waste, such as roll-ends and scraps, is seamless knitting technology. This technology reduces manufacturing time enabling of turning a yarn into a product with a few minutes with minimal or no cutting and sewing intervention. Because of no seams the seamless knitted garments provide comfortable fit to its wearer. The knitting structure may vary in different zones of the product to achieve support, compression, ventilation and/or shaping.

When seamless weaving technology was first introduced, it was mainly used for synthetic materials. Now, with the improvement of the technology, it can also be applied to various fibres [64]. Despite it benefits of reducing time and leftovers, it still cannot compete with cut and sew technology due to problems such as sizing, breast compression and insufficient support. [26]

Besides seamless knitting there are also sew-free technologies that enable join the components without using a sewing thread. There are different technologies used, such as welding, adhesive bonding, and laser seaming. All three involve melting and cooling thermoplastics in a joint to form a strong connection between different components. The advantages of the sew-free technologies are sleek appearance, excellent seam elasticity and comfort. From a circular economy point of view, sew-free technology reduces the number of materials used in the product (no thread is needed) and can, among other things, facilitate the recycling process. On the other hand, the use of such technology makes it difficult to separate the various components of the underwear if necessary. [26]

5.3 Product traceability

As mentioned above, the big issue with lingerie materials are material blends and various components within a product. A new platform called CircularID™ allows the identification of materials that are useful for regeneration, including disassembly and recycling. It also helps to identify the authenticity of products, simplifies the repair of clothing, and increases the transparency of the product life cycle. The working principle of CircularID™ is that brands incorporate a microscopic chip into every created product by weaving it into the fabric. The CircularID™ Protocol is structured in two parts: Product ID and Material ID. The Product ID contains all the information necessary to enable the commercial identification of the product for, circulation and monetization. The information is essential for the efficient sorting and reuse of the product to maximize its life. The Material ID contains all the information needed to identify the product materials to facilitate the management of product parts. This information is essential for the recovery of source materials, supporting component disassembly and mechanical and chemical recycling. [65] The question of how to enforce using CircularID™ (or any type of identifications labelling systems) is still an open question. The company hopes that governments will one day regulate how fashion brands report on the materials they use, similar to the regulation of plastic manufacturers. [66]

6 WORLD PRACTICES OF IMPLEMENTING CIRCULAR ECONOMY IN THE LINGERIE INDUSTRY

Circular economy approach is practiced in many different clothing sectors including lingerie industry. Despite of all the challenges and difficulties some brands and manufacturers have managed to make underwear more sustainable and brought the lingerie industry closer to circularity either through biodegradable lingerie set, take-back programs, or more sustainable materials.

6.1 The Very Good Bra

The Very Good Bra is an Australian based eco-lingerie brand who launched its first biodegradable zero post-consumer waste collection in 2018. Brand is using only natural components (e.g., fabric, sewing thread, labelling, and accessories) and all the materials are toxin free. In 2020 The Very Good Bra received the Good Design Award, which is Australia's oldest and the most prestigious international Awards for design and innovation. [67]

Main fabrics used are organic cotton and Tencel which are dyed using GOTS or REACH approved dyestuff. Elastics bands are made of natural rubber or Cradle to Cradle Gold Certified synthetic polymer which breaks down at end of life with no toxicity. Tencel sewing thread is manufactured from 100% cellulosic material and is Cradle to Cradle Gold Certified. Hook and eye pieces are made of 100% cotton, using cotton thread. Labels are made of organic cotton and printed with the pad-print technique, which is minimal waste, and uses Eco Passport Oeko-Tex inks. [67]

In order to avoid over production and also to finance production, sales are based on pre-orders. A bra costs about 60 euros (Figure 6.1.1) and panties 30 euros. [67]

Figure 6.1.1. The Very Good Bra [67]

6.2 The Big Favorite

The Big Favorite is a new circular underwear brand from USA established in 2020. The company produces t-shirts and underpants (Figure 6.2.1) from pima cotton that has a soft touch and durability due to longer staple fibres, longer fibres also make recycling easier. [68]

The Big Favorite offers its customers the opportunity to send their worn underwear back to the company by scanning the QR code on the clothing label to create a free shipping label. The Big Favorite collects, sorts and sanitize all the products before sending them to its textile recycling partner, who then sends the yarns to TBF's factory in Peru to produce new garments. [69] Since the company just launched, it does not yet have a supply of worn undergarments that can be used for production, which means that the current collection is made of 100% new yarn. But by 2023, the brand is aiming to have recycled 15 000 garments. In the meantime, they are looking for partners who are inventing new ways to recycle cotton repeatedly without losing its quality and value. [70]

Figure 6.2.1. The Big Favorite boxer brief [70]

6.3 Material manufacturers

Lingerie brands alone cannot bring circularity to this industry. The materials used in the production phase play important role as well. Many manufacturers of fabrics, accessories, trimmings, etc. have started to offer more sustainable choices in addition to traditional ones.

One of these companies are world leading bra cups and shoulder pads developer and producer **Muehlmeier** from Germany. Company is using 3D moulding technology combined with CNC machines to create high-quality products. In recent years, Muehlmeier has developed several sustainable options for bra cups and has set a target of at least 50% of the BraCup collection being ECO-Optimized products by 2022. In terms of circular economy systems, the company operates in both technical and biological cycle. It offers removable bra cups made of 100% recycled polyester. The mono material concept and removability make the recycling process easier. Company upcycles coffee grounds to produce bra cups with improved biodegradability and provides use for so called waste. Coffee Power BraCups are made of 25% polymerized coffee oil and the cover fabric is made from 84% bio polyester based on coffee grounds (Figure 5.3.1). Regarding the biological cycle, Muehlmeier has developed cups made from bio-based PLA that are biodegradable in composting plants and made using renewable sources. Biobased Latex BraCups consist of 96% natural latex that is retrieved from rubber trees (Figure 6.3.1). At the moment, all the above options are more expensive than the traditional collections offered and also require higher minimum quantities and prepayment. [71]

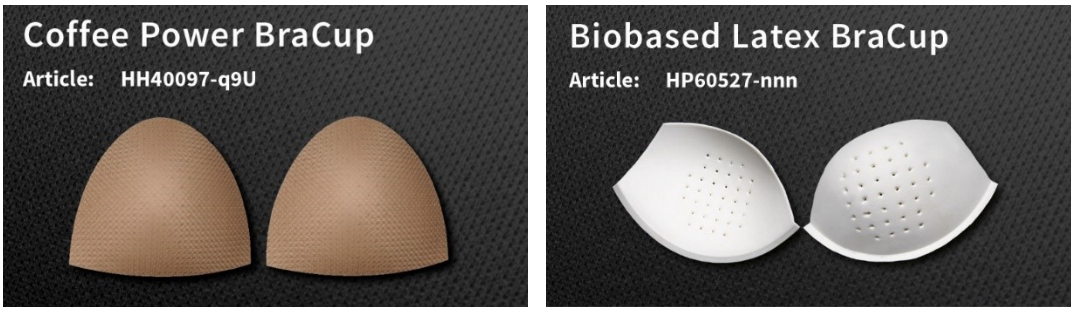


Figure 6.3.1. From the left: M-TEC® Coffee Power BraCups and M-TEC® Biobased Latex BraCups by Muehlmeier [71]

LYCRA® is a brand name that is producing elastane fibre – Lycra®. It has known to its good quality and innovations. In 2014 it launched bio-derived spandex that can be used with cotton and viscose staple fibres for wide variety of apparel fabrics and garments. [58] Approximately 70% of the Lycra® bio-derived spandex fibre comes from a renewable butanediol raw material source that is made from dextrose derived from corn. Behind this technology is company called Genomatica that developed a fermentation route to the chemical using genetically engineered E. coli bacteria to metabolize sugars into 1,4-butanediol. The quality of bio-derived spandex fibres is same as the oil-based spandex because the molecule is the same, just from different source. Using bio-derived spandex in the fabrics makes no difference to the final product, since it has good knitting, dying, and finishing performance. [59]

ROICA ™ is a high-quality stretchy fibre that is product of Asahi Kasei company. It has several advantages over rubber fibre including higher tensile strength and elasticity, availability of wider range of deniers and it is also lighter. It is produced by dry spinning method in worldwide. [72] In 2018 the company introduced their new product line which is the Roica Eco-Smart Spandex. There are two yarns in the selection, both eco-responsible and sustainable. First fibre is Roica 550, that has Cradle-to-Cradle certification and it breaks down without releasing harmful chemicals. The other fibre of the Eco-Smart line is Roica EF. It uses more than 50% of pre-consumer waste and is GRS (Global Recycled Standard) certified. [73]

In addition, many fabric and lace producers are adding more sustainable choices to their collection. To name few, the Italian lace producer **Iluna Group** is famous for its microfiber and tulle fabrics, rigid and elastic laces for the underwear. The company has its own Green Label collection, which presents a new responsible and sustainable approach to the planet and people, without sacrificing material aesthetics and quality. The Green Label collection includes GRS certified recycled polyamide and polyester yarns, ROICA ™ yarns and laces dyed with natural vegetable dyes. [74]

Willy Hermann is an Austrian based company who is manufacturing knitted fabrics for underwear, lingerie, sports and leisure wear and swimwear, as well as home and loungewear. Among other fabrics, company is producing fabrics from recycled polyamide, recycled elastane and recycled cotton. [75]

To bring a solution for disassembly and making recycling of different underwear component easier the company called **Wear2** has invented a technology which enables a quick and easy disassembly of clothing at end of life. This technology is using innovative microwave-triggered sewing thread and microwaves to break down the sewing thread that is holding garment pieces together (Figure 6.3.2). After disassembly, materials are transformed into mono streams allowing high-quality recycling with focus on fibre-to-fibre. [76]

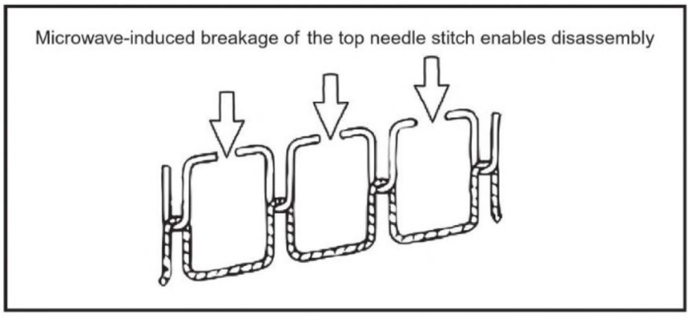


Figure 6.3.2. Targeted microwave induced breakage of sewing thread [79]

The heat-dissolving sewing thread also serves the same purpose. Special heat-dissolvable threads are created by **Resortecs®** that increase the recycle effectiveness and also repairs. There are several options in their list differ from dissolving temperature and fibre content. The highest disassembly temperature has Resortecs® 195°C made of bio-sourced polyamide and specially developed for workwear and jeans. The lowest disassembly temperature has Resortecs® 115°C, which is made of bio-sourced and bio-degradable polyester and developed for thermal sensitive material applications. [77]

7 MATERIALS AND METHODS

7.1 Concept of the circular lingerie set

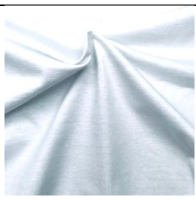
Considering the theoretical knowledge of the principles of circular economy and the main bottlenecks that prevent the production of lingerie from becoming more circular, a lingerie set has been developed during this thesis, which would take the above into account. The main criterion for the products developed was that they can enter the biological or technical cycle of the circular economy at the end of their life. The main desired parameters of the products to be created are:

- easy to recycle,
- compliance with the minimum requirements for fabrics used in lingerie,
- maximizing fabric utilization,
- considering trends,
- good fit and comfort,
- competitive prize,
- can be produced in small-scale production.

7.2 Materials

To test and compare the properties and performance of the fabrics, three conventional fabrics widely used in the lingerie industry and five recycled fabrics of similar composition were selected. The selected fabrics are presented in the Table 7.2.1, which contains general information of the fabrics provided by the manufacturer. The fabrics to be compared are set side by side in the table. "C" in the fabric name indicates conventional fabric and "A" indicates alternative fabric.

Table 7.2.1 Conventional and alternative fabrics used for testing

Conventional fabric	Basic information	Alternative	Basic information
 Fabric 1C. Green knitted PA	**Type:** Weft knit **COMP**: 80% Polyamide (PA) 20% Elastane (EL) **Width:** 150 cm **Weight:** 108±6 g/m^2 **Price:** 5,43 €/m **Supplier**: Lauma Fabrics, Latvia	 Fabric 4A. Grey knitted Rec PA	**Type:** Weft knit **COMP**: 83% Polyamide (mechanically recycled) (Rec PA) 17% Elastane (EL) **Width:** 150 cm **Weight:** 110 g/m^2 **Price:** 5,65 €/m **Supplier**: Carvico, Italy
 Fabric 2C. Green mesh PA	**Type:** Mesh **COMP**: 81% Polyamide (PA) 19% Elastane (EL) **Width:** 147 cm **Weight:** 69±7 g/m^2 **Price:** 3,56 €/m **Supplier**: Lauma Fabrics, Latvia	 Fabric 5A. Green mesh Rec PA	**Type:** Mesh **COMP**: 74% Polyamide (Recycled) (Rec PA) 26% Elastane (ROICA™) (EL) **Width:** 195 cm **Weight:** 125 g/m^2 **Price:** - **Supplier**: Penn Textile Solutions, Germany
 Fabric 3C. Blue knitted VI	**Type:** Weft knit **COMP**: 90% Viscose (VI) 10% Elastane (EL) **Width:** 155 cm **Weight:** 170 g/m^2 **Price:** 2,93 €/m **Supplier**: Rokiet, Poland	 Fabric 6A. White knitted Rec CO	**Type:** Weft knit **COMP**: 74% Cotton (CO) 19% Cotton (mechanically recycled) (Rec CO) 7% Elastane (EL) **Width:** 170 cm **Weight:** 145 g/m^2 **Price:** 8,72 €/m **Supplier**: Willy Hermann, Austria
		 Fabric 7A. Blue printed Refibra™	**Type:** Weft knit **COMP**: 50% Cotton (organic) (CO) 50% Lyocell (Tencel™ Refibra™) (CLY) **Width:** 155 cm **Weight:** 195 g/m^2 **Price:** 19,90 €/m **Supplier**: Purchased form Aarre, made in Portugal
		 Fabric 8A. Blue knitted Refibra™	**Type:** Weft knit **COMP**: 70% Cotton (organic) (CO) 30% Lyocell (Tencel™ Refibra™) (CLY) **Width:** 175 (±5%) cm **Weight:** 130 (±5%) g/m^2 **Price:** 12,19 €/m **Supplier**: Vilartex, Portugal

Two mechanically recycled fabrics that are selected for testing are green mesh recycled polyamide fabric (Fabric 5A) and white knitted recycled cotton fabric (Fabric 6A).

Mechanically recycled polyamide fabric contains of 74% Rec PA and 26% EL. Polyamide is made of pre-consumption waste generated during the production of polyamide yarn and is called Reco Nylon. The performance of the yarn made from 100% recycled polyamide is similar to ordinary polyamide 6 yarn, but in addition to good quality, it also significantly reduces the environmental impact. [78]

The mechanically recycled cotton fabric used in this thesis consists mainly of organic cotton with the addition of mechanically recycled cotton yarn and elastane (74% CO 19% Rec CO 7% EL). Mechanically recycled cotton called Recot2® is made of waste generated at various stages of production, such as yarn waste from a spinning mill and the cut edges of a knitting or weaving mill [79]. Due to the shorter fibres of mechanically recycled cotton fibres, they have to be blended with virgin cotton fibres to ensure the high quality of the yarn and fabric [79]. Therefore, Recot2® yarn consists of 50% mechanically recycled cotton with 50% virgin cotton added. The yarn has similar look and feel to conventional cotton yarn due to its special spinning technology. [80]

Three of the five alternative fabrics tested during this thesis were chemically recycled fabrics: grey knitted recycled polyamide fabric (Fabric 4A), blue printed Refibra™ (Fabric 7A) and blue knitted Refibra™ (Fabric 8A).

Chemically recycled polyamide fabric is made of 80% recycled polyamide and 20% elastane. The trademark of regenerated polyamide yarn is Econyl®. Econyl® yarn uses old fishing nets, industrial plastic, carpets, and fabric scraps to recover waste that would otherwise end up in the oceans or landfills. Through a radical regeneration and purification process, the polyamide waste is recycled back into a yarn that is identical to the polyamide 6 and has the same properties. [81]

The two other fabrics used in this thesis consist of lyocell fibres manufactured using Refibra™ technology. This technology takes post-production cotton residues and turns it into cotton pulp, which is added to the wood pulp. One fabric is made of 50% organic cotton and 50% Refibra™. The other fabric is made of 70% organic cotton and 30% Refibra™. The latter is also used to produce lingerie sets completed during the thesis, as it has advantages from the point of view of circular economy and also suitable properties for underwear. [10]

7.3 Materials testing methods

The test methods used in this thesis are based on ISO standards and they are common to lingerie fabrics to determine the properties of the fabric and its suitability for lingerie. The tests were performed in the Laboratory of Polymers and Textile Technology of

Tallinn University of Technology, and the summary of the performed tests is given below (Table 7.3.1).

Table 7.3.1. Materials testing method

Parameter	**Standard**	**Unit**
Mass per unit area	EVS-EN ISO 12127	g/m^2
Colour fastness to laundering	EVS-EN ISO 105-C06	Grades 1 to 5
Colour fastness to rubbing	EVS-EN ISO 105-X12	Grades 1 to 5
Pilling and fuzzing	EVS-EN ISO 12945-2	Grades 1 to 5
Air permeability	EVS-EN ISO 9237	l/m^2s
pH level	EVS-EN ISO 3071	-
Elasticity	EVS-EN ISO 20932-1	%
Colour fastness to perspiration	EVS-EN ISO 105-E04	Grades 1 to 5

The test specimens were conditioned according to ISO 139 if required by the testing standard. Standard atmospheric conditions are (65 ± 4) % relative humidity and (20 ± 2) °C. [82]

7.3.1 Mass per unit area

The test was conducted according to standard EVS-EN ISO 12127:2000 - Textiles – Fabrics - Determination of mass per unit area using small samples. The method is suitable for both woven and knitted materials and is used to determine the weight per square meter of fabric. [83]

To find the mass per unit area, the mass of the known fabric area is divided by its area and expressed in grams per square meters. Mass per unit area, M, in grams per square meter, is calculated using the following formula (7.3.1.1): [83]

$$M = \frac{m \cdot 10\,000}{A} \qquad (7.3.1.1)$$

Where:
M – mass per unit area, in g/m^2,
m - mass of a test specimen, in g,
A - area of the same test specimen, in cm^2. [83]

Five specimens of each fabric were cut from different parts of the fabric using scissors. Areas which were wrinkled or creased, selvedge, and not representative areas must be avoided. The samples were left under standard conditions for 24 hours until the test. The length and width of the samples were measured from three different locations to the nearest 1 mm and the areas of the samples were calculated from the average values of the lengths and widths of the samples. The individual specimens were weighted to the nearest 1 mg and mass per unit area was calculated using the formula above.

7.3.2 Colour fastness to laundering

The test was conducted according to standard EVS-EN ISO 105-C06:2010 - Textiles – Tests for colour fastness – Part C06: Colour fastness to domestic and commercial laundering. The objective to this test is to: [84]

- determine the resistance of the colour of textile of all kinds and in all forms to domestic or commercial laundering procedures used for normal household articles using a reference detergent,
- determine the colour loss and staining resulting from desorption and/or abrasive action.

The results were evaluated on a grey scale by assessing colour change and staining [84].

Apparatus and materials used:

- laboratory washing machine Linitest,
- stainless steel containers (Figure 7.3.2.1),
- teflon balls (Figure 7.3.2.1),
- a multifibre adjacent fabric,
- standard detergent Ece Non-Phosphate Reference Detergent (Figure 7.3.2.1),
- distilled water,
- grey scale for assessing change in colour,
- grey scale for assessing staining,
- colour assessment cabinet. [84]

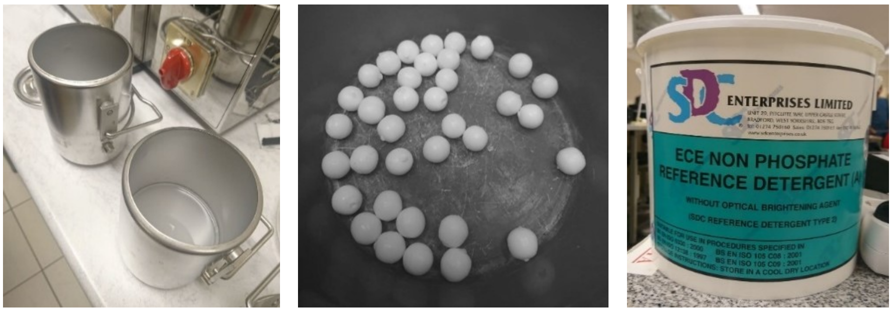


Figure 7.3.2.1. Materials used for testing from the left: stainless steel containers, teflon balls, standard detergent.

Two samples measuring (40 x 100) mm were cut from each fabric. The specimens were sewn together with a multifibre adjacent fabric on the shorter side of the specimen. To prepare the washing solution, 0,6 grams of standard detergent (Ece Non-Phosphate Reference Detergent) was added to 150 ml of distilled water. The solution was poured into the washing machine containers to which the Teflon balls and specimens were added. [84]

The wash regime was set to 30 minutes and the temperature was 30 °C (this is the washing temperature for most lingerie products). After washing, the specimens were rinsed under water at about 30 °C and placed in a drying oven at 60 °C. After drying, specimens were visually assessed using a grey scale in a colour assessment cabinet equipped with D65 artificial daylight. [84]

7.3.3 Colour fastness to rubbing

The test was conducted according to standard EVS-EN ISO 105-X12 - Textiles – Tests for colour fastness – Part X12: Colour fastness to rubbing. The objective to this test is to: [85]

- determine the colour fastness of a fabric when rubbing with a dry and wet rubbing cloth by evaluating the colour change of the specimen and the staining of a white standard cloth.

The results were evaluated on a grey scale by assessing colour change and staining. [85]

Apparatus and materials used:

- crockmeter SDL Atlas with a rubbing finger diameter of 16 mm and a downward force of 9 N (Figure 7.3.3.1),
- abrasive paper,
- standard cotton rubbing cloth,
- grey scale for assessing change in colour,
- grey scale for assessing staining,
- distilled water
- colour assessment cabinet. [85]

Four specimens measuring (120 x 170) mm were cut along a wale direction from each fabric - two for dry and two for wet rubbing. For dry rubbing, the specimen and standard cloth were fixed to the crockmeter (Figure 7.3.3.1) and the sample was rubbed in a straight line (along a wale direction) at a rate of one cycle per second 20 times (10 times fro and 10 times to) along a track. [85]

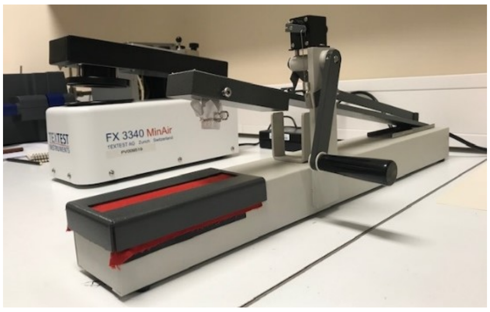


Figure 7.3.3.1. Crockmeter SDL Atlas

For wet rubbing, the standard fabric was first soaked in distilled water (the water content of the standard fabric must be 95 to 100%). The specimen and standard cloth were fixed to the crockmeter and the same procedure as for dry rubbing was repeated. Wet samples and standard fabrics were placed in the drying oven at 60 °C to dry. [85]

After drying, specimens were visually assessed using a grey scale in a colour assessment cabinet equipped with D65 artificial daylight. [85]

7.3.4 Pilling and fuzzing

The test was conducted according to standard EVS-EN ISO 12945-2:2020 - Textiles — Determination of fabric propensity to surface pilling, fuzzing or matting — Part 2: Modified Martindale method. The objective to this test is to: [86]

- determine fabric surface resistance to pilling and fuzzing while rubbing occurs.

The Martindale abrasion and pilling tester determines the abrasion resistance and pilling of textiles. Samples with a defined load are rubbed against known abrasives in a constantly changing direction, following the Lissajous figure. [86]

Apparatus and materials used:

- James Heal 5-position Martindale abrasion testing apparatus (Figure 7.3.4.1),
- test specimen holder and spindle, with a mass of 155 g,
- felt for a specimen holder, with a diameter of 90 mm,
- felt for a pilling table, with a diameter of 140 mm,
- abradant, with a diameter of 140 mm,
- circular sample cutter, with a diameter of 130 mm,
- colour assessment cabinet. [86]

Using a special circular cutting tool, three samples with a diameter of 130 mm were cut from each fabric. Abradant fabrics and sample fabrics were attached to the Martindale tester (Figure 7.3.4.1) [86]

Figure 7.3.4.1. James Heal Martindale abrasion and pilling tester

Test was performed in four stages – 125, 500, 1000 and 2000 rubs. After every stage all the specimens were detached from the tester and evaluated in colour assessment cabinet equipped with D65 artificial daylight. Fabrics were evaluated for both pill formation and pill volume as well as fuzzing. [86]

To evaluate, the test specimens were compared with images obtained from the literature (Figure 7.3.4.2).

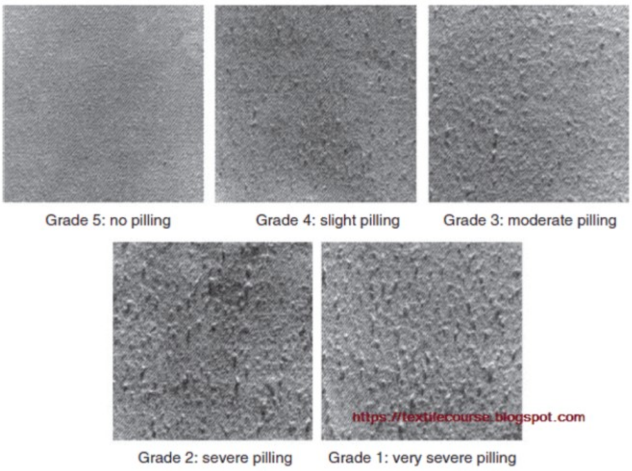


Figure 7.3.4.2. Pilling assessment comparison [87]

7.3.5 Air permeability

The test was conducted according to standard EVS-EN ISO 9237:2000 - Textiles - Determination of permeability of fabric to air. [88]

It was not necessary to cut samples for this test. Instead, large pieces of fabric were used to test air permeability. The test sample was placed in a round sample holder with sufficient tension to remove wrinkles (Figure 7.3.5.1). Selvedge and areas with wrinkles and creases should be avoided. The test area was 20 cm^2 and the pressure drop was 100 Pa. The air permeability tester FX 3340 MinAir used in this test has a measuring range of (15-1500) l/m^2s. The suction fan was started, and the result was recorded when the reading remained stable. The air permeability of each fabric was measured on one side of the fabric only, as no fabric surface has been specially treated. The test was repeated 10 times in different places on the fabric under the same conditions and the results are expressed in l/m^{2}s. [88]

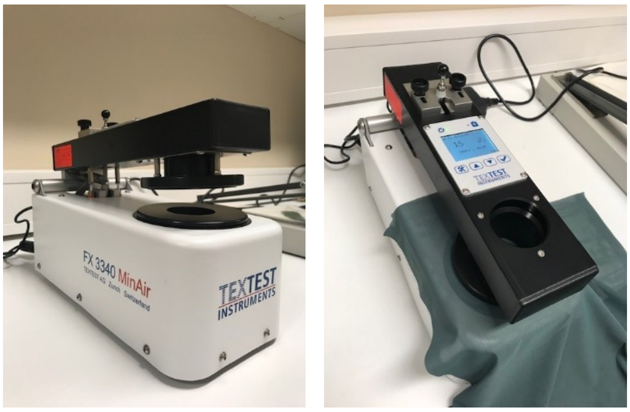


Figure 7.3.5.1. Air permeability tester FX 3340 MinAir

7.3.6 pH level

The test was conducted according to standard EVS-EN ISO 3071:2020 - Textiles — Determination of pH of aqueous extract. The pH level is measured electrometrically at room temperature using glass electrode. [89]

Apparatus and materials used:

- magnetic stirrer (Figure 7.3.6.1),
- stir bars,
- beakers with a capacity of 150 ml,
- glass rods,
- Metler Toledo MP 220 pH-meter with a resolution of 0,01 g (Figure 6.3.6.1),
- balance, with a resolution of 0,0001 g (Figure 6.3.6.1),
- flask with a stopper, with a capacity of 100 ml. [89]

Figure 7.3.6.1. Machinery for pH testing, from the left: balance, magnetic stirrer, pH- meter.

Two samples weighing (2,00 ± 0,05) grams were cut from each fabric. Each test specimen was placed in a flask with a stir bar and 100 ml distilled water. Flask was mixed by hand to ensure that the fabric was properly wetted out. The flask was then placed on a magnetic stirrer for 2 hours. [89]

After 2 hours, the fabrics were removed from the distilled water and pH-meter was calibrated. Extract was decanted into a beaker and electrode was immersed to a depth of at least 10 mm and allowed to stand until pH-value stabilized. The pH value and the temperature of the extracting solution was recorded. The second extract was then decanting into a second beaker, the electrode was immersed in the beaker without washing and the value was recorded after stabilization. Before measuring pH of different fabrics, the electrode must be rinsed thoroughly with a distilled water. [89]

7.3.7 Elasticity

The test was conducted according to standard EVS-EN ISO 20932-1:2018 – Textiles - Determination of the elasticity of the fabrics - Part 1: Strip tests. The method is suitable for different type and compositions of fabrics, excluding narrow fabrics. The objective to this test is to: [90]

- determine the extension at the maximum force and elongation,
- determine the permanent deformation.

Elongation, S, as a percentage, is calculated using the following formula (7.3.7.1). [90]

$$S = \frac{E}{L} x100 \quad (7.3.7.1)$$

Where:
S – elongation, %,
E – extension at maximum force on the fifth cycle, in mm,
L – initial length, in mm. [10]

To find the permanent deformation, C, as a percentage, the following formula was used: (7.3.7.2): [90]

$$C = \frac{Q - P}{P} x100 \quad (7.3.7.2)$$

Where:
C – permanent deformation, %,

Q – distance between applied reference marks; the permanent deformation after a specified recovery period, in mm,
P – initial distance between applied reference marks, in mm. [90]

Fabrics should be conditioned under standard atmospheric conditions for at least 20 hours in a tension free state and the prepared specimens should be conditioned for a further 4 hours in a tension free state to minimize the effects of handling during the preparations. [90] The deviation from the test requirements was that the specimens were not stored under the normal atmospheric conditions agreed in ISO 139 before the elasticity test.

Apparatus and materials used:

- tensile testing machine,
- calibrated metal rule,
- line clamps. [90]

Ten specimens measuring (50 x 250) mm were cut from each fabric. In the case of weft knitted fabrics, there were five warp specimens with their length parallel to the wales and five weft specimens parallel to the course. In the case of warp knitted fabrics, there were five warp specimens with their length parallel to the wales and five weft specimens at right angles to the wales. The 100 mm reference marks were drawn centrally on the fabric to determine the permanent deformation at the end of the test. [90]

Line clamps of the tensile testing machine were set the gauge length to 100 mm and the extension rate was set to 500 mm/min. Load cell with a maximum capacity of 500 N was used A specific load per cm width must be determined separately according to the standard for each fabric tested (Table 7.3.7.4). For this test, the pretension was set to 0,5 cN/cm width. [90]

Table 7.3.7.4. Applied loads (depending on the elastane content) [90]

Elastane content	**Loading / cm width**
≤ 5% elastane	3 N
5% < % elastane < 12%	4 N
12% to 20% elastane	5 N
> 20% elastane	7 N

Specimen was mounted centrally between the line clamps and test was started (Figure 7.3.7.5). After five cycles specimen was removed and measured after 1 min and after 30 min to determine the permanent deformation. [90]

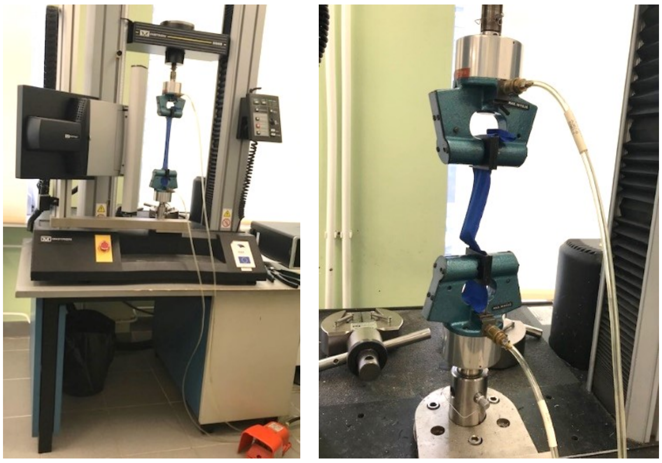


Figure 7.3.7.5. Tensile testing machine Instron 5866

7.3.8 Colour fastness to perspiration

The test was conducted according to standard EVS-EN ISO 105-E04:2013 - Textiles — Tests for colour fastness — Part E04: Colour fastness to perspiration. The objective of this test is to: [91]

- determine colour fastness and staining of fabric to human perspiration.

Specimen in contact with the adjacent fabric was tested in two different solutions – alkaline and acidic solution, both containing histidine. The results were evaluated on a grey scale by assessing colour change of the fabric and staining of adjacent fabric. [91]

Apparatus and materials used:

- frame of stainless steel,
- weight-piece, with a mass of 5 kg,
- acrylic resin plates, with a measure of 60 mm x 115 mm x 1,5 mm,
- oven, with a temperature of 37 °C,
- alkaline solution, containing per litre of distilled water:
  - 0,5 g of L-histidine monohydrochloride monohydrate ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$),
  - 5 g of sodium chloride ($NaCl$),
  - 2,5 g of disodium hydrogen orthophosphate dihydrate ($Na_2HPO_4 \cdot 2H_2O$).
- acid solution, containing per litre of distilled water:
  - 0,5 g of L-histidine monohydrochloride monohydrate ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$),
  - 5 g of sodium chloride ($NaCl$),
  - 2,2 g of sodium dihydrogen orthophosphate dihydrate ($NaH_2PO_4 \cdot 2H_2O$).
- pH-meter,
- sodium hydroxide solution,
- a multifibre adjacent fabric,

- flat-bottomed dish,
- glass rods,
- balance,
- grey scale for assessing change in colour,
- grey scale for assessing staining,
- colour assessment cabinet. [91]

Two samples measuring (40 x 100) mm were cut from each fabric. The specimens were sewn together with a multifibre adjacent fabric on the shorter side of the specimen. Alkaline and acid solutions were prepared in a ratio of 50:1 to the specimens. The pH level for each solution was measured using pH-meter. For alkaline solution it was brought to (8 ± 0,2) and for acid solution (5,5 ± 0,2) using 0,1 mol/l sodium hydroxide solution. [91]

Specimens were placed in a flat-bottomed dish and covered with a solution (Figure 7.3.8.1). Specimens were left in the solution for 30 min at room temperature. After 30 specimens were removed and excess water was wiped off using two glass rods. Specimens were now placed between acrylic resin plates and into a testing device using weight-piece to apply a pressure of (12,5 ± 0,9) kPa (Figure 6.2.8.1). Testing device with the specimens were placed in a drying oven for 4 hours at 37 °C. After 4 hours, specimens were opened and dried at the room temperature. Dried specimens were visually assessed using a grey scale in a colour assessment cabinet equipped with D65 artificial daylight. [91]

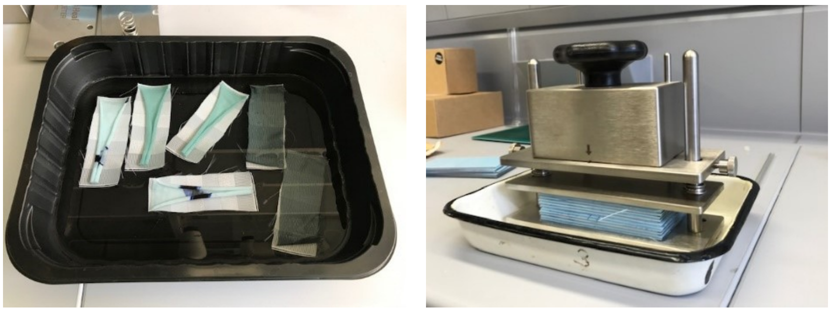


Figure 7.3.8.1. From the left:specimens in an alkaline solution, testing device with a weight-piece.

7.4 Processing machinery

7.4.1 Garment printer and hot-press

Direct inkjet garment printer Brother GT-341 was used for printing light and white materials (Figure 7.4.1.1). It uses CMYK colour model and water-based pigment inks. Printer includes up to 1200 dpi printing for high-quality photo printing. Better results are obtained when printing on cotton or cotton-polyester blends. To ensure ink stability, the printed area must be heat pressed. [92]

To cure the ink, MAXX® Clam Heat Press by Stahls was used (Figure 7.3.1.1). It has digital time and temperature readout, and the temperature range is (96-221) °C. [93]

Figure 7.4.1.1. From the left: Brother GT-341 Series textile printer and Stahls MAXX® Clam Heat Press

7.4.2 Sewing machines

The sewing machines used for sewing the lingerie set is shown in Table 7.4.2.1.

Table 7.4.2.1. Sewing machines used

Machine type	Name	Stitch type	Parameters
4-thread overlock machine	Kansai UK series UK-1014H-40M-2x4	514	Needle spacing: 2 mm; Overedge width: 4 mm
Cover stitch machine	Kansai WX-8803D	406, 407, 602, 605	Needle spacing: 3,1 mm; Stitch density: 3-6 stitches per cm
Lockstitch machine	Brother S-7200C-403	301	Thread trimmer
Zig-zag machine	Fomax	304, 321	Different stitch densities and widths

8 MATERIAL TESTING RESULTS AND DISCUSSION

8.1 Mass per unit area

Results of the mass per unit are presented in Table 8.1.1. The full test results and the calculations are given in Appendix 2. According to the fabric's classification by the weight (as referred in paragraph 3.1.2), the lightweight fabrics tested in this thesis were a green mesh weighing (66,4 ± 0,6) g/m^2, and a green knitted polyamide fabric weighing (98,6 ± 1,4) g/m^2. Medium weight fabrics were a blue knitted viscose fabric, grey knitted recycle polyamide, green recycled mesh, white knitted recycle cotton, blue printed Refibra™ and blue knitted Refibra™.

Table 8.1.1. Mass per unit area test results including average mass and standard deviation

Fabric	**M, g/m²**	**Standard deviation, g/m²**	**Classification by the weight**
Fabric 1 Green knitted PA	98,6	1,4	Light
Fabric 2 Green mesh PA	66,4	0,6	Light
Fabric 3 Blue knitted VI	178	2,4	Medium
Fabric 4 Grey knitted Rec PA	111	1,0	Medium
Fabric 5 Green mesh Rec PA	124	1,0	Medium
Fabric 6 White knitted Rec CO	141	1,1	Medium
Fabric 7 Blue printed Refibra™	180,	0,8	Medium
Fabric 8 Blue knitted Refibra™	147	1,3	Medium

8.2 Colour fastness to laundering

The colour fastness to domestic and commercial laundering results are presented in a Table 8.2.1. The evaluation was based on grey scale by assessing staining of a standard fabric and colour change of the specimens. Grades were ranging from 1 to 5 where 5 indicates no staining/no loss of colour and 1 indicates severe staining/loss of colour. The minimum requirement for a jersey products and corsetry (including bras) is 4 out of 5 [96].

To distinguish comparable fabrics, conventional fabrics are marked in pink and alternatives in blue, and comparable fabrics are placed under each other.

Table 8.2.1. Results of colour fastness to laundering

Fabric	A multifibre adjacent fabric, staining						**Fabric colour change in grey scale**
	Filament Triacetate	Bleached Cotton	Spun Polyamide (Nylon 6.6)	Spun Polyester (Dacron 54)	Spun Polyacrylic (Orlon 75)	Spun Viscose	
Fabric 1C. Green knitted PA	5	5	5	5	5	5	5
Fabric 4A. Grey knitted Rec PA	5	5	5	5	5	5	5
Fabric 2C. Green mesh PA	5	5	5	5	5	5	5
Fabric 5A. Green mesh Rec PA	5	5	5	5	5	5	5
Fabric 3 Blue knitted VI	5	5	5	5	5	5	5
Fabric 6 White knitted Rec CO	-	-	-	-	-	-	-
Fabric 7 Blue printed Refibra™	5	5	5	5	5	5	5
Fabric 8 Blue knitted Refibra™	5	5	5	5	5	5	5

All fabrics tested got the highest grade and showed no staining or colour loss. Although the blue knitted viscose fabric did not stain the multifibre adjacent fabric, the water in the washing container was slightly blue after the washing cycle. White knitted mechanically recycled fabric was not tested because white could not stain the other fabrics or show colour loss.

8.3 Colour fastness to rubbing

The colour fastness to rubbing results are presented in a Table 8.3.1. The evaluation was based on grey scale by assessing staining of a standard fabric and colour change of the tested fabrics. Grades were ranging from 1 to 5 where 5 indicates no staining/no loss of colour and 1 indicates severe staining/loss of all colours. The minimum requirement for a jersey products and corsetry (including bras) is 4 out of five [96].

Table 8.3.1. Results of colour fastness to rubbing test

Sample fabric	**Dry rubbing**		**Wet rubbing**	
	Sample fabric (colour change)	Standard fabric (staining)	Sample fabric (colour change)	Standard fabric (staining)
Fabric 1C. Green knitted PA	4/5	5	4/5	5
Fabric 4A. Grey knitted Rec PA	5	5	5	5
Fabric 2C. Green mesh PA	5	5	5	5
Fabric 5A. Green mesh Rec PA	5	5	5	5
Fabric 3 Blue knitted VI	4	5	3/4	4/5
Fabric 6 White knitted Rec CO	-	-	-	-
Fabric 7 Blue printed Refibra™	5	5	4	5
Fabric 8 Blue knitted Refibra™	5	5	4	5

According to the results, five out of seven fabrics tested were affected by rubbing. The dark green mesh fabric, the grey knitted recycled polyamide fabric and the green recycled mesh fabric received the highest scores in all categories, indicating that the friction and rubbing did not affect the colour of the fabric. The test results may have been influenced by the fabric structure, which makes the colour change more difficult to see (for example in the case of mesh) and the different colours of the tested fabrics (some darker than others). The lowest grade in the colour fastness to rubbing had a blue knitted viscose fabric, wet rubbing test result was below the minimum requirements.

8.4 Pilling and fuzzing

The fabric propensity to pilling and fuzzing average results after 125, 500, 1000 and 2000 rubs are presented in a Table 8.4.1. The full test results and the photos of the specimens after each cycle are given in Appendix 3 and 4. Grades were ranging from 1 to 5, where 5 indicates no pilling and 1 indicates very severe pilling. The minimum requirement for a jersey products and corsetry (including bras) is 3-4 and at least 2000 cycles are required [96].

To distinguish comparable fabrics, conventional fabrics are marked in pink and alternatives in blue, and comparable fabrics are placed side by side.

Table 8.4.1. Average results of pilling and fuzzing after rubbing cycles

Number of pilling rubs	Fabric 1C. Green knitted PA	Fabric 4A. Grey knitted Rec PA	Fabric 2C. Green mesh PA	Fabric 5A. Green mesh Rec PA	Fabric 3A. Blue knitted VI	Fabric 6A. White knitted Rec CO	Fabric 7A. Blue printed Refibra ™	Fabric 8A. Blue knitted Refibra ™
125	5	5	5	5	5	5	5	5
500	5	5	5	5	4	5	5	5
1000	4	5	5	5	4	4	5	4
2000	4	5	5	5	3	4	5	4

The best results were obtained by green conventional mesh fabric and green recycled mesh fabric. Even after 2000 cycles there were no pilling and fuzzing on the fabric surfaces. A comparison of conventional and recycled polyamide fabrics showed that the recycled fabric had better resistance to surface pilling and fuzzing than the conventional polyamide fabric. Conventional blue knitted viscose fabric showed the worst results, after 125 cycles there were signs of surface fuzzing and after 500 cycles pills began to form. The two Refibra™ fabrics showed quite high resistance to surface pilling and fuzzing, especially the blue printed fabric, which did not form any pills after 2000 cycles. The other Refibra™ fabric showed slight fuzzing after 500 cycles and pilling after 2000 cycles. Mechanically recycled cotton fabric started to form some surface pills after 1000 cycles.

8.5 Air permeability

The results of air permeability test are presented on the Figure 8.5.1 that illustrates average air permeability with standard deviations. The full test results are given in Appendix 5.

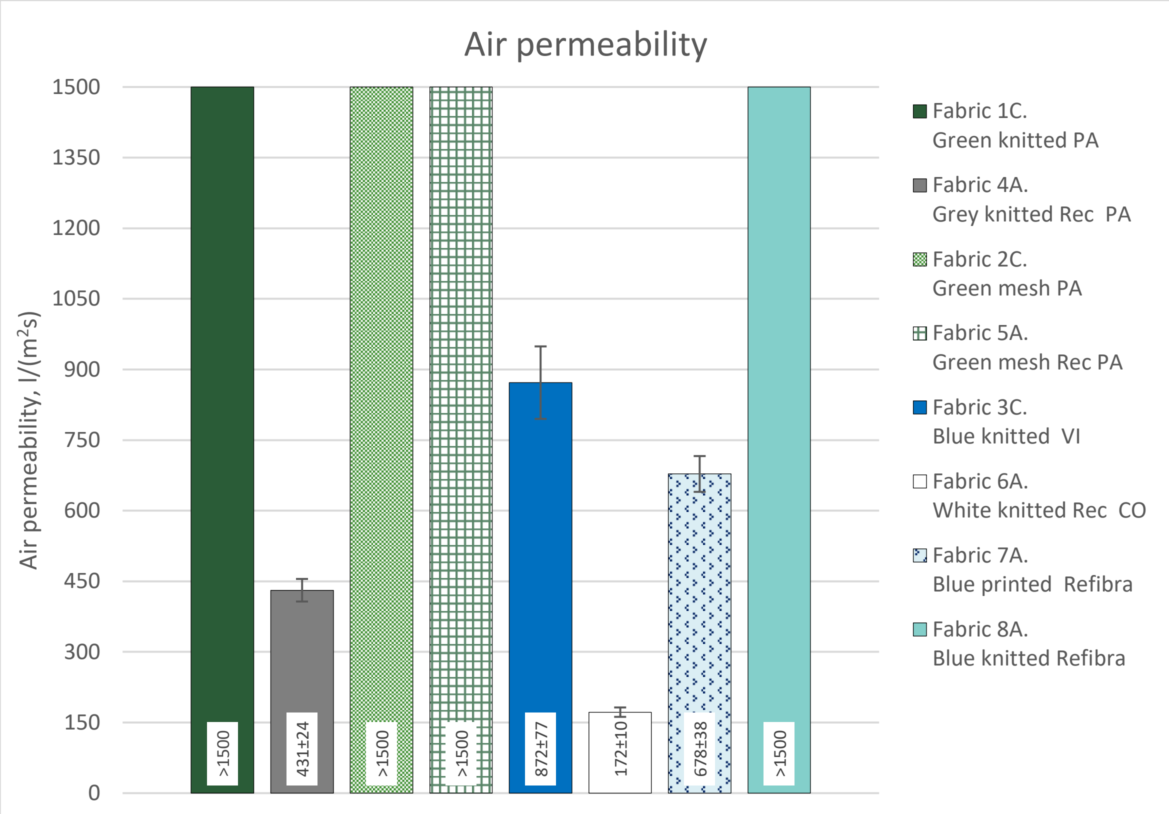


Figure 8.5.1. Results of air permeability

Four out of eight fabrics exceeded the measuring range of the device which is 15-1500 l/m^2s. The two mesh fabrics - conventional and recycled - have a permeable structure with tiny holes within the fabric which makes the air flow through the fabric easy. The green knitted polyamide fabric and blue knitted Refibra™ fabric are also lightweight fabrics, composed of loosely knitted thin yarns, causing unobstructed air movement. Three of those fabrics – green mesh fabric, green knitted polyamide and blue knitted Refibra™ fabric have the lowest surface density of the eight fabrics as well.

Of the remaining five fabrics, the lowest air permeability was white mechanically recycled cotton fabric with a result of (172 ± 10) l/m^2s, followed by a grey recycled polyamide fabric with an average value of (431 ± 24) l/m^2s, a blue printed Refibra™ fabric with an average of (678 ± 38) l/m^2s and a blue knitted fabric with the result of (872 ± 77) l/m^2s.

8.6 pH level

The results of the pH level of the fabrics are presented in Figure 8.6.1. The full test results are given in Appendix 6.

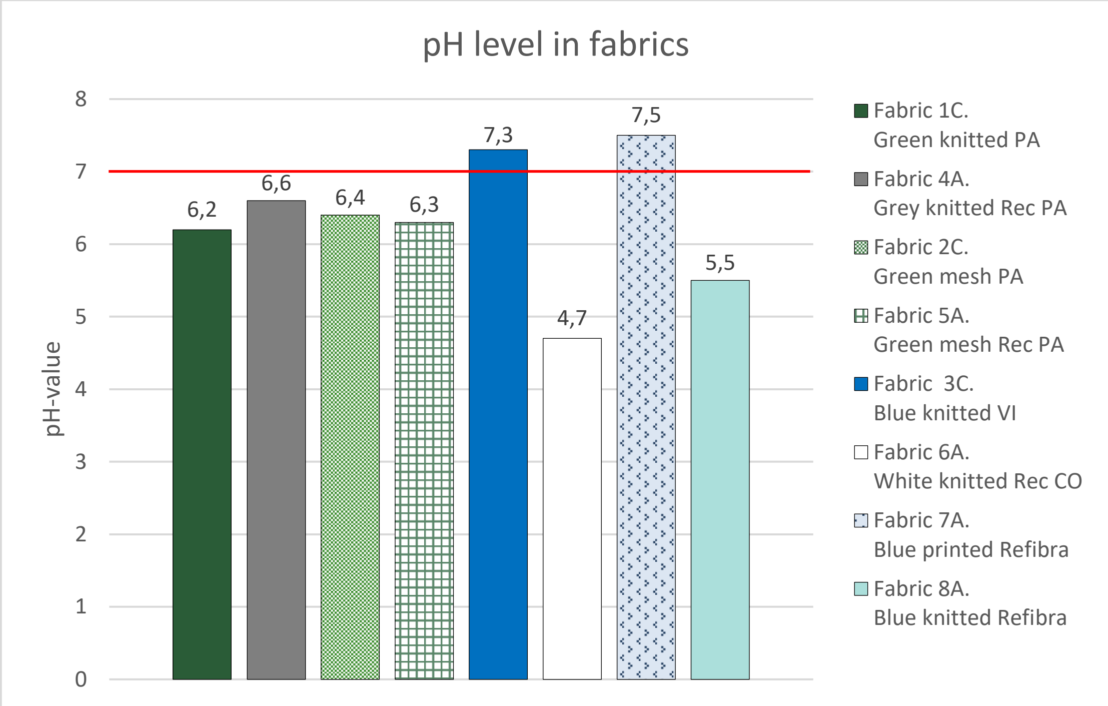


Figure 8.6.1. Results of pH level in fabrics

The pH level of all eight tested fabrics was in the range of Oeko-tex standard requirements (4,0–7,5). The pH of the six fabrics tested was below neutral 7.0, meaning that the aqueous extract of these fabrics was acidic, and the two fabrics tested - blue woven viscose fabric and blue printed Refibra™ - were above neutral pH, indicates that the aqueous extract of these fabrics were alkaline.

8.7 Elasticity

The results of elasticity test are presented in Figure 8.7.1 and 8.7.2. The detailed results of the elasticity test are given in Appendix 7, and the obtained graphics are in Appendix 8-15.

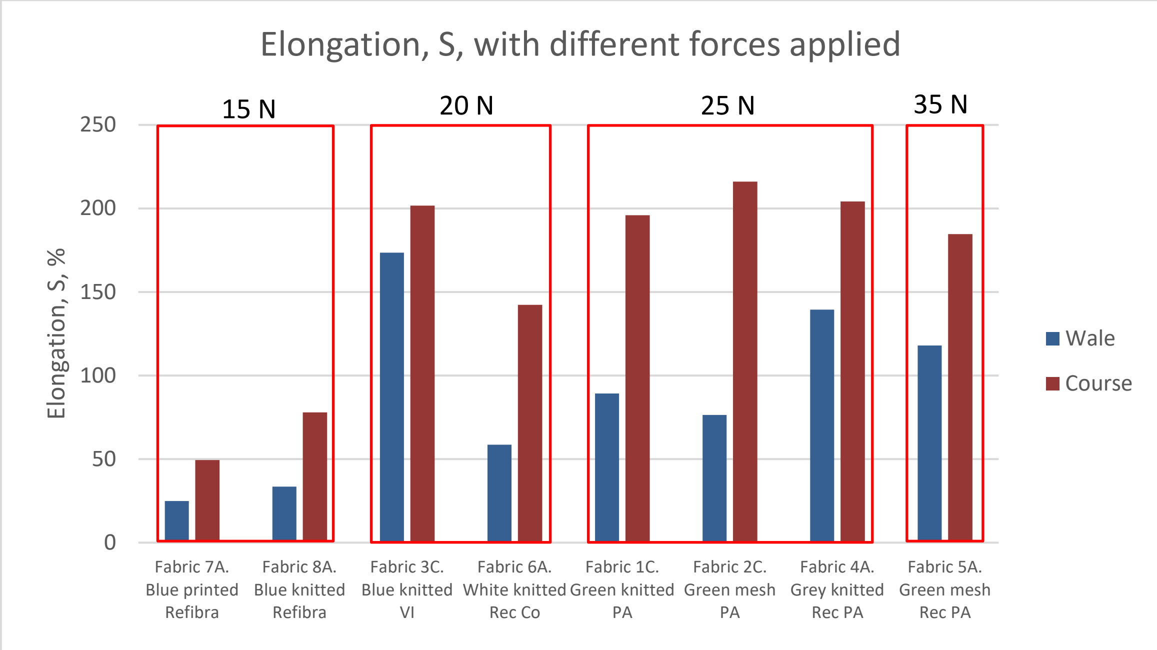


Figure 8.1.1. Results of elongation with different forces applied

Figure 8.7.1 shows the results of the elongation. Different loads were subjected (loads are shown above the columns), depending on the elastane content of the fabric. Fabrics with similar elastane content were compared. In all eight fabrics, the elongation in the course direction was higher than the elongation in the wale direction, which was a predictable result among knitted fabrics.

The lowest load, 15 N, was subjected to non-elastane fabrics – blue knitted Refibra™ and blue printed Refibra™ fabric. Blue knitted Refibra™ fabric showed the highest value in both directions, 34% in wale and 78% in course direction. This may have been due to a looser knit structure.

Fabrics with an elastane content of up to 12% were subjected to a load of 20 N, blue knitted viscose fabric (10% elastane) and white knitted recycled cotton fabric (7% elastane). The elongation of the blue viscose fabric had higher elongation in both wale and course direction (174% and 202%, respectively) than the white knitted recycled cotton fabric with elongation of 59% and 142%. Blue viscose fabric has a looser knit structure and also a higher elastane content than white cotton fabric.

25 N load was subjected to three fabrics with elastane content of 12% to 20% - grey knitted polyamide (20% elastane), green mesh polyamide (19% elastane) and grey recycled polyamide fabric (20% elastane). The highest elongation had green mesh polyamide fabric in course direction – 216% of its initial length. In wale direction the highest elongation had grey knitted recycled polyamide fabric – 139%.

The elastane content of green recycled mesh was the highest of the fabrics tested and the highest load of 35 N was subjected. Considering the magnitude of the force and the mesh loose structure, the elongation of the fabric was quite modest being 118% in wale direction and 185% in course direction [72].

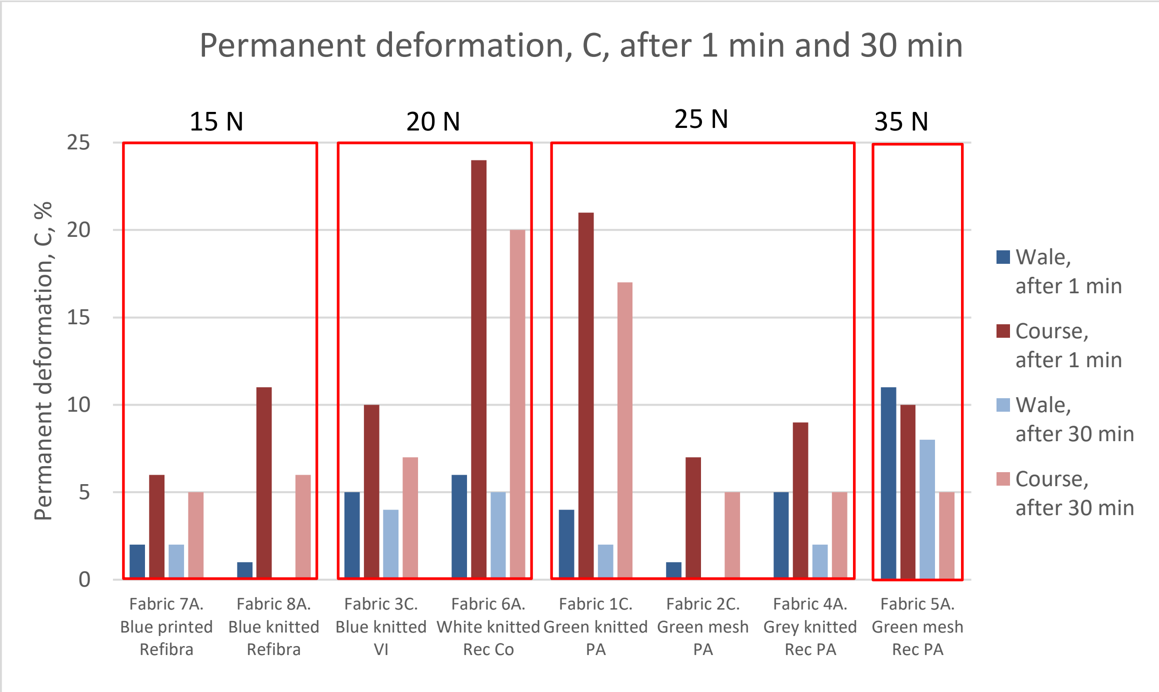


Figure 8.7.2. Results of permanent deformation with different foces applied

In the first fabric group, where a force of 15 N was applied, the greater permanent deformation in the course direction was the blue knitted Refibra™ fabric, which was 11% after the 1-minute period and 6% after 30 minutes. Blue printed Refibra™ fabric permanent deformation in the course direction was 6% after 1 min and 5% after 30 minutes. In the wale direction, the blue knitted Refibra™ fabric showed a small permanent deformation after both 1 and 30 min, 1% and 0%, respectively. The results are affected by the percentage of elongation at the time of extension, which was higher for blue knitted Refibra™ fabric.

In the second fabric group, where a force of 20 N was applied, the white recycled cotton fabric showed a greater permanent deformation in all categories. This fabric also has a lower elastane content than the comparable blue viscose fabric, 7% and 10%, respectively.

The third group was subjected to a force of 25 N, the largest permanent deformation in the course direction had a green polyamide fabric - 21% after 1 minute and 17% after 30 minutes. The green mesh polyamide fabric suffered the lowest permanent deformation in all categories, despite its high elongation percentage. The slight deformation of the mesh fabric may be due to the structure of the mesh, which has a better recovery after extension.

The green recycled mesh fabric, to which a force of 35 N was applied, was the only fabric of the eight to have a greater permanent deformation in the wale direction, despite a greater elongation in the course direction.

8.8 Colour fastness to perspiration

The results of the colour fastness test are shown in Table 8.8.1. The test was performed with an acidic artificial perspiration mixture having a pH of 5,35 and with an alkaline artificial perspiration mixture with a pH of 7,8.

The evaluation is based on grey scale by assessing staining of a standard fabric and colour change of the tested fabrics. Grades are ranging from 1 to 5 where 5 indicates no staining/no loss of colour and 1 indicates severe staining/loss of all colours. According to the minimum requirement for a jersey products and corsetry (including bras) is 4 out of 5 [3].

Table 8.8.1. Results of colour fastness to perspiration test

Fabric	A multifibre adjacent fabric, staining												Fabric colour change	
	Filament Triacetate		Bleached Cotton		Spun Polyamide (Nylon 6.6)		Spun Polyester (Dacron 54)		Spun Polyacrylic (Orlon 75)		Spun Viscose			
	pH 5,35	pH 7,8	pH 5,35	pH 7,8	pH 5,35	pH 7,8	pH 5,35	pH 7,8	pH 5,35	pH 7,8	pH 5,35	pH 7,8	pH 5,35	pH 7,8
Fabric 1C. Green knitted PA	4/5	4/5	5	4/5	4/5	4/5	3/4	3/4	4	3/4	5	5	5	5
Fabric 4A. Grey knitted Rec PA	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fabric 2C. Green mesh PA	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fabric 5A. Green mesh Rec PA	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fabric 3 Blue knitted VI	4/5	4/5	5	5	4/5	4/5	2/3	3	3/4	3/4	5	4/5	4/5	4/5
Fabric 6 White knitted Rec CO	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fabric 7 Blue printed Refibra	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Fabric 8 Blue knitted Refibra	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Six of the eight fabrics tested in this thesis were not affected by the perspiration test for colour fastness in acidic solution. These fabrics did not stain the adjacent multi-fibre standard fabric or fade during the test. The green knitted polyamide fabric did not fade during the test, but stained parts of the standard fabric. For example, the staining of the polyester part result was 3/4, below the minimum requirement, which is 4. The blue woven viscose fabric had the worst performance of the eight fabrics tested fabrics. It heavily stained the standard fabric, with the lowest result 2/3 and also the fabric itself faded during the test, with the result of 4/5.

Six out of eight fabrics tested during this thesis colour fastness were not affected by perspiration with the alkaline mixture. Those fabrics did not stain multifibre adjacent standard fabric nor faded during the perspiration test. Green knitted polyamide fabric did not fade during the test but stained standard fabric and some results were even under minimum requirement, which is 4. The blue knitted viscose fabric did not give a very good result either, it was also the only fabric that faded during the colour fastness test to perspiration.

8.9 Summary of test results

Tests on eight different fabrics showed that the results of conventional and recycled alternatives were relatively equal. In some categories, recycled fabrics showed even better results than conventional fabrics. All five recycled fabrics also met the minimum requirements for lingerie fabrics in each test performed.

The colour fastness test to rubbing and the colour fastness to perspiration showed that the alternative fabrics showed better results than the conventional fabrics. All eight fabrics tested achieved maximum grade in colour fastness to laundering.

One concern with recycled fabrics before performing the tests was their resistance to pilling and fuzzing, especially on mechanically recycled cotton fabric. However, alternatives fabrics showed even better results in the pilling and fuzzing test than conventional fabrics, including mechanically recycled cotton fabric.

The pH level of all eight tested fabrics remained within the minimum requirements for fabrics in direct contact with the skin.

The air permeability results showed large differences between the fabrics and were related to the structure and weight of the fabric.

The importance of the elasticity test was to explore whether fabrics that do not contain elastane are enough stretchy to provide comfort, but also do they recover after stretching. Test results proved that two chemically recycled fabrics, made of cotton / lyocell mix, that did not contain elastane, had satisfactory results in elongation and recovered elongation.

Biodegradability, the use of mono materials and compliance with the minimum requirements for lingerie fabrics became decisive in the fabric selection of the lingerie set developed during the thesis. These criteria were met by one of the fabrics tested and Vilartex's light blue knitted fabric made of Refibra™ and organic cotton was chosen as the fabric. In addition to cotton, this fabric also contains chemically recycled cotton, which is produced with a method that allows higher quality fibres than mechanically recycled ones. The fabric can be considered as mono materials because it contains only cellulose fibres and does not contain elastane, which would make recycling difficult. Finally, the properties and performance of the fabric meet the requirements of lingerie.

8.10 Parameters for garment printer and hot-press

A garment printer was used to print the care instructions and fibre content on the fabric (Figure 8.10.1). A label was printed before the patterns were cut out; in actual production, this should be done on pieces that have already been cut to avoid fabric waste.

As the fabric used for the lingerie set is light and thin, the main challenge was to avoid ink seeping into the right side of the fabric and remain visible. To prevent this, grey was used instead of black to print the text, and the colour intensity was set to 6 out of 10.

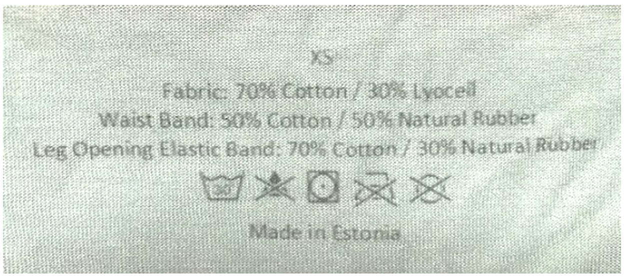


Figure 8.10.1. Care instructions and fibre content printed on the fabric

9 PRODUCT DESIGN AND DEVELEPMENT OF LINGERIE SET

9.1 Product design

The lingerie set “2°UP” is inspired by contrasts – light and dark, airy and heavy, rough and smooth, aspiration and surrender (Mood board are shown in Appendix 16). Contrasts are very important in creating an image, these are differences that allow comparison and are employed to create rhythm and to strengthen the focus of the problem. The name “2°UP”, alludes to climate change - if global temperatures rise by more than 2°C above pre-industrial levels, the consequences will be severe and irreversible.

The lingerie set “2°UP” is inspired by the growing trend towards simplicity, comfort and gender neutrality (Figure 9.1.1).

Figure 9.1.1. Technical drawings of triangle bra and tanga panties

Triangle bra is a soft bra without underwire and hook-and-eye closure on the back. The bra has lined cups that provide extra coverage and support. There is a 40 mm wide elastic band under the bust, which provides the necessary support for the breasts. 6 mm soft elastic band is sewn on the back and sides of the bra. The 9,5 mm wide shoulder straps are adjustable with a slide on the back and covered with a fabric for softness. The triangle bra is constructed to maximize the use of the fabric, but still to provide perfect fit and aesthetic appearance.

Tanga panties are a with moderate coverage panties, which is a mixture of thongs and bikini panties. The tangas have a 28 mm wide soft elastic waistband and 6 mm soft elastic band sewn into a leg opening. The hygiene material is the same as the main fabric. The patterns in this style are simple and allow for maximum use of the fabric.

The collection uses biodegradable materials such as organic cotton, chemically recycled cellulosic fibres and natural rubber. The aim is to use mono materials and as few different materials as possible in the model to facilitate recycling processes. The pattern blocks focus on maximizing the use of the fabric without sacrificing appearance and fit.

The collection is designed for environmentally conscious person who respects natural materials, and appreciates comfort, and simplicity. The "2°UP" collection is every-day lingerie set that is comfortable, and easy to maintain. At the end of its life, the product can be either composted or mechanically or chemically recycled to produce new materials.

9.1.1 Materials

The choice of materials affects whether the product enters biological or technical circle in terms of the circular economy. The aim of this thesis is to use mono-fibre fabric and biodegradable materials to decrease microplastic pollution and to allow products to be involved in either biological or technical metabolism (Table 9.1.1.1). When the product enters the biological cycle, it returns to the system through composting and anaerobic digestion. Once a product enters the technical cycle, it can be easily reused due to the use of mono materials.

Table 9.1.1.1. Material list

Material	**Photo of the material**	**Composition**	**Most important technical properties**	**Place of use**
Fabric		70% Cotton (organic) 30% Lyocell (Tencel™ Refibra™)	Good elasticity, light weight, good resistance to pilling	Main fabric
Wide elastic band, 40 mm		65% Cotton (organic) 35% natural rubber	Soft, strong enough for support	Under bust band

Material	Photo of the material	Composition	Most important technical properties	Place of use
Wide elastic band, 28 mm		50% Cotton (organic) 50% natural rubber	Soft	Tanga waist band
Narrow elastic band, 9,5 mm		50% Cotton (organic) 50% natural rubber	Strong, durable	Shoulder straps
Narrow light elastic band, 6 mm		70% Cotton organic 30% natural rubber	Soft	Bra side and back seam, leg openings
Slides 10 mm and rings 12 mm		Polyamide coated metal	Strong, corrosion resistant	Shoulder straps
Sewing thread, #120 (planned to use)		100% Viscose (Tencel™)	Strong, good elasticity	All seams
Sewing thread, regular and textured, #120 (used)		100% Polyester	Strong, good elasticity	All seams

To achieve 100% biodegradability, all materials used in the product must be biodegradable or must be removed before entering to the biological cycle. Therefore, the aim was to use viscose thread, which has good elasticity for sewing lingerie fabrics, but at the same time is strong and biodegradable. Due to the small number of companies who are offering viscose thread, the high minimum quantities and the lack of the desired colour, polyester thread was used instead of viscose.

9.2 Pattern making

To reduce fabric waste created during the cutting process, patterns were created in a way that maximizes fabric use. Depending on the arrangement of the patterns on the layout drawing, the patterns were changed as necessary to maximize the use of the fabric.

Patterns were created using the 2D flat patternmaking method using Gerber AccuMark Pattern Design software. Patternmaking method used is called the Haggar's method, which uses bodice and builds a bra pattern on it. The basic measurements for making the patterns are taken from the Ann Haggar's book "Pattern Cutting for Lingerie, Beachwear and Leisurewear" women's standard size chart and have been slightly modified according to the dimensions of the real body measurements. The measurements correspond to the size number 8 and the product of this collection corresponds to the size number XS [97].

Patterns were constructed using the same book and were modified according to the styles and to maximize fabric usage. To create a triangle bra pattern, the bodice was first constructed considering the measurements of the body. Secondly, the classic bra was constructed on the bodice pattern, and finally the bra pattern was changed to consider the design of the triangle bra, the actual body measurements, fit and to ensure better fabric consumption (Figure 9.2.1). After the first fitting, the triangle bra pattern was slightly modified. The tip of the dart was shifted 0,5 toward the side seam and front edge of the cup front was shifted 1 cm from the top point toward the centreline.

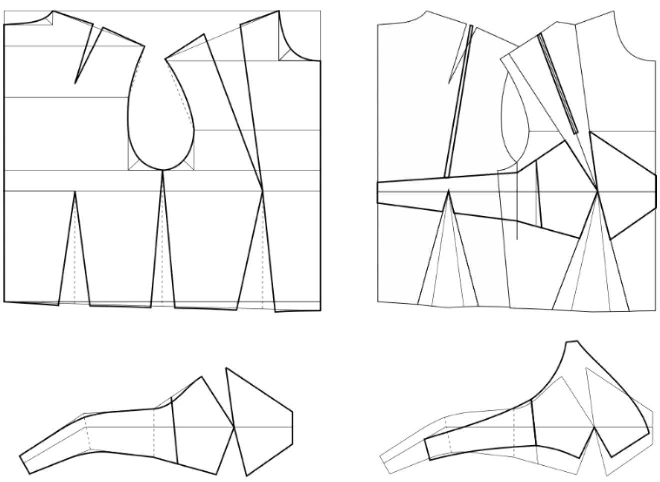


Figure 9.2.1. Bodice, bra basic pattern and custom-fitted triangle bra pattern

A bikini panty pattern was used to construct the tanga panty pattern. It was slightly modified to improve fit and fabric consumption (Figure 9.2.2). After the first fitting, there were small changes in tanga panty pattern. The front and back pattern part waistline were raised by 1 cm.

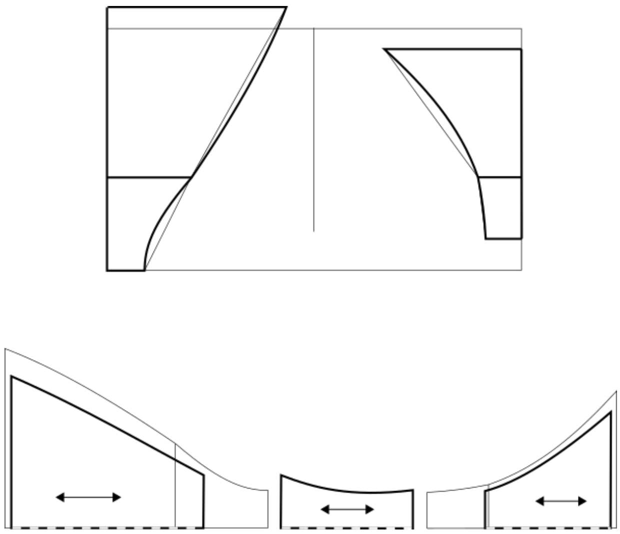


Figure 9.2.2. Bikini panty pattern and custom-fitted tanga panty pattern

The list of triangle bra and tanga panty pattern pieces are given in Appendix 17 and sectional drawings are given in Appendix 18.

After finishing the XS patterns for bra and panty, size grading was done in the range of XS to XL. Layout markers were done using Easy Marking software by Gerber. Both products (sizes XS-XL) were placed together on the layout markers which is showed in Appendix 19. The utilization of the fabric was 82,05%, which is relatively high in the lingerie production.

Tables below (Table 9.2.3 and 9.2.4) shows the measurements needed for patternmaking.

Table 9.2.3. Measurements for panties, XS

Name of the measurement	Value, cm
Hip girth	80
Body rise (depth of the crutch)	26,4

Table 9.2.4. Measurements for bras, XS

Name of the measurement	Value, cm
Nape to waist length	40
Bust girth	81
Back width	34
Shoulder length	12,4
Waist girth	62
Neck base girth	35,5

Direct printing on fabric was used to indicate care instructions and materials composition. This method reduces the materials used in the product and, compared to the sewn labels that are usually cut off by the customer, the printed labels remain on the product and provide information on the materials used to the recycler. Clear labelling from the main fabric to the accessories can facilitate easy identification and sorting in recycling facilities.

Care instructions and the material composition are in accordance with EU regulation of textile fibre names and related labelling and marking of the fibre composition of textile products. The regulation establishes the label contents, the exact names of textile fibres that shall be used to describe the fibre composition on the label, the order of the materials on the label, etc. [98] Labels printed on the triangle bra and tangas are presented in Figure 9.2.5.

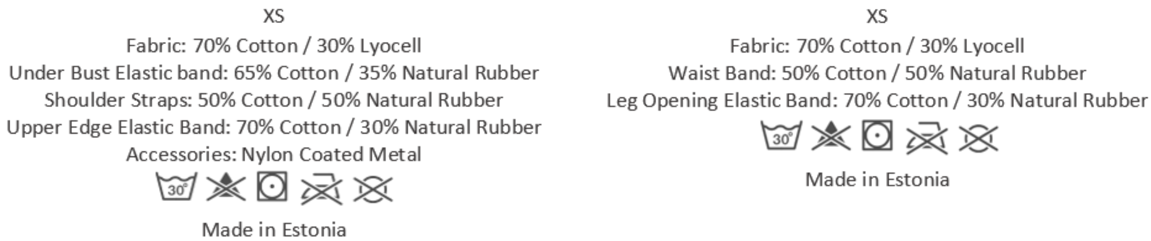


Figure 9.2.5. Care instructions and fibre compostion printed on a fabric (from the left: triangle bra and tanga)

9.3 Price calculations

The price of the lingerie set considers direct material costs and direct labour. Factory overheads, such as indirect labour and indirect materials, and overheads are not included in costing. Direct material costs are based on the prices of small quantities of material ordered online. Labour costs are calculated based on the price list of small-scale lingerie production and packaging as well as cutting are included to the processing cost. Price does not include label printing on the fabric. Detailed processing sequences with processing times are presented in Appendix 20.

The material cost calculations and processing cost are showed in Table 9.3.1 and 9.3.2

Table 9.3.1. Total cost for triangle bra

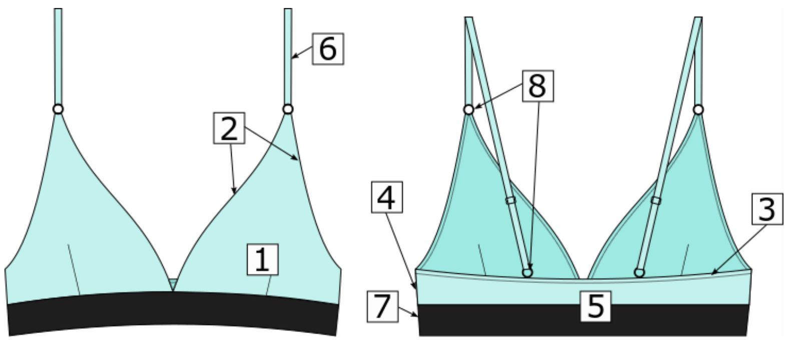
Material	Consumption, m	Price, €/m	Price per item, €
Fabric	0,12	12,19	1,46
Wide elastic band, 40 mm	0,62	5,08	3,15
Narrow elastic band, 6 mm	0,98	1,33	1,30
Shoulder strap, 9,5 mm	0,96	1,24	1,19
Ring, 12 mm	4	0,014	0,06
Slide, 12 mm	2	0,015	0,03
Thread	30,	0,0025	0,08
		Total cost of materials:	**7,97**
		Total processing cost:	**7,46**
		Total cost:	**15,43**

Table 9.3.2. Total cost for tanga panties

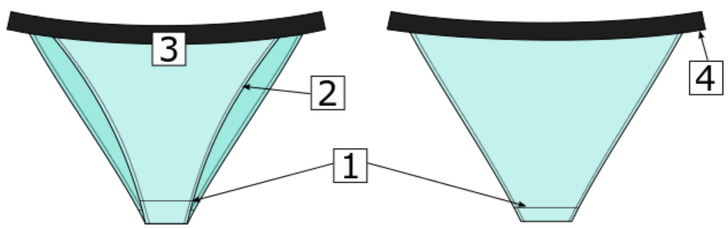
Material	Consumption, m	Price, €/m	Price per item, €
Fabric	0,02	12,19	0,24
Wide elastic band, 28 mm	0,65	3,69	2,40
Narrow elastic band, 6 mm	1,0	1,33	1,33
Thread	20,0	0,0025	0,05
		Total cost of materials:	**4,02**
		Total processing cost:	**2,62**
		Total cost:	**6,64**

9.4 Product specification

Specification sheet for triangle bra 2UP-TBRA

Collection:	**Season:**	**Product type:**	**Model:**	**Process engineer and designer:**	
2°UP	All year	Triangle bra	2UP-TBRA	Katre Worth	
Main fabric:	**Wide elastic band:**	**Narrow elastic band:**	**Shoulder straps:**	**Slides and rings:**	**Sewing thread:**
Vilartex VLT 5148 Jersey E-ICEBLUE **COMP:** 70% CO (organic) 30% Lyocell (Tencel Refibra™)	James Tailoring ECO ORGANIC ELASTIC, 40 mm Black **COMP:** 65% CO (organic) 35% natural rubber	James Tailoring ECO ORGANIC ELASTIC, 6 mm Ecru **COMP:** 70% CO (organic) 30% natural rubber	James Tailoring ECO ORGANIC ELASTIC, 9,5 mm Ecru **COMP:** 50% CO (organic) 50% natural rubber	Santoul Slide 10 mm Ring 12 mm Black **COMP:** Polyamide coated metal	Amann Group Saba #120 Sabatex #120 Light blue **COMP:** 100% PL
			**Machinery:** 4-thread overlock machine 2-needle cover stitch machine 3-needle cover stitch machine Single needle lockstitch Zig-zag machine **Needle:** size 70	**Sewing technology:** 1. Cup dart: stitch type 301; seam allowance 5 mm 2. Cup edges: stitch type 514 + 304; seam allowance 6 mm 3. Back: stitch type 514 + 406; seam allowance 6 mm 4. Side seam: stitch type 514; seam allowance 5 mm 5. Under bust elastic band: stitch type 407, seam allowance 8 mm 6. Shoulder straps: stitch type 514; seam allowance 5 mm 7. Under bust elastic band connecting: stitch type 514 + 301 + 321 8. Shoulder straps connecting to a bodice: stitch type 301	
Care instructions: 					

Specification sheet for tanga panties 2UP-TANGA

Collection:	**Season:**	**Product type:**	**Model:**	**Process engineer and designer:**
2°UP	All year	Tanga panties	2UP-TANGA	Katre Worth
Main fabric:	**Wide elastic band:**	**Narrow elastic band:**	**Sewing thread:**	
Vilartex VLT 5148 Jersey E-ICEBLUE **COMP:** 70% CO (organic) 30% Lyocell (Tencel Refibra™)	James Tailoring ECO ORGANIC ELASTIC, 28 mm Black **COMP:** 50% CO (organic) 50% natural rubber	James Tailoring ECO ORGANIC ELASTIC, 6 mm Ecru **COMP:** 70% CO (organic) 30% natural rubber	Amann Group Saba #120 Sabatex #120 Light blue **COMP:** 100% PL	
			**Machinery:** 4-thread overlock machine 2-needle cover stitch machine 3-needle cover stitch machine Single needle lockstitch Zig-zag machine **Needle:** size 70	**Sewing technology:** 1. Crotch: stitch type 514; seam allowance 5 mm 2. Leg opening: stitch type 514 + 406; seam allowance 6 mm 3. Waist band: stitch type 407, seam allowance 8 mm 4. Waist band connecting: stitch type 514 + 301 + 321
Care instructions: 				

10 DISCUSSION

During the master's thesis, three different conventional and five different recycled alternatives were tested, which had a similar composition to conventional fabrics. The recycled fabrics showed excellent results for all the properties tested and met all the minimum requirements set for lingerie fabrics. Concerns about the elasticity of the fabric if it does not contain elastane did not prove to be a significant drawback and can be compensated by the choice of fabric structure and product design.

Despite of the suitable properties of recycled fabrics, their availability and choice of designs is still rather limited, especially for fabrics that are made of chemically recycled cellulose fibres. Another aspect among recycled fabrics is that the actual amount of recycled fibre in these fabrics is relatively low. An example of this is the fabric used in the thesis, which consists of 70% organic cotton and 30% lyocell. The lyocell in this fabric is made from up to 30% recycled cotton waste, which means that the proportion of recycled fibres in this fabric is only up to 10%.

In terms of accessories and trimmings, it is even more difficult to replace traditional options with alternatives. The choice of materials on the market is poor and their quality is often lower than the quality of conventional materials, which are mainly made of man-made fibres. Due to the difficulty of finding alternatives to trimmings, polyester thread was used instead of the previously planned viscose thread.

Another concern about the processability of alternative fabrics and trimmings was refuted during the sewing process of lingerie set. All the materials chosen for a set were equally processable with conventional methods. Photo of the developed lingerie set is presented in Appendix 21.

To understand the circular concept of the developed lingerie set, which should consider all aspects, from raw material extraction to material processing, production and disposal/recycling, a material flow chart was composed (Figure 10.1). The flow chart illustrates the processing steps for each group of materials used and the end-of-life phase.

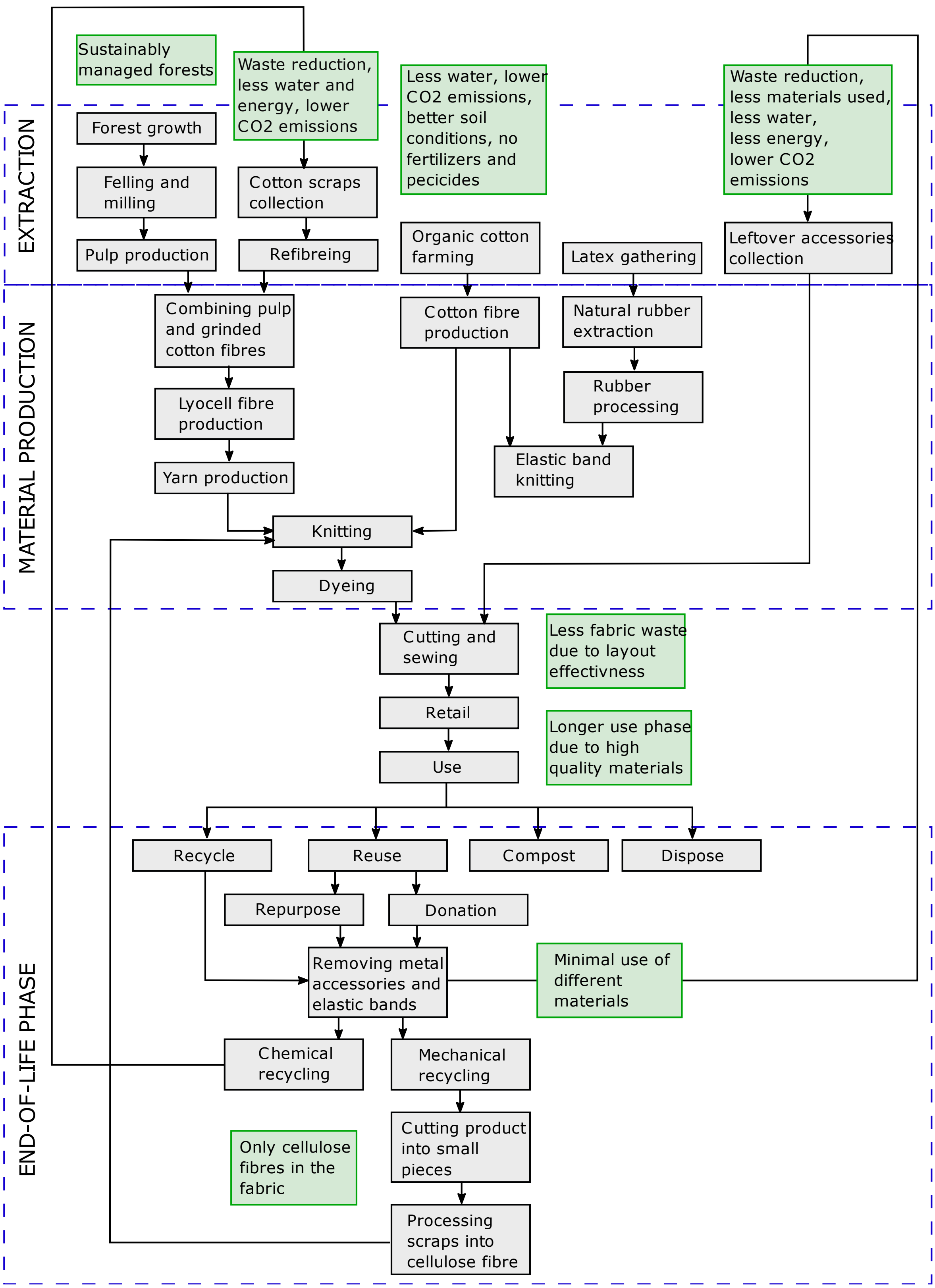


Figure 10.1. Materials flow chart

In addition to creating a more sustainable product, it is also important that it can compete with similar products currently on the market in terms of properties, quality, design, and price. Developed lingerie set was compared with similar products on the market to assess its competitiveness. The price of the developed product is calculated based on the material price, production price and with the mark-up percentage of about 200%. The comparison is presented in Table 10.2.

Table 10.2. Product comparison

Photo of the product			
Brand	Calvin Klein	Organic Basics	Set developed during the master thesis
Brand awareness	Well-known	Well-known in certain groups	Not known
Price, €	39,9 + 21,9 = 61,8	74,0	35,9 + 15,9 = 50,9
Fabric composition	53% CO 35% MD 12% EL	95% CO (GOTS organic) 5% EL	70% CO (organic) 30% Lyocell (Tencel™ Refibra™)
Composition of trimmings and accessories	Not specified	Not specified	Natural rubber and cotton (organic) for elastic bands; polyamide coated metal for accessories
Country of manufacturer	China	Turkey	Estonia
Quality	High	High	High
Recyclability	Only mechanical due to fibre mix	Only mechanical due to fibre mix	Chemical and mechanical
Biodegradable	No	No	Yes (except rings and slides)

SUMMARY

The lingerie industry, as part of the textile and fashion industry, has been blamed for a "take-make-dispose" model and overall negative impact on the environment. Due to the complexity of lingerie, the transition from a linear to a circle system may be more difficult than in other parts of the clothing sector.

The aim of this thesis was to study the main aspects of the circular economy, focusing on materials and applying these principles in the production of lingerie. To achieve this goal, sustainable alternatives to widely used conventional lingerie fabrics were explored; alternative and conventional fabrics were tested, and their quality and performance were compared; and finally, methods to facilitate the recyclability of the lingerie set were researched.

For better understanding of the lingerie industry and how to make it more circular, the theoretical part of this thesis examined lingerie materials and recycled alternatives to these materials, basic requirements for lingerie fabrics, circular economy principles and difficulties in implementing these principles in lingerie production, product development and production processes, and finally, possible solutions for the product at the end of its life.

The practical part was divided into two main parts. At first conventional fabrics and recycled alternatives with a similar composition were tested to identify differences in quality and performance. To test the basic properties of the lingerie fabrics, several tests were performed. Mass per unit area, colour fastness to laundering, rubbing and perspiration, resistance to pilling and fuzzing, air permeability, pH level, and elasticity of three conventional and five recycled fabrics were tested. The recycled fabrics showed excellent results in all the properties tested. The results of some tests were even better for the recycled fabrics than for the conventional fabrics. These properties were colour fastness to rubbing and perspiration and resistance to pilling and fuzzing. Based on the results of the tests, the recycled fabric to be used in the lingerie set developed during the thesis was selected.

The second part of the practical work was dedicated to product development process, which included the selection of fabrics, trimmings and accessories, pattern making, the selection of processing technology and price calculations. The whole development process was based on the principles of the circular economy, and the lingerie set was designed so that at the end of its life it could enter either biological or technical metabolism to be recycled or composted. The design and production technology were chosen so that the lingerie set could be produced in a small production line if desired.

Also, the price of the lingerie set is competitive with the price points of similar products currently offered on the market.

The goal set at the beginning of the thesis to apply the principles of circular economy for the development of a lingerie set was achieved. Recycled alternatives to conventional fabrics showed excellent results during testing and met all the minimum requirements for lingerie fabrics. Despite the suitable properties of recycled fabrics, their availability and design range are still quite limited, especially for recycled cellulose fibres. Regarding the accessories and trimmings needed to produce lingerie, it is more difficult to replace the conventional options with alternatives - the range of materials offered on the market is poor and their quality is often lower than for conventional materials, which are mainly made of man-made fibres.

The lingerie set developed during the thesis was a small attempt to introduce the possibilities of creating a circular lingerie. To offer a variety of styles, including more complex ones, extensive research is needed on sustainable materials, including trimmings and accessories, as well as advanced recycling technologies.

KOKKUVÕTE

Pesutööstust nagu ka tekstiili- ja moetööstust on kritiseeritud selle negatiivses mõjus keskkonnale ning muudatused selles tööstusharus on möödapääsmatud. Aluspesu tootmise keerukuse tõttu võib aga lineaarselt ringsele süsteemile üleminek olla raskem kui ülejäänud rõivasektori valdkondades.

Käesoleva magistritöö eesmärk oli uurida ringmajanduse põhiaspekte, keskendudes materjalidele ja rakendades neid põhimõtteid aluspesu tootmisel. Selle eesmärgi saavutamiseks uuriti jätkusuutlikke alternatiive laialt kasutatavatele tavapärastele pesukangastele; testiti alternatiivseid ja tavapäraseid kangaid ning võrreldi nende kvaliteeti ja omadusi; ning viimasena analüüsiti aluspesu ringlussevõtu hõlbustamise meetodeid.

Pesutööstuse paremaks mõistmiseks ja selle ringsemaks muutmiseks uuriti magistritöö teoreetilises osas aluspepesu materjale ja ümbertöödeldud toormes valmistatud alternatiivseid materjale, põhinõudeid aluspesu kangastele, ringmajanduse põhimõtteid ja raskusi nende põhimõtete rakendamisel aluspesupesu tootmisel, tootearendust ja tootmisprotsesse ning lõpuks võimalikke lahendusi tootele selle eluea lõppedes.

Lõputöö praktiline osa jagunes veel omakorda kaheks. Esimeses uuriti sarnase koostisega tavapäraseid kangaid ja alternatiivseid kangaid, et leida kvaliteedi ja omaduste erinevusi. Aluspesu kangaste põhiomaduste testimiseks viidi läbi mitu katset kolme tavapärase ja viie ümbertöödeldud kangaga. Need testid hõlmasid pindtihedust, värvipüsivust pesemise, hõõrdumise ja higi toimele, vastupidavust hõõrdumisele, õhuläbilaskvust, pH taset ja elastsust. Alternatiivsed kangad näitasid suurepäraseid tulemusi kõigis testides. Mõne testi tulemused olid alternatiivsete kangaste puhul isegi paremad kui tavaliste kangaste puhul. Nendeks omadusteks olid värvipüsivus hõõrdumisele ja higi toimele ning vastupidavus hõõrdumisele. Testide tulemuste põhjal valiti välja alternatiivne kangas, mida kasutati aluspesu tootmiseks antud magistritöö käigus.

Praktilise töö teine osa oli pühendatud tootearendusprotsessidele, mis hõlmas kangaste, abimaterjalide ja aksessuaaride valimist, lõigete valmistamist, töötlemistehnoloogia valimist ja hinnakalkulatsioone. Kogu arendusprotsess põhines ringmajanduse põhimõtetel ja pesukomplekt loodi nii, et selle eluea lõppedes siseneks see kas bioloogilisse või tehnilisse ringlusesse. Toote disain ja tehnoloogia põhines eeldusel, et pesukomplekti saaks soovi korral toota ka väikesel tootmisliinil. Samuti on pesukomplekti hind konkurentsivõimeline praegu turul pakutavate sarnaste toodetega.

Magistritöö alguses seatud eesmärk rakendada ringmajanduse põhimõtteid aluspesu väljatöötamisel saavutati. Alternatiivsed kangad näitasid katsetamise ajal suurepäraseid tulemusi ja vastasid kõigile pesukangastele seatud miinimumnõuetele. Vaatamata ringlussevõetud kangaste sobivatele omadustele on nende kättesaadavus ja disaini valik endiselt üsna piiratud, eriti ümbertöödeldud tselluloosikiudude puhul. Pesu tootmiseks vajalike aksessuaaride ja abimaterjalide osas on tavapäraste võimaluste asendamine alternatiividega veelgi keerulisem - turul pakutavate materjalide valik on kesine ja nende kvaliteet on sageli madalam kui tavapäraste materjalide puhul.

Magistritöö käigus välja töötatud pesukomplekt oli väike katse tutvustada ringse süsteemi rakendemise võimalikkust aluspesu tootmisel. Erinevate ning keereukamate disainide, pakkumiseks on vaja põhjalikumalt uurimustööd jätkusuutlikke materjalide osas, sealhulgas aksessuaare ja abimaterjale, ning ümbertöötlemise tehnoloogiate osas.

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APPENDICES

Appendix 1 Different types of bras and panties

Figure A1.1. Types of bras [99]

Figure A1.2. Types of panties [100]

Appendix 2 Mass per unit area results

Table A2. 1. Mass per unit are results

Fabric	Specimen nr	Width (mm)	Length (mm)	Mass (g)	M g/m²
Fabric 1 Green knitted PA	1	101	100	0,984	97,4
	2	100	100	0,978	97,8
	3	100	100	0,989	98,9
	4	100	100	1,008	100,8
	5	100	100	0,980	98,0
			Average:		**98,6**
			Standard deviation:		**1,4**
Fabric 2 Green mesh PA	1	100	101	0,671	66,5
	2	101	100	0,667	66,0
	3	102	100	0,680	66,7
	4	100	101	0,678	67,1
	5	99	102	0,662	65,6
			Average:		**66,4**
			Standard deviation:		**0,6**
Fabric 3 Blue knitted VI	1	101	99	1,746	174,6
	2	101	100	1,793	177,5
	3	102	99	1,811	179,3
	4	102	100	1,829	179,3
	5	102	101	1,863	180,9
			Average:		**178,3**
			Standard deviation:		**2,4**
Fabric 4 Grey knitted Rec PA	1	101	100	1,119	110,7
	2	100	100	1,108	110,8
	3	100	100	1,110	111,0
	4	100	100	1,112	111,2
	5	100	100	1,087	108,7
			Average:		**110,5**
			Standard deviation:		**1,0**
Fabric 5 Green mesh Rec PA	1	100	99	1,222	123,4
	2	100	99	1,236	124,9
	3	100	99	1,232	124,5
	4	101	100	1,263	125,0
	5	101	101	1,253	122,8
			Average:		**124,1**
			Standard deviation:		**1,0**

Fabric	**Specimen nr**	**Width (mm)**	**Length (mm)**	**Mass (g)**	**M g/m^2**
Fabric 6 White knitted Rec CO	1	101	101	1,429	140,1
	2	100	101	1,426	141,1
	3	101	101	1,449	142,1
	4	100	100	1,425	142,5
	5	100	100	1,400	140,0
			Average:		**141,1**
			Standard deviation:		**1,1**
Fabric 7 Blue printed Refibra	1	100	100	1,802	180,2
	2	100	100	1,800	180,0
	3	100	101	1,833	181,4
	4	100	101	1,812	179,4
	5	100	100	1,802	180,2
			Average:		**180,2**
			Standard deviation:		**0,8**
Fabric 8 Blue knitted Refibra	1	100	100	1,478	147,8
	2	100	101	1,486	147,1
	3	100	100	1,508	149,3
	4	100	100	1,457	145,7
	5	100	101	1,493	147,8
			Average:		**147,6**
			Standard deviation:		**1,3**

Appendix 3 Pilling and fuzzing test results

Table A3. 1. Pilling and fuzzing test results

	Pilling				**Fuzzing**			
Number of pilling rubs	Result 1	Result 2	Result 3	**Average**	Result 1	Result 2	Result 3	**Average**
Fabric 1. Green knitted PA								
125 rev.	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	4	4	4	**4**
1000 rev.	5	4	5	**5**	4	3	4	**4**
2000 rev.	4	4	4	**4**	4	3	4	**4**
Fabric 2. Green mesh PA								
125 rev.	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	5	5	5	**5**
1000 rev.	5	5	5	**5**	5	5	5	**5**
2000 rev.	5	5	5	**5**	5	5	5	**5**
Fabric 3. Blue knitted VI								
125 rev	5	4	5	**5**	4	4	4	**4**
500 rev.	4	4	4	**4**	3	3	4	**3**
1000 rev.	3	3	4	**3**	4	4	4	**4**
2000 rev.	3	3	3	**3**	4	4	4	**4**
Fabric 4. Grey knitted Rec PA								
125 rev	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	4	5	5	**5**
1000 rev.	5	5	5	**5**	4	4	5	**4**
2000 rev.	5	5	5	**5**	4	4	4	**4**
Fabric 5. Green mesh Rec PA								
125 rev	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	5	5	5	**5**
1000 rev.	5	5	5	**5**	5	5	5	**5**
2000 rev.	5	5	5	**5**	5	5	5	**5**
Fabric 6. White knitted Rec CO								
125 rev	5	5	5	**5**	4	5	5	**5**
500 rev.	4	5	5	**5**	4	4	4	**4**
1000 rev.	4	4	4	**4**	4	4	4	**4**
2000 rev.	3	4	4	**4**	3	3	4	**3**
Fabric 7. Blue printed Refibra™								
125 rev	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	5	5	5	**5**
1000 rev.	5	5	5	**5**	4	4	5	**4**
2000 rev.	5	5	5	**5**	4	4	5	**4**
Fabric 8. Blue knitted Refibra™								
125 rev	5	5	5	**5**	5	5	5	**5**
500 rev.	5	5	5	**5**	4	4	5	**4**
1000 rev.	4	5	5	**5**	4	4	4	**4**
2000 rev.	4	4	4	**4**	3	3	4	**3**

Appendix 4 Pilling and fuzzing test photos

Figure A4.1. Fabric 1C. Green knitted PA after 2000 rubs

Figure A4.2. Fabric 4A. Grey knitted Rec PA after 2000 rubs

Figure A4.3. Fabric 2C. Green mesh PA after 2000 rubs

Figure A4.4. Fabric 4A. Green mesh Rec PA after 2000 rubs

Figure A4.5. Fabric 3C. Blue knitted VI after 2000 rubs

Figure A4.6. Fabric 6A. White knitted Rec CO after 2000 rubs

Figure A4.7. Fabric 7A. Blue printed Refibra after 2000 rubs

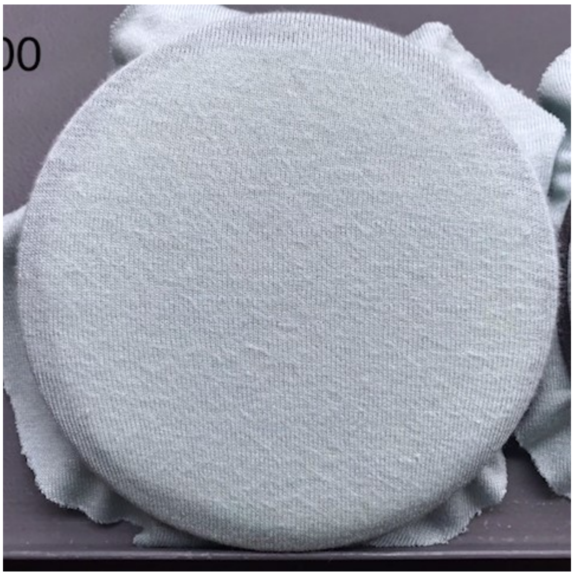


Figure A4.8. Fabric 8A. Blue knitted Refibra after 2000 rubs

Appendix 5 Air permeability results

Table A5. 1. Air permeability results

Fabric	Test no.									
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**
Fabric 1C. Green knitted PA	Exceeded the measuring range of the device									
Fabric 2C. Green mesh PA	Exceeded the measuring range of the device									
Fabric 5A. Green mesh Rec PA	Exceeded the measuring range of the device									
Fabric 8A. Blue knitted Refibra™	Exceeded the measuring range of the device									
Fabric 3C. Blue knitted VI	774	815	888	958	903	957	943	857	735	888
Average:	**(872±77) l/m²s**									
Fabric 4A. Grey knitted Rec PA	409	431	448	452	471	386	429	439	431	416
Average:	**(431±24) l/m²s**									
Fabric 6A. White knitted Rec CO	177	179	166	167	159	165	184	171	164	191
Average:	**(172±10) l/m²s**									
Fabric 7A. Blue printed Refibra™	689	652	652	654	707	738	694	617	724	652
Average:	**(678±38) l/m²s**									

Appendix 6 pH value in fabrics results

Table A6. 1. pH value test results

Fabric	Test nr.	Temp. of extracting solution	pH-value
Fabric 1C. Green knitted PA	1	26,2	6,1
	2	26,1	6,2
		Average:	**6,2**
Fabric 2C. Green mesh PA	1	24,8	6,4
	2	24,9	6,4
		Average:	**6,4**
Fabric 3C. Blue knitted VI	1	25,8	7,4
	2	25,7	7,3
		Average:	**7,3**
Fabric 4A. Grey knitted Rec PA	1	24,9	6,5
	2	24,7	6,6
		Average:	**6,6**
Fabric 5A. Green mesh Rec PA	1	23,2	6,3
	2	23,4	6,3
		Average:	**6,3**
Fabric 6A. White knitted Rec CO	1	23,0	4,6
	2	22,8	4,7
		Average:	**4,7**
Fabric 7A. Blue printed Refibra™	1	23,8	7,4
	2	23,6	7,5
		Average:	**7,5**
Fabric 8A. Blue knitted Refibra™	1	23,1	5,5
	2	23,0	5,4
		Average:	**5,5**

Appendix 7 Elasticity test results

Table A7.1. Elasticity test results of Fabric 1C. Green knitted PA

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 1C. Green knitted PA 20% EL	1	Wale	100	24	97	97	104	4	102	2	96	98
	2		100	24	87	87	103	3	102	2	97	98
	3		100	24	88	88	104	4	102	2	96	98
	4		100	24	89	89	105	5	103	3	95	97
	5		100	24	84	84	103	3	101	1	97	99
	Average:			**24**	**89**	**89**	**104**	**4**	**102**	**2**	**96**	**98**
	Standard deviation:			**0,1**	**5,1**	**5,1**	**0,8**	**0,8**	**0,7**	**0,7**	**0,8**	**0,7**
	1	Course	100	24	196	196	121	21	117	17	79	83
	2		100	24	197	197	122	22	118	18	78	82
	3		100	24	197	197	121	21	116	16	79	84
	4		100	24	198	198	122	22	118	18	78	82
	5		100	24	191	191	120	20	117	17	80	83
	Average:			**24**	**196**	**196**	**121**	**21**	**117**	**17**	**79**	**83**
	Standard deviation:			**0,1**	**2,6**	**2,6**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**

Table A7.2. Elasticity test results of Fabric 2C. Green mesh PA

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 2C. Green mesh PA 19% EL	1	Wale	100	24	76	76	101	1	100	0	99	100
	2		100	24	76	76	101	1	100	0	99	100
	3		100	24	76	76	101	1	100	0	99	100
	4		100	24	77	77	101	1	100	0	99	100
	5		100	24	77	77	101	1	100	0	99	100
	Average:			**24**	**76**	**76**	**101**	**1**	**100**	**0**	**99**	**100**
	Standard deviation:			**0,1**	**0,5**	**0,5**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
	1	Course	100	24	218	218	107	7	104	4	93	96
	2		100	24	215	215	109	9	105	5	91	95
	3		100	25	214	214	107	7	104	4	93	96
	4		100	24	218	218	108	8	106	6	92	94
	5		100	24	215	215	106	6	104	4	94	96
	Average:			**24**	**216**	**216**	**107**	**7**	**105**	**5**	**93**	**95**
	Standard deviation:			**0,2**	**1,8**	**1,8**	**1,1**	**1,1**	**0,9**	**0,9**	**1,1**	**0,9**

Table A7.3. Elasticity test results of Fabric 3C. Blue knitted VI

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 3C. Blue knitted VI 10% EL	1	Wale	100	19	173	173	105	5	104	4	95	96
	2		100	19	177	177	105	5	104	4	95	96
	3		100	20	169	169	104	4	103	3	96	97
	4		100	20	176	176	106	6	104	4	94	96
	5		100	19	172	172	105	5	104	4	95	96
	Average:			**19**	**174**	**174**	**105**	**5**	**104**	**4**	**95**	**96**
	Standard deviation:			**0,3**	**3,2**	**3,2**	**0,7**	**0,7**	**0,4**	**0,4**	**0,7**	**0,4**
	1	Course	100	20	197	197	107	7	104	4	93	96
	2		100	20	202	202	111	11	108	8	89	92
	3		100	19	204	204	110	10	108	8	90	92
	4		100	20	203	203	111	11	107	7	89	93
	5		100	19	203	203	110	10	108	8	90	92
	Average:			**20**	**202**	**202**	**110**	**10**	**107**	**7**	**90**	**93**
	Standard deviation:			**0,1**	**2,7**	**2,7**	**1,6**	**1,6**	**1,7**	**1,7**	**1,6**	**1,7**

Table A7.4. Elasticity test results of Fabric 4A. Grey knitted Rec PA

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 4A. Grey knitted Rec PA 20% EL	1	Wale	100	24	140	140	105	5	102	2	95	98
	2		100	27	138	138	104	4	101	1	96	99
	3		100	24	141	141	105	5	103	3	95	97
	4		100	24	139	139	105	5	102	2	95	98
	5		100	25	139	139	105	5	103	3	95	97
	Average:			**25**	**139**	**139**	**105**	**5**	**102**	**2**	**95**	**98**
	Standard deviation:			**1,3**	**1,4**	**1,4**	**0,4**	**0,4**	**0,8**	**0,8**	**0,4**	**0,8**
	1	Course	100	25	200	200	109	9	106	6	91	94
	2		100	24	205	205	109	9	105	5	91	95
	3		100	25	199	199	107	7	104	4	93	96
	4		100	24	206	206	108	8	105	5	92	95
	5		100	24	209	209	110	10	106	6	90	94
	Average:			**24**	**204**	**204**	**109**	**9**	**105**	**5**	**91**	**95**
	Standard deviation:			**0,1**	**4,2**	**4,2**	**1,1**	**1,1**	**0,8**	**0,8**	**1,1**	**0,8**

Table A7.5. Elasticity test results of Fabric 5A. Green mesh Rec PA

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 5A. Green mesh Rec PA 37% EL	1	Wale	100	34	116	116	110	10	107	7	90	93
	2		100	34	119	119	111	11	108	8	89	92
	3		100	34	119	119	113	13	109	9	87	91
	4		100	34	118	118	110	10	107	7	90	93
	5											
	Average:			**34**	**118**	**118**	**111**	**11**	**108**	**8**	**89**	**92**
	Standard deviation:			**0,1**	**1,4**	**1,4**	**1,4**	**1,4**	**1,0**	**1,0**	**1,4**	**1,0**
	1	Course	100	34	184	184	109	9	105	5	91	95
	2		100	34	185	185	110	10	106	6	90	94
	3		100	34	186	186	110	10	105	5	90	95
	4											
	5											
	Average:			**34**	**185**	**185**	**110**	**10**	**105**	**5**	**90**	**95**
	Standard deviation:			**0,2**	**1,2**	**1,2**	**0,6**	**0,6**	**0,6**	**0,6**	**0,6**	**0,6**

Table A7.6. Elasticity test results of Fabric 6A. White knitted Rec CO

Fabric	**Test nr.**	**Direction**	**Initial lenght, mm**	**Load on the fifth cycle, N**	**Extension at max load on the fifth cycle, mm**	**Elongation, S, %**	**Distance between reference marks Q, after 1 min, mm**	**Permanent deformation, C after 1 min, %**	**Distance between reference marks Q, after 30 min, mm**	**Permanent deformation, C after 30 min, %**	**Recovered elongation, D after 1 min, %**	**Recovered elongation, D after 30 min, %**
Fabric 6A. White knitted Rec CO 7% EL	1	Wale	100	20	58	58	106	6	104	4	94	96
	2		100	19	59	59	107	7	105	5	93	95
	3		100	19	56	56	107	7	105	5	93	95
	4		100	19	58	58	106	6	105	5	94	95
	5		100	19	60	60	105	5	104	4	95	96
	Average:			**19**	**59**	**59**	**106**	**6**	**105**	**5**	**94**	**95**
	Standard deviation:			**0,2**	**1,6**	**1,6**	**0,8**	**0,8**	**0,5**	**0,5**	**0,8**	**0,5**
	1	Course	100	19	140	140	124	24	120	20	76	80
	2		100	20	144	144	125	25	120	20	75	80
	3		100	20	145	145	123	23	120	20	77	80
	4		100	20	143	143	123	23	120	20	77	80
	5		100	19	140	140	124	24	121	21	76	79
	Average:			**20**	**142**	**142**	**124**	**24**	**120**	**20**	**76**	**80**
	Standard deviation:			**0,1**	**2,0**	**2,0**	**0,8**	**0,8**	**0,4**	**0,4**	**0,8**	**0,4**

Table A7.7. Elasticity test results of Fabric 7A. Blue printed Refibra

Fabric	Test nr.	Direction	Initial lenght, mm	Load on the fifth cycle, N	Extension at max load on the fifth cycle, mm	Elongation, S, %	Distance between reference marks Q, after 1 min, mm	Permanent deformation, C after 1 min, %	Distance between reference marks Q, after 30 min, mm	Permanent deformation, C after 30 min, %	Recovered elongation, D after 1 min, %	Recovered elongation, D after 30 min, %
Fabric 7A. Blue printed Refibra 0% EL	1	Wale	100	14	25	25	102	2	101	1	98	99
	2		100	14	22	22	102	2	102	2	98	98
	3		100	14	26	26	103	3	102	2	97	98
	4		100	14	26	26	102	2	102	2	98	98
	5		100	14	25	25	103	3	103	3	97	97
	Average:			**14**	**25**	**25**	**102**	**2**	**102**	**2**	**98**	**98**
	Standard deviation:			**0,1**	**1,6**	**1,6**	**0,5**	**0,5**	**0,7**	**0,7**	**0,5**	**0,7**
	1	Course	100	14	48	48	106	6	105	5	94	95
	2		100	14	48	48	105	5	105	5	95	95
	3		100	14	50	50	106	6	105	5	94	95
	4		100	14	51	51	107	7	106	6	93	94
	5		100	14	50	50	106	6	105	5	94	95
	Average:			**14**	**49**	**49**	**106**	**6**	**105**	**5**	**94**	**95**
	Standard deviation:			**0,1**	**1,4**	**1,4**	**0,7**	**0,7**	**0,4**	**0,4**	**0,7**	**0,4**

Table A7.8. Elasticity test results of Fabric 7A. Blue knitted Refibra

Fabric	**Test nr.**	**Direction**	**Initial lenght, mm**	**Load on the fifth cycle, N**	**Extension at max load on the fifth cycle, mm**	**Elongation, S, %**	**Distance between reference marks Q, after 1 min, mm**	**Permanent deformation, C after 1 min, %**	**Distance between reference marks Q, after 30 min, mm**	**Permanent deformation, C after 30 min, %**	**Recovered elongation, D after 1 min, %**	**Recovered elongation, D after 30 min, %**
Fabric 8A. Blue knitted Refibra 0% EL	1	Wale	100	14	33	33	101	1	100	0	99	100
	2		100	14	32	32	101	1	100	0	99	100
	3		100	14	34	34	100	0	100	0	100	100
	4		100	14	33	33	101	1	100	0	99	100
	5		100	14	35	35	102	2	101	1	98	99
	Average:			**14**	**34**	**34**	**101**	**1**	**100**	**0**	**99**	**100**
	Standard deviation:			**0,3**	**1,2**	**1,2**	**0,7**	**0,7**	**0,4**	**0,4**	**0,7**	**0,4**
	1	Course	100	14	78	78	113	13	108	8	87	92
	2		100	15	79	79	111	11	106	6	89	94
	3		100	14	76	76	110	10	105	5	90	95
	4		100	14	80	80	112	12	108	8	88	92
	5		100	14	76	76	108	8	105	5	92	95
	Average:			**14**	**78**	**78**	**111**	**11**	**106**	**6**	**89**	**94**
	Standard deviation:			**0,2**	**1,9**	**1,9**	**1,9**	**1,9**	**1,5**	**1,5**	**1,9**	**1,5**

Appendix 8. Elasticity test graphs: Fabric 1C. Green knitted PA

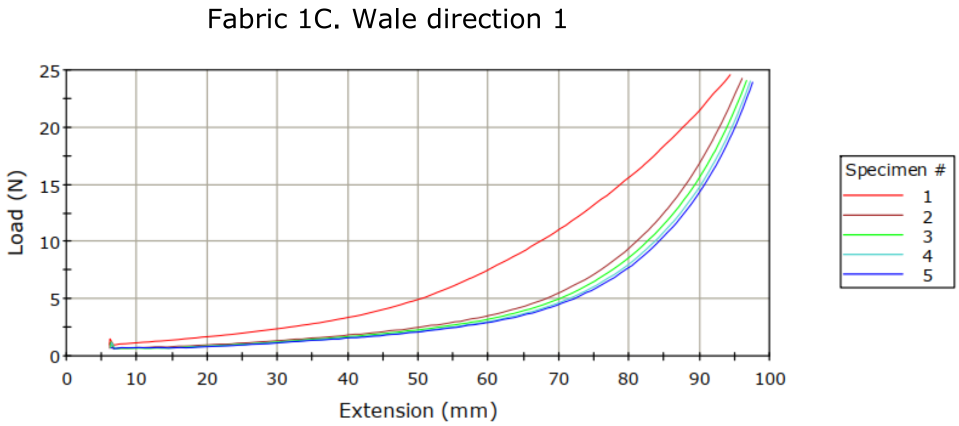


Figure A8.1. Fabric 1C. Green knitted PA specimen 1, wale direction

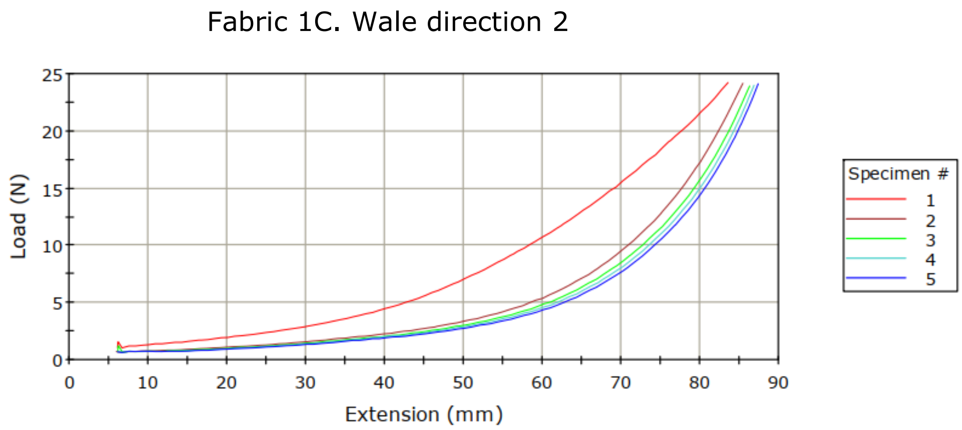


Figure A8.2. Fabric 1C. Green knitted PA specimen 2, wale direction

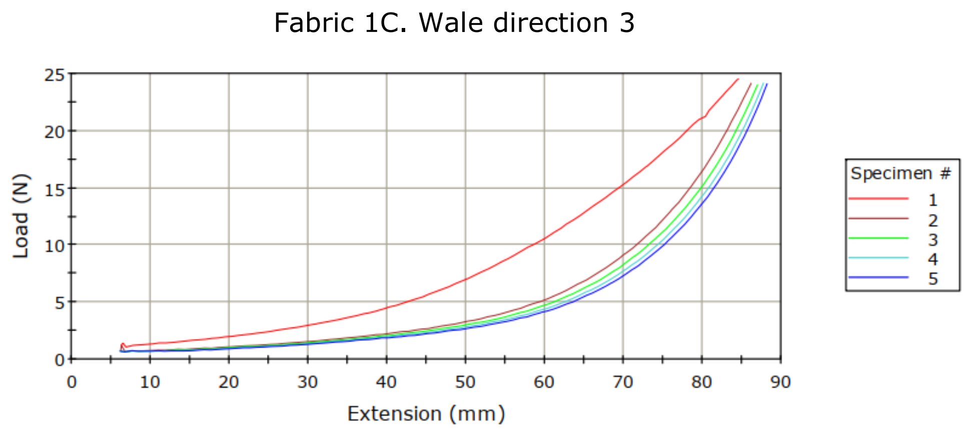


Figure A8.3. Fabric 1C. Green knitted PA specimen 3, wale direction

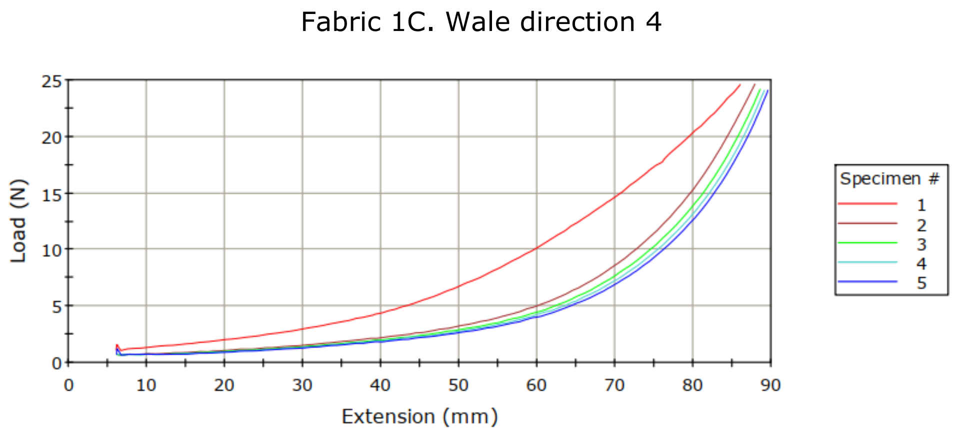


Figure A8.4. Fabric 1C. Green knitted PA specimen 4, wale direction

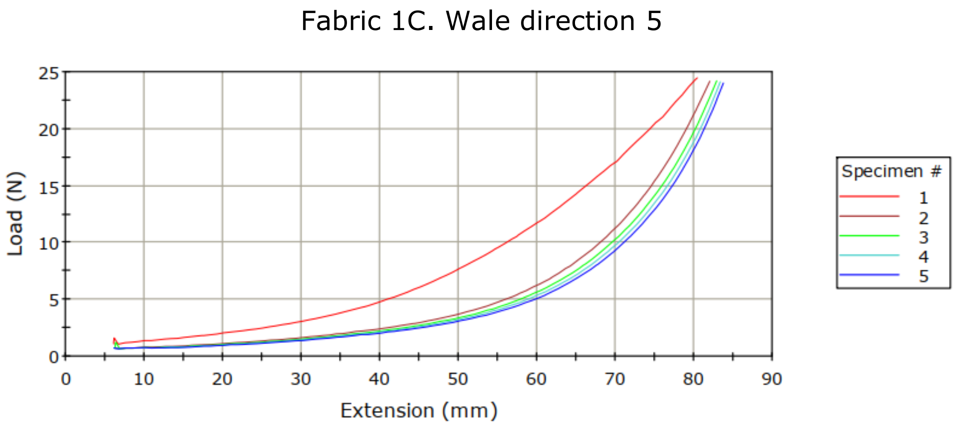


Figure A8.5. Fabric 1C. Green knitted PA specimen 5, wale direction

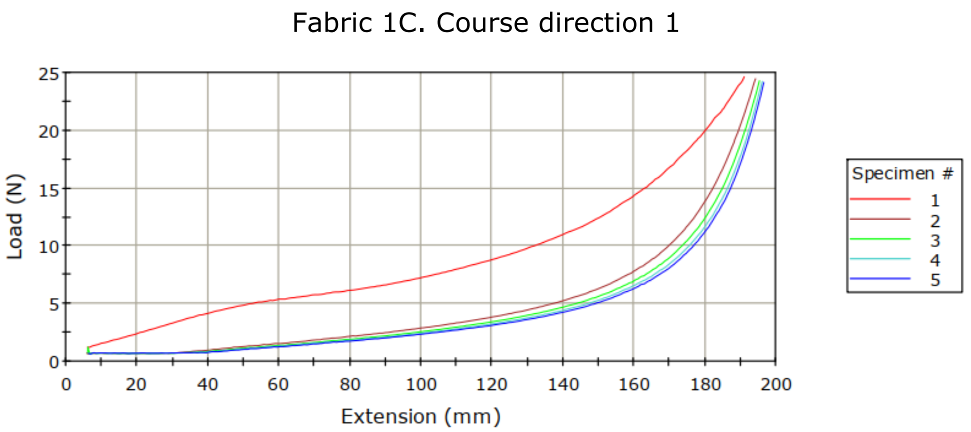


Figure A8.6. Fabric 1C. Green knitted PA specimen 1, course direction

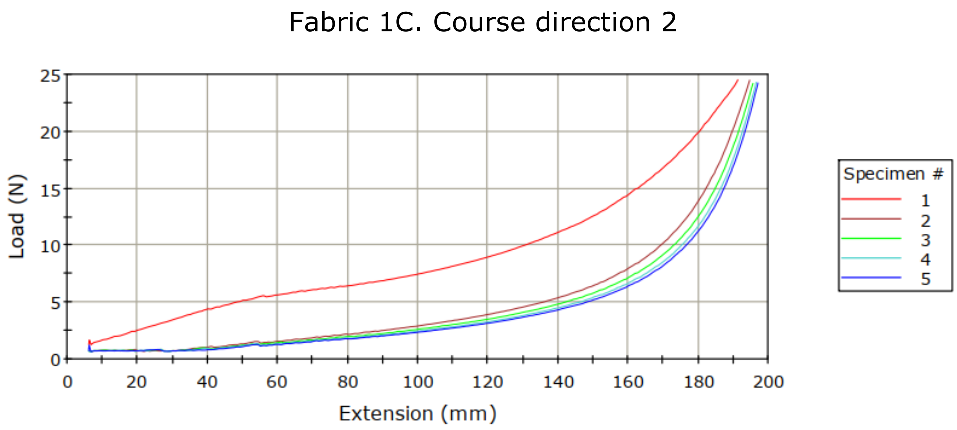


Figure A8.7. Fabric 1C. Green knitted PA specimen 2, course direction

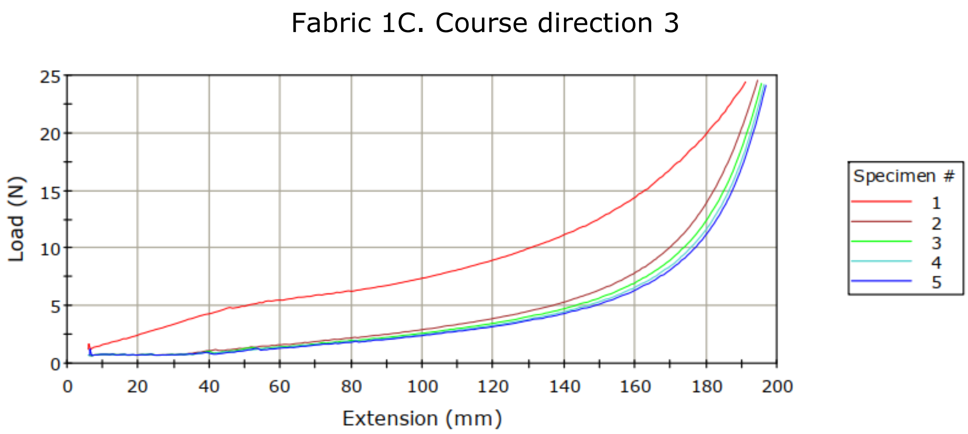


Figure A8.8. Fabric 1C. Green knitted PA specimen 3, course direction

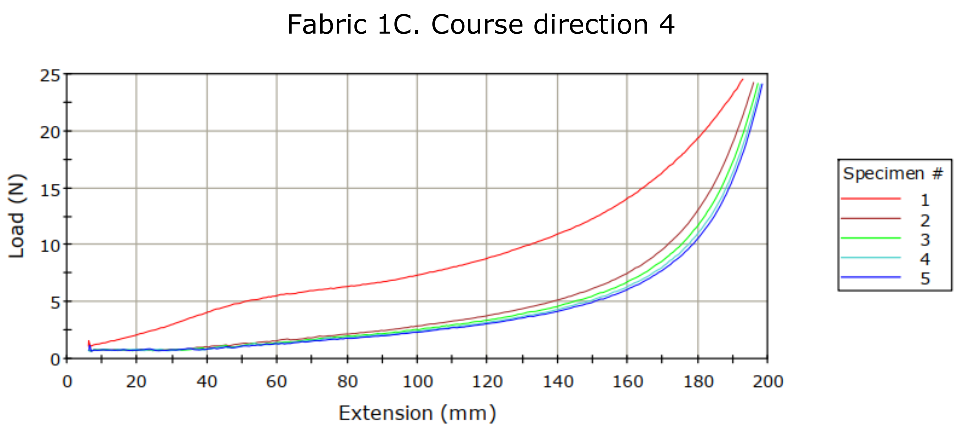


Figure A8.9. Fabric 1C. Green knitted PA specimen 4, course direction

Fabric 1C. Course direction 5

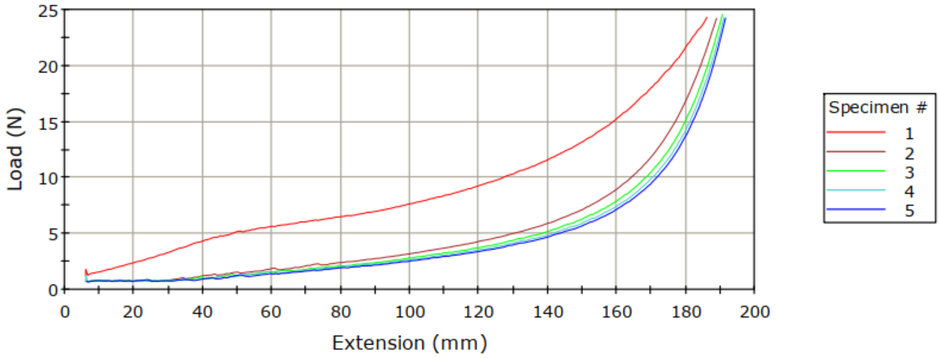


Figure A8.10. Fabric 1C. Green knitted PA specimen 5, course direction

Appendix 9. Elasticity test graphs: Fabric 2C. Green mesh PA

Fabric 2C. Wale direction 1

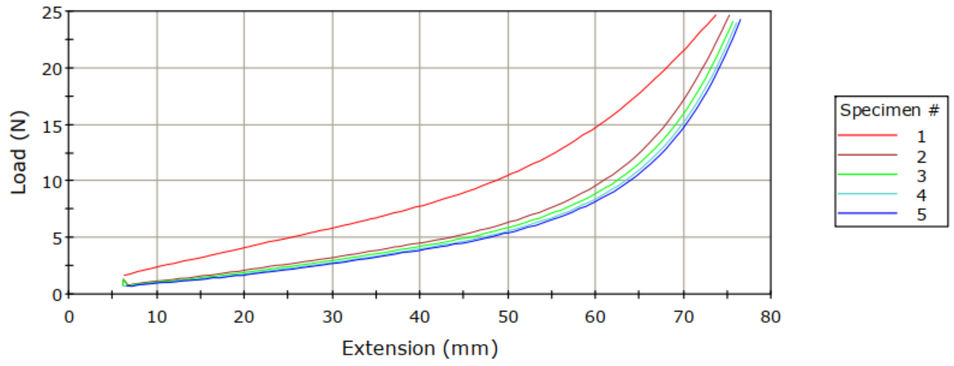


Figure A9.1. Fabric 2C. Green mesh PA specimen 1, wale direction

Fabric 2C. Wale direction 2

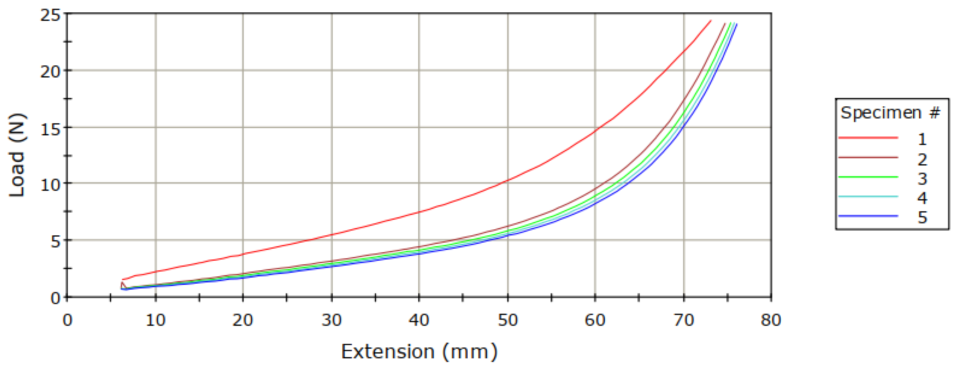


Figure A9.2. Fabric 2C. Green mesh PA specimen 2, wale direction

Fabric 2C. Wale direction 3

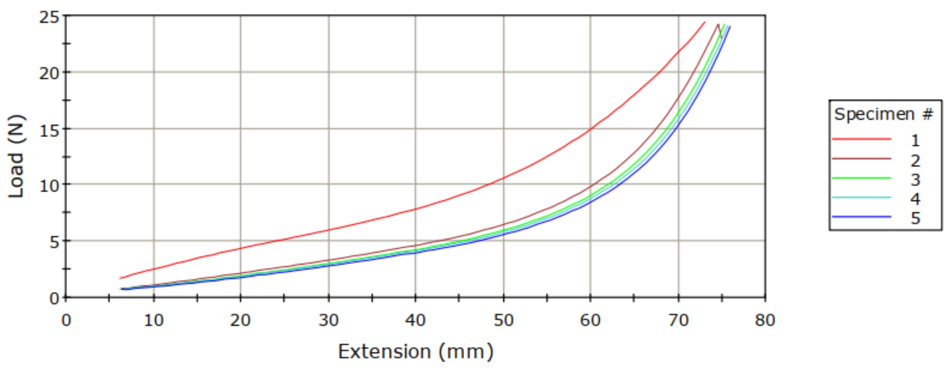


Figure A9.3. Fabric 2C. Green mesh PA specimen 3, wale direction

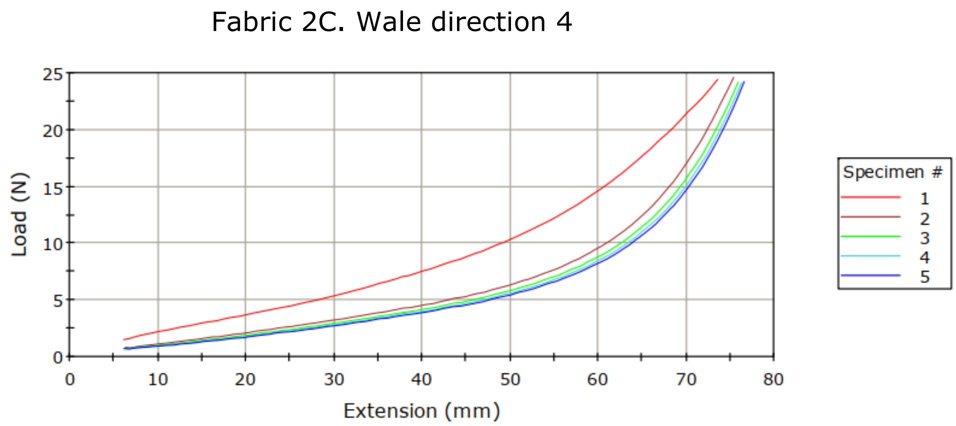


Figure A9.4. Fabric 2C. Green mesh PA specimen 4, wale direction

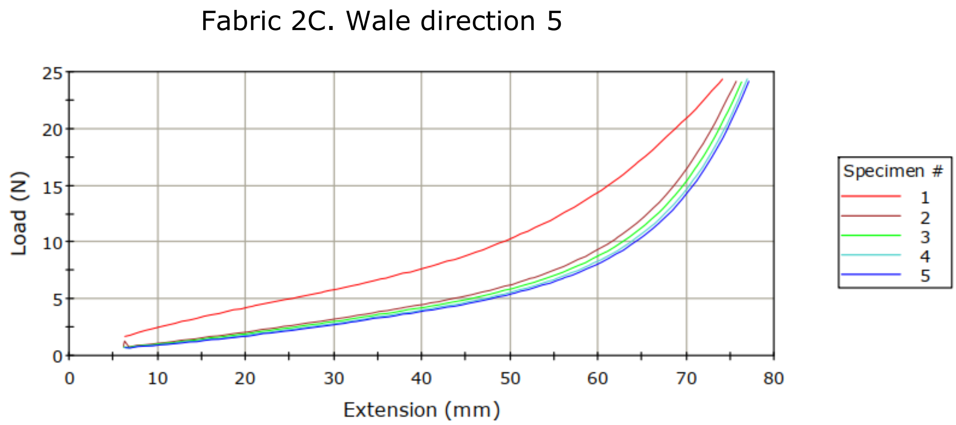


Figure A9.5. Fabric 2C. Green mesh PA specimen 5, wale direction

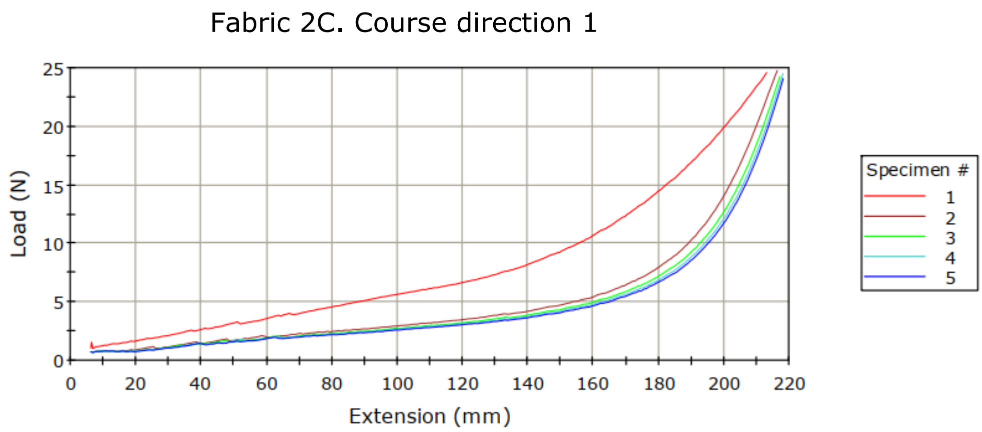


Figure A9.6. Fabric 2C. Green mesh PA specimen 1, course direction

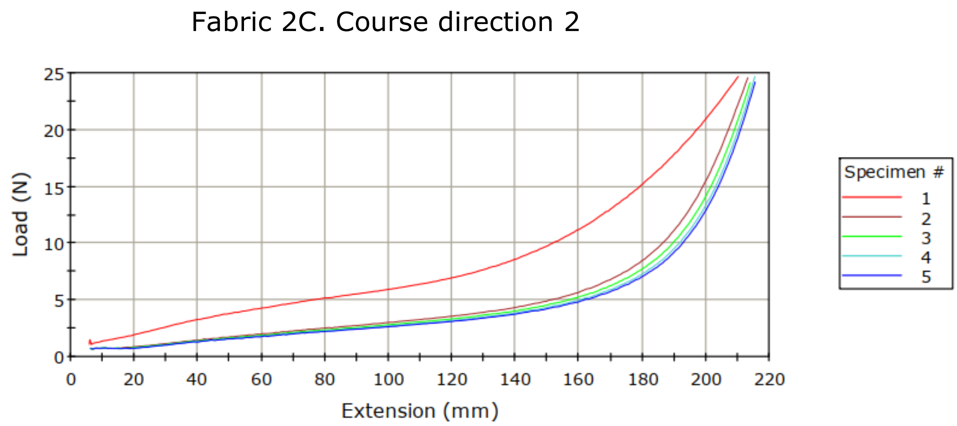


Figure A9.7. Fabric 2C. Green mesh PA specimen 2, course direction

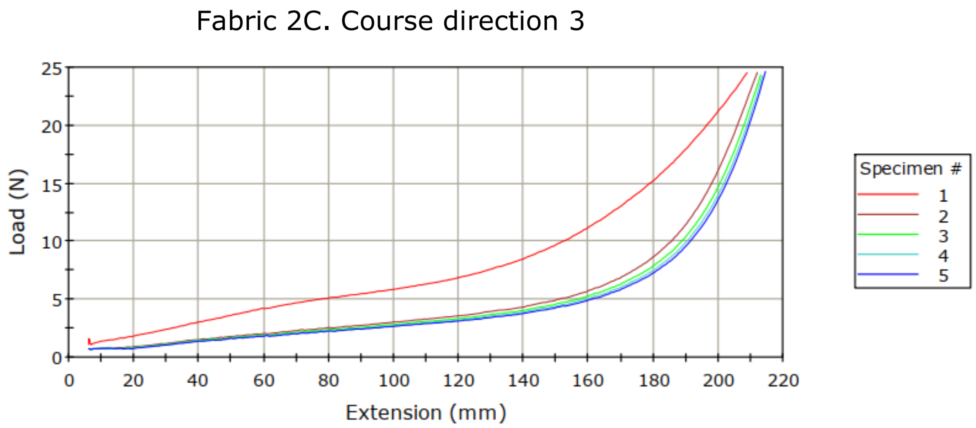


Figure A9.8. Fabric 2C. Green mesh PA specimen 3, course direction

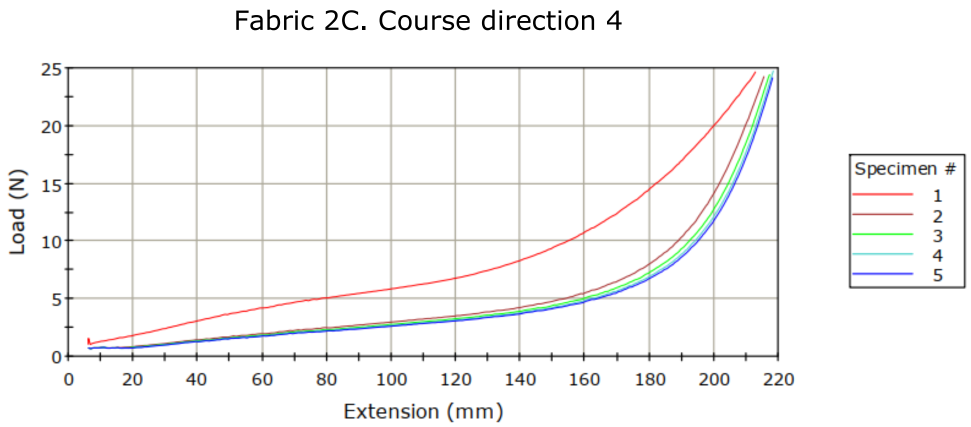


Figure A9.9. Fabric 2C. Green mesh PA specimen 4, course direction

Fabric 2C. Course direction 5

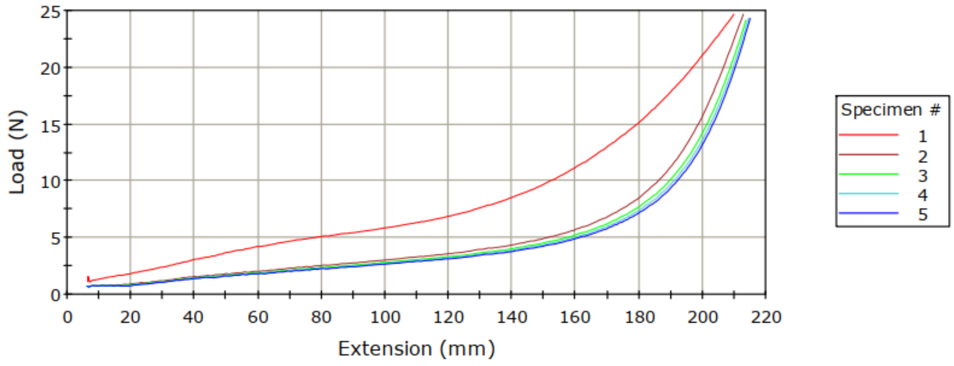


Figure A9.10. Fabric 2C. Green mesh PA specimen 5, course direction

Appendix 10. Elasticity test graphs: Fabric 3C. Blue knitted VI

Fabric 3C. Wale direction 1

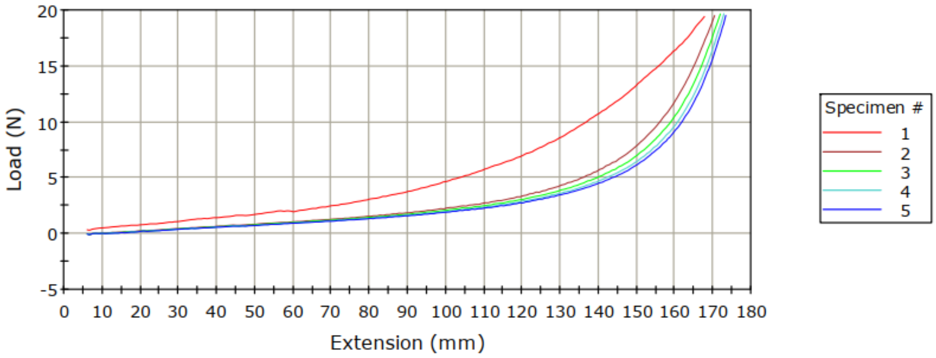


Figure A10.1. Fabric 3C. Blue knitted VI specimen 1, wale direction

Fabric 3C. Wale direction 2

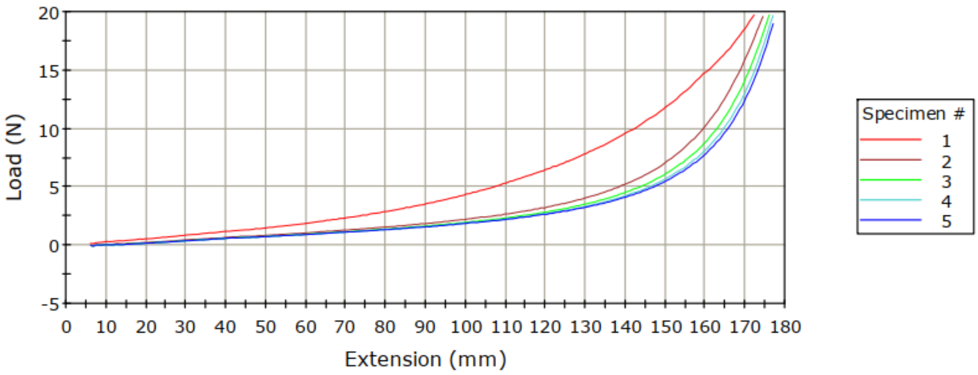


Figure A10.2. Fabric 3C. Blue knitted VI specimen 2, wale direction

Fabric 3C. Wale direction 3

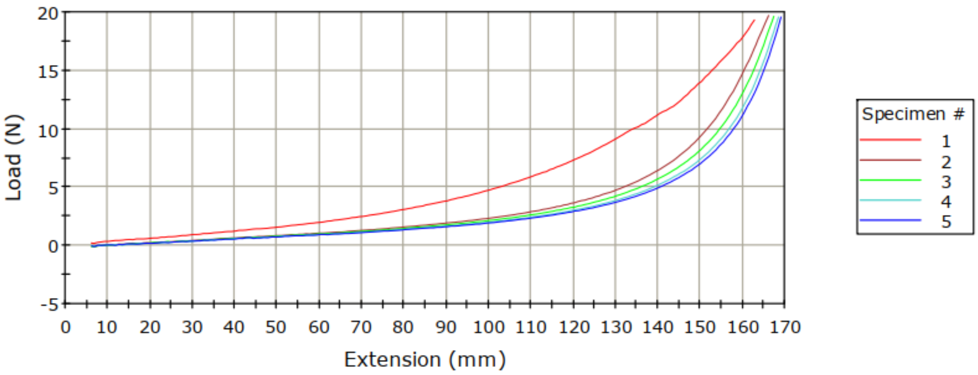


Figure A10.3. Fabric 3C. Blue knitted VI specimen 3, wale direction

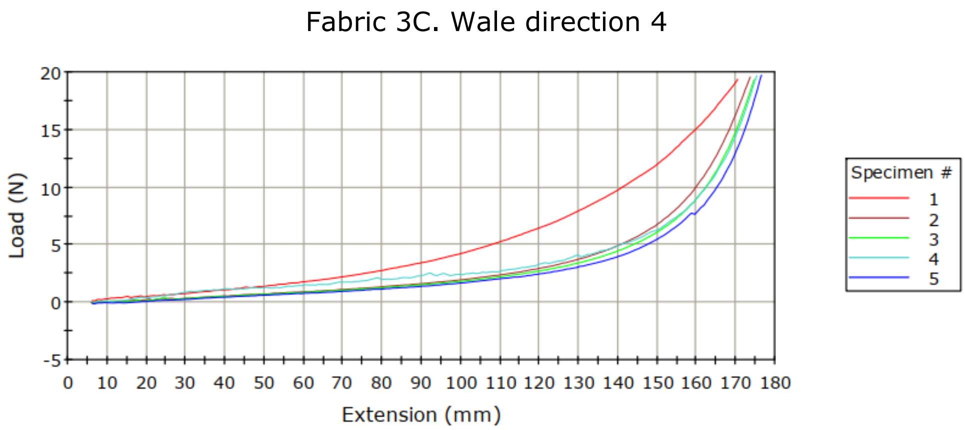


Figure A10.4. Fabric 3C. Blue knitted VI specimen 4, wale direction

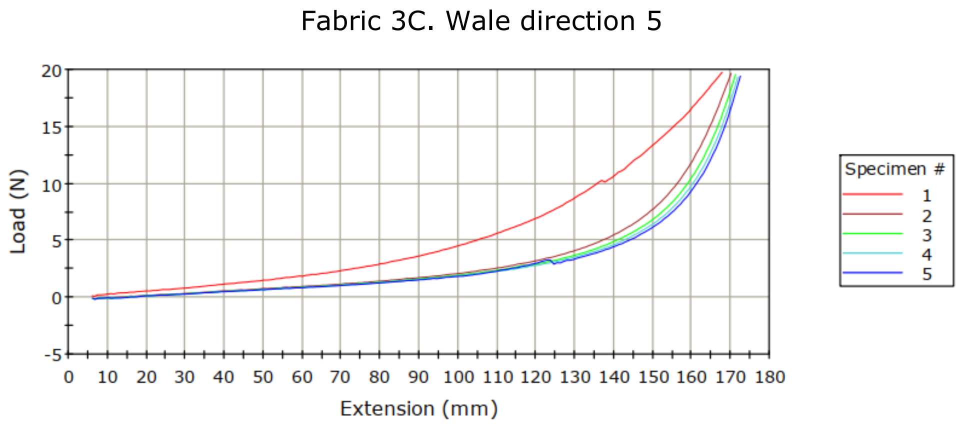


Figure A10.5. Fabric 3C. Blue knitted VI specimen 5, wale direction

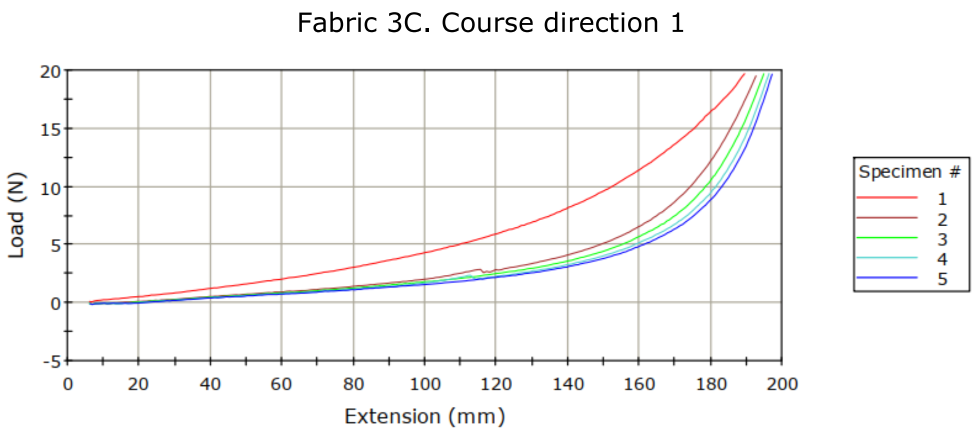


Figure A10.6. Fabric 3C. Blue knitted VI specimen 1, course direction

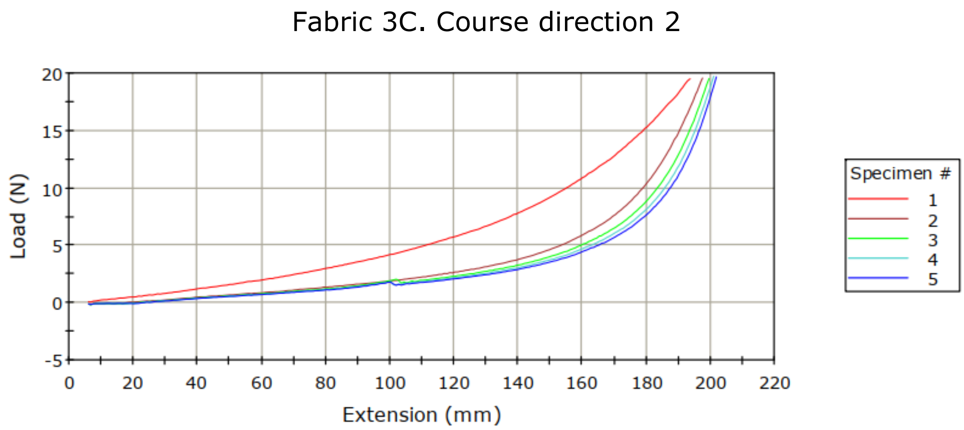


Figure A10.7. Fabric 3C. Blue knitted VI specimen 2, course direction

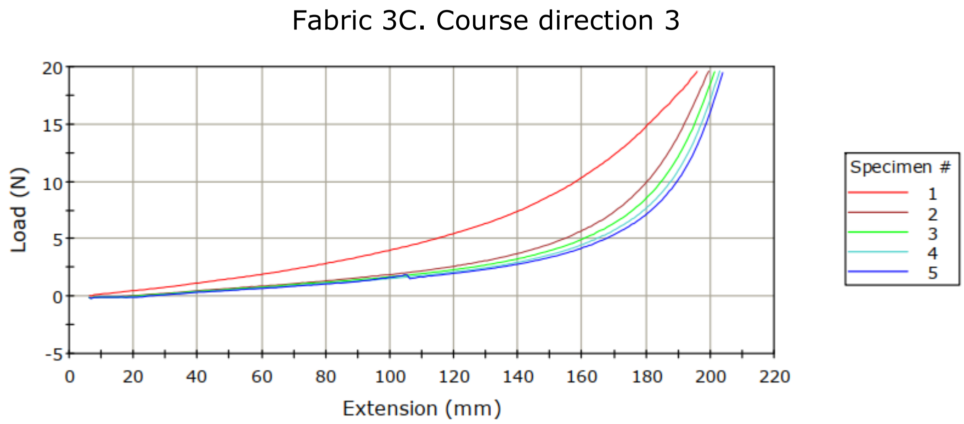


Figure A10.8. Fabric 3C. Blue knitted VI specimen 3, course direction

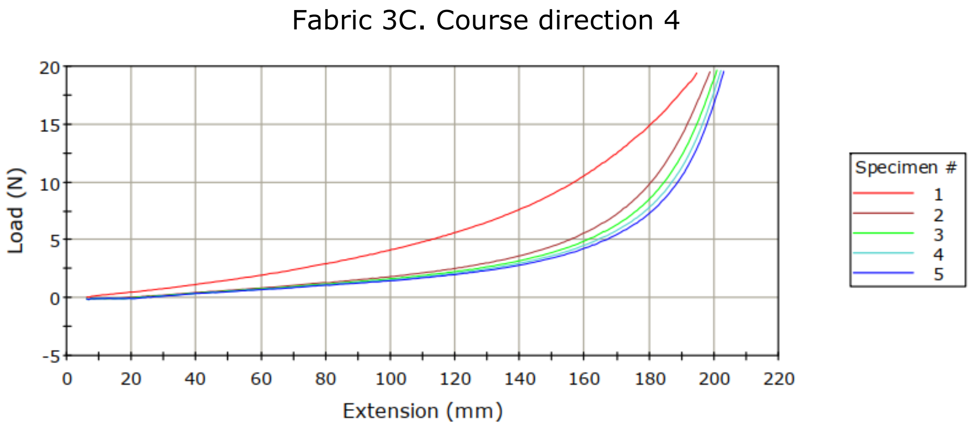


Figure A10.9. Fabric 3C. Blue knitted VI specimen 4, course direction

Fabric 3C. Course direction 5

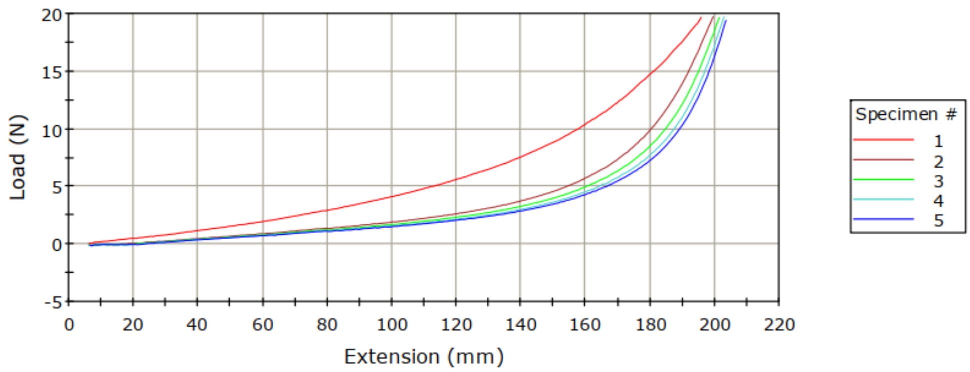


Figure A10.10. Fabric 3C. Blue knitted VI specimen 5, course direction

Appendix 11. Elasticity test graphs: Fabric 4A. Grey knitted Rec PA

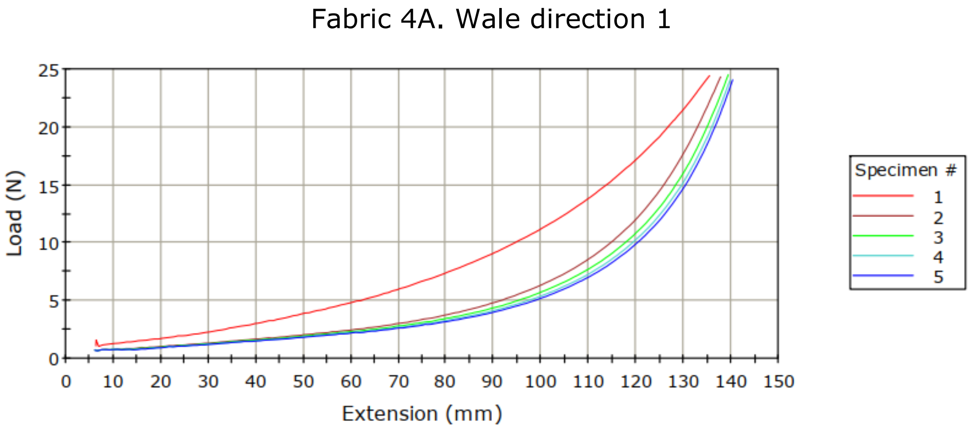


Figure A11.1. Fabric 4A. Grey knitted Rec PA specimen 1, wale direction

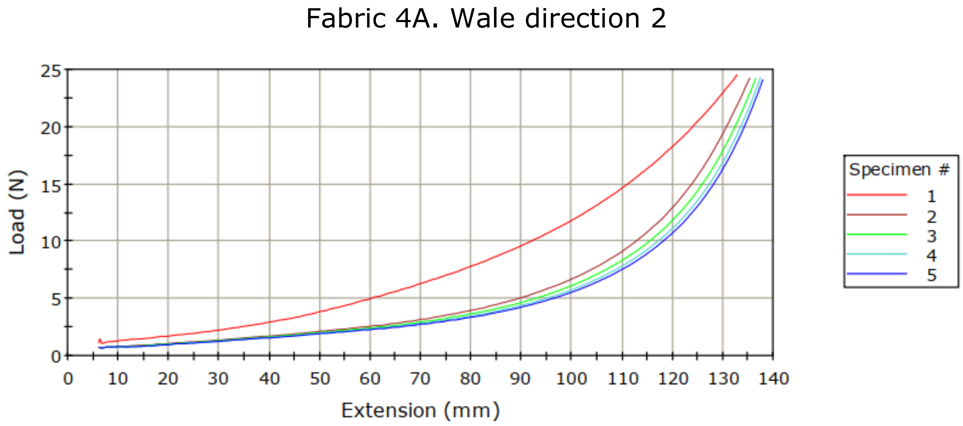


Figure A11.2. Fabric 4A. Grey knitted Rec PA specimen 2, wale direction

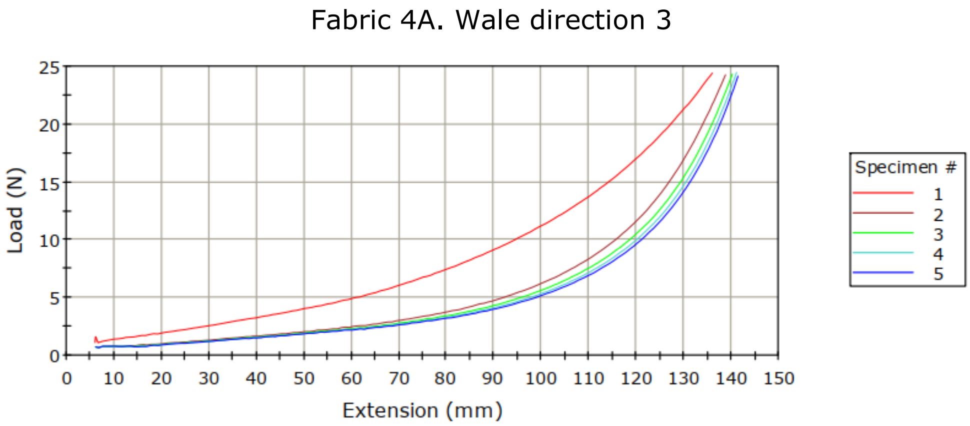


Figure A11.3. Fabric 4A. Grey knitted Rec PA specimen 3, wale direction

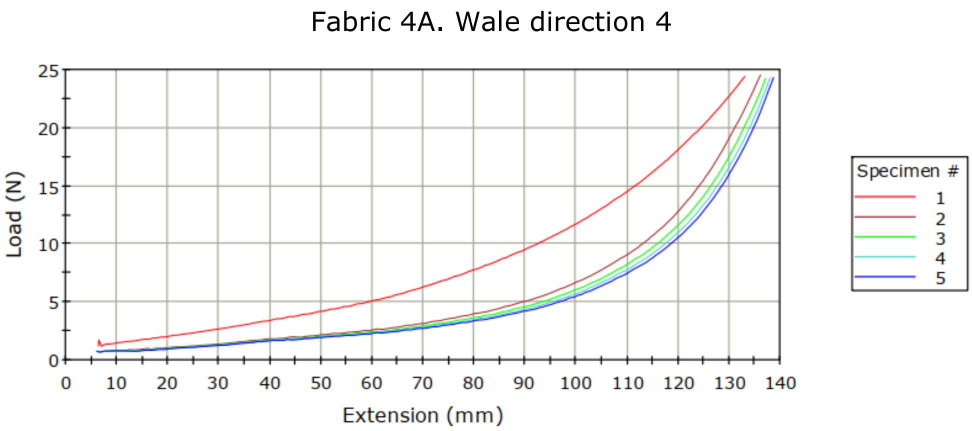


Figure A11.4. Fabric 4A. Grey knitted Rec PA specimen 4, wale direction

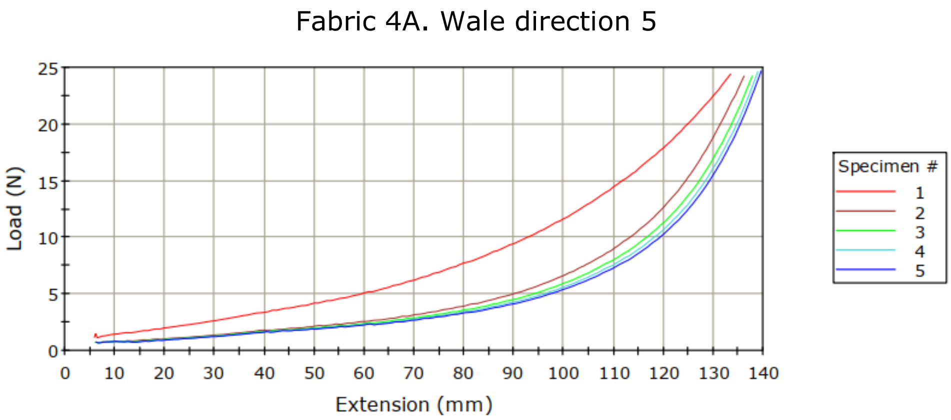


Figure A11.5. Fabric 4A. Grey knitted Rec PA specimen 5, wale direction

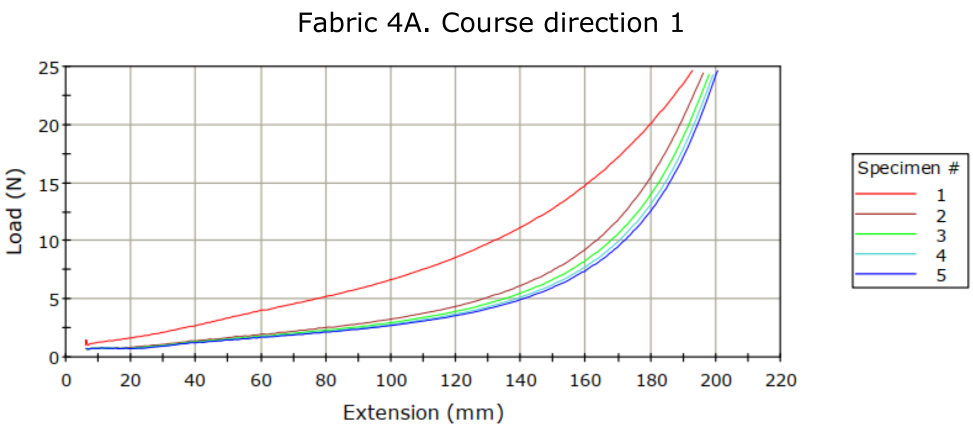


Figure A11.6. Fabric 4A. Grey knitted Rec PA specimen 1, course direction

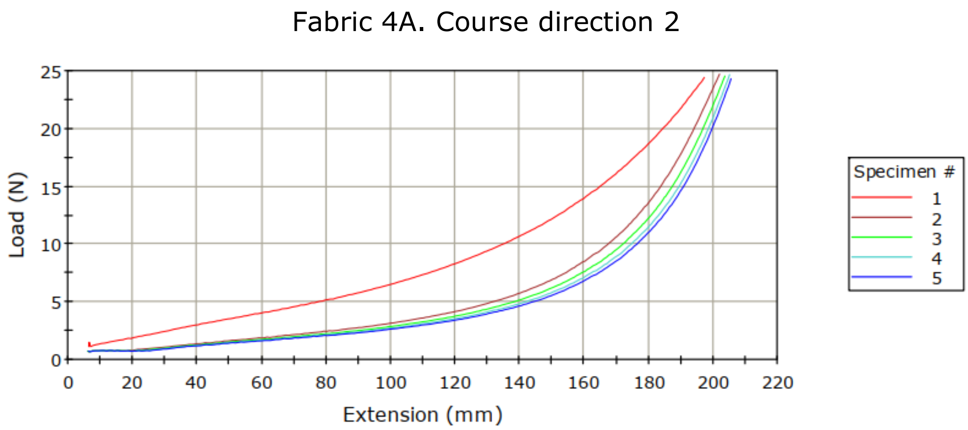


Figure A11.7. Fabric 4A. Grey knitted Rec PA specimen 2, course direction

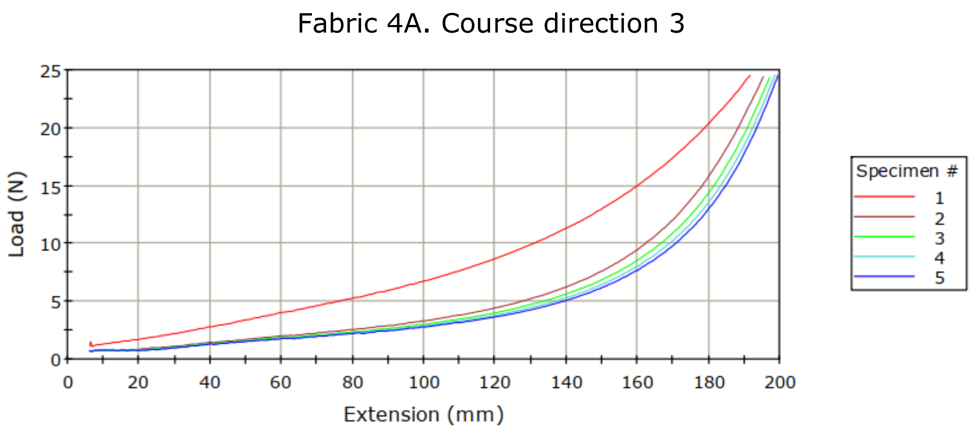


Figure A11.8. Fabric 4A. Grey knitted Rec PA specimen 3, course direction

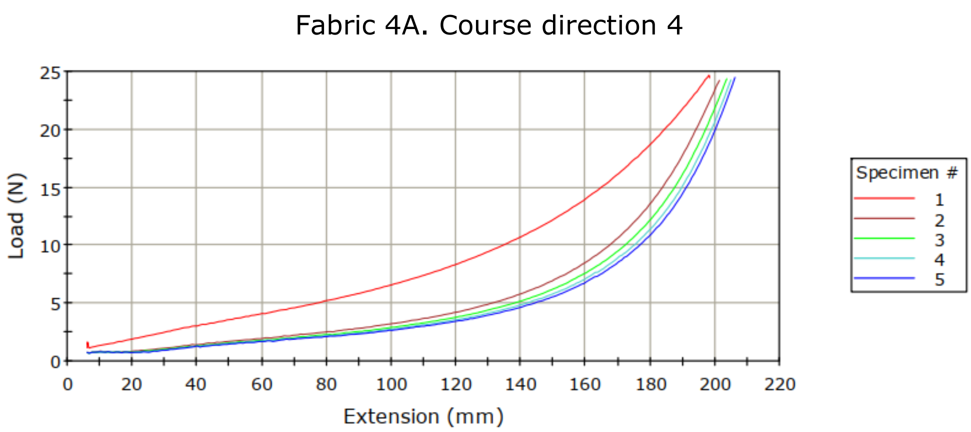


Figure A11.9. Fabric 4A. Grey knitted Rec PA specimen 4, course direction

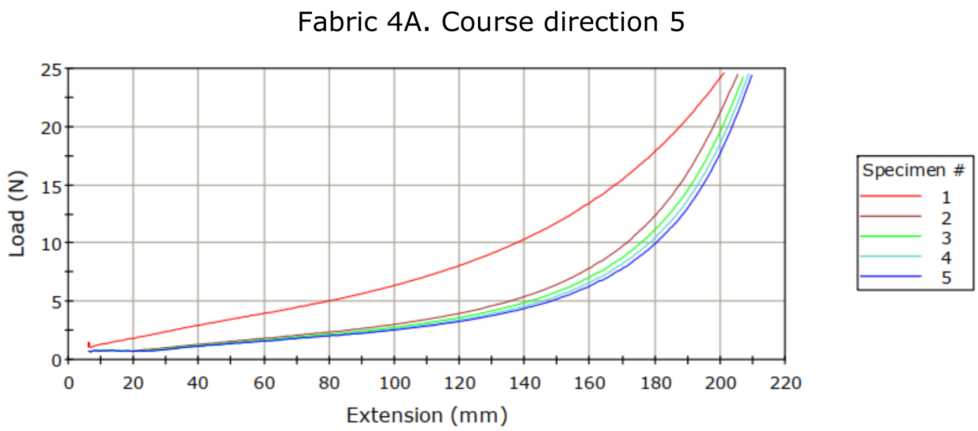


Figure A11.10. Fabric 4A. Grey knitted Rec PA specimen 5, course direction

Appendix 12. Elasticity test graphs: Fabric 5A. Green mesh Rec PA

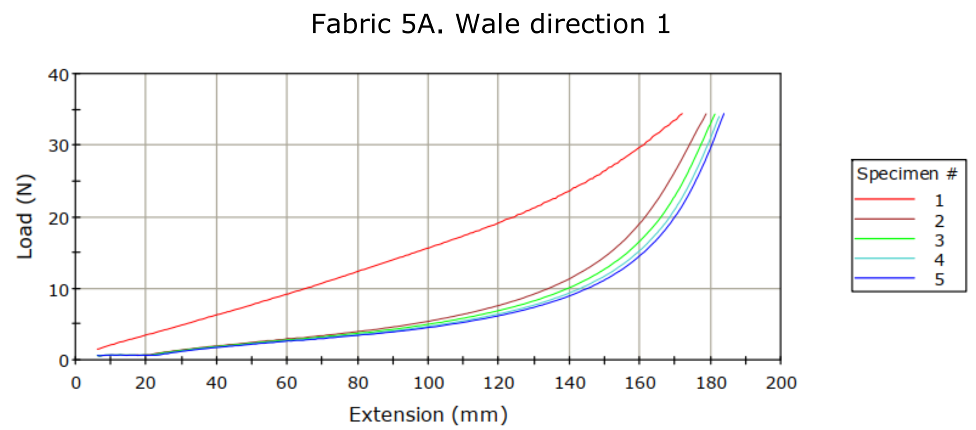


Figure A12.1. Fabric 5A. Green mesh Rec PA specimen 1, wale direction

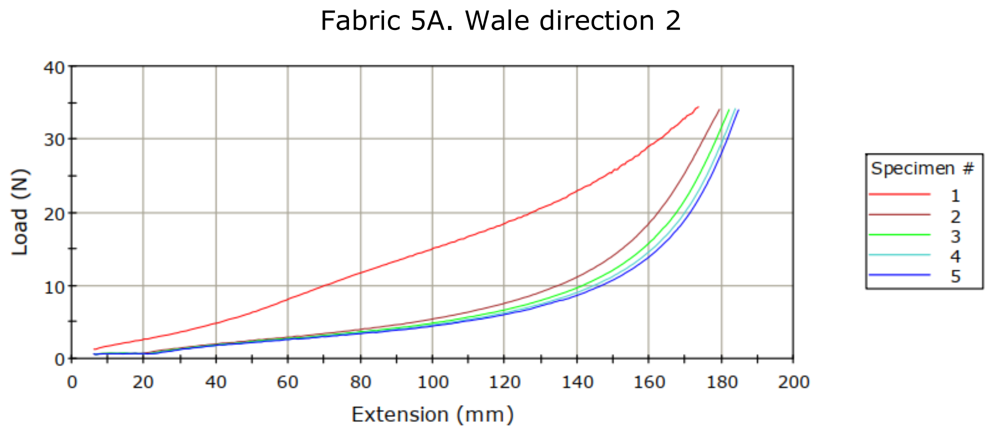


Figure A12.2. Fabric 5A. Green mesh Rec PA specimen 2, wale direction

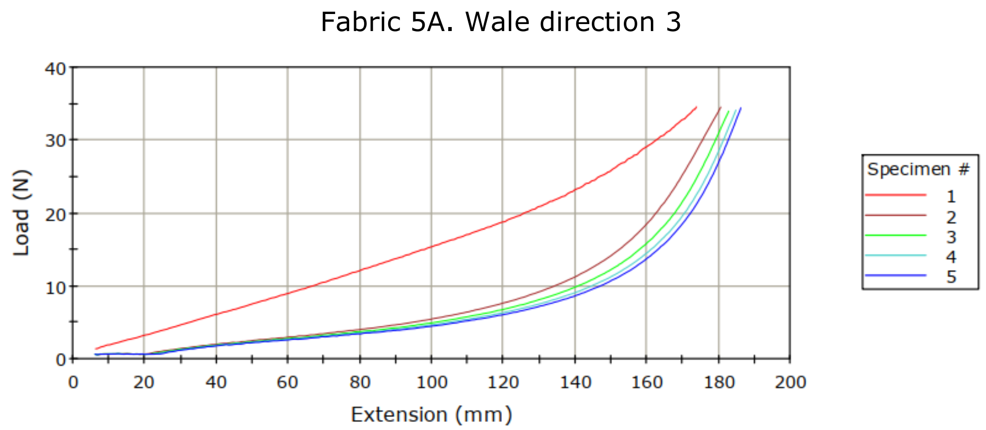


Figure A12.3. Fabric 5A. Green mesh Rec PA specimen 3, wale direction

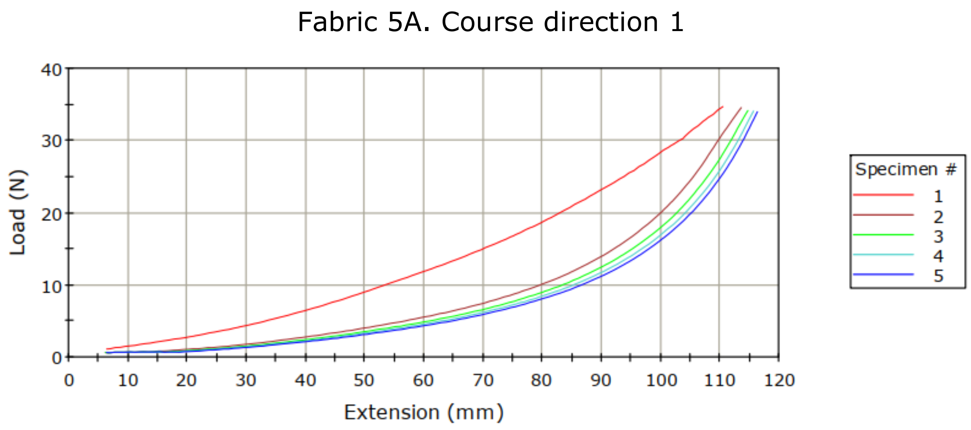


Figure A12.4. Fabric 5A. Green mesh Rec PA specimen 1, course direction

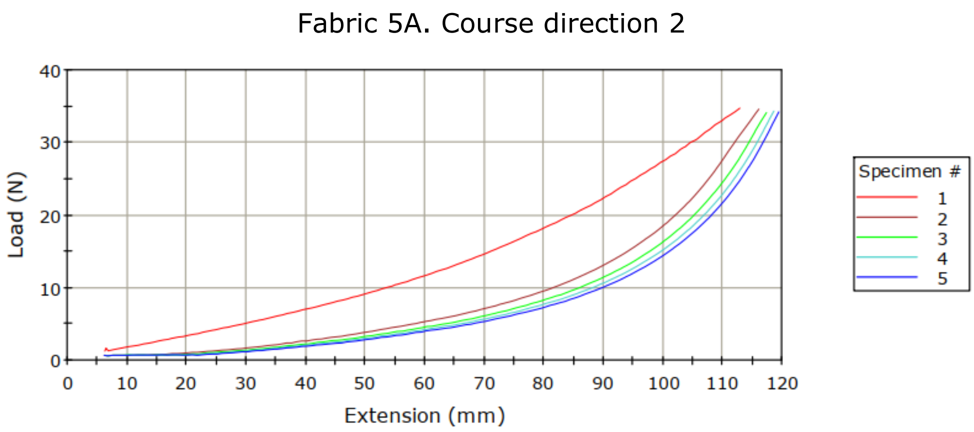


Figure A12.5. Fabric 5A. Green mesh Rec PA specimen 2, course direction

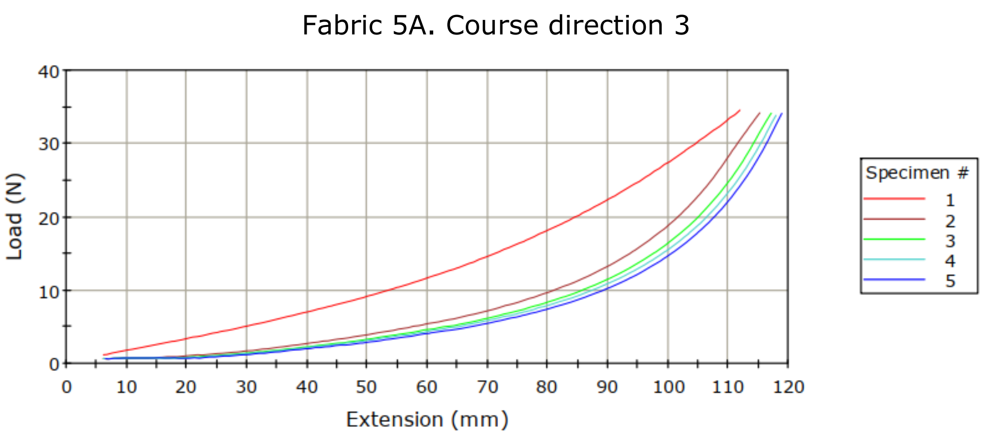


Figure A12.6. Fabric 5A. Green mesh Rec PA specimen 3, course direction

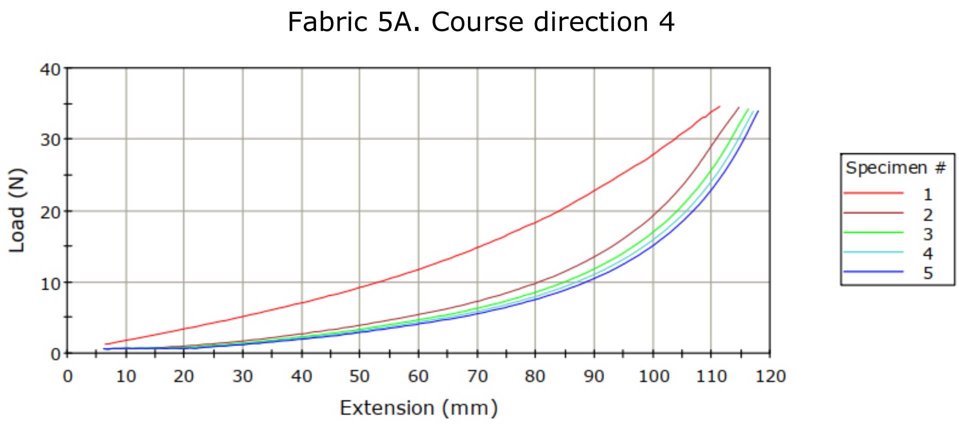


Figure A12.7. Fabric 5A. Green mesh Rec PA specimen 4, course direction

Appendix 13. Elasticity test graphs: Fabric 6A. White knitted Rec CO

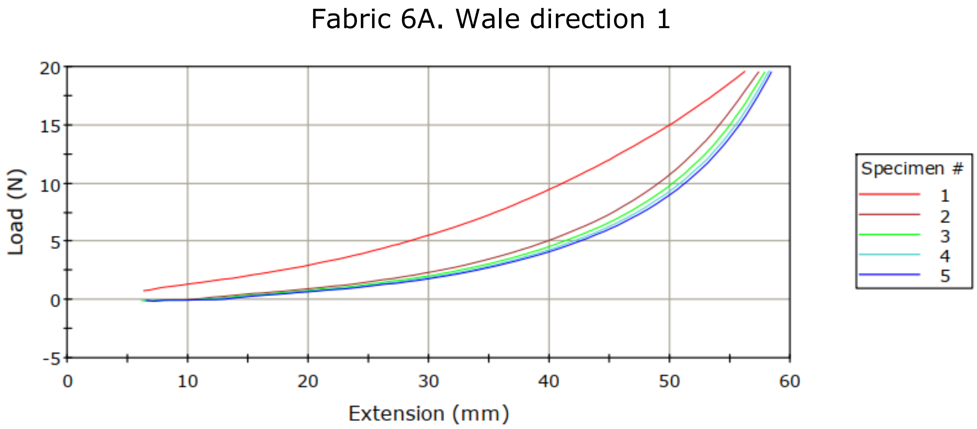


Figure A13.1. Fabric 6A. White knitted Rec CO specimen 1, wale direction

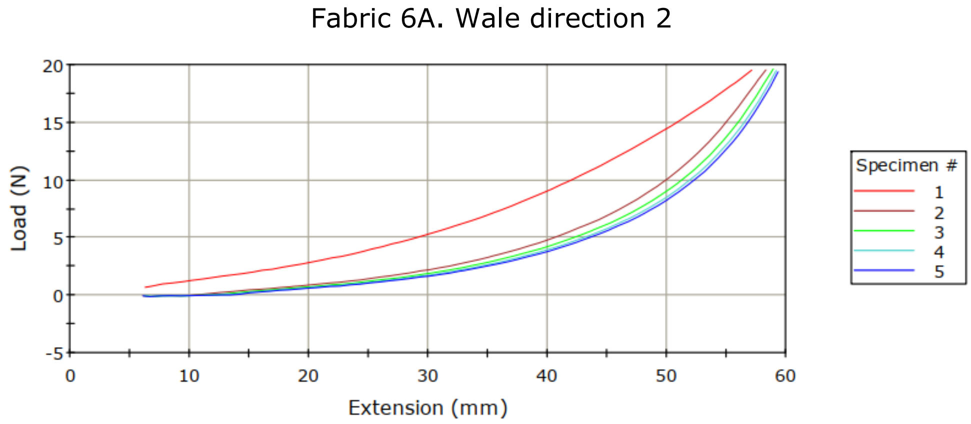


Figure A13.2. Fabric 6A. White knitted Rec CO specimen 2, wale direction

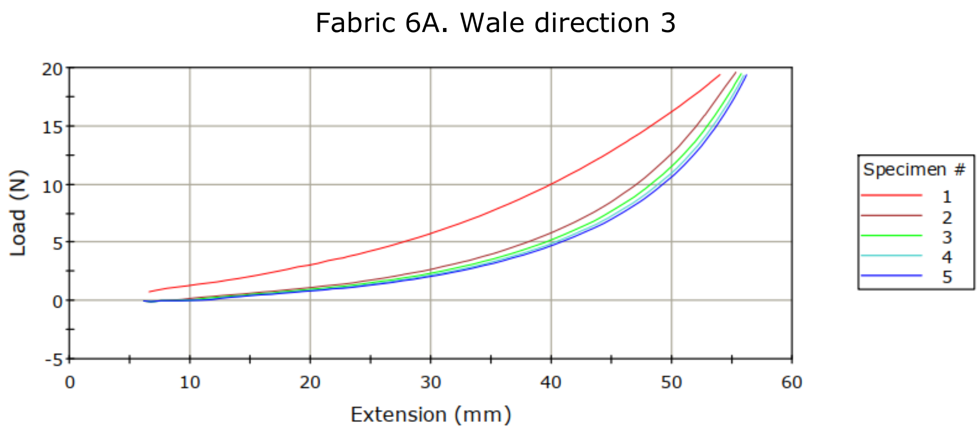


Figure A13.3. Fabric 6A. White knitted Rec CO specimen 3, wale direction

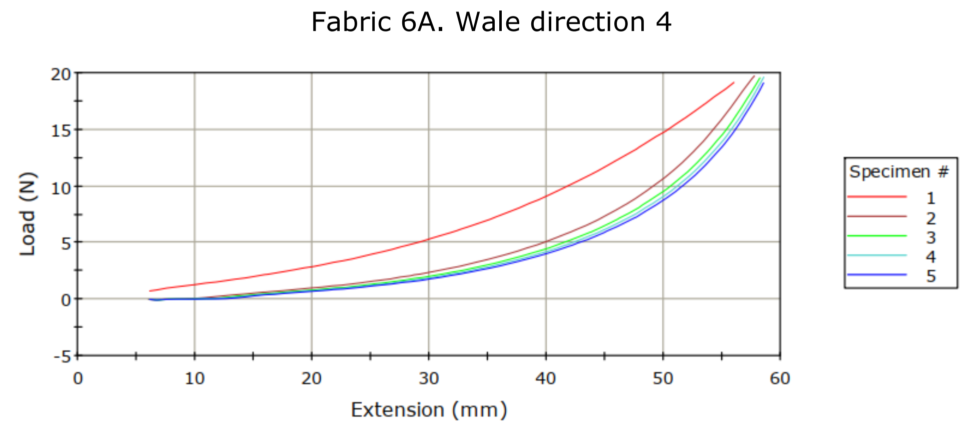


Figure A13.4. Fabric 6A. White knitted Rec CO specimen 4, wale direction

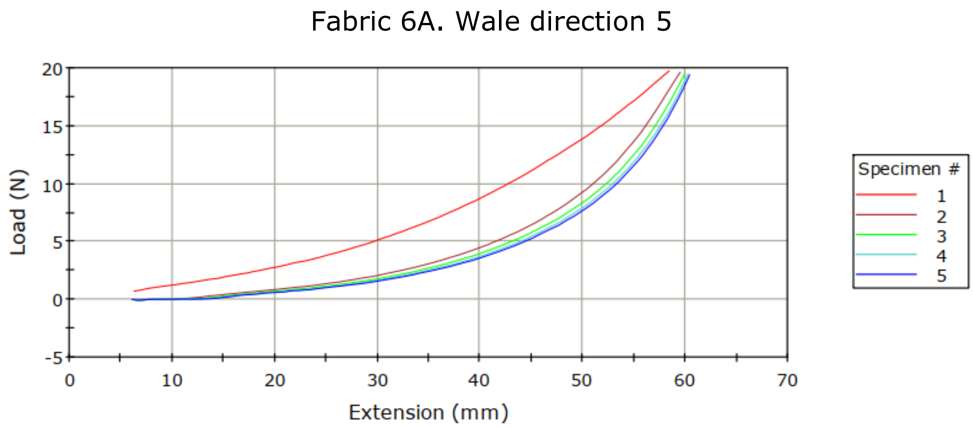


Figure A13.5. Fabric 6A. White knitted Rec CO specimen 5, wale direction

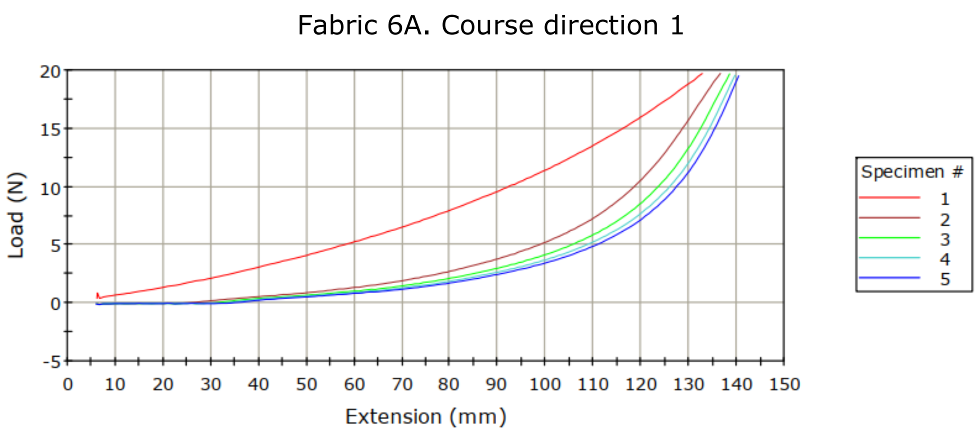


Figure A13.6. Fabric 6A. White knitted Rec CO specimen 1, course direction

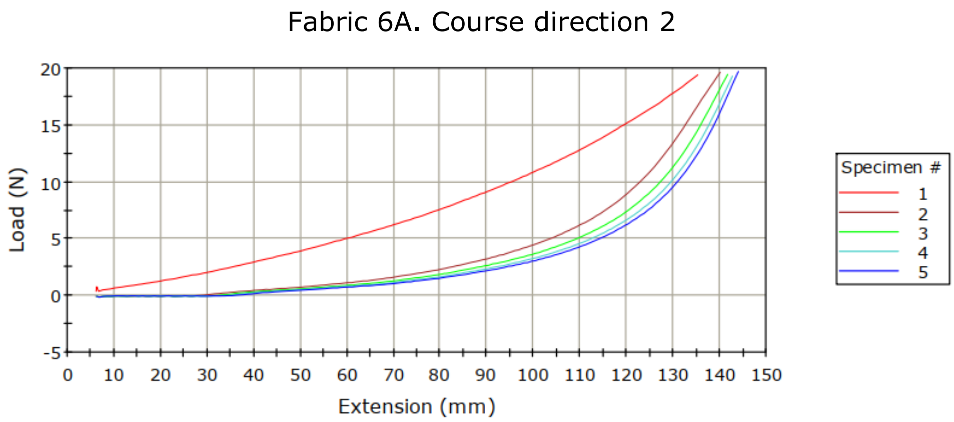


Figure A13.7. Fabric 6A. White knitted Rec CO specimen 2, course direction

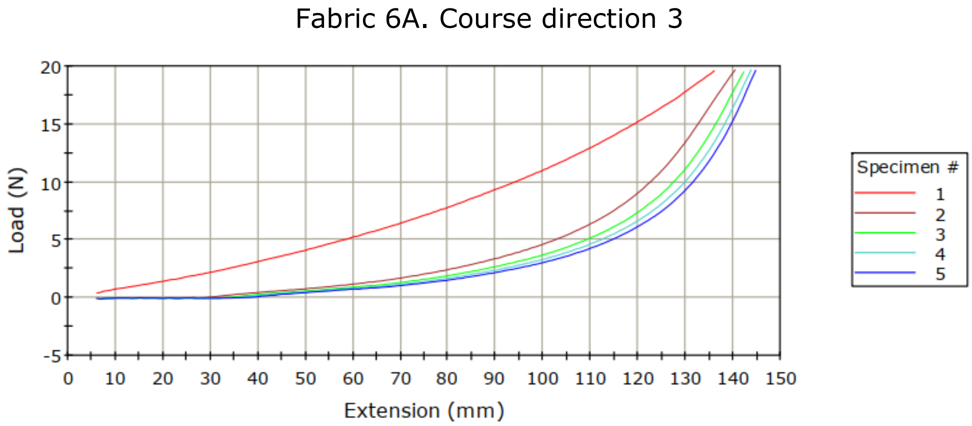


Figure A13.8. Fabric 6A. White knitted Rec CO specimen 3, course direction

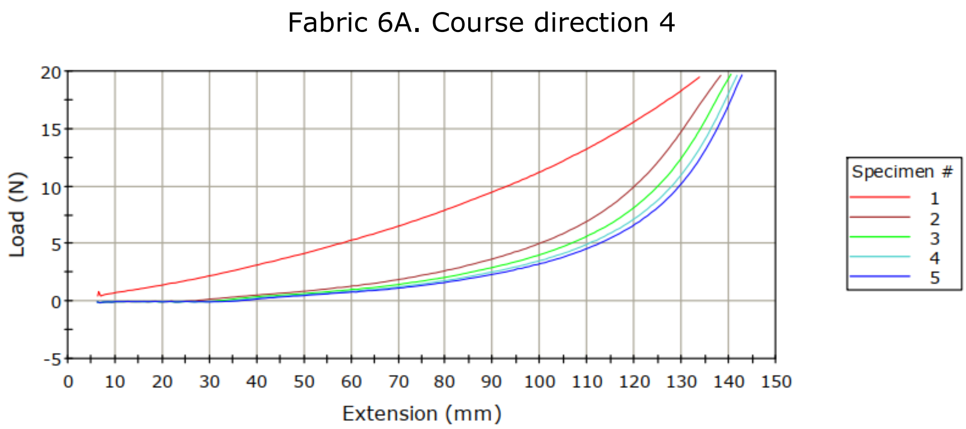


Figure A13.9. Fabric 6A. White knitted Rec CO specimen 4, course direction

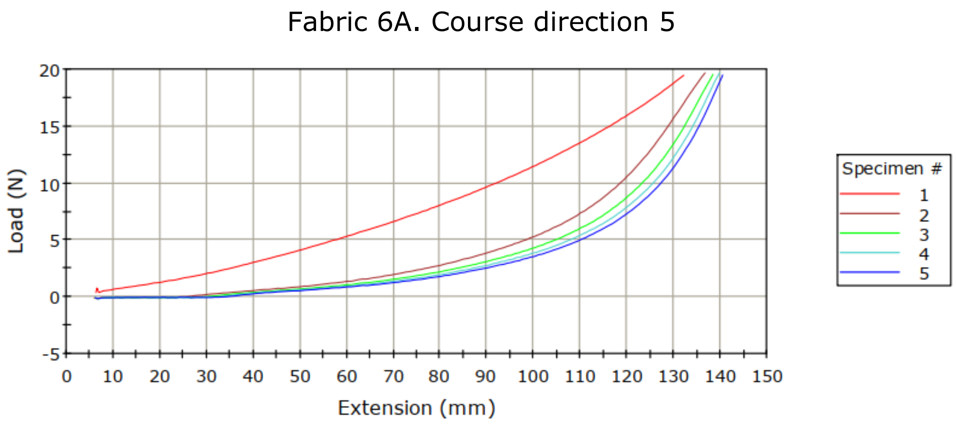


Figure A13.10. Fabric 6A. White knitted Rec CO specimen 5, course direction

Appendix 14. Elasticity test graphs: Fabric 7A. Blue printed Refibra™

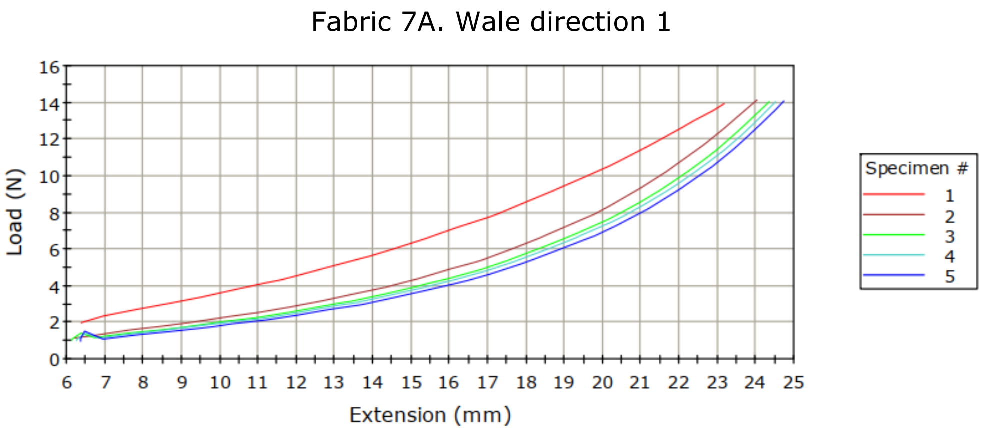


Figure A14.1. Fabric 7A. Blue printed Refibra™ specimen 1, wale direction

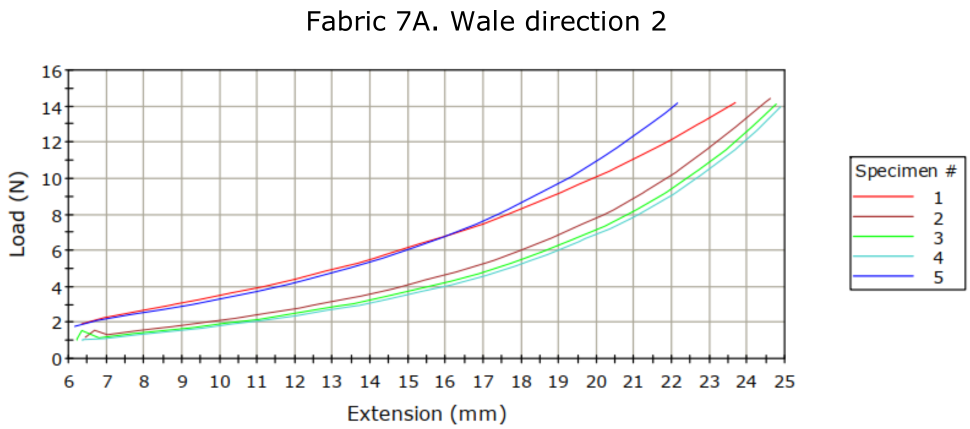


Figure A14.2. Fabric 7A. Blue printed Refibra™ specimen 2, wale direction

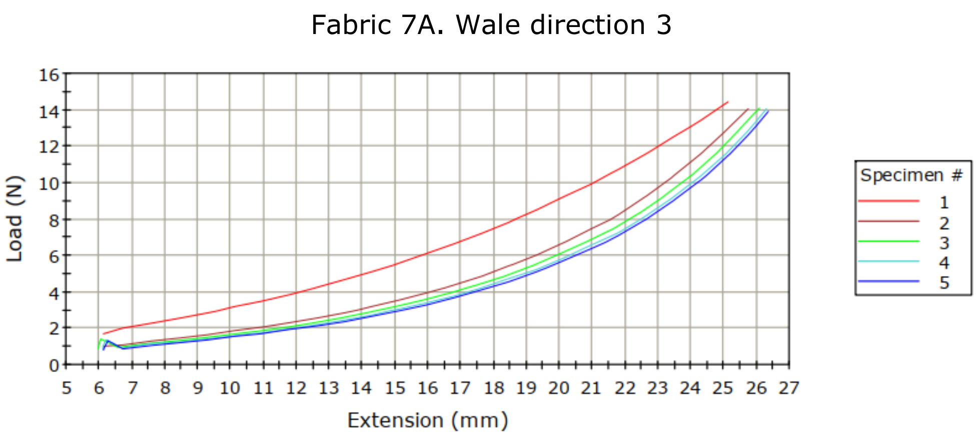


Figure A14.3. Fabric 7A. Blue printed Refibra™ specimen 3, wale direction

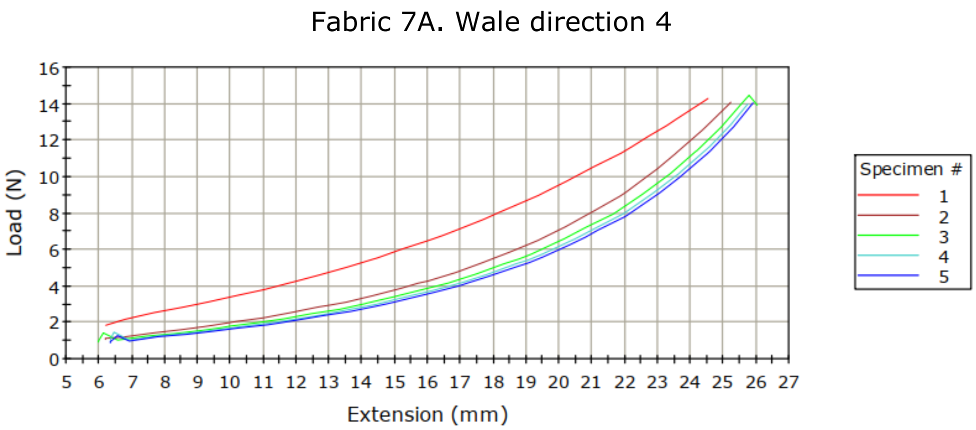


Figure A14.4. Fabric 7A. Blue printed Refibra™ specimen 4, wale direction

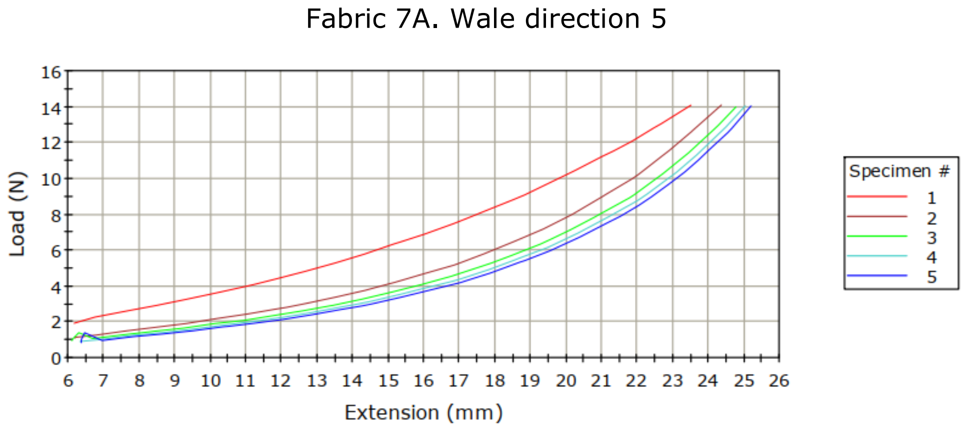


Figure A14.5. Fabric 7A. Blue printed Refibra™ specimen 5, wale direction

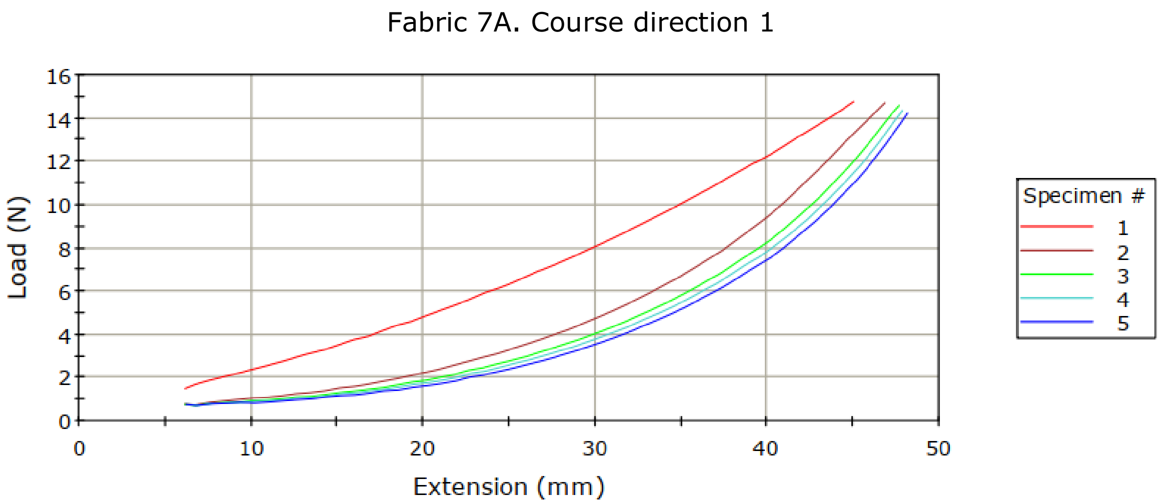


Figure A14.6. Fabric 7A. Blue printed Refibra™ specimen 1, course direction

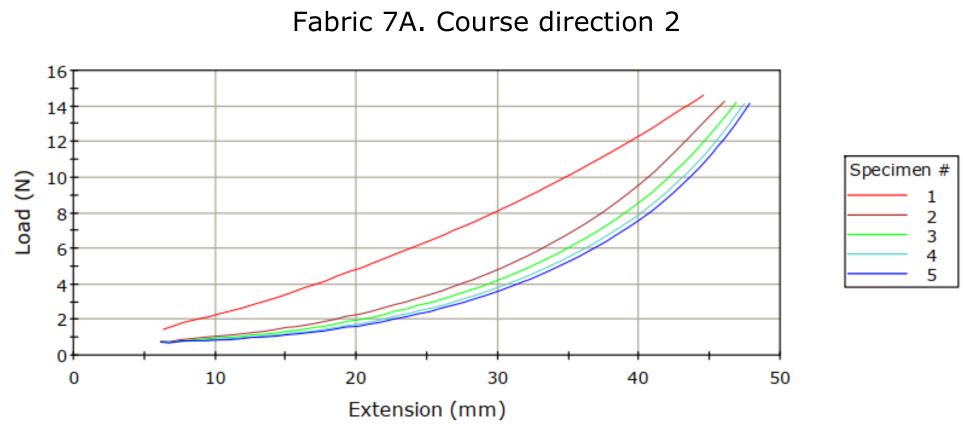


Figure A14.7. Fabric 7A. Blue printed Refibra™ specimen 2, course direction

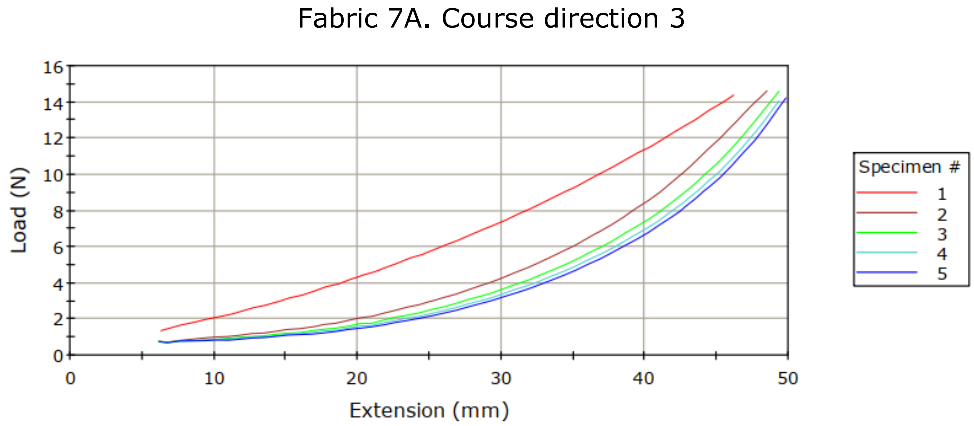


Figure A14.8. Fabric 7A. Blue printed Refibra™ specimen 3, course direction

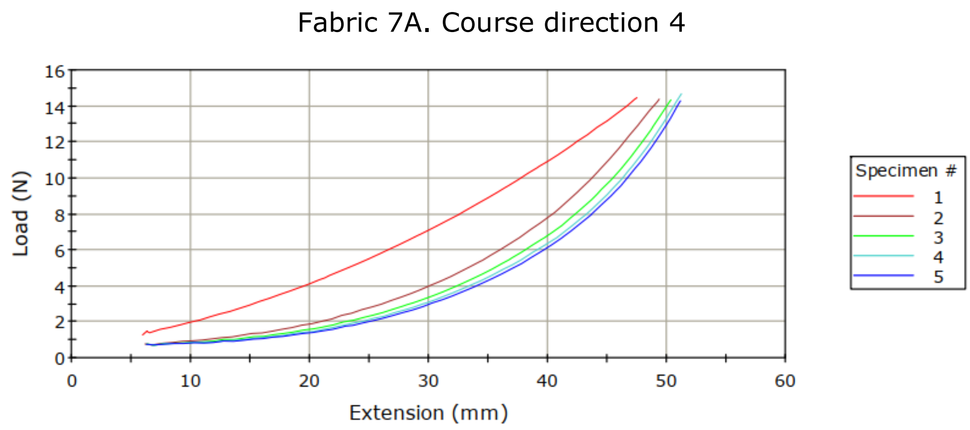


Figure A14.9. Fabric 7A. Blue printed Refibra™ specimen 4, course direction

Fabric 7A. Course direction 5

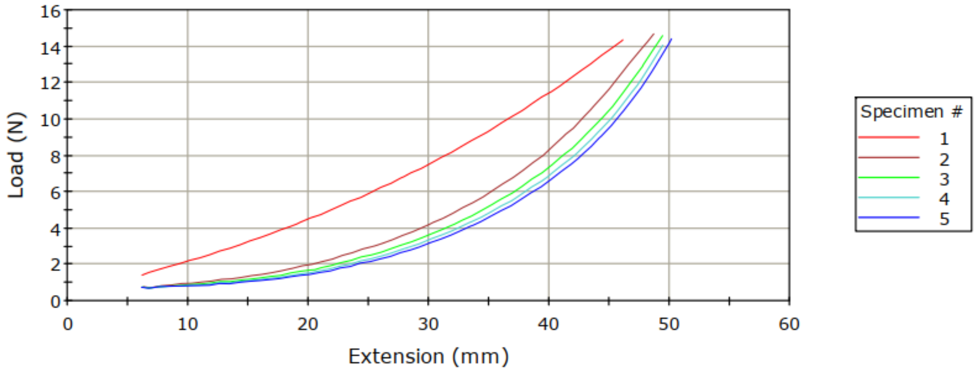


Figure A14.10. Fabric 7A. Blue printed Refibra™ specimen 5, course direction

Appendix 15. Elasticity test graphs: Fabric 8A. Blue knitted Refibra™

Fabric 8A. Wale direction 1

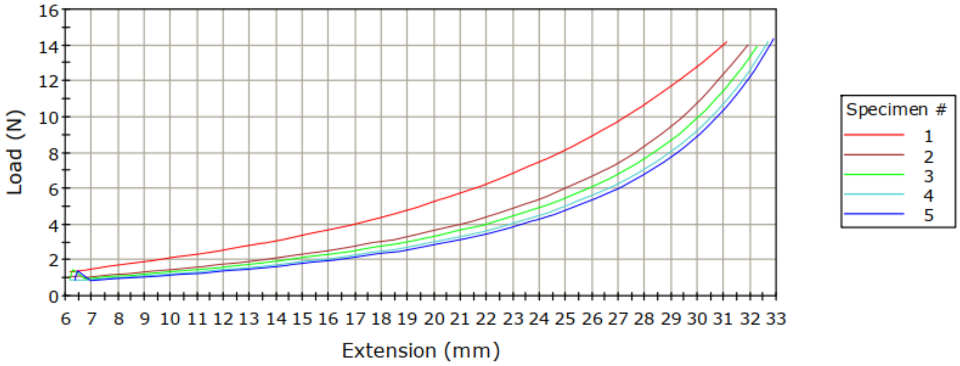


Figure A15.1. Fabric 8A. Blue knitted Refibra™ specimen 1, wale direction

Fabric 8A. Wale direction 2

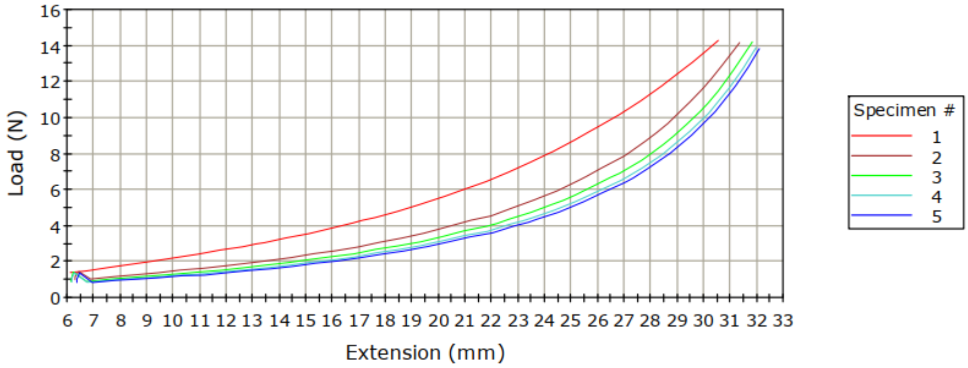


Figure A15.2. Fabric 8A. Blue knitted Refibra™ specimen 2, wale direction

Fabric 8A. Wale direction 3

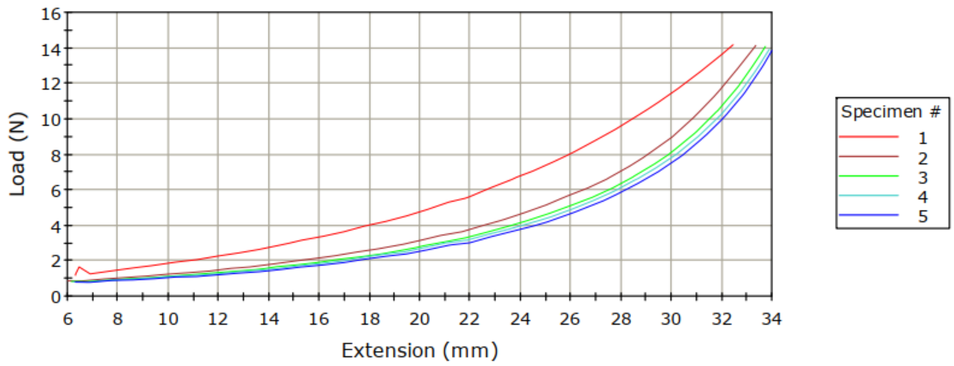


Figure A15.3. Fabric 8A. Blue knitted Refibra™ specimen 3, wale direction

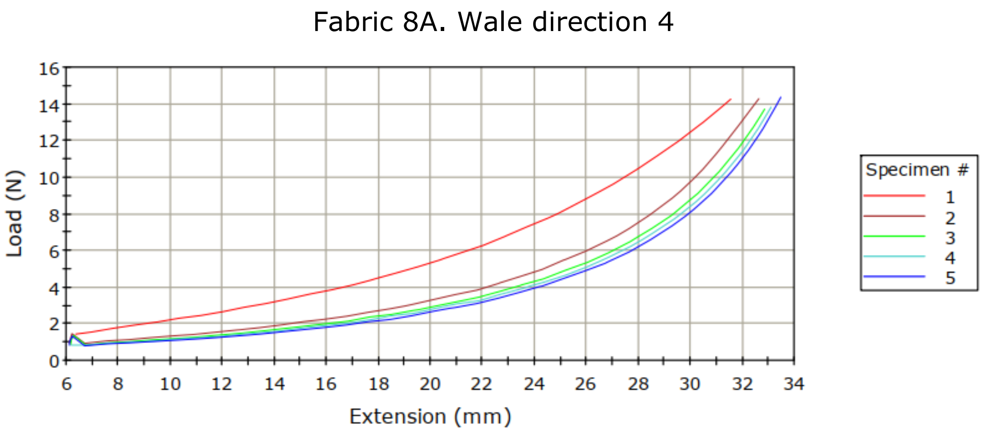


Figure A15.4. Fabric 8A. Blue knitted Refibra™ specimen 4, wale direction

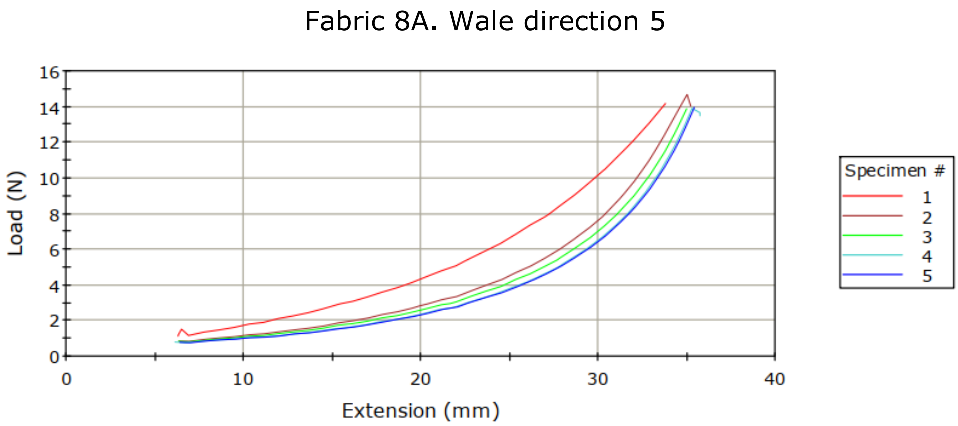


Figure A15.5. Fabric 8A. Blue knitted Refibra™ specimen 5, wale direction

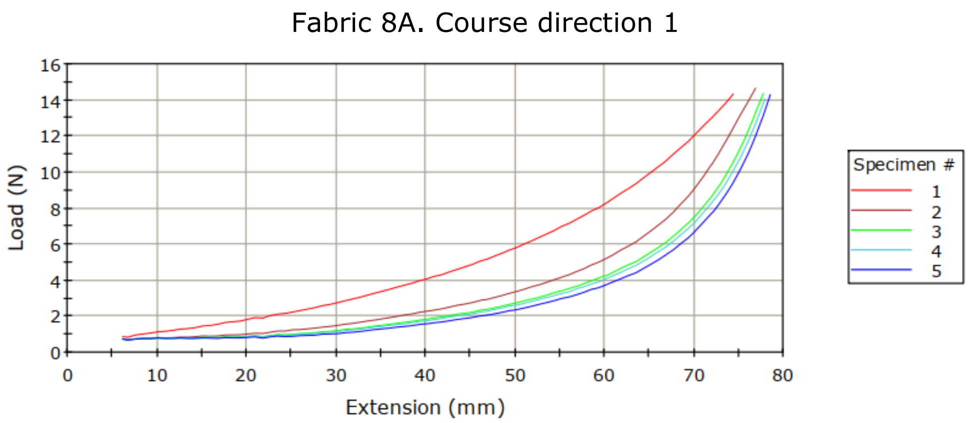


Figure A15.6. Fabric 8A. Blue knitted Refibra™ specimen 1, course direction

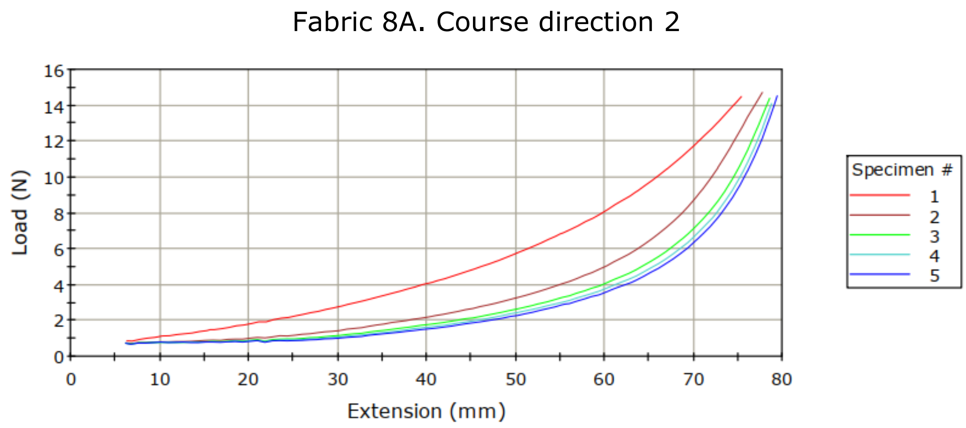


Figure A15.7. Fabric 8A. Blue knitted Refibra™ specimen 2, course direction

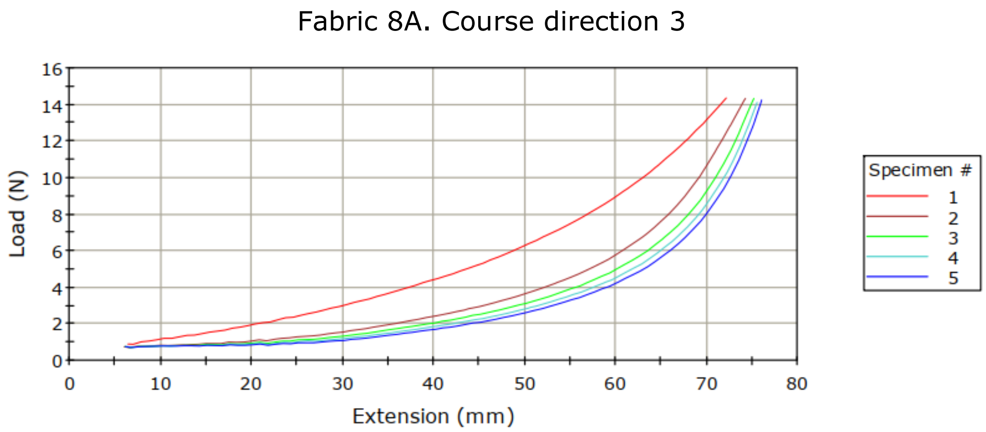


Figure A15.8. Fabric 8A. Blue knitted Refibra™ specimen 3, course direction

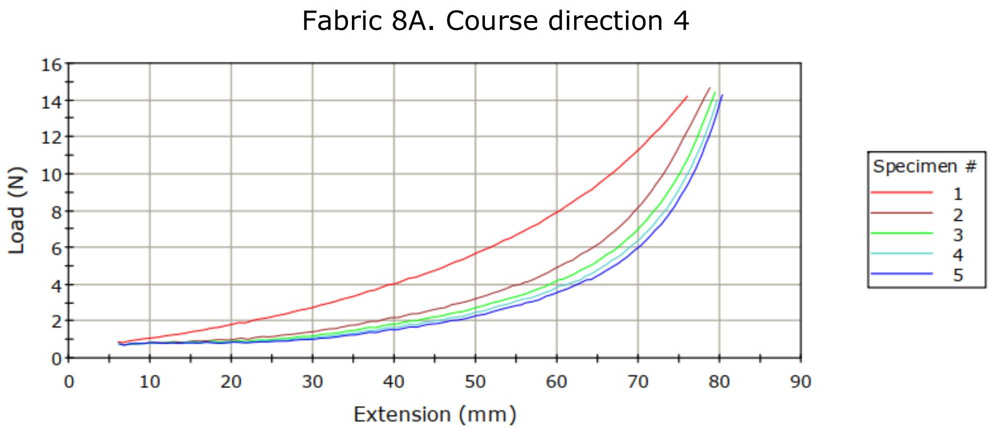


Figure A15.9. Fabric 8A. Blue knitted Refibra™ specimen 4, course direction

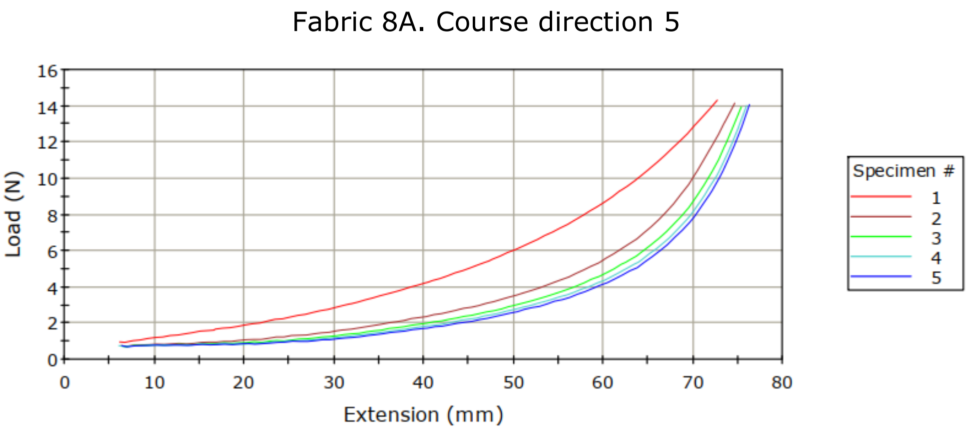


Figure A15.10. Fabric 8A. Blue knitted Refibra™ specimen 5, course direction

Appendix 16 Mood board

Figure A16.1. Collection mood board

Appendix 17 Pattern pieces

Table A17.1. List of patterns for triangle bra

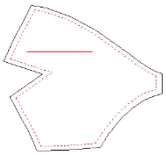
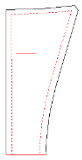
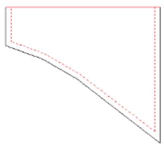
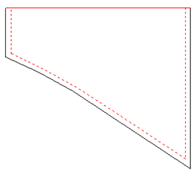
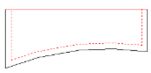
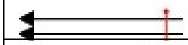
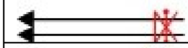
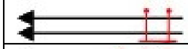
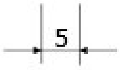
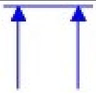
No.	Piece image	Piece name	Single pieces	Mirrored pairs	Material
1.		Cup	4	-	Blue knitted Refibra™
2.		Back	-	1	Blue knitted Refibra™
3.		Shoulder strap	2	-	Blue knitted Refibra™

Table A17.2. List of patterns for tanga panty

No.	Piece image	Piece name	Single pieces	Mirrored pairs	Material
1.		Front	-	1	Blue knitted Refibra™
2.		Back	-	1	Blue knitted Refibra™
3.		Crotch	-	2	Blue knitted Refibra™

Appendix 18 Sectional drawings

Table A18.1. Explanation of symbols used in sectional drawings

Sectional drawing	Description
	Main fabric
	Elastic band
	Accessory, ring
	Right side
	Single needle lockstitch
	4-thread overlock
	2-needle cover stitch
	3-needle cover stitch
	3-step zig-zag
	Zig-zag
	Measurement
	Section location

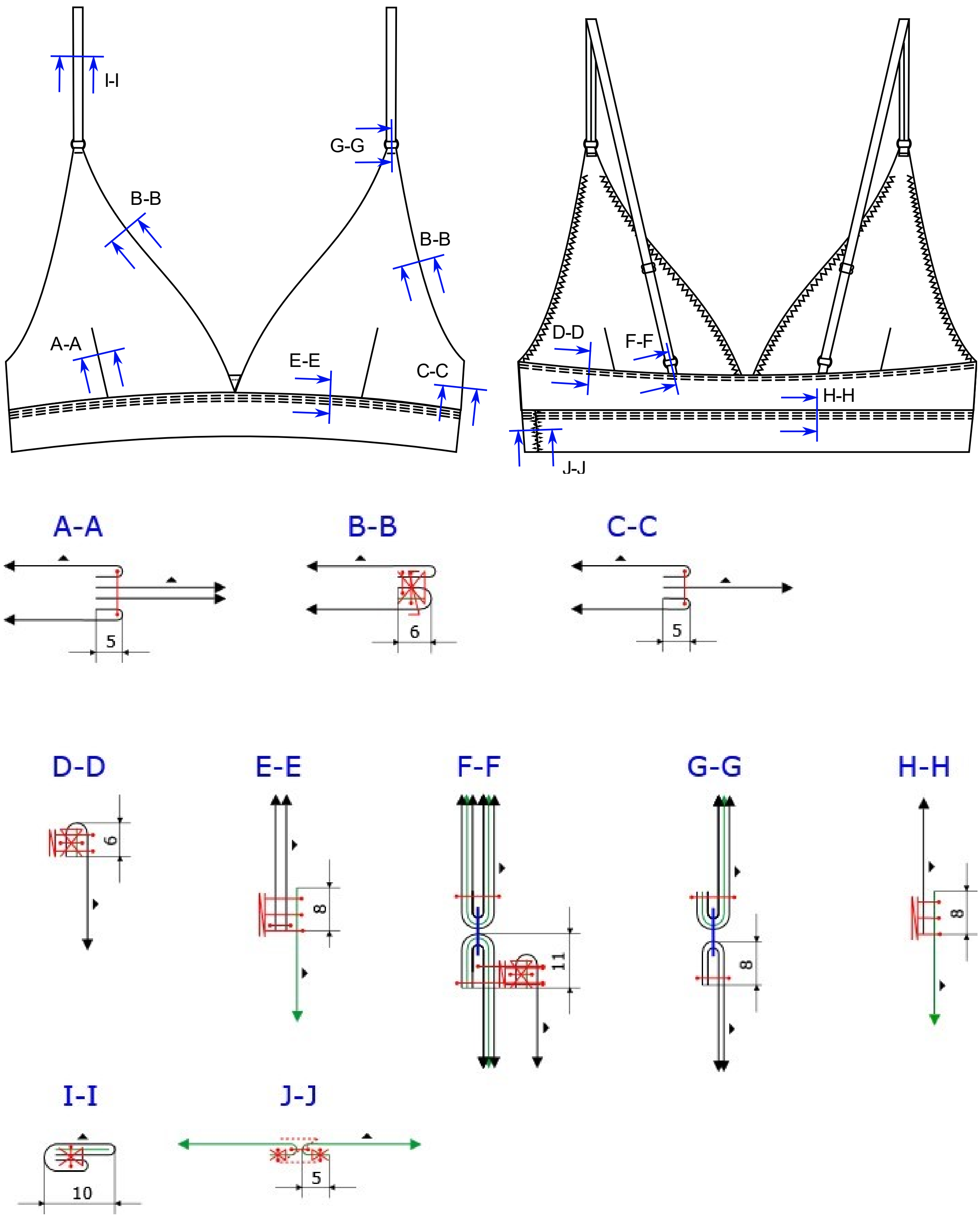


Figure A18.2. Sectional drawings of the triangle bra

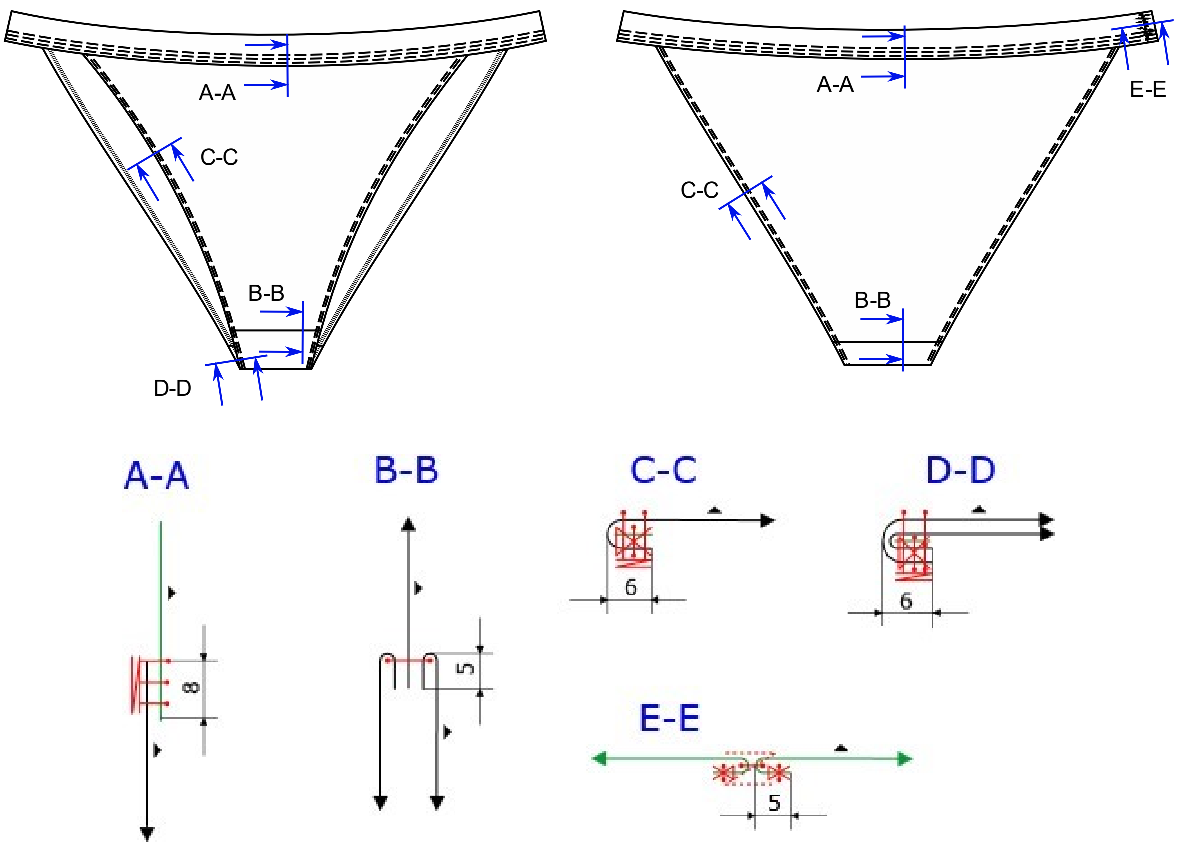


Figure A18.3. Sectional drawings of the panty

Appendix 19 Layout marker

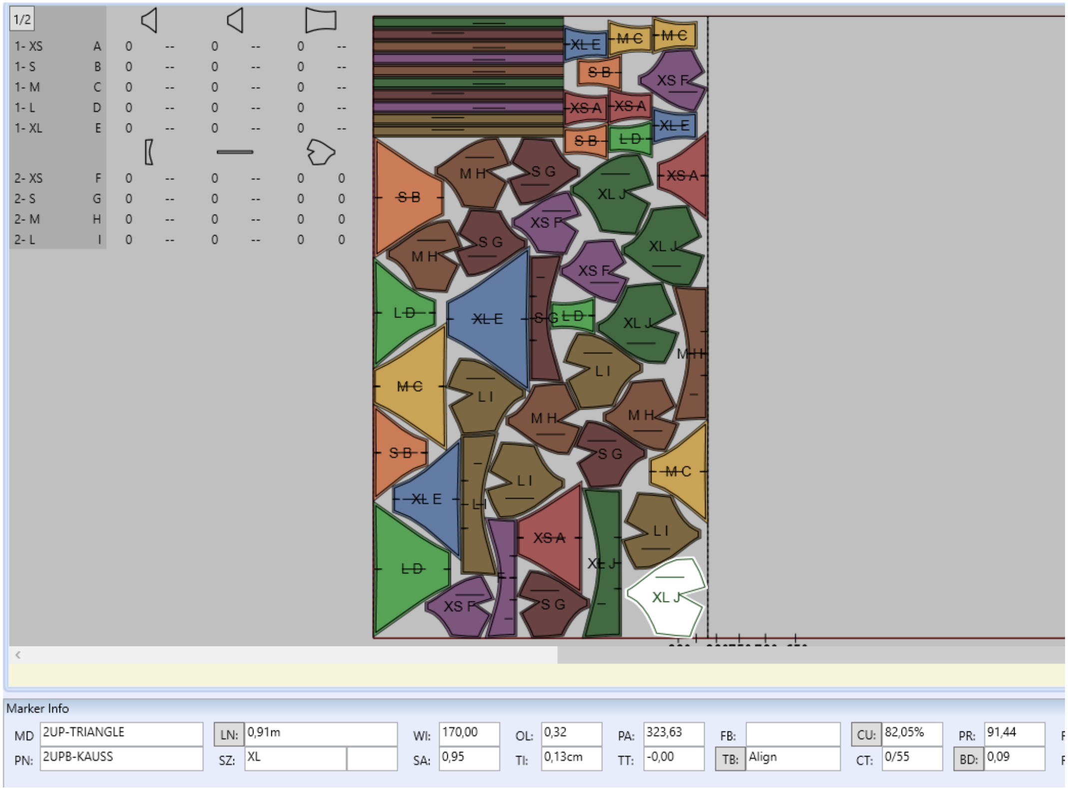


Figure A19.1. Layout marker for bras and panties, size range XS-XL

Appendix 20 Production technology

Table A20.1. Processing technology and processing times of the triangle bra

No.	Description of the operation	Machine type	Technical conditions	Processing time, min
1.	Printing the labels	Textile printer	Ink: 6%	-
2.	Fixing the print	Heat press	Temp: 180°C Time: 35 sec	-
3.	Cutting the patterns	By hand		-
4.	Cutting the elastic band to size	By hand	Measurement: 61 cm	0,2
5.	Overlocking the ends of the elastic band	4-thread overlock machine	Seam allowance: 5 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	0,3
6.	Sewing the elastic band	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,2
7.	Top stitching the elastic band seam	Zig-zag machine	Stitch type: 321 Stitch length: 4 mm Stitch width: 7 mm Needle: RG 70 Thread: polyester #120	0,2
8.	Sewing the shoulder straps	4-thread overlock machine	Seam allowance: 5 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	1,95
9.	Turning the shoulder straps around	By hand		2,2
10.	Cutting the shoulder straps to size	By hand	Measurement: 2x45 cm; 2x6 cm (back parts)	0,2
11.	Sewing the shoulder straps with slides	Single needle lockstitch machine	Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	1,65
12.	Sewing the shoulder strap back parts on the back	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,9

No.	Description of the operation	Machine type	Technical conditions	Processing time, min
13.	Tacking the front edge of the bra cups	Single needle lockstitch machine	Seam allowance: 3 mm Stitch type: 301 Stitch density: 4 stitches/cm Needle: SUK 70 Thread: polyester #120	1,1
14.	Sewing elastic band on the front edge of the bra cups	4-thread overlock machine	Seam allowance: 6 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	1,8
15.	Top stitching the front edge of the bra cups	Zig-zag machine	Seam allowance: 1 mm from the edge Stitch type: 304 Stitch length: 2,7 mm Stitch width: 2 mm Needle: RG 70 Thread: polyester #120	1,8
16.	Sewing cup darts	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	1,5
17.	Tacking the side edge of the bra cups	Single needle lockstitch machine	Seam allowance: 3 mm Stitch type: 301 Stitch density: 4 stitches/cm Needle: SUK 70 Thread: polyester #120	1,2
18.	Sewing elastic band on the side edge of the bra cups	4-thread overlock machine	Seam allowance: 6 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	1,6
19.	Top stitching the front edge of the bra cups	Zig-zag machine	Seam allowance: 1 mm from the edge Stitch type: 304 Stitch density: 5 stitches/cm Stitch height: 2,7 mm Needle: RG 70 Thread: polyester #120	1,9
20.	Sewing elastic band on the back upper edge	4-thread overlock machine	Seam allowance: 6 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	0,95
21.	Top stitching the back upper edge	2-needle cover stitch machine	Seam allowance: 2 mm from the edge Stitch type: 406 Stitch density: 4 stitches/cm Needle: FFG 70 Thread: polyester #120	1,16

No.	Description of the operation	Machine type	Technical conditions	Processing time, min
22.	Sewing the side seams	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,65
23.	Tacking the bra cups lower edge	Single needle lockstitch machine	Seam allowance: 3 mm Stitch type: 301 Stitch density: 4 stitches/cm Needle: SUK 70 Thread: polyester #120	1,3
24.	Sewing under the bust elastic to the bodice	3-needle cover stitch machine	Seam allowance: 6 mm Stitch type: 407 Stitch density: 4 stitches/cm Needle: FFG 70 Thread: polyester #120	1,2
25.	Sewing fastening stitch on the elastic band	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,22
26.	Sewing rings on the cups	Single needle lockstitch machine	Seam allowance: 2 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	1,1
27.	Sewing rings on the back	Single needle lockstitch machine	Seam allowance: 2 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	1,1
28.	Breaking the tacking thread	By hand		
29.	Cleaning the product from the thread and elastic bands ends	By hand		
			Total processing time:	**26,38**

Table A20.2. Processing technology and processing time of the tanga panty

No.	**Description of the operation**	**Machine type**	**Technical conditions**	**Processing Time, min**
1.	Printing the labels	Textile printer	Ink: 6%	-
2.	Fixing the print	Heat press	Temp: 180°C Time: 35 sec	-
3.	Cutting the patterns	By hand		-
4.	Cutting the elastic band to size	By hand	Measurement: 69 cm	0,2
5.	Overlocking the ends of the elastic band	4-thread overlock machine	Seam allowance: 5 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	0,2
6.	Sewing the elastic band	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,3
7.	Top stitching the elastic band seam	Zig-zag machine	Stitch type: 321 Stitch length: 4 mm Stitch width: 7 mm mm Needle: RG 70 Thread: polyester #120	0,2
8.	Sewing crotch pieces on the front part	4-thread overlock machine	Seam allowance: 5 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	0,65
9.	Sewing crotch pieces on the back part	4-thread overlock machine	Seam allowance: 5 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	0,43
10.	Tacking the crotch sides together	Single needle lockstitch machine	Seam allowance: 3 mm Stitch type: 301 Stitch density: 4 stitches/cm Needle: SUK 70 Thread: polyester #120	0,7
11.	Sewing the elastic band on the leg openings	4-thread overlock machine	Seam allowance: 6 mm Stitch type: 514 Stitch density: 5 stitches/cm Needle: RG 70 Thread: polyester #120	1,3
12.	Top stitching the leg openings	2-needle cover stitch machine	Seam allowance: 2 mm from the edge Stitch type: 406 Stitch density: 4 stitches/cm Needle: FFG 70 Thread: polyester #120	2,32

No.	Description of the operation	Machine type	Technical conditions	Processing time, min
13.	Measuring and marking of the back and front centres of the elastic band	By hand		0,46
14.	Sewing elastic band to the panties	3-needle cover stitch machine	Seam allowance: 6 mm Stitch type: 407 Stitch density: 4 stitches/cm Needle: FFG 70 Thread: polyester #120	1,2
14.	Sewing fastening stitch on the elastic band	Single needle lockstitch machine	Seam allowance: 5 mm Stitch type: 301 Stitch density: 5 stitches/cm Needle: SUK 70 Thread: polyester #120	0,22
15.	Breaking the tacking thread	By hand		
16.	Cleaning the product from the thread and elastic bands ends	By hand		
Total processing time:				**8,18**

Appendix 21 Lingerie set 2°UP

Figure A21.1. Lingerie set 2°UP