TAMPERE UNIVERSITY OF TECHNOLOGY

SAMI RANTASALO

PROPAGATION OF FLEXURAL PROPERTIES FROM FIBRE TO FABRIC

Master's thesis

Examiners: Professor Jyrki Vuorinen
Professor Ali Harlin
University Lecturer Marja Rissanen
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ABSTRACT

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Good handle, drape and flexibility are valued when assessing textiles. These properties are manifestations of fabric behaviour under low stress. Yarn and fabric properties are influenced by the constitutive fibre properties. Knowing these interrelations would allow making fibres with properties known to produce wanted results in yarns or fabrics. The main object of this thesis is to examine the interrelations of fibres' and fabrics' flexibility influencing properties.

A selection of cellulose-based fibres and fabrics were chosen for characterization. A novel fibre characterization platform was used to measure individual fibre flexibility. Fabrics were characterized using Kawabata Evaluation System, implementations of Cusick's drape test and Shirley stiffness tester. A fabric extraction method using a funnel nozzle (modified ring method) was built and used to evaluate fabric handle. Secondary objective was to also evaluate these assessment methods and their suitability for fabric evaluation.

The results showed the positive relation of fibre modulus and flexibility. Fibre properties also influence the fabric properties, although the influence is only to an extent. The mechanics of a fabric under stress depends on the fabric type and structure. These mechanics can be heavily influenced with macro level structural changes like texturing in non-woven fabrics.

Fibre characterization platform fulfilled expectations but needs more development. The extraction method results, stress-deviation-curves, were not used fully in this thesis and require more research. The maximum extraction force values calculated from the curves duly did not correlate well with the other measurements.

Rest of the fabric characterization methods gave comparable results and showed good interrelations (between 58-90 %). KES and the stiffness tester are designed for specific fabrics, but were capable to measure other fabric types as well. Biggest issues with KES are the high price and result reproducibility. Corresponding properties can be measured with less expensive, separate appliances.

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Tekstiilien käsituntuma, laskeutuvuus ja taipuisuus ovat tärkeitä laatuominaisuuksia, jotka ovat myös ilmentymiä kankaan käyttäytymisestä matalien voimien alaisena. Kuitujen ominaisuudet vaikuttavat kuiduista muodostuvien lankojen ja kankaiden ominaisuuksiin. Tuntemalla näiden yhteydet voitaisiin kuidut valmistaa tietyillä ominaisuuksilla halutunlaisen langan tai kankaan saamiseksi. Tämän diplomityön päätavoitteena oli tutkia kuitujen ja kankaiden taipuisuuteen vaikuttavien ominaisuuksien välisiä yhteyksiä.

Työhön valittiin karakterisoitavaksi selluloosapohjaisia kuituja ja kankaita. Kuitujen taipuisuutta mitattiin kehitetyllä kuitujen karakterisointijärjestelmällä. Kankaiden karakterisointiin käytettiin Kawabata Evaluation System -laitteistoa (KES) sekä sovelluksia Cusick:n laskeutuvuus- ja Shirley jäykkyyssmittalaitteista. Kankaiden käsituntuman arvioimiseen rakennettiin ja hyödynnettiin suuttimen lävitse tapahtuvaa kankaan vetokoetta (modified ring method). Toissijainen tavoite työssä oli arvioida käytettyjä menetelmiä ja niiden soveltuvuutta kankaiden arvioimisessa.

Tulokset vahvistavat kuitujen alkumodulin ja taipuisuuden välisen yhteyden. Myös kuitujen ominaisuuksien vaikutus kankaiden ominaisuuksiin todennettiin. Vaikutus on kuitenkin rajallista ja riippuvaista kankaan tyypistä ja rakenteesta. Tähän vaikutusmekaniikkaan voidaan vaikuttaa makrotasolla esimerkiksi teksturoinnilla, kuten nähtiin kuitukankaiden yhteydessä.

Kuitujen karakterisointijärjestelmä osoittautui hyväksi, mutta kehitystä vaativaksi mittausjärjestelmäksi. Kankaan vetokokeen todellisia tuloksia, saatuja voimapoikkeama-käyriä, ei tämän työn yhteydessä tulkittu tarkemmin, ja ne vaativat enemmän tutkimista. Käsituntumaa kuvaavat maksimivoimat eivät odotetusti korreloineet muiden tulosten kanssa.

Loput kankaiden karakterisointimenetelmistä tuottivat vertailukelpoisia tuloksia, korreloiden toisiinsa hyvin (58-90%). KES ja jäykkyysmittalaite ovat molemmat tietyille kangastyypeille suunniteltu, mutta soveltuivat myös muille kankaille. Suurimmat KES:n ongelmat ovat hintavuus ja tuloksien toistettavuus. Vastaavat ominaisuudet voidaan mitata halvemmilla erillisillä vaihtoehdoilla.

PREFACE

This master's thesis was written at the Department of Material Science at Tampere University of Technology (TUT). It was part of a national project called Design Driven Value Chains in the World of Cellulose (DWoC).

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I owe my deepest gratitude to my family for all the support along the way, especially to my parents - kiitos isä ja äiti! It took its time, but here we are!

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Sami Rantasalo
sami.rantasalo@iki.fi

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

2HB	Hysteresis in bending
η	Fibre shape factor in flexural rigidity
ε	Fibre shape factor in torsional rigidity
ρ	Density
B	Bending rigidity
CO	Cotton
CV	(Cellulose) Viscose
E	modulus
EL	Percentual fibre elongation at break
F	Load, force or stress
h_e	Elastic thickness
I	Moment of inertia
K	Yarn twist factor
L	Length
MIC	Micronaire value of a fibre
n	Specific shear modulus
N_e	Yarn count
PLA	Poly(lactic acid)
R	Specific flexural rigidity
SF	Short fibre content
STRb	Fibre bundle tenacity
T	Linear density of a fibre
UHM	Upper half mean length of a fibre - the average length of the longest one-half of the fibres
UI	Uniformity index of fibre length
v	Poisson's ratio

LIST OF TERMS AND ABBREVIATIONS

Drape	Deformation of a fabric due to its own weight when suspended
Drape coefficient	Ratio between the 2-dimensional projected areas of a draped and undraped (flat) specimen
Force Couple	In mechanics, a couple is a system of forces with a resultant moment but no resultant force

CMD	Vertical to production direction (See MD). Cross-machine, weft or course direction
CV	Coefficient of variance, a normalized measure of dispersion of a probability distribution or frequency distribution
MD	The direction the product is moving during the production. Machine, warp or wale direction
MFQI	Modified fibre quality index
SEM	Scanning electron microscope
TB	Technical back - the lower side of a fabric from the structural point of view
TF	Technical front - the upper side of a fabric from the structural point of view

1. INTRODUCTION

Environmental consciousness and ethical awareness, enforced by international policies, is prompting for more efficient material use and recycling, especially as the consumption is ever growing. Raw materials becoming more scarce and environmental issues are changing the international trade of textiles among others. The textile industry has taken initiatives for reduction of its environmental impact and for improvement of social conditions. Designers are looking into their design processes and explore innovative materials to minimize or replace the environmentally wearing alternatives. Consumers are demanding more sustainable choices in design, production and materials.

Finnish wood industry produces annually 30 million cubic metres of wood biomass. This wood raw material is currently used mainly by the pulp and paper, timber and energy industries. Recycling the biomass in textile processes would provide a competitively priced, environmentally sound, renewable, locally produced raw material. It would also have a financial inducement to the industries involved, bringing new uplift to the declining prices and demand. [20]

Design Driven Value Chains in the World of Cellulose (DWoC) [48] is a joint national project aiming at meeting the environmental and economic goals, providing new business and value chains based on Finnish wood cellulose derivatives. The current market dominating [44], environment burdening materials, such as cotton and polyester, and products could be replaced with environment friendly cellulose-based alternatives. The innovative products can range from technical and clothing textiles to piece goods.

In order to replace a product with a new one, at the very least the existing properties and characteristics have to be realized. Some of the properties can be evaluated easily by comparing measurement data. In the context of textile products, especially consumer products, achieving for example specific level of fabric handle or fabric drape, both manifestations of flexural properties, is significant. Due to the complexity of fabric structures and often subjective haptic evaluation methods, assessment is more complicated and available methods may not give results directly comparable with each other. This calls for available methods themselves to be reviewed and the results generated to be evaluated.

Textile products comprise of several structural layers, produced in consecutive phases: for example fibre, yarn and knitted fabric. Each layer influences the properties of the next level in some way. The evaluation and interconnection of the influences between layers and their properties are, in spite of all the research, still not unambiguous. If the properties of fabrics could be forecasted for example from the fibre properties, it would save resources in development and allow pure top-down development.

This master's thesis, as part of the DWoC-project, undertakes the task of characterizing different cellulose based fibres and fabrics to provide developmental information. Emphasis is on flexural properties that are related to fabric drape and handle, characteristics valued in consumer textiles. Methods used are evaluated in order to find robust methods for future assessment processes. The relationship of fabric inter-level properties, namely relation of fibre and fabric flexural characteristics, is explored based on the methods and measurements implemented.

The materials chosen for this thesis were cellulose-based. This was to gather information from products similar to those produced in the DWoC-project. Three main fabric structure types (woven, knitted and non-woven) were chosen to have some level of a comparison between the structures. Selected fabrics represented simple fabric structures to minimize the complexity and effect of the structure in measurements. Novel cellulose-based fibres were evaluated in parallel with commercial fibres.

The yarn level of the fibre-yarn-fabric hierarchy was excluded from this thesis as it would have broadened the subject in excess. With as complex structure as woven and knitted fabrics are it must be acknowledged that excluding yarn level leaves quite a few inter-level relations unaddressed. With non-woven fabrics this can naturally be disregarded.

In this work evaluation is confined mainly to the low stress behaviour of fabrics and to the related mechanical properties in fibres and fabrics. Low stress in this context is clearly in the elastic region. Common tests used in the field of textiles were chosen and some of the newer, promising methods yet to establish themselves were looked into.

The structure of this master's thesis begins with the theory part - introducing the properties and characteristics related to the research work. Next the materials and methods are described. Results and discussion portion presents the measurement data acquired and explains the impact of the individual results. Finally conclusions about the results are given, answering the research problems set forth and providing possible future research proposals.

2. IMPACT OF TEXTILE STRUCTURES AND PROPERTIES ON FABRIC FLEXURAL PROPERTIES

For this thesis the structure of fabrics has been divided into three hierarchical levels: fibre, yarn and fabric. Knitted and woven fabrics include all three levels, but non-woven fabrics lack the yarn level due to the manufacturing process. It is also a possibility to create yarns or yarn like structures omitting the specific fibre level, but this option is also disregarded in this work. These fore mentioned three levels, their measurable mechanical properties and interconnections are discussed in this chapter in the context of flexibility.

2.1 Fibre

This section covers the fibre properties measurable or derivable from one or more measurements and how these properties are reflected in flexural properties. The sub-fibre structures, such as polymer or cell level structures largely determine the abilities of a fibre to withstand and recover from mechanical forces, during for example bending [14, pp. 109]. Due to the scope of this thesis, neither the details of fibre fine structures nor the fibre production themes, such as extrusion and its effects on fibre properties, will be discussed.

First the flexural and torsional rigidity of a fibre is looked into, giving us a context in which reflect the properties to. Next up is the dimensional properties of a fibre, properties giving the fibre its form and feel followed by interactive properties - how the fibre reacts to external forces and manipulation.

2.1.1 Flexural and torsional rigidity

Flexural rigidity or resistance to bending, stiffness, is defined by Morton & Hearle [36] as the force couple needed to bend a fibre to unit curvature. Similarly torsional rigidity is the force couple needed to create unit angular deflexion between the ends of a fibre of unit length. Torsional rigidity, or rotational stiffness, is the resistance of a fibre against twisting.

Flexural rigidity can be calculated from other fibre properties dismissing the direct effect of the length of the specimen, as is shown in equation 2.1, where η is the shape factor, E specific modulus [N/tex], T the linear density of the fibre [tex] and ρ is the density [g/cm^3].

$$Flexural\ rigidity = \frac{1}{4\pi}\eta\frac{ET^2}{\rho}10^{-3}\ Nmm^2[36] \tag{2.1}$$

Flexural rigidity independent of fineness, specific flexural rigidity, is given by the equation 2.2.

$$R_f = \frac{1}{4\pi}\eta\frac{E}{\rho}10^-3\frac{Nmm^2}{tex^2}. \tag{2.2}$$

Specific torsional rigidity of a fibre of unit linear density is given by the equation 2.3, where n is specific shear modulus [N/tex], εis shape factor and ρis density [g/cm^3].

$$R_t = \frac{\varepsilon n}{\rho} \times 10^-3N\ mm^2/tex^2[36, pp.\ 399 - 402] \tag{2.3}$$

The ratio of shear stress and shear strain defines the shear modulus. It is a quantity used to measure the stiffness of materials and describes the fibre's response to shear stress. Unit used in this context is kN/mm^2.

As can be seen from equations 2.2 and 2.3, both are dependent on the moduli (tensile and shear) and fibre dimensional properties. Choice of linear density has the highest impact in the rigidity of a fibre - a coarser fibre leads to higher internal stresses and stiffer fibres. In table 2.1 there are specific rigidity values presented for selected fibres.

Table 2.1: Flexural and torsional properties of fibres [36, pp. 421]

Fibre	Specific flexural rigidity ($mNmm^2/tex^2$)	Modulus (GPa)		Specific torsional rigidity ($mNmm^2/tex^2$)	Shear modulus ($kN/mm2$)
		bending	tension		
Cotton	0.53		7.7	0.16	
Viscose rayon					
Fibro (staple)	0.35	10	8.7	0.058 - 0.083	0.84 - 1.2
Vincel (high wet modulus)	0.69	20		0.097	1.4
Secondary acetate	0.25		4.2	0.064	
Triacetate	0.25		3.8	0.091	

2.1.2 Dimensional properties

Fibre length

Fibres are either staple or filaments of infinite length. Natural fibres, excluding silk, are all staple fibres of naturally existing and varying lengths. Filaments, which include silk, can also be cut to controlled length staple fibres. This does not exclude the variance in the man-made fibre lengths as there is always some kind of variables introduced in the processes. Nano-fibres, even though within the scale of billionth of the reference unit, are nevertheless staple fibres.

Man-made fibres can be made into any length and fineness, changing the production parameters. With natural fibres the fibre length and fineness are quite strongly correlated [36, pp. 89]. Cotton fibre length can vary a lot, depending for example on the type of cotton, maturity, end-use etc. Indian cotton for instance rates between 16 and 42 mm [15, pp. 113].

Length of individual fibres in a fibrous structure affects their overlap, influencing common frictional surface, and thus the coherence acquirable by for example twist in a yarn. Long and high friction fibres enable lower yarn twist, which is usually preferable, and also allow finer yarns to be made.

Fibre fineness

Because of the wide scale of different kind of fibres and variation between and within fibres, there are several ways of looking at the fibre transverse dimensions. One used term is fibre fineness, which does not imply any geometry for the shape or its uniformity. Linear density or titre, weight of a given length of fibre, may be one of the most general ways of defining fibre fineness in textile industry context. It became more popular due to limitations in technology to accurately measure the often varying cross-sectional areas of fibres. Most common units for linear density are denier, which is of United States origin, and the metric measure tex. By definition denier is the weight in grams of 9000 meters and tex is the weight in grams of 1000 meters of a given linear material.

Some commercial viscose fibres are offered in the grades of 1.3 and 1.7 dtex [12]. Those fibres fall in the lower end of cotton fibre fineness (1-4 dtex) [15, pp. 116].

The term fibre diameter, which implies circular geometrical cross-section, is in general use related to fibre fineness, but should probably be restricted to fibres conforming to the implication. Even then the cross-section may not be uniform along the fibre length or between fibres of the same source. Defining the fibre fineness through cross-sectional area takes the shape into account and helps in comparing fibres. Using diameter or cross-sectional area to define fibre fineness is typical in the context of natural fibres. Due to the variation between singular fibres mean fibre diameter (MFD) is often used.

Fibre maturity is a factor included in cotton classification to have a more complete definition of characteristics. Micronaire is a property, function of both fibre linear density (fineness) and maturity, measured by resistance to airflow. It is a similar measure, but as stated, not equivalent to fibre linear density. Desirable micronaire values for cotton range between 3.5 and 4.1. [49]

Regardless of the definition, structures with more fine fibres rate higher in different handle assessments. Flexural properties, including fabric handle, are better with finer fibres, which in turn allow finer yarns to be made.

Cross-sectional shape

There is a great variation of cross-sectional shapes of fibres - by nature or by choice. Natural fibres have characteristic shapes [30, pp. 23] - for example cotton a bean like - that can vary due to external factors such as maturity. Cross-sectional shape of man-made fibres is up to a degree to the spinning design, affected by extrusion method, the spinneret used and after-processing. Removal of solvent during some extrusion methods may produce a serrated cross-section [39], which is evident for instance in fibres such as viscose.

Shape Factor, the ratio of the fibre cross-sectional shape perimeter to the circular shape of the same denier per filament (dpf) value, is a value determined either by theoretical calculations or, with most complicated shapes, by experiments [17]. The measure represents the different cross-sectional shapes of fibres in an inter-fibre comparable form used in for example rigidity calculations.

It must be noted, that there is a difference between shape factors for flexural and torsional rigidity, denoted by η and ε respectively. Shape factors related to flexural rigidity for some common fibres are listed in table 2.2. For cotton η has been defined in some sources [50, pp. 113] as 0.70 and ε as 0.71 [36, pp. 433]. Both factors have a value of 1 for a circular shape.

Table 2.2: Fibre flexural rigidity and shape factor values [36, pp. 416]

Fibre	**Shape factor η**	**Specific flexural rigidity** ($mNmm^2/tex^2$)
Viscose	0.74	0.19
Acetate	0.67	0.08
Nylon	0.91	0.14
Glass	1.0	0.89

Wang et al.[51] introduced in their paper a new way to measure profiled fibre shape factor using digital imaging technique. This new measure, CVr2, shows good robustness regarding noise and good resolution with cross-sectional shapes with deep depressions.

Fibres with symmetrical cross-sectional shape also display symmetric mechanical behaviour in bending. With asymmetrical cross-sectional shapes bending deviates from the ones with circular cross-sections, inducing bending deformation and also torsion. Comparison between hollow and solid fibres, circular and shaped fibres shows that using hollow round fibres tend to lead to more rigid fabrics. [37] [5, pp. 60] Cross-sectional shapes influence also the surface area of the fibre, possibly reflecting in inter-fibre friction.

Density

The density or volumetric mass density of an object is its mass per unit volume (g/cm^3). Due to external variables and conditions, such as moisture or impurities in natural materials, the total mass is taken into regard when calculating the density of fibre(s). The influence of measuring conditions is usually minimized using standard conditions and conditioning (See for example SFS-EN ISO 139 [46]).

The weight of a fibre ensemble, such as a yarn or fabric, is influenced by the density of the fibres it is made of. Measuring the density of fibre is easy regarding weighing the fibre, but defining the volume of a fibre due to eq. differences in fibre and surface structures can be challenging.

Ordinary textile fibres range between 1.1 and 1.6 g/cm^3 [36, pp. 416] and some are shown in table 2.3. Specific volume, the reciprocal of density, is used in some context.

Table 2.3: Densities of some common textile fibres [36, pp. 184]

Fibre	**Density** (g/cm^3)		**Specific volume** (cm^3/g)	
	dry	**65 % r.h.**	**dry**	**65 % r.h.**
Cotton (lumen filled)	1.55	1.52	0.64	0.66
Viscose rayon	1.52	1.49	0.66	0.67
Secondary acetate, triacetate	1.31	1.32	0.76	0.76
Polylactic acid (PLA)		1.25		0.80
Polyester (PET)	1.39	1.39	0.72	0.72

Fibre crimp

Crimp can be seen as the hairiness in a yarn and is the principal feature governing the bulkiness and specific volume of yarns and fabrics [35]. Fibre crimp can be defined as waves, bends, twists or curls along the fibre length, be it in two or three dimensions. It is expressed as crimps per unit length and can be of natural existence, as it mostly is with natural fibres, or artificially imposed.

The stress-strain curve of a fibre generally consists of three different mechanisms: removal of slack, crimp removal and fibre stretching. Simplified the crimp removal takes place in the non-linear region in-between, but defining the exact points is complicated. The crimp removal has been defined at a time by empirical data to happen below 1 cN/tex, but later empirical testing has proved the definition of the region to be more complex. More precise results to measure the crimp can be gained by defining the slack and tensile regions, and deducting the crimp region from the data. [3]

Fibre curvature is an objective measurement of fibre curving degree on a given length of fibre, used to predict fibre crimp frequency. Fibre curvature is associated with fibre diameter and length. [33] It must be noted that this measurement [2] has been simplified to regard the three dimensional fibre only in two dimensions by projection.

Crimp affects the volumetric properties or volumetric bulk, influencing haptic properties. It may also act as a buffer under stress before the fibre is straightened and tensile properties are engaged. Crimp increases the cohesion between fibres, which is a desirable for example with slick fibres, and also tensile strength and compression behaviour of a fibre assembly [5, pp. 63].

2.1.3 Stress related behaviour

Tensile stress and strain

When applying force along the fibre axis the fibre resists the force. Under the gradually increasing load the fibre elongates until it ruptures. This behaviour can be expressed with a load-elongation or tensile stress-strain curve, which is characteristic to each fibre.

In textile technology comparing different types of fibres regardless of their dimensions and in terms of their weight is of interest. In this context load is usually replaced with specific stress:

$$Specific\ stress = \frac{load}{\frac{mass}{unit\ length}} = \frac{load}{linear\ density}. \tag{2.4}$$

The elongation of the fibre is expressed as tensile strain or percentage extension:

$$Tensile\ strain = \frac{elongation}{initial\ length}. \tag{2.5}$$

The unit for specific stress using linear density is grams per denier (g/den) or newtons per tex (N/tex). Regardless of the used units, the shape of the curve stays as is shown in figure 2.1.

The stress-strain curve can be divided into points and segments which represent the inside workings of the fibre under stress. The curve and its parts can be used to derive information such as calculating the total work from the area defined by the curve and specific points.

Fibre tensile stress-strain curves with the effect of crimp excluded start with a segment generally depicting a linear portion – stress being proportional to strain. This is called initial, tensile, elastic or Young's modulus. It indicates how easily the fibre extends under small stress. The smaller the initial modulus the less stress is needed to elongate the fibre.

The initial elastic, reversible deformation of a fibre changes into plastic, permanent

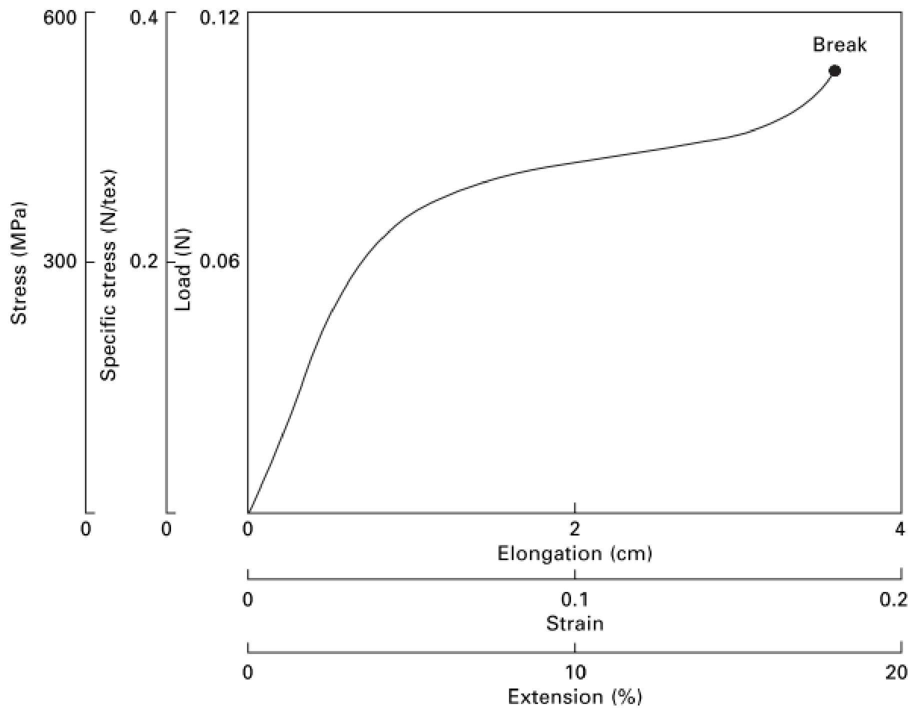


Figure 2.1: Hypothetical load-elongation curve [36, pp. 276]

deformation at the yield point in the tensile stress-strain curve. This can be described as the flattening of the curve or decrease in slope.

Stretching the fibre over the yield point and leaving it with a permanent set - mechanical conditioning, causes the fibre to behave differently compared to the unchanged fibre. This can be used to an advance by gaining altered properties not available otherwise. Not all fibres exhibit a distinguishable yield point [14, pp. 110].

Not all fibres have a hardening point as some rupture beforehand, but this is the point where the tensile stress-strain curve begins to climb again. After this point the structure of the fibre starts to give way and eventually the fibre ruptures. It is also notable, that before this deformation limit a fibre can still partially recover (elastic recovery).

Tenacity, or fibre strength, is the maximum tensile force measured in elongating a fibre to its rupture point. The specific stress at that rupturing point is called tensile strength at break, giving a measure how a fibre can resist steady forces. After gaining the maximum tensile strength, the fibre may still continue to elongate – tensile strength at break may thus be lower than fibre tenacity.

Elongation tells us how much the fibre can extend under mechanical force. The elongation at the moment a fibre is ruptured is a quantity describing the maximum stretching a fibre can withstand. It can be expressed by the actual, the fractional, or the percentage increase in length.

The energy required to break the fibre is defined by work of rupture. It can be calculated from the area defined by the tensile stress-strain curve from zero load to rupture point. This measure answers how the fibre can withstand sudden shocks of given energy along the length of the fibre.

Elastic recovery or elasticity is the behaviour of a fibre when stress is removed. A fibre under stress still performing elastically, having not reached the yield point, can recover partially or fully it's state after the removal of stress. Elastic recovery can be defined as the ratio of elastic extension and total extension, with complete recovery having the value of 1 or 100 %.

Elastic recovery can be used to estimate how much stress a fibre can bear without permanent damage. The speed of contraction is lower than the extension under stress.

Resilience is defined as the ratio of recovered work after elastic recovery and the total work done when fibre was extended to the point before recovering. This measure is connected with the tendency to wrinkle with higher values indicating wrinkle-free fabrics. [14, pp. 112]

Creep and relaxation

Creep is the continued deformation under constant load – either extension or recovery – that happens after the initial deformation caused by the change of load. Timescale for creep is from minutes to months.

Relaxation is the time-dependent response of the fibre under stress. Fox example stress relaxation is observed when stress gradually decays in a fibre under static elongation. Similarly relaxation of torque occurs in twisting a fibre.

Compressive properties

Hu and Chan [18] in their paper studied fabric drape and low-stress mechanical properties acquired with KES-F instruments. They concluded that compressional properties acquired had little to do with drape characteristics.

Fibre friction

Friction is by definition the resisting force opposing the relative movement between two surfaces in contact. Friction between fibres is something that can be made use of but has also disadvantages. Cohesion helps in twisting yarns and also influences the tensile properties of fabrics but may cause problems in processing.

Modelling fibre friction is a complex task and often quantified through experimenting. It is common to approximate the relationship between the frictional force and normal load for fibres with the equation 2.6, first introduced by Bowden and Young. It is obvious that the equation does not satisfy the available experimental data.

$$F = aN^n, \tag{2.6}$$

where a and n are friction indexes, experimental constants, and N is the normal force [11].

The fibre surface area is largely affected by the specific surface, surface rheological properties, fineness and length of the fibre. The contact surface area between the surfaces is also affected by the elastic deformation of the fibre. In addition to the environmental factors (for instance force and speed) and processing (such as finishing) other factors affecting fibre friction are fibre weight and crimp.

2.2 Yarn

Yarns can be composed of fibres, either staple or filament, or other comparable forms and compounds of the mentioned. In textile context suitability for knitting, weaving or other intertwining would be a criterion, but with ever broadening end uses it might not be a priority. Yarn structure, excluding those composed of a single filament, are held together by a binding mechanism.

Based on the constructive description, threads fulfil the definition of a yarn. Threads however refer to products used to join pieces of fabric together, by sewing or other means.

2.2.1 Flexural and torsional rigidity

Due to the fibre orientations or paths taken by the fibres in a yarn, they undergo both flexural and torsional behaviour when a yarn is bent. Modelling the bending resistance of a yarn is complicated, as the mechanisms at work inside the yarn(s) change depending on the external settings as well. If the inter-fibre slip is high, the constituent fibres work individually against the bending force. If the fibre coherence is high, the yarn acts like a solid rod. Both extremes are possible to be calculated with beam bending models, but the in-between areas are hard to capture. [5, pp. 18]

Turning one end of a yarn around its axis is what gives a yarn its twist (see chapter 2.2.2) and also inflicts yarn torsional properties such as residual torque, torsional rigidity, deformation and torsional recovery. Yarn torsional rigidity is the ratio of the inflicted torsional moment and twist angle - the initial modulus in a torque-twist curve [16].

Fibre friction, yarn twist and forces contributing to the cohesion of the fibres and yarn influence the bending resistance or stiffness of the yarn. These include the fabric structures, especially the loop structures of knitted fabrics.

Torsional rigidity and residual torque, force trying to untwist the yarn, have been shown to affect at least knitted fabric thickness [16]. This phenomenon, especially after washing, is probably due to the loop structures allowed to rearrange themselves to a sort of a minimum energy state. Yarns with high torsional rigidity in similar structures should show similar behaviour under compression, requiring higher compressional work. With woven fabrics the influence is most probably lower, with more linear structures compared to knitted structures.

2.2.2 Yarn composition

Single or one-ply yarns are filament yarns or made from staple fibres spun and twisted together. Filament yarns can be mono- or multifilament, twisted or untwisted. Wound yarn consists of two or more yarns wound together without twist. Plied or folded yarn consists of two or more single yarns twisted together. Cabled yarns consist of plied and/or single yarns twisted together or their multiplications.

Yarns are classified by their structural properties: yarn count, number of filaments, direction and amount of twist and number of yarns in the case of plied and cabled yarns. The classification values are used to distinguish commercial yarns and can be written down from the viewpoint of the final yarn or from inside-out, from the viewpoint of single yarns.

Spinning method

One method used to bind staple fibres together to form a yarn is called spinning. The process of extruding, the formation of man-made filament fibres, is often referred to as spinning as well. The difference should be acknowledged between forming fibres and converting fibre to yarn. The process of producing a yarn by spinning includes several stages according to the used fibres, fibre length, etc. During the latter stages, the process may include manipulating partially aligned yarn preforms – sliver and roving.

The subject of spinning and its impact on yarn properties is a collection of numerous different stages and their individual influences on the yarn properties. Kumar and Ishtiaque in their article [29] have thoroughly discussed these issues. They conclude that carding is the most important process stage affecting the properties of preforms and yarn.

The four main spinning methods are ring, air-jet, rotor and friction spinning. Depending on the spinning method used, excluding other variables, the resulting yarns differ in geometrical arrangement of the constitutive fibres. The differences in the staple yarn structural parameters constitute of mean fibre position, helix angle of the fibres, fibre migration factor, fibre packing densities, percentage of hooks and their extents, the number of fibres in the yarn cross section and yarn diameter [34; 19]. Some of these differences are visualized in figure 2.2.

Fibres in ring-spun yarns are fairly well aligned with the yarn axis. According to Choi [30, pp. 37] fibre type and yarn twist level has the largest impact on the fibre distribution in the cross-section of an undeformed ring spun yarn.

Fibres in rotor spinning tend to be less aligned with the yarn axis and more even in diameter when compared to ring-spun yarns. Rotor spun yarns have a smooth, even surface.

The surface layer fibres, wound helically around the central core of fibres, bind the yarn together, making it less fuzzy or hairy in Air-jet spun yarns. Uniformity is high in air-jet spun yarns, comparing to that of ring-spun yarns.

Yarn count or number

Fineness of a yarn can be defined, like fibre fineness, directly or indirectly, with linear density or length of yarn per unit weight accordingly. In yarn context the

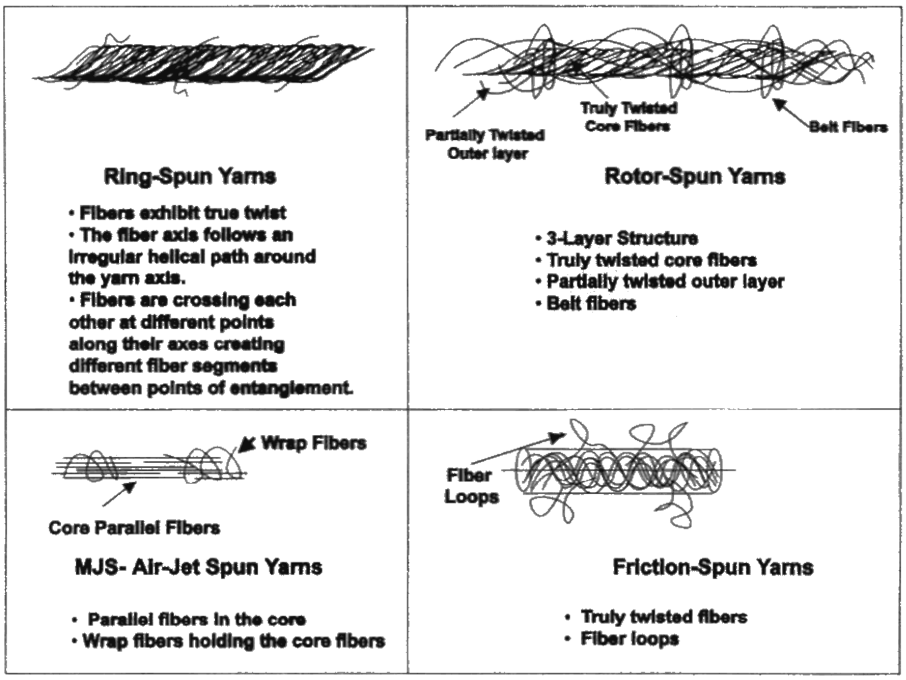


Figure 2.2: Different fibre arrangements of different spinning methods [8]

relationship between the length and the weight of a yarn is called yarn count or yarn number.

As yarns are composed of fibres, the fibre fineness has a major effect in the yarn level as well. Finer fibres allow finer yarns to be spun. With a set yarn count the number of fibres in cross-section depends on the fibre fineness.

As the yarn count increases, naturally the fabric density rises. As has been brought up earlier high density requires more force to bend an object.

Yarn diameter

Fineness may be defined with yarn diameter or thickness as well. The problem of defining the diameter of a yarn without compressing it or using optical systems trying to distinguish the definitive outer edges of uneven surfaces has led to favouring of linear density. The use of yarn diameter or thickness still has its uses when for example estimating yarn covering power.

To overcome the mentioned challenges, modelling and estimation of the yarn diameter is needed. For direct count system empirical yarn diameter formulas have been developed by Peirce and El Mogahzy et al. [7]. These expressions are listed in table 2.4 as derivatives of yarn count N_e. Yarn diameter and packing coefficient have reciprocal relationship [29, pp. 119].

Table 2.4: Empirical Formulas of Yarn Diameter [7]

Yarn type	Expression	Units	Source
Ring spun	$d = \frac{1}{28\sqrt{N_e}}$	Inch	Peirce (1937)
Ring spun	$d = -0,10284 + \frac{1592}{\sqrt{N_e}}$	Mm	El Mogahzy (1993)
Rotor spun	$d = -0,16155 + \frac{1951}{\sqrt{N_e}}$	Mm	El Mogahzy (1993)
MJS Air-Jet yarn	$d = -0,09298 + \frac{15872}{\sqrt{N_e}}$	Mm	El Mogahzy (1993)

Yarn volumetric density

Yarn bulk, or volumetric density, measures how much space a given amount of yarn takes. It is affected by fibre bulk and crimp, and is controllable with yarn count and twist.

Twist

Twist is quintessential in staple fibre yarns, providing the force to hold the individual fibres together. Filaments in multifilament yarns need some cohesive forces to hold them from fraying. Constituent fibres are more easily extracted from a yarn with reduced twist level constituting to hairiness (thus pilling), fabric hand and lower abrasion properties of a fabric.

Twist is most often expressed as the number of turns per unit length. Due to different yarn counts this is not specific enough. Twist is the helical angle of fibres to yarn axis that defines the effect on the yarn properties. Twist factor, denoted with the letter K, relates twist level of a yarn to yarn count (in tex system) like Khanum et al. [28] showed with equation 2.7.

$$twist\ (turns\ per\ metre) = \frac{K}{\sqrt{tex}} = \frac{tan\theta}{2\pi\sqrt{\frac{tex\times10^{-3}}{\rho\pi}}}. \tag{2.7}$$

Yarns of different linear densities need different amounts of twist for the same twist-wise properties. Twist factor is in theory a universal quantity enabling one to compare different yarn twists. As always, used units and numbering systems should be noted when comparison is made.

Twisting a yarn leads to yarn contraction or packing and actually changes the yarn count [28]. With decreased diameter and specific volume, yarn tensile and volumetric related properties are affected. Other properties include among others the yarn covering power, compressibility, handle and friction. It is notable that during manipulation and processing unintentional twist may be introduced to the yarn.

Twist direction may have influence in bending, either resisting or complying with the bending direction. This could have effect in the loop behaviour in knitted fabrics under stress.

Fibre friction (See section 2.1.3) is one of the largest factors defining the amount of twist needed to hold fibres together in a yarn. Other factors include eq. fibre length and fineness, as was discussed earlier, both influencing the inter-fibre contact surface area and friction.

Yarn density

Yarn density is influenced by the yarn count, fibre fineness and yarn twist. Yarn count (yarn weight per length or thickness) is affected by the fibres in yarn cross-section, constituent fibres' fineness and mechanical processes involved in producing a yarn. Depending on the volumetric boundaries, yarn hairiness and external compressional forces can change the measure.

Yarn hairiness

Yarn hairiness, or the quantity and quality of protruding fibres from the main body of the yarn, is a property that is hard to quantize unambiguously. The number and length of the hairs vary independently and vary along the length of the yarn.

Previous work [43, pp. 118] shows us that the number of hairs falls of exponentially as their length increases – there are more short hairs than longer ones. Existence of short hairs outside the main yarn body has an impact on the yarn and fabric handle, as the short hairs may prick the skin.

The total number of hairs is influenced among others by the spinning system, fibre breakage, fibre length and yarn twist. According to literature [43, pp. 119] the yarn count is linearly related to the percentage of hairs exceeding 3 mm in length from the total number of hairs.

It must be noted that the measurements of hairiness are highly dependent on the method used. All the manipulation, even during the measurement, may influence the results.

2.2.3 Stress related behaviour

Fibre tensile properties have an impact on yarn tensile properties, but according to research done by El Messiry & Abd-Ellatif the correlation between single fibre tenacity and yarn tenacity is low. Tenacity of a fibre bundle has a better correlation with yarn tenacity – yarn tenacity being a function of several fibre characteristics.[34]

El Messiry and Abd-Ellatif also introduced an evaluative index for fibre quality evaluation. The modified fibre quality index (MFQI), used to predict cotton yarn tenacity from fibre properties, is given by the equation 2.8. The fibre length is expressed by the upper half mean UHM [mm], fibre length uniformity index with UI, fibre bundle tenacity with STRb [cN/tex], EL is the percentual fibre elongation at break, MIC representing the micronaire value (representing the fibre fineness and maturity) and SF is the percentual short fibre content.

$$MFQI = UHM \times \ UI \times \ STRb \times \frac{(1+EL)\times(1-SF)}{MIC}. \tag{2.8}$$

The fibres in a yarn do not stay uniformly distributed along the yarn cross-section. Higher level of fibre migration, such as with ring spun yarns, corresponds with higher yarn breaking tenacity. Rotor spun yarns show lower breaking tenacity, followed by friction spun yarns. Air-jet yarns have though lesser tensile and elongation properties. [19]

Packing density of fibres along the yarn cross-section shows when measuring rupture elongation. According to the results of Huh, Kim and Oxenham [19] the results decline the closer the packing density of fibres is to the yarn axis. Ring spun yarn has fairly uniform distribution, while rotor yarns show the tendency of near centre and friction yarns near surface packing density.

2.3 Fabric

The three types of fabrics covered in this work are woven fabrics, knit fabrics and non-woven fabrics. Compound fabrics and twisted and knotted fabrics are not discussed. Of the fabric types discussed, non-woven fabric is composed of webs of fibres, usually bonded together mechanically or chemically. The other two, woven and knit, constitute of yarns interlaced at right angles or intermeshed loops of yarn, respectively. The structure of fabrics defines multitude of fabric properties, but the fibre and yarn properties are reflected in the product as well.

Fabrics can be evaluated from several different aspects. The most common evaluation has been through mechanical and aesthetical properties – does it look good and does it last. Mechanical properties are measurable and unambiguous. Aesthetics instead are quite subjective subject – what looks good is up to debate.

In this chapter fabrics are inspected from the point of assessing for their low stress behaviour. Flexibility of a fabric, among other characteristics, is manifested as drape and fabric handle.

2.3.1 Flexural and torsional rigidity

A fabric can be modelled as a planar plate, a shell or a membrane in mechanical models [30, pp. 13]. The plate model in its simplest form, modelling the fabric as flat, uniform thickness and of homogenous isotropic material, is similar to the beam model, but in more dimensions. The equation for flexural rigidity of a plate is given in equation 2.9 as the moment per unit length per unit of curvature, where E is Young's modulus, h_e the elastic thickness and v Poisson's ratio.

$$D = \frac{E \times h_e^3}{12(1 - v^2)} \tag{2.9}$$

There are numerous rigidity model proposals [30], of different levels of complexity. Some of the models implement experimental values, which implicate of the complexity of the task. Such model is implemented in the cantilever method to measure the bending length and rigidity of fabric.

2.3.2 Dimensional and structural properties

Fabric count, depending on the fabric type, may refer to number of threads or stitches per unit length or area [26; 21]. Fabric is called balanced when fabric count is same in both directions and used yarns are of equal size and character. High fabric count is usually gained with finer yarns, and vice versa. Fabric count, in combination with yarn number and used (fabric specific) structure characterize the fabric density.

If the fabric is regarded as a plate, filled with yarns, we can conclude that the thickness and density is influenced by count of yarns or fabric count. Combined with the fibre and/or yarn bulk influencing the fabric volumetric density they have a impact on flexural properties and handle as well.

Thickness of a isotropic plate would clearly influence the bending resistance, or rigidity, but fabrics usually consist of anisotropic structure and materials. Thickness may vary significantly, depending on the structure and texture, influencing the simplified bending models.

Mass per surface area, or grammage, in itself is not a descriptive property regarding fabric flexibility without knowledge of fabric thickness. But if weight is the only variable, it can be used to estimate the bending behaviour for the advantage of lighter fabric.

2.3.3 Stress related behaviour

When a woven fabric is subjected to stress, it behaves in discontinuous way showing as a non-linear curve in a stress-strain curve. The initial response, regarded as Young's modulus of the fabric, denoting the tensile property of the fabric and probably due to the frictional resistance in and between yarns. As these forces have been overcome, the gentle slope is due to redistribution of crimp in the fabric structure. After the crimp has decreased, the steep curve portrays the yarns in the fabric resisting the load. [30, pp. 55]

Knit fabrics in mechanical property sense are often regarded as variants of woven fabrics. Although there are similarities between the fabric types, the load-extension behaviour of knit fabrics differs from that of woven fabrics. The parts of structure resisting bending and torsion make up the majority of the fabrics resistance to for instance extension. [30, pp. 67] As a rough simplification it could be said, that knit fabrics add the loop structure to the behavioural chain of woven fabrics.

The mechanical properties of spunlaced nonwoven fabrics are based on the mechanical properties of the constituent fibres and their entanglement. The intensity of the hydroentanglement is believed to be combination of the spunlaced process and the fibre properties. [32]

Main interests in the context of this thesis are drape, handle and other behaviour associated with low force manipulation. So focus is given to the lower region of the stress-strain curve.

Drape and handle

Drape is the way in which fabric hangs. The way it hangs, is assumedly one possible equilibrium state achieved after the fabric has been subjected to stress induced by its own weight and it has undergone the applicable stress-strain behavioural phases described earlier.

The assessment of drape has been simplified (e.g. British standard BS 5058) to evaluate the difference between the projected area of a supported, freely draping sample and the maximum area of similar sample. In this sense it is an evaluation of structural behaviour, not a true measure.

Fabric hand

As the fabric hand is mostly a subjective assessment of physical measurements, it is not really a property of the fabric but rather of the evaluator. Based on this, the fabric hand or handle is not listed as a property in itself in this thesis. Measurements that can be regarded as an evaluative value of fabric hand are nevertheless used - for instance the maximum force in fabric extraction through an orifice.

Stress-strain curve

As a fabric might be structurally discontinuous, fabrics show different extension response during the lower and higher extension regions. Due to anisotropic nature of woven and knit fabrics, they show different properties according to the relation of the load and structure.

Fabric tensile properties are derivative of its sub-structures and those of yarns and/or fibres. Depending on the fabric structure the scope of structural levels involved varies. For instance with light knit fabrics, only decreasing of crimp and loop rearrangement may be involved during draping.

2.4 Finishing

Different finishing processes can be used to modify the properties of fibres, yarns and fabrics to a high extent. In some cases the changes to for instance fabrics are greater that can be achieved by other productional means [40, 457]. Unfortunately this is a topic too extensive for this thesis and will not be discussed in more details.

3. MATERIALS

This chapter is all about the materials researched during the thesis. Emphasis is put on the more unfamiliar materials, as the more common materials are diversely covered in fundamental literature. Some of the fibres and fabrics made available through research groups and organisations may be of developmental grade not representing fully the commercial varieties or not commercially available.

3.1 Fibres

All the fibres are listed in table 3.1 with the codes used in this thesis (fibre code), material and fibre type. All the fibres are though staple fibres.

Biocelsol fibres were made available through researchers at Tampere University of Technology, where they are being developed. Dissolving grade pulp is treated with enzymes to achieve an alkali soluble form and the alkaline cellulose solution is wet spun into Biocelsol fibres. This process lacks any carbon disulphide, which is common in the viscose method, giving an eco-friendly alternative for instance for viscose with similar or better mechanical properties. [47]

VTT has been researching cellulose carbamate (CCA) for a while and has been successful in improving the synthesis and dissolution processes, enabling fibre manufacturing. These regenerated cellulose based, linter utilizing fibres are more ecologically produced compared for example to traditional viscose method.

Cotton fibres are natural, pure cellulose staple length fibres. Cotton fibre diameter is in the lower end of textile fibres and fairly uniform along its length. It twists around its axis, resembling a flat twisted ribbon and the cross-sectional shape of mature cotton resembles kidney-bean.

Ioncell fibres were kindly provided for this thesis by Aalto University. The fibres are spun using a novel, ionic cellulose spinning solvent. Using this method fibres with mechanical properties topping the known commercial regenerated cellulose fibres can be realized - economically, safely and nature friendly. [45]

Poly(lactic acid) (PLA) is a thermoplastic linear aliphatic polyester derived from starch. Due to its chemical structure it is fully biodegradable. [10] Cotton and viscose need no introduction. The cotton, viscose and PLA used in this thesis were all kindly offered by Suominen Corporation.

Table 3.1: Sample fibres used in the measurements

Fibre code	Material	Fibre type
BCS	Biocelsol	Staple
CCA	Cellulose Carbamate	Staple
CO	Cotton	Staple
ION	Ioncell-F	Staple
CV	Viscose	Staple
PLA	Poly(lactic acid)	Staple

3.2 Fabrics

A jersey knit fabric, plain-woven fabric and spunlaced non-woven fabric were chosen as the structures to be measured, representing the most common fabric types. In addition using the simplest structures of each fabric type, the complexity and possible effect on the measurements were tried to be kept in minimum. In order to have comparable data, the fabric materials were chosen to match the fibres.

All the fabrics involved in this thesis are listed in table 3.2. Given grammage and other producer provided information are listed in Appendix (table A.1). Measured properties are listed in chapter 5. Close-up images of the fabrics are in figures from A.1 to A.7 in Appendix.

Table 3.2: Sample fabrics used in the measurements

Fabric code	Material	Fabric type
FCO	CO (100 %)	Woven, plain
ECV	CV (100 %)	Woven, plain
OCO	CO (100 %)	Knit, jersey
OCV	CV (100 %)	Knit, jersey
BCP	CV-PLA (65-35 %)	Non-woven, spunlaced
BPCC	CV-PLA-CO (50-35-15 %)	Non-woven, spunlaced, hydro embossed
BCV	CV (100 %)	Non-woven, spunlaced

4. METHODS

Methods applied during the thesis are represented in this chapter. Some of the methods are available as international standards and are described only briefly. Any deviations from standards will be duly noted in the results. All sample fabrics were conditioned according to ISO 139:1979 [46] standard, in flat tension-free state for over 24 hours.

4.1 Fibre characterization

The linear density and tensile properties of fibres were determined with the use of an appliance (Textechno Favigraph). It makes use of the vibroscope method, defined by DIN EN ISO 1973: 1995-12 [22], where the fibre loading and test length are constant. Number of specimen per sample was 50.

Fibre bundles were embedded in epoxy resin (Sigma Aldrich Sigma-45359) with the help of postdoctoral researcher Mari Honkanen from TUT. Hardened samples were then broken after exposing to liquid nitrogen. Acquired cross-cut samples were processed with conductive coating and sputtered for scanning electron microscope (SEM). Sputtering and image acquisition with a Philips XL 30 SEM was done by project researcher Jarmo Laakso at TUT.

A microrobotic platform able to manipulate and characterize singular fibres was used to measure fibre flexural properties. The platform has been created and developed by the Micro- and Nanosystems Research Group of Tampere University of Technology, at the Department of Automation Science and Engineering. The platform, initially developed for paper fibres, allows direct characterization of singular fibres.

In the characterization process the fibre is regarded as a fixed beam with both ends fixed. The single fibre is grasped with two microgrippers and bent to a fixed deflection by applying force to the middle of the fibre with a push-type force sensor as the deflector. Fibre deflection is determined from a position sensor attached to the force sensor. Point of force is determined and measures are acquired through a machine vision system.

In their paper [41] Saketi and Kallio present how they have implemented the beam theory in their platform. Building on the theory introduced also in the theory part of this thesis, they have derived the equation for maximum deflection, y_{max}, in equation 4.1.

$$y_{max} = \frac{-FL^3}{192EI}, \tag{4.1}$$

where E is young's modulus, I moment of inertia of the beam, F concentrated intermediate load and L beam length. Flexibility, the inverse of bending stiffness, is given in the form of equation 4.2.

$$Flexibility = \frac{1}{EI} = \frac{192 \times y_{max}}{-FL^3}. \tag{4.2}$$

With textile fibres, most have some level of crimp, forced or natural. This would induce a need for pretension before measurements. Applying pretension or axial tension overly complicates the equation for flexibility and would have been difficult to implement and control with the used platform.

Due to the current setup of the microrobotic platform, there was no way to determine the tension between the two grippers. So no pretension was used during the measurements. After gripping the specimen with the manipulators, it was straightened based on visual evaluation.

There is some hysteresis in the positioning of the platform manipulators, and y_{max} couldn't be kept constant. This lead to the decision of EI being calculated per measurement cycle and a mean value is given per measurement. All the measurements were executed in a non-standard environment. 10 specimens per sample were characterized with 10 cycles of measurements. Weight of the fibre was neglected as well.

4.2 Fabric characterization

Structural elements in knitted fabrics are stitches and threads in woven fabrics. The number of wales and courses per centimetre for the knitted fabrics were determined according to SFS-EN 14971 [26] standard. Number of threads per unit length for the woven fabrics was determined according to SFS-EN 1049-2 [21].

A traversing counting glass with aperture width of 5 mm was used for measuring both stitches and threads per unit length. In SFS-EN 14971 it conforms to method A and in SFS-EN 1049-2 to method C. Measuring length of 30 mm was used for the latter.

Preliminary test and the actual measuring were conducted in five different places. For knitted fabrics the wales and courses were calculated, for woven fabrics the threads in manufacturing direction (MD) and perpendicularly (CMD). The results are given as arithmetic mean values in both directions per sample.

Mass per unit area was determined according to SFS-EN 12127 standard [24]. Five specimen of 100 cm^2 per sample were cut with a cutting device. The specimens were weighed in the conditioned state with a digital analytical balance with 0.1 mg readability. Results are given as the mean mass per unit area in grams per square metre, rounded to three significant figures.

Fabric thickness was determined with appliance conforming with SFS-EN ISO 5084 [23]. Thickness measured by the appliance is defined by the standard as "Perpendicular distance between two reference plates exerting a pressure of 1 kPa or less". Ten 20 cm^2 specimen were cut per sample and measured with 1 kPa pressure. The appliance provided arithmetic mean thickness values for each measurement round.

Low stress behaviour

Most of the methods and measurements assessing the fabric bending or flexural properties - drape, handle or other similar behaviour - have in common the low stress behaviour. The reversible behaviour of the fabric is evaluated haptically or optically, subjectively (e.g. Kawabata total handle value) or objectively (Cusick's drape coefficient). In this thesis only objective measurements were put into practise. Methods used involve external force, such as pulling or pushing the fabric, or the fabric is allowed to rearrange itself under its own weight, what happens for example when a fabrics drape.

Kawabata Evaluation System of Fabrics

The mentioned Kawabata Evaluation System of Fabrics (KES-F), a commercial system made available in Japan since the 60s, was used to evaluate two different low stress behaviours of fabrics. KES-F is designed for evaluating instrumental parameters believed to represent fabric handle and these parameters are interpreted in conjunction with subjective fabric assessment. Two of the measuring devices were used in this thesis, the fabric compressibility (KES-FB3) and fabric bending (KES-FB2) devices.

Fabric compressibility was, as said, carried out with the KES-FB3 device. Standard settings for pressure and speed were used, gauge length adjusted according to the fabric thickness. The automated device presses the sample between two plates until the maximum pressure of 50 gf/cm^2 is reached and then reverting to the initial state, drawing a force-deflection-curve. Five measurements were taken per specimen, of which the linearity of compression curve (LC), compression energy (WC) and compression resilience (RC) were calculated.

Fabric bending measurements were realized with KES-FB2 device. The device has a vertical sample holder, with a static torsional moment measuring end and a moving, swivelled end following a semi-circular path. A bending moment-curvature-curve is generated, when the moving end cycles between two curvature extremes - curvature of - 2.5 and 2.5 cm^{-1}. From the curve bending rigidity (B) and hysteresis of bending moment (2HB) are measured.

Cusick's drape meter

Another method used to measure fabric bending properties, or flexural rigidity, is described in SFS-EN ISO 9073-7 [25]. It is a standard for measuring the bending length of non-woven fabrics, from which the flexural rigidity can be calculated. In this thesis it was used for woven and knit fabrics as well, despite the standard being specifically for non-woven fabrics.

The standard defines the bending length as "length of a rectangular strip of fabric, fixed at one end and free at the other, that will bend under its own weight to an angle of 7,1°". "Ratio of small changes in bending moment per unit width of the material to corresponding small changes in curvature" is the flexural rigidity by definition. [25]

Six specimens, oblong strips of fabric, per sample were cut out with scissors along the manufacturing direction (MD) and perpendicularly (CMD). Supported specimen were manually moved along their length on a platform until the overhanging part of the fabric bent to a given angle of 41,5°. The bending length, which is half of the measured overhang length, was measured four times, changing the orientation, for each specimen.

Flexural rigidity can be calculated from the bending length, using the equation 4.3:

$$G = m \times C^3 \times 10^{-3}, \tag{4.3}$$

where m is the mass of the test piece per unit area $[g/m^2]$ and C is the overall mean bending length $[cm]$. In this equation the acceleration due to gravity has been rounded to 10 m/s^2.

Drape coefficient

The European Standard EN ISO 9073-9 describes a drape evaluation method including the determination of drape coefficient. The principle of the measuring method is as follows: The circular specimen of the fabric being tested is held horizontally between smaller concentric discs, and the exterior ring of fabric is allowed to drape into folds around the lower supporting disc. The drapability of the specimen is evaluated using rings of paper or image processing technology, method A or B, accordingly.

The apparatus used in both methods, Drape Meter, to measure drape coefficient and defined in the standard is based on using parallel light to illuminate a sample from beneath. This creates an exact contour on a flat horizontal translucent surface, projecting the 3D shape of the sample as a 2D area on the surface. Method A describes how the contour can be traced on a material with a known mass per area, cut and weighed - giving the projected area through its mass. The standard also gives a somewhat limited description of the method B - a setup with a digital camera and computer software using image analysis to calculate characteristics from the acquired contour images. [27]

With no available Drape Meter or other ready-made apparatus and software, available materials were implemented to build a setup depicted in figure 4.1. The method B was implemented in defining the drape coefficient. A high-power light source was used to lighten up a white sheeting background used as a diffusor. This created enough contrast between the sheeting and the specimen on the sample stand above. Further above held commercial web camera connected to a laptop was used to capture images of the samples after the standard defined 30 second delay. Between measurements, each sample was rested on flat surface for at least 5 minutes, undraped.

Image analysis on the captured images was implemented with Matlab (See Appendix A.3. Due to contrast between the sample and the sheeting background, the contour of the sample could be detected mainly without manual image processing.

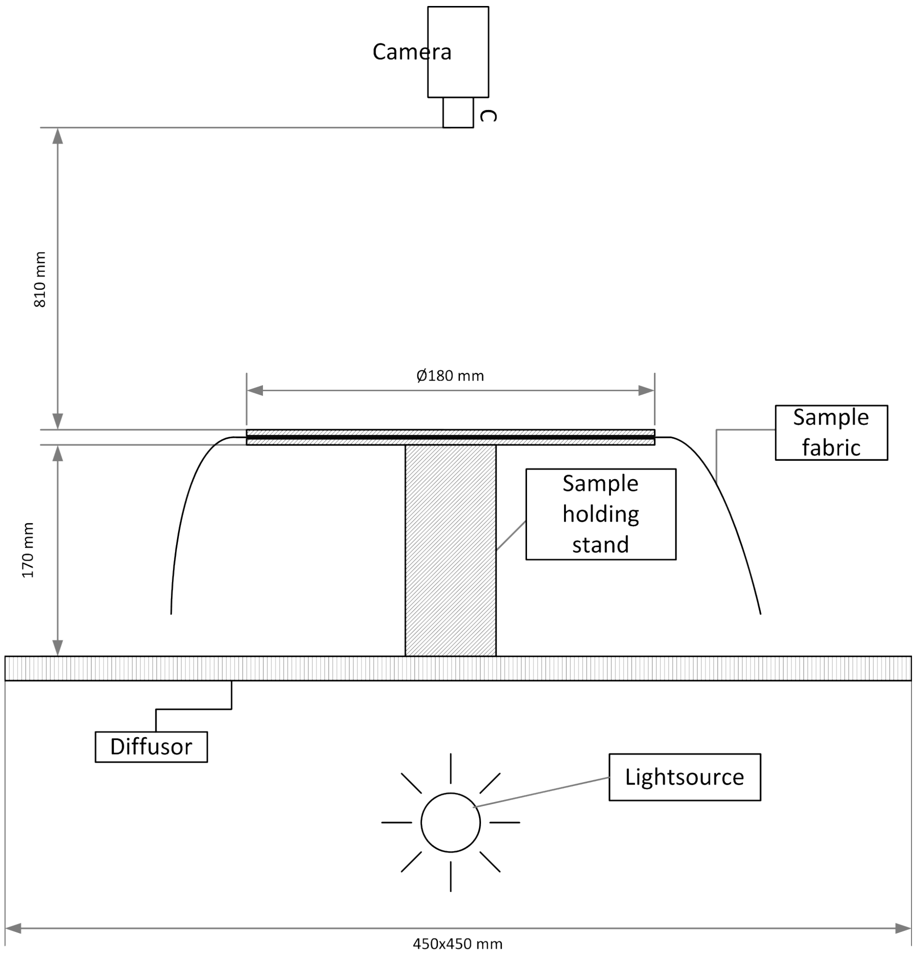


Figure 4.1: Setup for measuring drape coefficient

With the acquired contour information, the area of the sample could be calculated. The ratio between the real-world measures and digital measures in pixels was achieved using a stiff calibration sample with a known diameter.

Modified ring method

In simplicity a ring method is mechanically pulling fabric sample through a ring and measuring the resistance (force). It is not a method giving a singular value, but the acquired force-deflection curve reflects the different mechanics and forces affecting the fabric when pulled through the orifice. Several different sample sizes, sample shapes and ring types have been used during the research in the area [13; 6; 9]. The analysis of the curve shapes [6; 38] is another subject of high interest.

In this work a solid funnel was chosen, implementing the findings of others [13; 6], but not least due to material availability and producibility. The steel funnel was milled at TUT according to the design shown in appendix A.2. The surface was not polished nor coated. Instead of a pushing needle used for example in KTU-Griff-Tester device [9], a rigid pulling pin attached to a tensile tester sensor was used. A plastic bead was used to hold the fabric while pulling it through the funnel. No supporting plates were implemented.

After initial system testing deflection speed of 10 mm/min was chosen as the faster speeds gave less detailed curves. Bead diameter of 9 mm was chosen as it was big enough to inhibit specimen from slipping off the pin, still being as small as possible not to interfere with the measurements.

A small incision of 3 mm was made into the centre of the 250 mm circular specimen to allow the pulling pin to be inserted through the fabric. The bead was clipped on the bottom of the pulling pin and the fabric was allowed to drape freely over the bead. The specimen was then pulled up, eventually exiting the funnel entirely with no more interaction with the funnel. The force-displacement curve was produced by the tensile tester for 5 specimens per sample.

Maximum force was used as the indicator of fabric stiffness, as is in ASTM D4032-94 standard [1]. Maximum force was given as a mean value, calculated from the specimen measures.

5. RESULTS AND DISCUSSION

This chapter presents the results and discussion of the original research questions posed in the introduction to this thesis. Topics follow the hierarchical structure of fabrics - fibre level followed by fabric level. The individual results are presented and discussed, ending in a level-wise comparison of results.

5.1 Fibre characterization

5.1.1 SEM-imaging

Scanning electron microscope images were acquired for all the fibres examined in this thesis. Figure 5.1 shows the scale-like surface structure of BCS. The fibre has a round, elliptical cross-section.

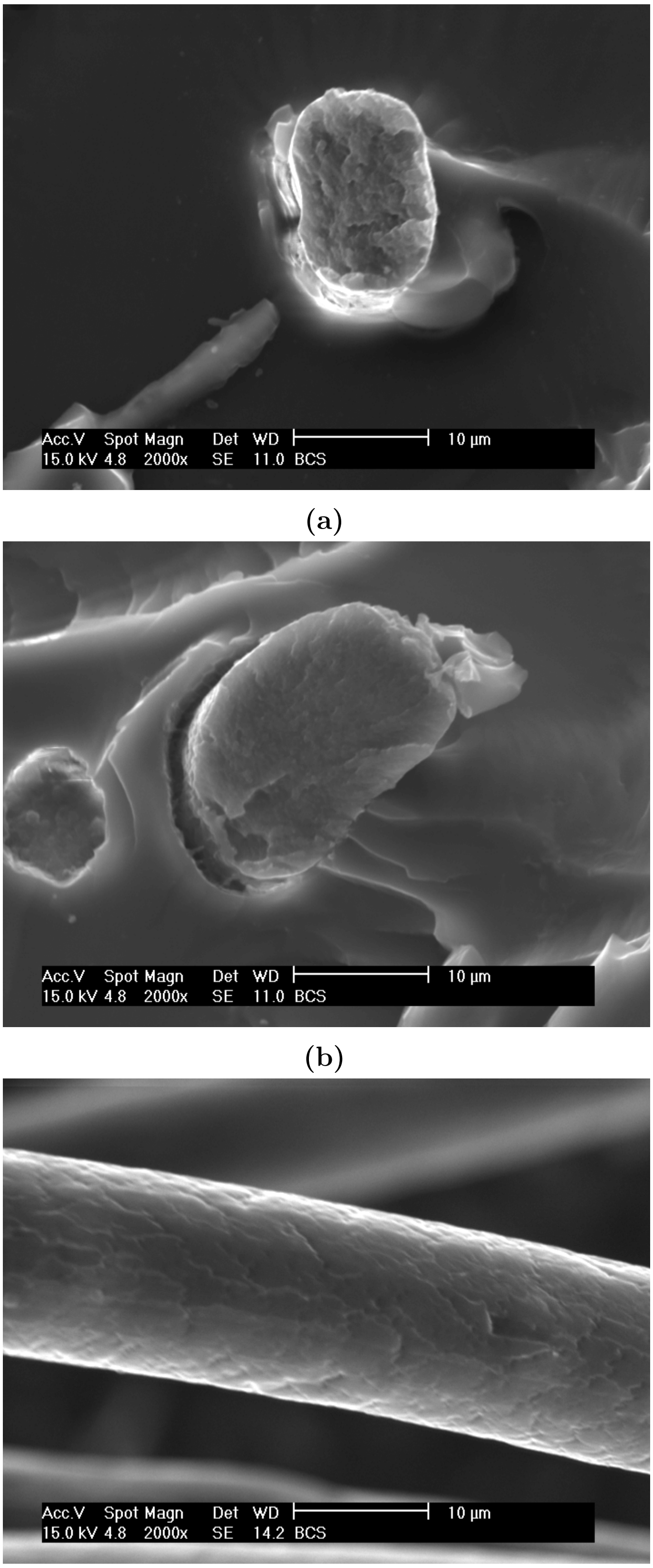
Figure 5.3 gives a good show of the familiar structure of cotton fibre. The fibre is twisted and has a bean like cross-section.

Viscose in figure 5.5 shows the crenulated cross-section and twist of the fibre. Images in figure 5.2 show the smooth surface of the CCA fibres. The cross-section, reminding that of viscose, shows the fibrillated inner structure.

ION-fibres, shown in figure 5.4, have a clear fibril structure core held together by the fibre skin. The surface on the round fibre is smooth.

Unfortunately the specimen preparations failed with PLA. But from the acquired images, figure 5.6, we still can see the smooth surface and circular cross-section of the fibre.

The resin method used to prepare the samples produced mainly good specimens for scanning electron microscopy. Due to the nature of SEM some materials, especially PLA, were sensitive for prolonged exposure.

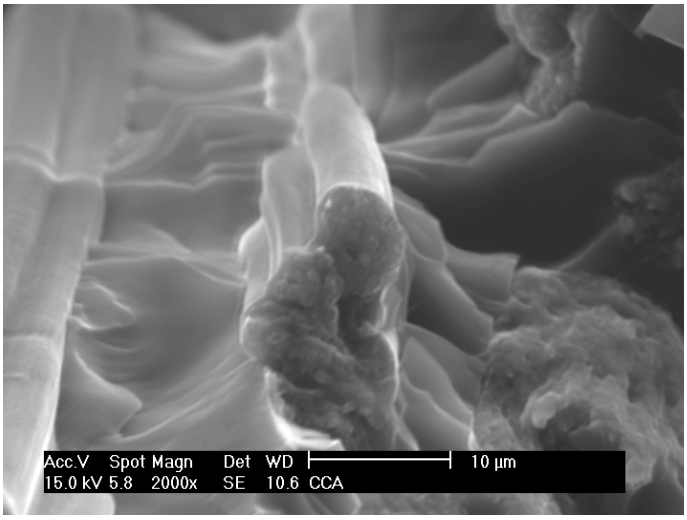


(a)

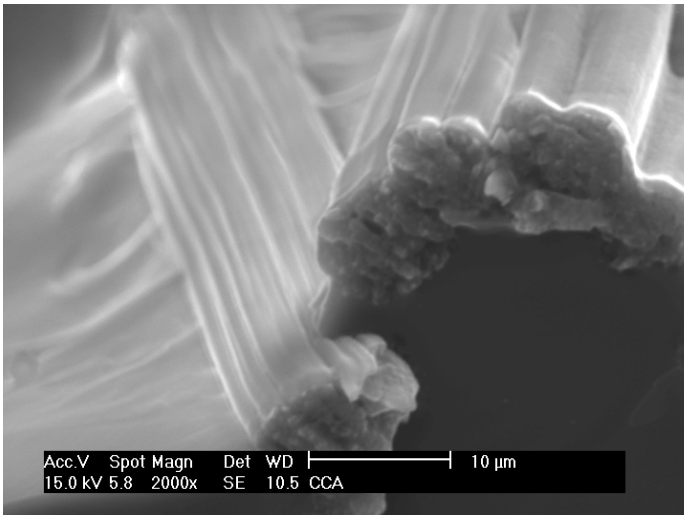
(b)

(c)

Figure 5.1: SEM-pictures of BCS - Biocelsol fibres



(a)



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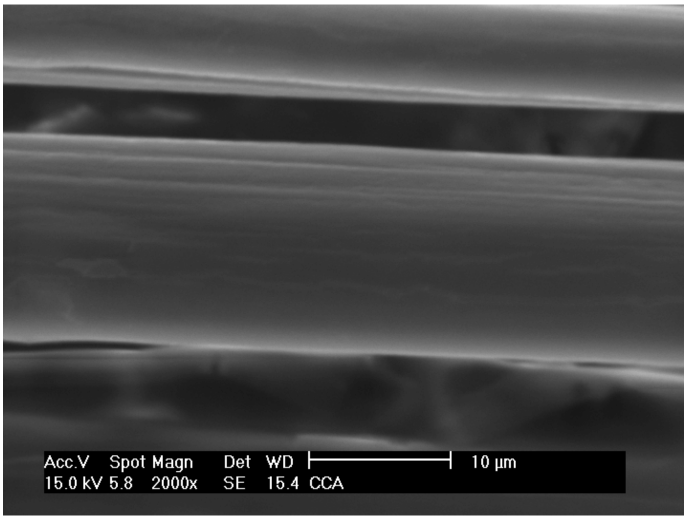
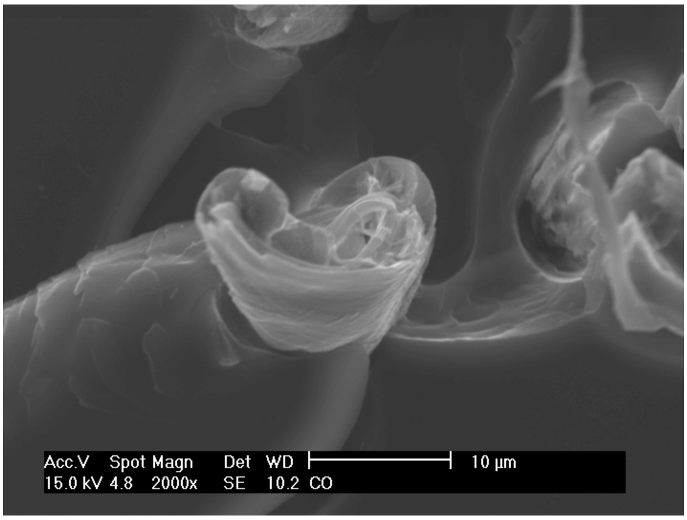
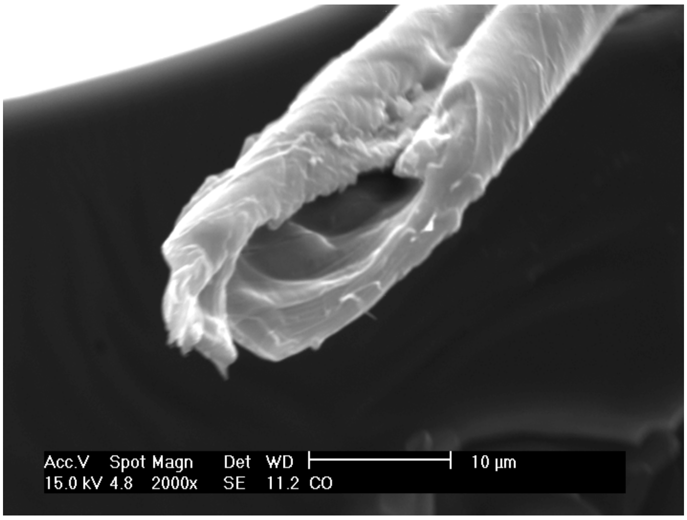


(c)

Figure 5.2: SEM-pictures of CCA - Cellulose Carbamate fibres



(a)



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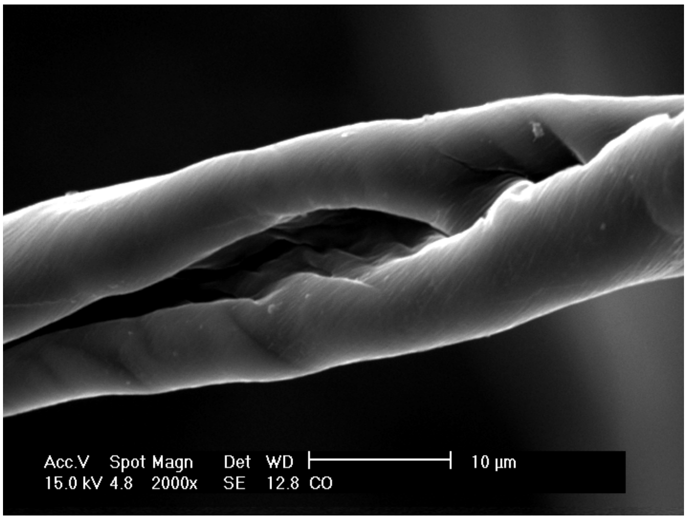
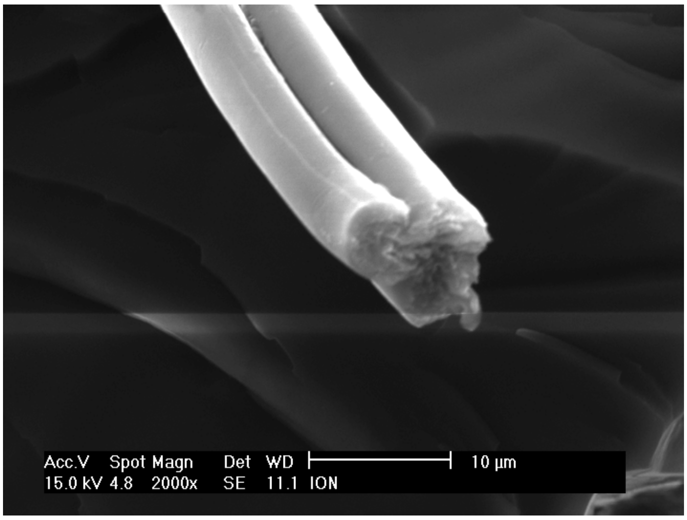
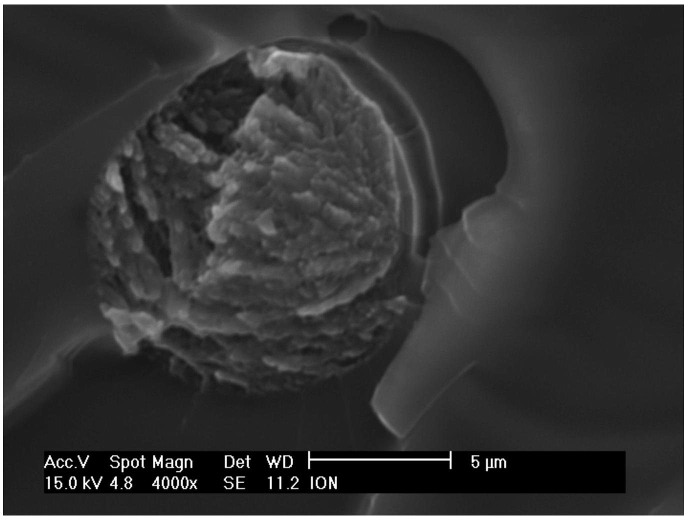


(c)

Figure 5.3: SEM-pictures of CO - Cotton fibres



(a)



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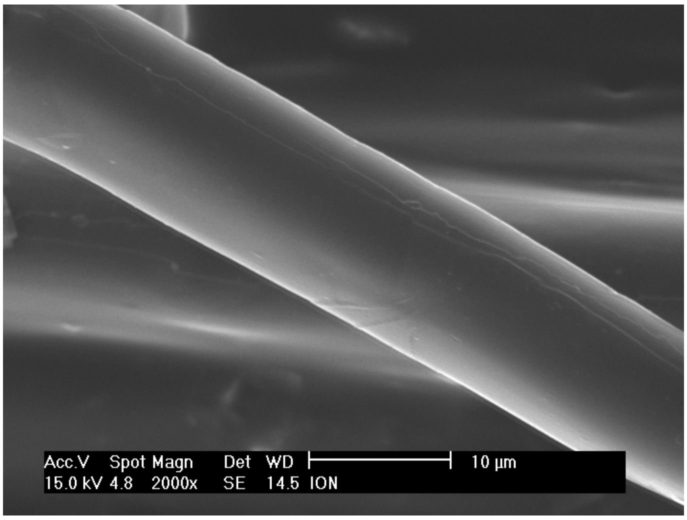
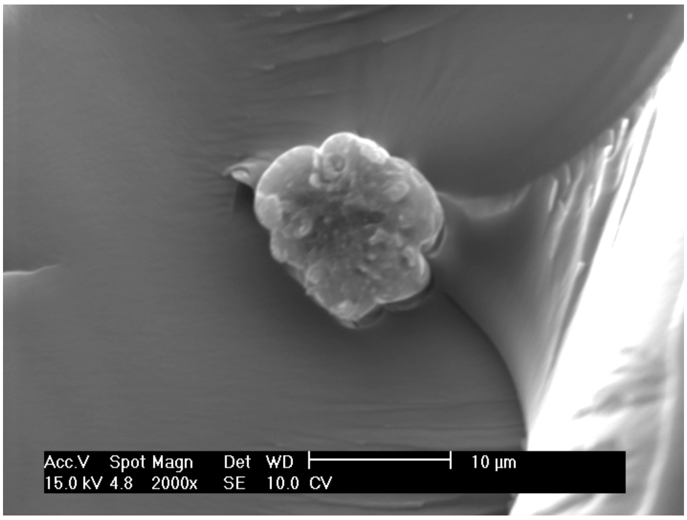


(c)

Figure 5.4: SEM-pictures of ION - Ioncell fibres



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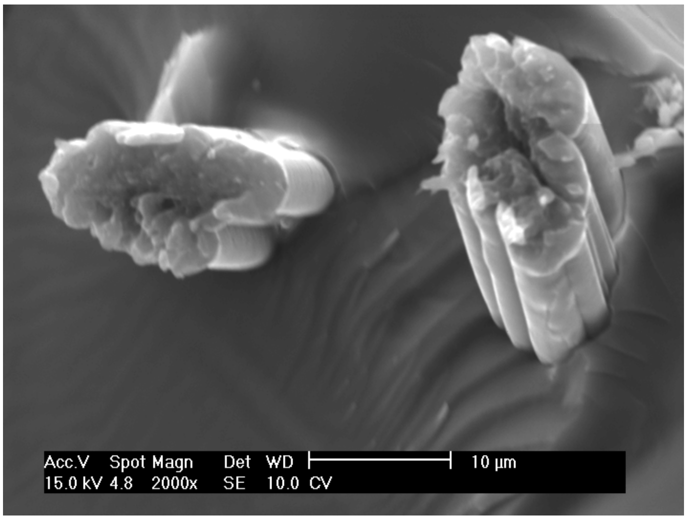

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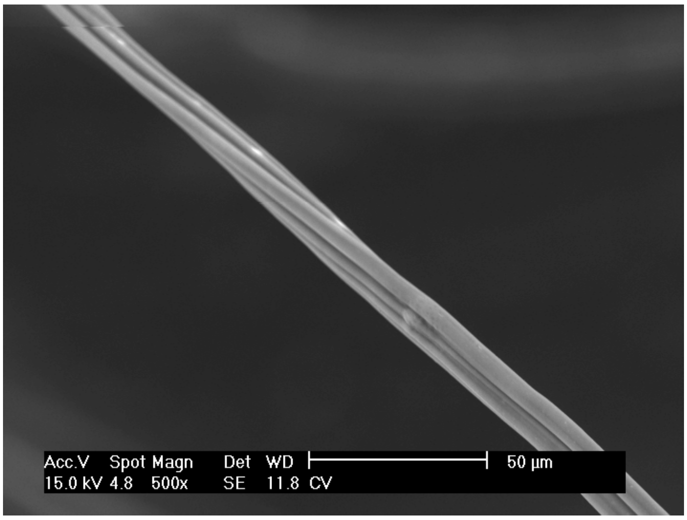
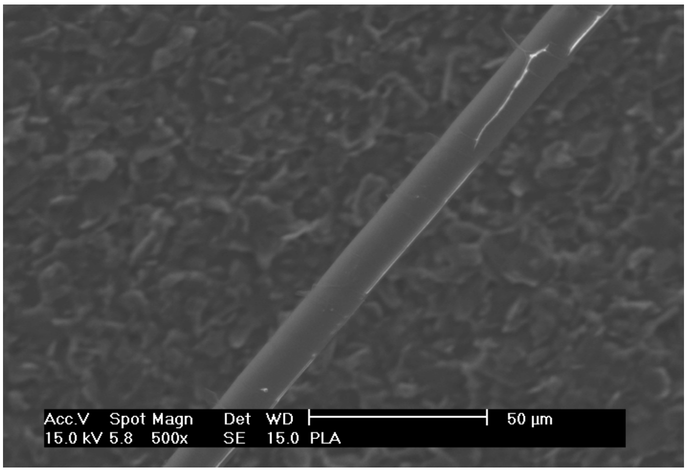
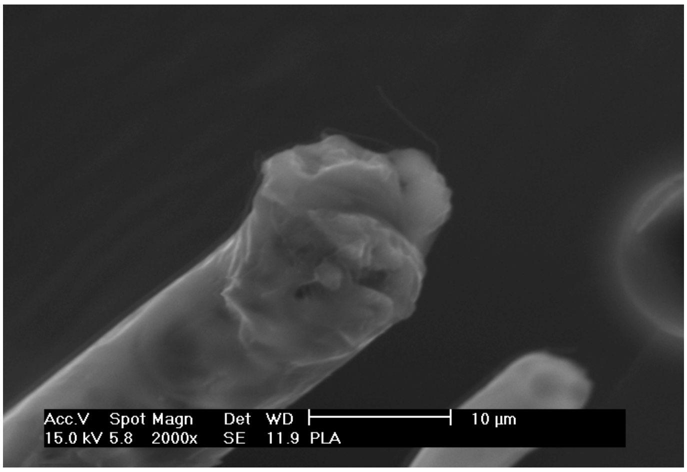


(c)

Figure 5.5: SEM-pictures of CV - Viscose fibres



(a)



(b)

Figure 5.6: SEM-pictures of PLA - Poly(lactic acid) fibres

5.1.2 Mechanical properties

The fundamental mechanical properties of the fibres were evaluated using Textechno Favigraph and the results are shown in table 5.1. Used load cell was 20 cN and 100 mg pretension weight was used in most of the measurements executed. With PLA and CO fibres the gauge length and test speed had to be changed to adapt to the fibre lengths. Gauge length of 10 mm and test speed of 10 mm/min were used for the two fibre types, the rest were measured with 20 mm and 20 mm/min values respectively.

Table 5.1: Fibre mechanical properties

Fibre	Linear density [dtex]	Tenacity [cN/dtex]	Mod.E 1(0..1%) [cN/dtex]	Elongation [%]
BCS	2.04 ± 0.33	1.14 ± 0.18	38.32 ± 4.44	15.90 ± 3.94
CCA	1.71 ± 0.21	1.7 ± 0.20	48.44 ± 5.29	14.75 ± 2.24
CO	1.68 ± 0.48	2.54 ± 1.08	32.35 ± 17.77	8.31 ± 2.61
ION	1.63 ± 0.16	4.46 ± 0.56	106.51 ± 13.31	7.25 ± 1.19
CV	1.80 ± 0.12	2.11 ± 0.14	42.50 ± 5.16	17.38 ± 1.16
PLA	1.70 ± 0.23	1.9 ± 0.72	25.04 ± 10.09	33.76 ± 10.72

Looking at the linear density values, the fibres are mostly in the same scale with BCS and ION representing the extremes. If put in fineness order, the fibres follow the same pattern in tenacity values as well, in reverse order ION having the highest tenacity value.

The spinning method and it's parameters have a large effect on the sub-fibre structure and the properties of the fibre. BCS, CCA and CV are all wet spun fibres, that usually form a skin-core structure during the process, visible in the SEM-pictures in chapter 5.1.1. The core exhibits more porous fibril structure, also dependant on spinning parameters, and may induce better flexibility in the fibre. [52, pp. 326-345]

Depending on the end use, PLA can be produced with quite a broad range of tenacity values [31]. The content and arrangement of the three stereoisomers have an effect on the mechanical performance of the PLA fibres. Melt spun fibres often display high orientation resulting in high tenacity, but the sampled PLA showed low tensile properties and high elongation.

The higher level of variance in the measurements for CO is explainable through the nature of the fibres. Natural fibres tend to vary a lot compared to man-made fibres. Cause for high variance with PLA may be due to high crimp in the measured fibres. Also the shorter gauge length may show in the reliability of the measurements.

5.1.3 Flexibility

Results of the individual fibre flexibility, the reciprocal of flexural rigidity (of a bar), measurements are listed in table 5.2, where a high value represents high flexibility. Seven specimens were measured per sample, with ten measurement cycles executed per specimen. 10 µm deflection from the rest state of the fibre was created, producing vertical force to the centre of the fibre, for 5 seconds. Between every cycle there was a 5 second rest with no external force applied.

During the measurements some of the sensitive force sensors were broken, leading to the need to change the type of sensors in the middle way. The measuring process also involved visual operations, such as defining the fibre measure length and centring the force sensor in relation to the fibre. These factors may have had an impact on the results achieved. The low amount of measurements had its impact on the results as well, with the variation being relatively high.

The ION fibres were probably produced in small batches in multiple rounds. This may have caused the used sample to have fibre specimen from several different spinning batches, increasing the variance.

Table 5.2: Individual fibre flexibility properties

Fibre	Measure length [µm]	Load [µN]	Flexibility [$nN^{-1}m^{-2}$]
BCS	727.20	154.10	38.21 ± 17.83
CCA	967.44	109.32	29.80 ± 17.55
CO	938.75	240.28	12.31 ± 5.50
ION	760.37	369.12	20.29 ± 21.92
CV	697.54	208.04	28.97 ± 7.56
PLA	1008.60	139.49	16.04 ± 5.42

BCS shows best performance in flexibility, the viscose fibre CV showing good flexibility as well. Cotton fibre (CO) has the lowest flexibility, conforming to the description of cotton fibres being inelastic and rigid.

From the equation 2.1 we see the relation between fibre flexural rigidity and fibre shape, tensile modulus, density and thickness. Fineness has the most influence in the flexural rigidity, in the power of four. Resistance to bending is heavily related to fibre fineness, in other words the finer the fibre the higher the flexibility should be [36, pp. 103] [4, pp. 210]. Disregarding the high variation, the flexibility values listed in table 5.2 do not seem to follow the generalization.

The initial or Young's modulus indicates the extension under small stress, and could be regarded as a pointer to the behaviour in measurements with similar stress conditions. The method implemented in measuring the fibre flexibility uses low forces and as such one might prefer to compare flexibility values with the initial modulus values of the fibres.

5.1.4 Result comparison

In figure 5.7 the mean values of the characterization results have been visualised, showing the relation of fibre modulus and flexibility. The difference between the measurements for ION is explainable with the high variation. With renewed flexibility measurements and using fibres from same batch, the correlation might be higher. Disregarding ION the Pearson's correlation coefficient between the two measurements is over 60 %.

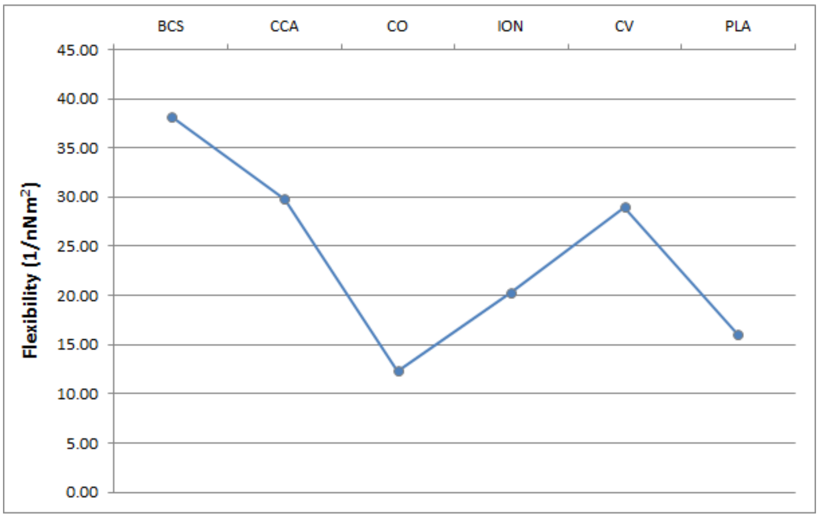
5.2 Fabric characterization

Sample BCV was manufactured into dimensions not adequate for all the measurements, thus some of the measurements were not carried out on this material. The fundamental properties of the fabrics: fabric type, thickness, mass per unit area and stitches/threads per unit length are listed in the table 5.3.

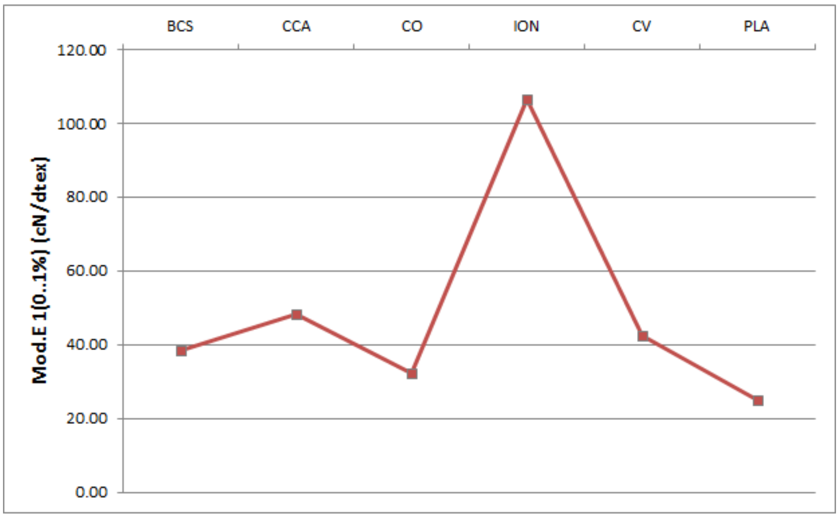
Table 5.3: Fabric fundamental properties

Fabric type	**Sample**	**Thickness [mm]**	**Mass per unit area [g/m^2]**	**Stitches/threads per unit length (MD/CMD) [cm^{-1}]**
Woven	FCO	0.34 ± 0.01	131 ± 0.95	25/20
	ECV	0.25 ± 0.01	136 ± 1.02	48/36
Knit	OCO	0.65 ± 0.01	197 ± 2.30	14/19
	OCV	0.65 ± 0.01	202 ± 4.73	13/18
Non-woven	BCP	0.58 ± 0.02	56.9 ± 3.53	-/-
	BPCC	0.77 ± 0.03	55.1 ± 1.64	-/-
	BCV	0.58 ± 0.01	78.2 ± 2.44	-/-

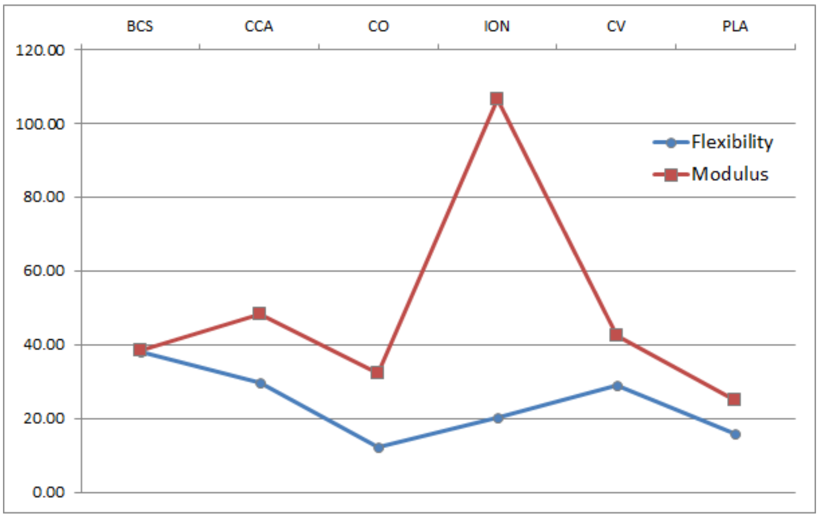
Looking at values we can see the masses per unit area are generally the same according to the fabric type. BCP and BCV have the same thickness, but differ in mass per unit area. BCP is 35% PLA, which has a lower density than viscose, lowering the mass of BCP compared to BCV consisting only of viscose. BCP and BPCC have similar mass per unit area, but differ in thickness. This is due to the hydro embossed dots in BPCC, making it thicker.



(a) Flexibility



(b) Modulus



(c) Modulus and Flexibility

Figure 5.7: Fibre Characteristics

The woven fabrics differ in threads per unit length, ECV with nearly double the yarn density compared to FCO. Finer viscose fibres and probably yarns as well show in thickness and mass per unit area of the woven fabrics. The knitted fabrics are almost identical.

5.2.1 Compression

Compression properties acquired with the Kawabata system are listed in table 5.4. The characteristics of the fabric yarn levels - such as the yarn twist - most likely have a high impact on the compressional behaviour but, again, will not be discussed in this work.

Table 5.4: Fabric compression properties

Fabric	Linearity in compression (LC)	Work of compression (WC) [gfcm/cm^2]	Compressional resilience (RC) (%)	Compressibility (EMC) (%)
FCO	0.27 ± 0.04	0.16 ± 0.02	46.68 ± 3.42	50.28 ± 2.56
ECV	0.28 ± 0.03	0.13 ± 0.01	81.99 ± 5.85	59.25 ± 2.27
OCO	0.31 ± 0.02	0.40 ± 0.02	36.30 ± 1.58	51.12 ± 3.47
OCV	0.28 ± 0.02	0.27 ± 0.03	46.51 ± 1.95	45.36 ± 3.14
BCP	0.43 ± 0.02	0.24 ± 0.02	48.05 ± 2.70	42.64 ± 2.94
BPCC	0.42 ± 0.03	0.56 ± 0.04	46.30 ± 2.22	56.01 ± 2.69
BCV	0.49 ± 0.02	0.33 ± 0.03	50.88 ± 1.49	39.03 ± 3.39

The woven fabrics have the lowest work of compression (WC) values. Knit fabrics often have a more open and volumetric structure compared to woven fabrics, requiring more force, though low, to compress the fabric. Also yarn slippage may occur in earlier stages of the compression process inducing frictional forces.

The non-woven and knitted fabrics gave similar WC results, with BPCC and OCO differing with moderately high values. BPCC's higher value is most likely due to the texturized form and thickness of the fabric. The mentioned volumetric structure combined with rigid fibres may be the cause for OCO having higher value.

The viscose fabrics, ECV and OCV, show higher compressional resilience (RC) values compared to their cotton counterparts. The nature of viscose fibres might induce creep in the fabric, showing as resilience in the measurements with the used measuring speed.

5.2.2 Bending

The bending properties of fabrics, more specifically the bending rigidity (B) and hysteresis in bending (2HB), were measured with Kawabata system and the results are listed in table 5.5. The correlation between B and 2HB has been proved to be high [42] so the latter will not be examined.

Problems occurred while positioning samples in the KES equipment, especially with the more limp knit fabrics. This may have resulted in measuring fabrics in biased directions, showing as excessive variation in some of the results.

Table 5.5: Fabric bending properties

Fabric	**MD**		**CMD**	
	Bending rigidity (B) [gfcm^2/cm]	**Hysteresis in bending (2HB) [gfcm/cm]**	**Bending rigidity (B) [gfcm^2/cm]**	**Hysteresis in bending (2HB) [gfcm/cm]**
FCO	0.14 ± 0.02	0.14 ± 0.02	0.040 ± 0.01	0.042 ± 0.01
ECV	0.04 ± 0.001	0.02 ± 0.001	0.034 ± 0.003	0.019 ± 0.001
OCO	0.03 ± 0.01	0.03 ± 0.02	0.017 ± 0.01	0.012 ± 0.02
OCV	0.003 ± 0.003	0.003 ± 0.01	0.003 ± 0.002	0.007 ± 0.01
BCP	0.09 ± 0.03	0.10 ± 0.01	0.006 ± 0.001	0.012 ± 0.01
BPCC	0.05 ± 0.01	0.06 ± 0.01	0.005 ± 0.001	0.008 ± 0.004
BCV	0.11 ± 0.06	0.13 ± 0.05	0.007 ± 0.001	0.006 ± 0.004

The effect of material is evident in bending rigidity - both cotton fabrics are clearly more rigid than their viscose counterparts (table 5.5). This is more evident with the knit fabrics which are quite similar by their fundamental properties (table 5.3). Similarly the fabric type or construct influences fabric behaviour with woven fabrics having higher bending rigidity values.

Regardless of BPCC being the thickest of the three non-woven fabrics, it has the lowest bending rigidity. The embossed dots in BPCC (see figure A.6) add to the total thickness of the fabric, but due to the uneven volumetric or vertical structure it should perhaps be disregarded in evaluation in this context. Visually inspected BPCC seems structurally less dense (along fabric area), but there was no specific testing to support this.

It seems the dots add another level of structure to the BPCC fabric, contributing to the bending properties: bending along the structure (bending in cross machine direction) shows better results than across the structure (machine direction). Similar structural bending behaviour may be seen in the other fabrics as well. For example both woven fabrics have fewer threads along the production direction (MD) bending compared to cross-production direction (CMD) bending. The other two non-woven fabrics show a oriented structure along the machine direction and the knit structures align with the production direction (MD) as well. The bending rigidity values would confirm the trend.

The already mentioned influence of fibre material seems not to correlate with the values measured for BCP and BCV. Moderate variation may explain the reverse results, but with a shared thickness they do differ in mass per unit area, denoting of differences in density. The higher density of BCV shows as a higher elastic modulus of the material (here the fabric) and respectively as a higher bending rigidity.

5.2.3 Flexural rigidity

The flexural rigidity of every fabric was evaluated with the cantilever method, calculated from the bending length, both along the production direction (MD) and perpendicular to the production direction (CMD). Evaluation results for fabric flexural rigidity, expressed as flexural rigidity of a plate, are listed in table 5.6. The measurement is similar to fabric bending, giving similar results.

Table 5.6: Fabric flexural rigidity properties

Fabric	**Direction**	**Flexural rigidity [mNcm]**
FCO	MD	2.59 ± 0.68
	CMD	0.55 ± 0.06
ECV	MD	0.34 ± 0.08
	CMD	0.36 ± 0.05
OCO	MD	0.62 ± 0.05
	CMD	0.24 ± 0.02
OCV	MD	0.02 ± 0.003
	CMD	0.04 ± 0.004
BCP	MD	2.16 ± 0.22
	CMD	0.10 ± 0.02
BPCC	MD	0.97 ± 0.10
	CMD	0.09 ± 0.01
BCV	MD	3.02 ± 0.30
	CMD	0.08 ± 0.01

See chapter 5.2.2 for more detailed analysis, but in short there is a notable difference between results along the production direction (MD) and across (CMD). This is due to structural alignment and bias. Also the influence of fibre material, fabric type and in the case of the non-woven fabrics the density shows in the flexural rigidity.

5.2.4 Drape coefficient

Drape coefficient values are listed in 30 cm sample size for every fabric sample. According to the standard used in the measurements another sample size was used for those fabrics nearing the extremities of the drape coefficient scale with the initial sample size. This allows bringing out more precise differences.

With samples in table 5.7 showing low values, a smaller sample size was used. This was the case with the viscose based fabrics, ECV and OCV, and the cotton fabric OCO.

Table 5.7: Fabric drape

Fabric	Sample size (cm)	Side	Drape coefficient
FCO	30	Front	51.28 ± 2.63
		Back	58.82 ± 1.76
ECV	30	Front	20.35 ± 0.35
		Back	21.82 ± 0.67
	24	Front	54.83 ± 1.24
		Back	67.21 ± 1.90
OCO	30	Front	22.06 ± 0.89
		Back	21.08 ± 1.24
	24	Front	62.29 ± 6.99
		Back	59.71 ± 3.10
OCV	30	Front	3.35 ± 0.11
		Back	3.15 ± 0.21
	24	Front	11.00 ± 0.32
		Back	10.50 ± 0.24
BCP	30	Front	54.74 ± 2.10
		Back	57.55 ± 3.61
BPCC	30	Front	44.87 ± 1.45
		Back	46.60 ± 6.16
BCV	No measurements made		

The low drapability of woven fabrics and higher drapability of knit fabrics are axioms represented in basic literature (for example [14]) and supported by the results. Knitted fabrics show a high difference with low forces (initial modulus) compared to woven fabrics [30, pp. 67-68]. This is explainable with the knitted fabrics' loop structure, allowing the dispersion of the low forces into structural rearrangement (freedom of yarn slippage). The non-woven fabrics have a less homogeneous structure and a higher level of bonding between individual fibres.

Looking at the measured values, the viscose knitted fabric (OCV) has the best drape with clearly the lowest drape coefficient. The non-woven BCP and woven FCO are the fabrics with next best drape.

Non-woven fabrics should have the closest relation between the fibre and fabric performance, with no yarn-level structure involved. Based on this notion and the raw material consistency, BCP with more viscose and no cotton compared to BPCC should show a better drape. As suggested earlier, the texture of BPCC may induce flexural properties overweighing the effects of the fibre level.

Influence of the side of the fabric is mainly negligible, even though the woven fabrics show a difference between the front and back. The woven fabrics are structurally identical on both sides, so the difference may be due to a measuring error or possible finishing. The non-woven fabric, BPCC, with PLA “patches” on the technical back on the other hand shows no notable difference in the drape between the sides.

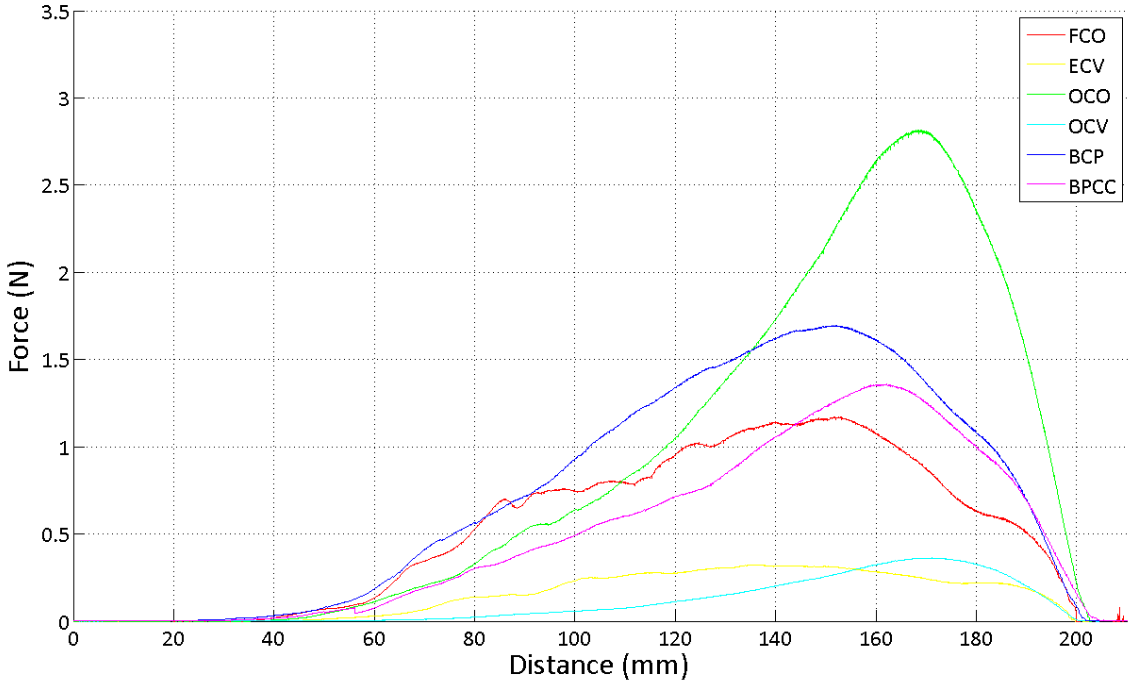
The effect of fibre and yarn surface properties, including and inducing friction, probably have an effect on the capability of intra-structural rearrangement of a fabric. With plain woven-fabrics there is a high level of contact between the yarns and thus intra-structural friction.

5.2.5 Funnel nozzle extraction method

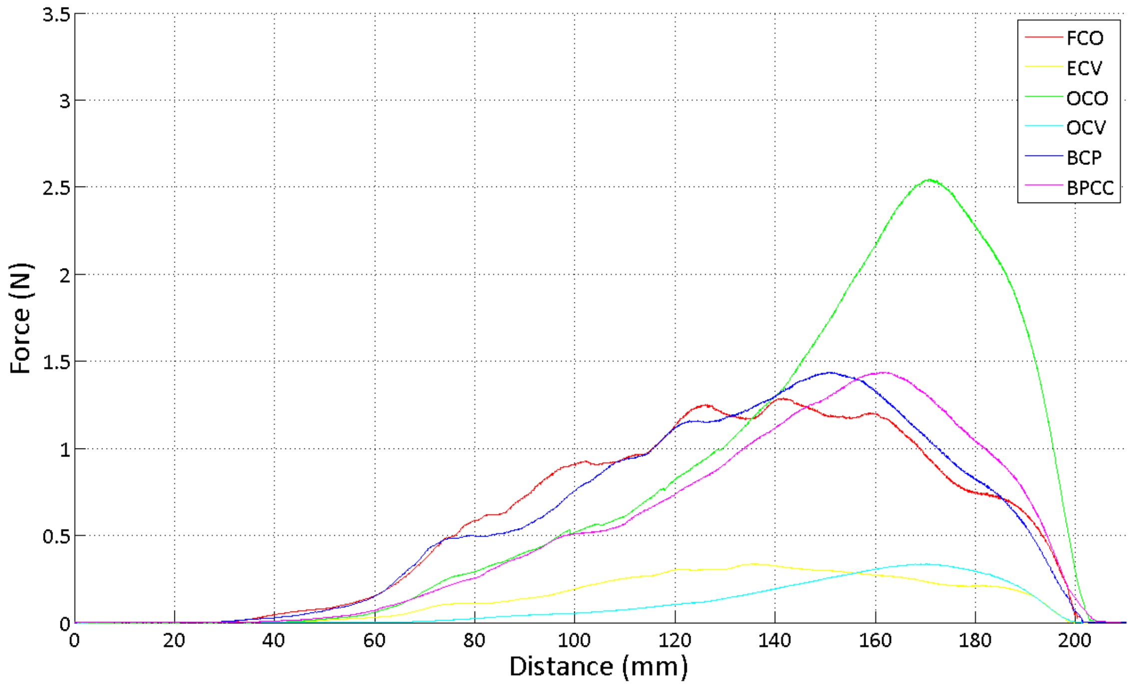
The force-deflection curves acquired with the funnel nozzle extraction method are shown as mean (value) curves in figure 5.8. The maximum force values are listed in table 5.8. Even though calculating mean value curves for a sample flattens the curve shapes compared to individual curves (for example figure 5.9), the difference between samples is distinguishable. This allows the categorization of fabrics or following characteristic changes due to parameter changes for example.

The results listed in table 5.8 show that viscose based fabrics (ECV and OCV) need clearly the least work to be extracted through the nozzle, regardless of the fabric structure. Cotton based fabrics need more work, interestingly the cotton knit having the largest values. The differences between sides are negligible.

Slip-stick effect was evident throughout the measurements with the used funnel. Ideally the used extraction orifice would have so polished surface that there would be next to none friction inflicted by it. Unfortunately the surface was in this case fairly rough. This might be the reason for higher force values with materials more adjusting to the shape of the funnel, for example the knitted fabrics, creating more friction surface area.

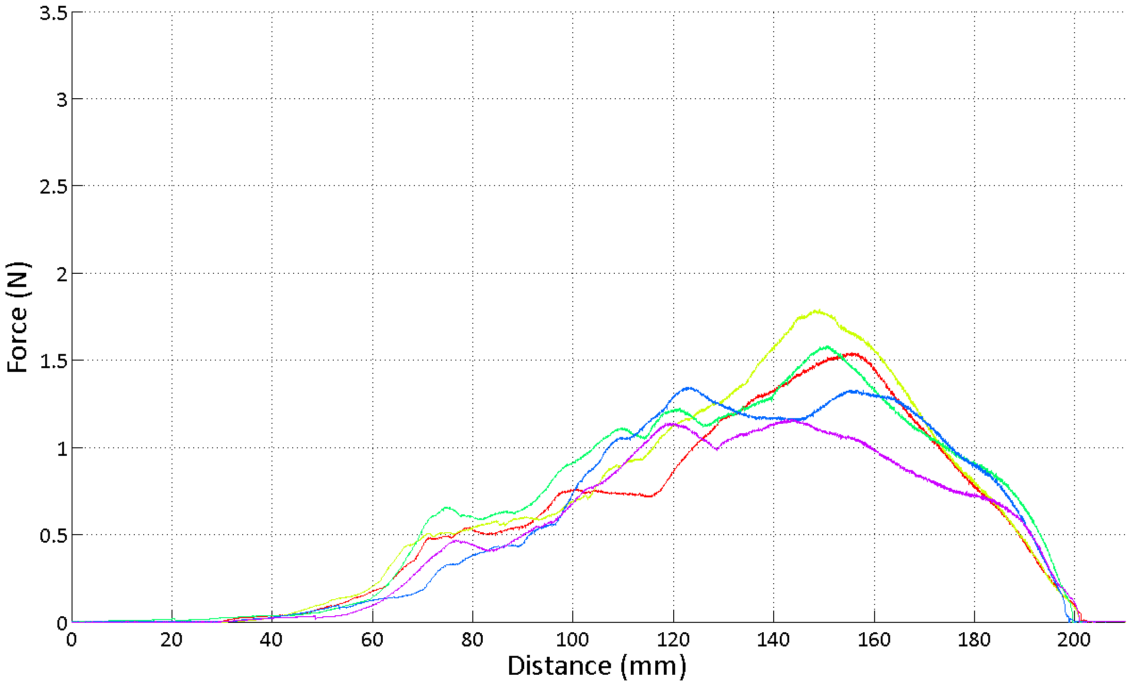


(a) Technical front

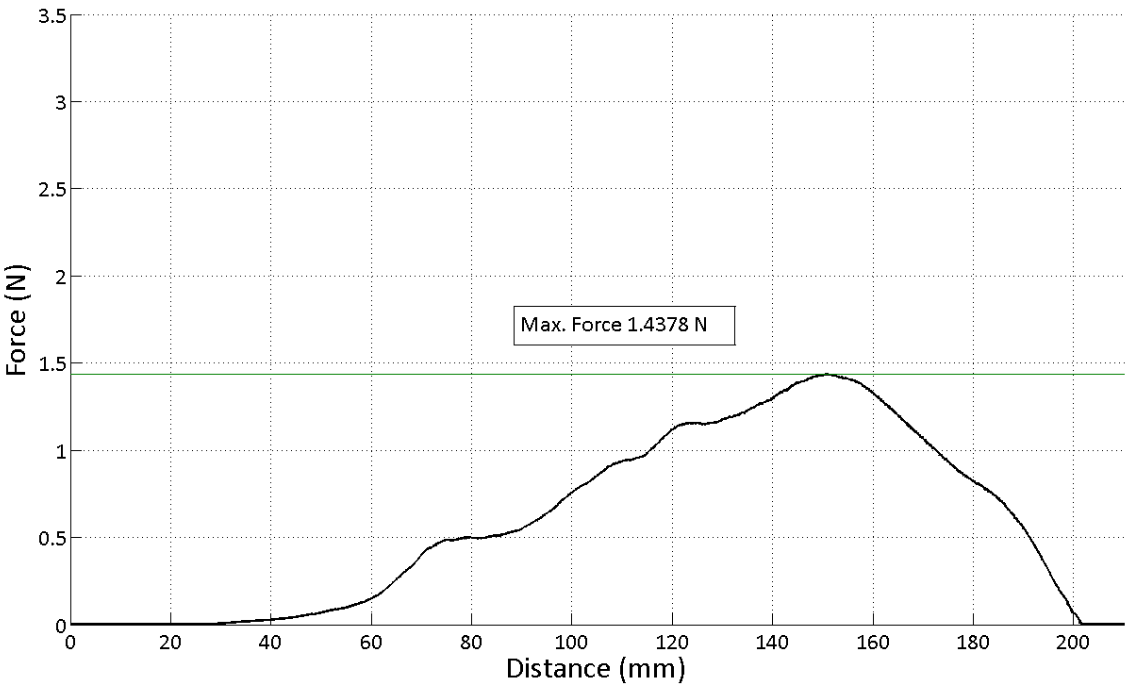


(b) Technical back

Figure 5.8: Fabric force-deflection mean curves during funnel nozzle extraction



(a) Individual measurement curves



(b) Mean curve

Figure 5.9: Examples of fabric force-deflection curves during funnel nozzle extraction

Table 5.8: Fabric extraction from a funnel nozzle

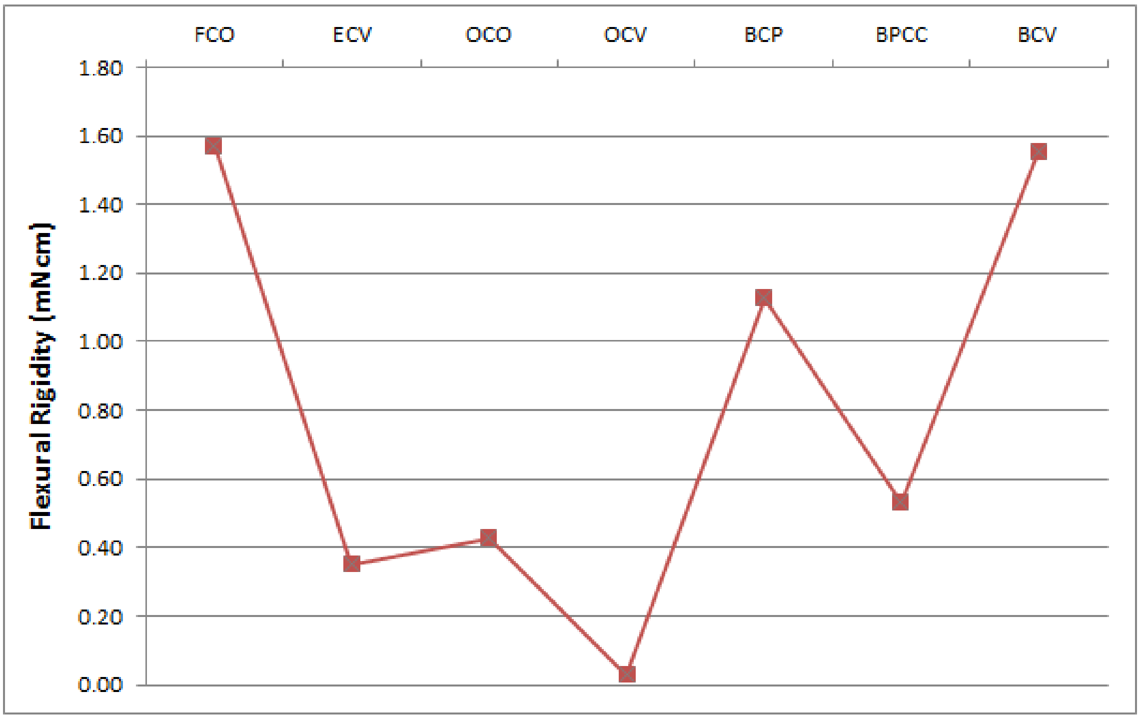
Fabric	Side	Maximum force [N]	Work [$Nm \times 10^{-3}$]
FCO	TF	1.37 ± 0.22	107.94 ± 17.29
	TB	1.54 ± 0.21	122.53 ± 13.98
ECV	TF	0.38 ± 0.05	30.67 ± 2.95
	TB	0.38 ± 0.03	29.55 ± 1.87
OCO	TF	2.90 ± 0.31	186.24 ± 21.78
	TB	2.57 ± 0.47	160.19 ± 13.33
OCV	TF	0.38 ± 0.06	21.78 ± 2.84
	TB	0.34 ± 0.05	20.20 ± 2.73
BCP	TF	1.79 ± 0.22	150.82 ± 11.06
	TB	1.48 ± 0.24	134.65 ± 17.45
BPCC	TF	1.39 ± 0.17	125.27 ± 25.54
	TB	1.47 ± 0.16	127.64 ± 23.66

5.2.6 Result comparison

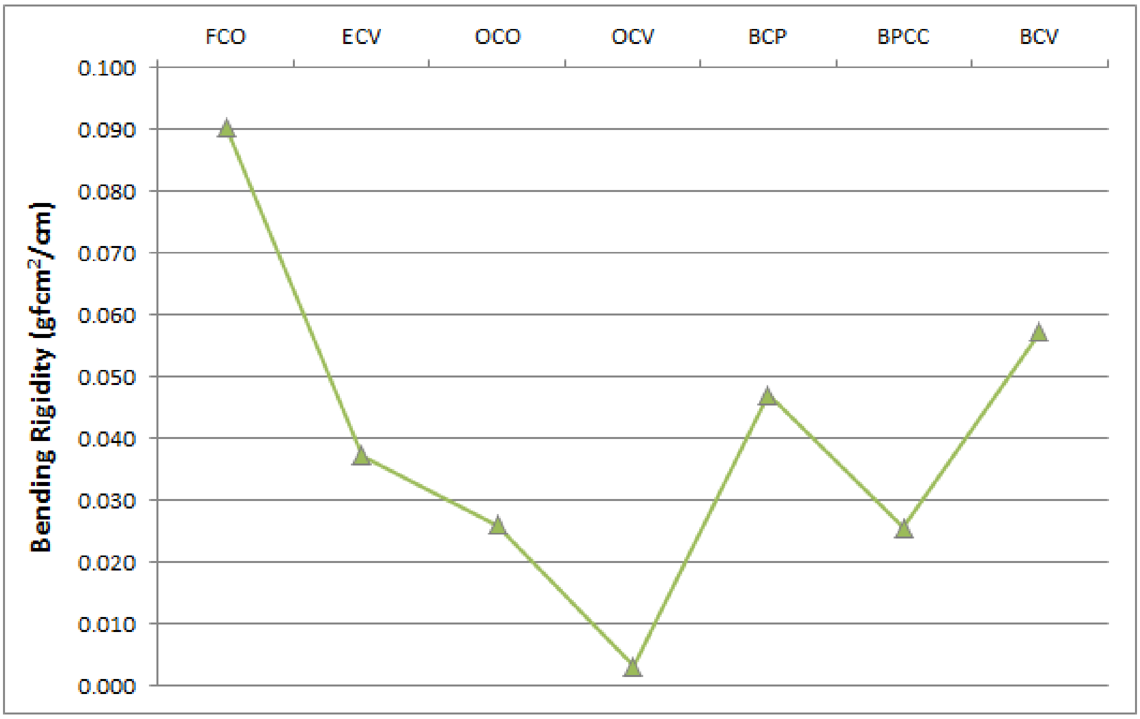
Figure 5.10 shows the fabric-wise mean results gathered from the fabric characterization methods. Drape was measured with different size samples with the acquired coefficients given as percentage values. To make the values easier to present, the values from smaller sample size were divided by 100. This allows the values to be presented logarithmically between 0 and 100 percent in the same figure and makes comparison possible.

In figure 5.11 the examined fabrics have been ordered in ranking order (1 is best) according to the carried out measurements. Mean values of the individual measurements were used to rank the fabrics, disregarding the differences between measurement directions and/or fabric sides.

Pearson's correlation coefficients between the measurements are listed in table 5.9 in order of correlation. It is clear, that the maximum extraction force does not correlate too highly with the other measurements, besides work of compression. As is expected, there is high correlation between drape, flexural rigidity and bending rigidity.

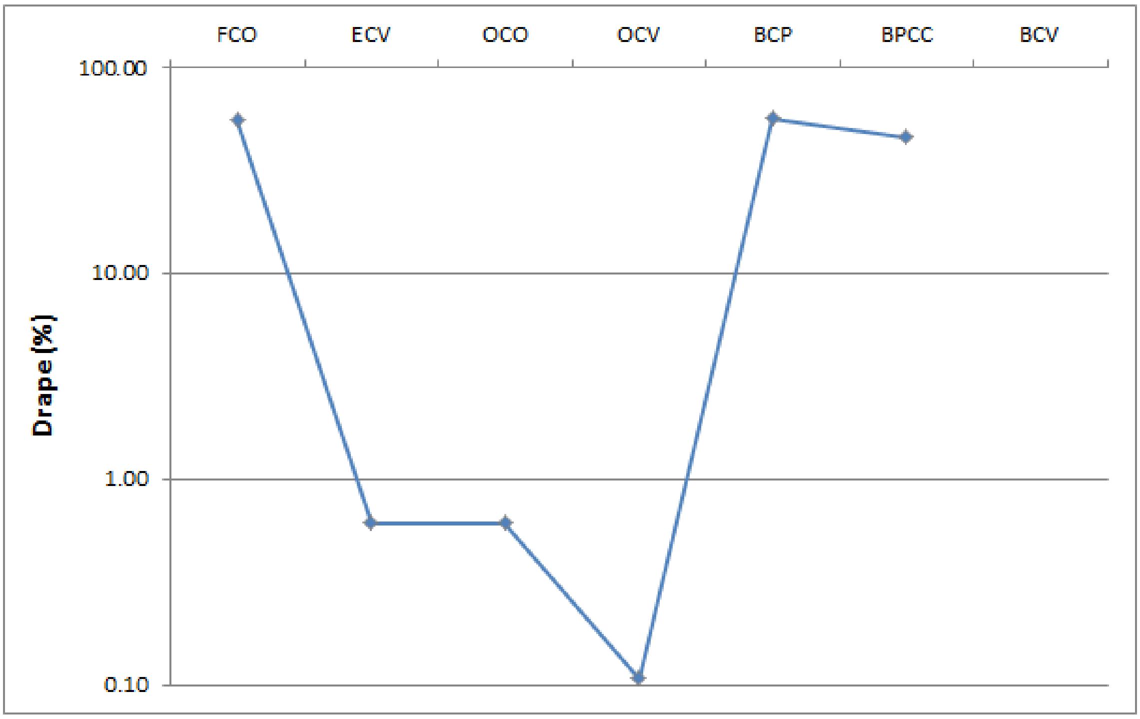


(a) Flexural rigidity

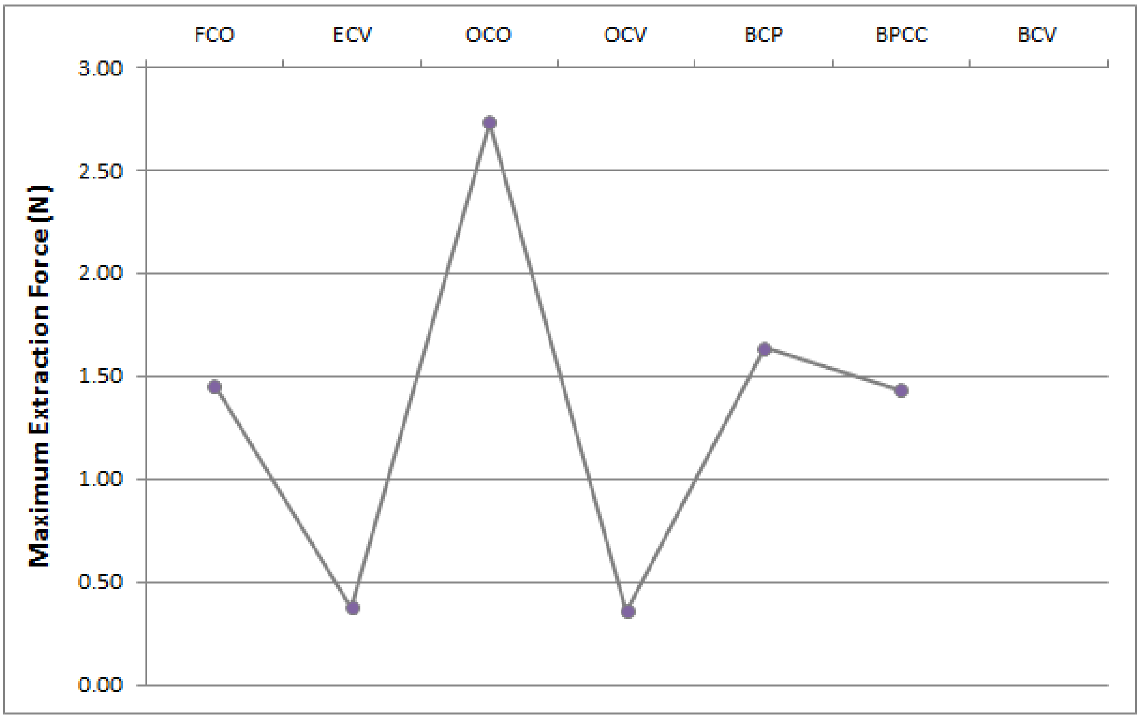


(b) Bending rigidity

Figure 5.10: Fabric characteristics



(c) Drape



(d) Extraction force

(continued) Fabric characteristics

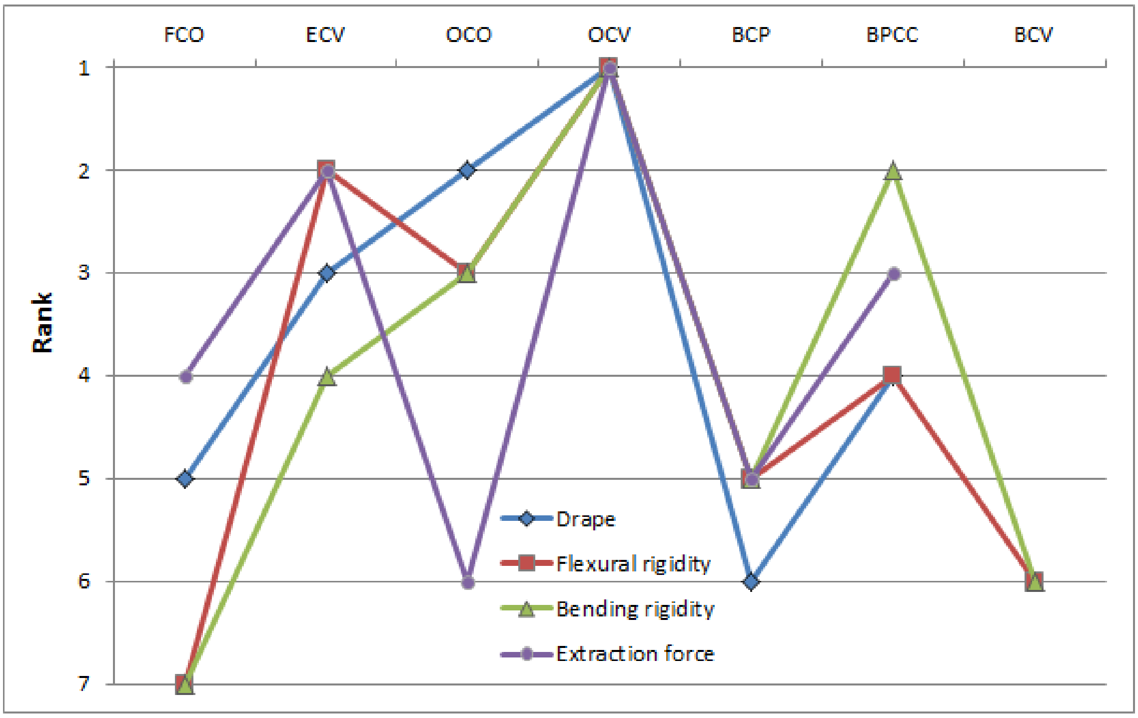


Figure 5.11: Fabric ranking

Table 5.9: Correlation between fabric characterization measurements

Measurement	Measurement	Pearson's Correlation Coefficient (%)
Flexural rigidity	Bending rigidity	90.34
Drape coefficient	Flexural rigidity	83.75
Compressional resilience	Bending rigidity	82.65
Flexural rigidity	Compressional resilience	78.16
Drape coefficient	Bending rigidity	65.76
Drape coefficient	Linearity in compression	65.46
Compressional resilience	Drape coefficient	58.30
Extraction force	Work of compression	40.63
Flexural rigidity	Extraction force	32.72
Drape coefficient	Extraction force	22.44
Extraction force	Bending rigidity	19.7

6. CONCLUSIONS

Dividing fabric structures into levels from the point of manufacturing or intermediate products may make it easier to reflect the complexity in more comprehensible way. The complex inter-level interactions necessitate simplified models and somewhat crude deductions until more specific and extensive models can be built.

More work is needed to measure and model inter- and intra-level relations. Ideally the processes from fibre to yarn and from yarn to fabric could be controlled and divided into phases. Minimizing the number of variables in order to reproduce the process with only a few varying parameters would give more information on the relationships under scrutiny.

6.1 Fibres

The novel fibres (BCS, CCA and ION) were characterized, producing more information for the individual development projects. Especially the individual fibre bending properties help comparing established commercial fibres. The novel fibres fare well compared to the commercial counterparts, giving support to the new wave of cellulose based fibres and other products.

Even though some of the novel fibres are partially still in developmental stage, the properties already compare well to those of commercial fibres. Ioncell fibres (ION) had the highest tenacity values, with a clear marginal to cotton (CO) and viscose (CV), and were the stiffest of the novel trio. Biocelsol (BCS) had the lowest tenacity, around that of wool, and was the bulkiest of all the fibres measured. It was the most flexible fibre in comparison to others - over three times more flexible than cotton. In Biocelsol and Cellulose Carbamate (CCA) we have successors for polyester.

6.2 Flexural relationship between fibres and fabric

As would be expected, there is a connection between the fibre and fabric levels' properties and low stress behaviour. This has been discussed in literature and the effects could be seen in the measurements of this thesis as well. Defining the level of influence on the other hand requires more testing.

Most notable difference between behaviour in fibre and fabric levels arose with the non-woven fabrics. This is probably due to the nature of the structure of the examined non-woven fabrics. As the structure is somewhat fixed there is not so much of a structural allowance, to allow the external forces to disperse into, nor possibility of rearrangement.

With woven and knitted fabrics the influences of forces propagates through the structural levels, as it seems the structures allow for rearrangement at least to a level. In non-woven fabrics the fibre-fabric-structures seemed to be less adjusting and in a sense more rigid. The solid form can be evidently texturized to a more adjustable and flexible form, imitating in a sense the wale and course structure of knitted fabrics.

The BPCC non-woven fabric's distinguishable texture gave another level of structure to the fabric, allowing it to behave more like for instance a knit fabric. It might be possible, that if the dimensional or volumetric differences in the texture are high enough, the mechanical behaviour may not be uniform.

There were no fabrics made of the novel fibres available for research, but taking from the results for the other fibre-fabric pairs some theoretical estimation can be derived. As has been stated before, the effect of yarn level is not taken into account and thus these are only approximations.

Biocelsol (BCS) and Cellulose Carbamate (CCA) fibres are in the same scale of flexibility compared to viscose (CV). This would implicate woven or knit fabrics with similar flexural properties, even with the differences in fibre fineness. Also fabric handle should be good or even better. Ioncell (ION) fibres should assess better than cotton (CO) and PLA.

6.3 Method evaluation

Fibre characterization

The fibre characterization platform has been in frequent use, gaining commercial interest, and the opportunity to use it was met with great interest. As the theoretical background is solid, the only flaws in this case were the lack of environmental control and finding the best sensors. At the time of writing this thesis the platform still required an operator with knowledge of the system, but during the discussion with the research group, it was evident that it is a commercializable system that can be automatized to a higher degree.

Fabric characterization

The Funnel nozzle extraction method supported the other results in determining low stress behaviour of fabrics. With the current setup it is already possible to categorize different fabrics according to their rigidity.

The variance between the extraction measurements of same fabric differed remarkably from each other, even though maintaining visually identifiable shapes. The curves seemed to be unsynchronized so to speak, suggesting the samples undergo similar interactions but may reach specific phases depending on previous state. This might be more controllable using sample support plates.

The implementation of the fabric drape standard and appliance worked well, even though no parallel testing was to avail. The used method proved to be fast and simple, requiring little investment and only everyday equipment. The results showed good correlation with other methods. The method may be vulnerable to

The Kawabata evaluation system (KES) is a costly and time consuming evaluation system, which has gained many competitors and some criticism in the course of time. It can be replaced by several other specific methods and machines, with lower costs, but as a stand-alone system the KES still is the most comprehensible system. Another downside is low result repeatability even with same authors and samples.

KES was originally developed for specific fabrics and not as a generic assessment system. This was evident for instance in the sample holder of the Kawabata bending measuring appliance. Similar problem arose with the cantilever method, which is modestly priced alternative and correlated highly (over 90%) with KES bending results. Nevertheless the used cantilever method was highly manual and visually estimated measuring system aimed at (supposedly more rigid) non-woven fabrics.

6.4 Future Work

Fibre flexibility test were carried out in non-standard conditions. More tests should be carried out to get more reliable results, and preferably using standard conditions. Also the stability of the used specimen should be confirmed to exclude any statistical deviations arising from different production parameters.

Hopefully the fibre characterization system will be automated and in the long run commercialized. This would standardize the process and lead to a more robust system to be established in the industry.

The yarn level measurements and research was excluded in this thesis, but it should definitely be looked into. Hopefully this will be carried out using fibres characterized in parallel and controlling as many parameters as possible. Ultimately the fabric level will be included in similar fashion.

The influence of texturizing and other macro-level structural manipulation should be researched more. Especially the significance of topographical or volumetric differences is an interesting topic.

The resolution of the methods should be looked into by doing the tests with samples similar to each other. This would make a better method evaluation and allow possible improvements to be proposed.

As the funnel nozzle extraction system was built up for this thesis from scratch, the settings and details still need more work. First the surface of the funnel should be polished or coated to minimize the tribological influence on the fabric. The use of supporting plates should also be looked into to see how they would influence the curve shape. More thorough testing of the bead size influence would be ideal as well.

Current force-deflection curve analyses should be examined closer. More automated (initial) analysis of the shape and areas should be implemented as well.

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A. APPENDIX

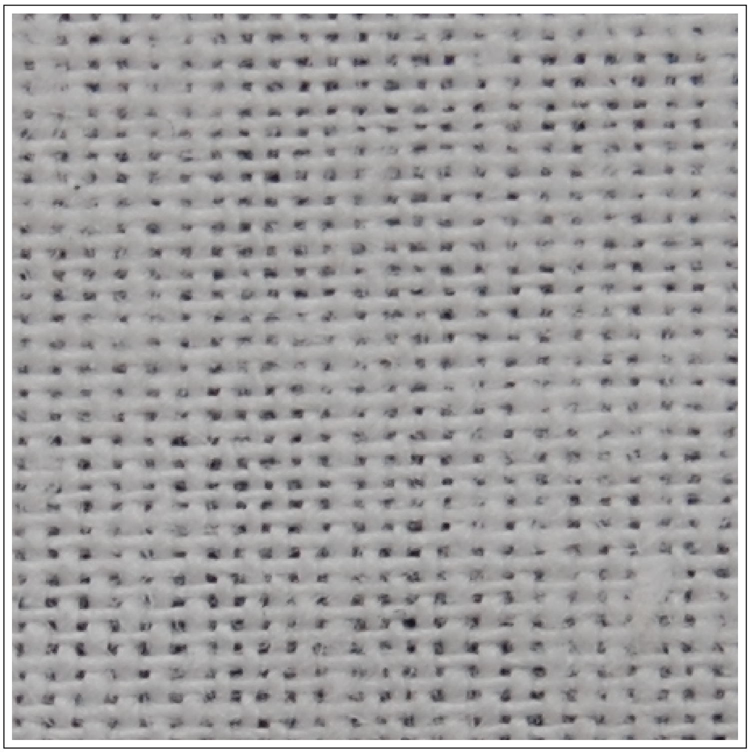
A.1 Material information

Table A.1: Sample fibres used in the measurements with given information

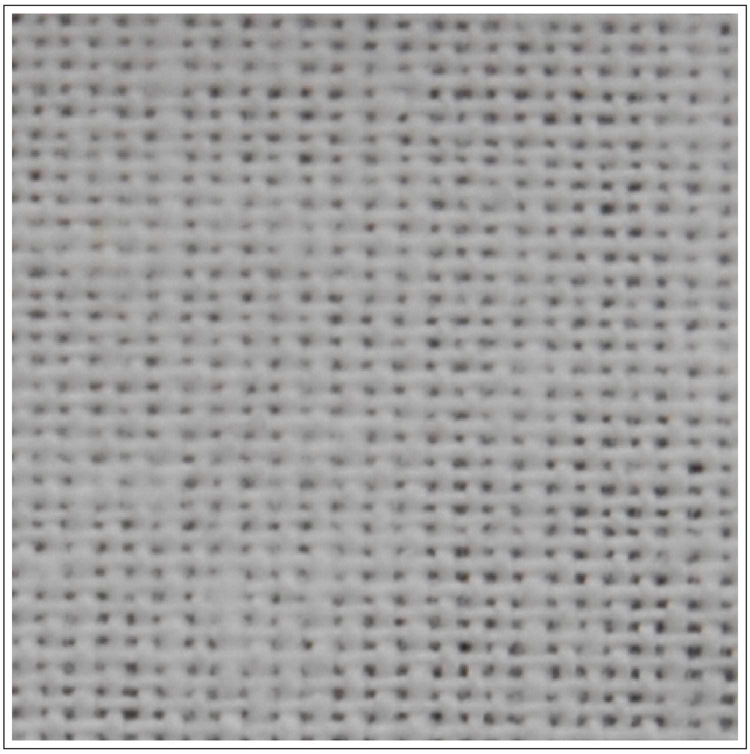
Company	Trade name	Fibre code	Material	Fibre type	Given linear density [dtex]	Given elongation at break [cN/tex]
Tampere University of Technology	Biocelsol	BCS	Biocelsol	Staple		
VTT Technical Research Centre of Finland	CCA	CCA	Cellulose Carbamate	Staple	-	
Suominen Corp.	Cotton	CO	Cotton	Staple	-	
Aalto University	Ioncell-F	ION	Ioncell	Staple	-	
Lenzing	Lenzing Viscose (LAG)	CV	Viscose	Staple	1.7	22
Suominen Corp.	-	PLA	Poly(lactic acid)	Staple	-	

Table A.2: Sample fabrics used in the measurements with given information

Company	Trade name	Fabric code	Material	Fabric type	Given grammage [g]	Producer notes
Suominen Corp.	Biolace	BCV	CV (100%)	Non-woven, spunlaced	70	
Suominen Corp	Biolace	BCP	CV-PLA (65-35 %)	Non-woven, spunlaced	55	Grade B9135-16-55 Developmental
Suominen Corp.	Biolace	BPCC	CV-PLA-CO (50-35-15 %)	Non-woven, spunlaced, hydro embossed	55	Grade B9535KN-110-55
Orneule Oy	Single	OCO	CO (100 %)	Knit, jersey	180	Grade A64065
Orneule Oy	Kreppi Single	OCV	CV (100 %)	Knit, jersey	175	Grade 9134
Finlayson Oy	-	FCO	CO (100 %)	Woven, plain	-	-
Eurokangas Oy	Lemmikki	ECV	CV (100 %)	Woven, plain	-	-



(a) Technical front



(b) Technical back

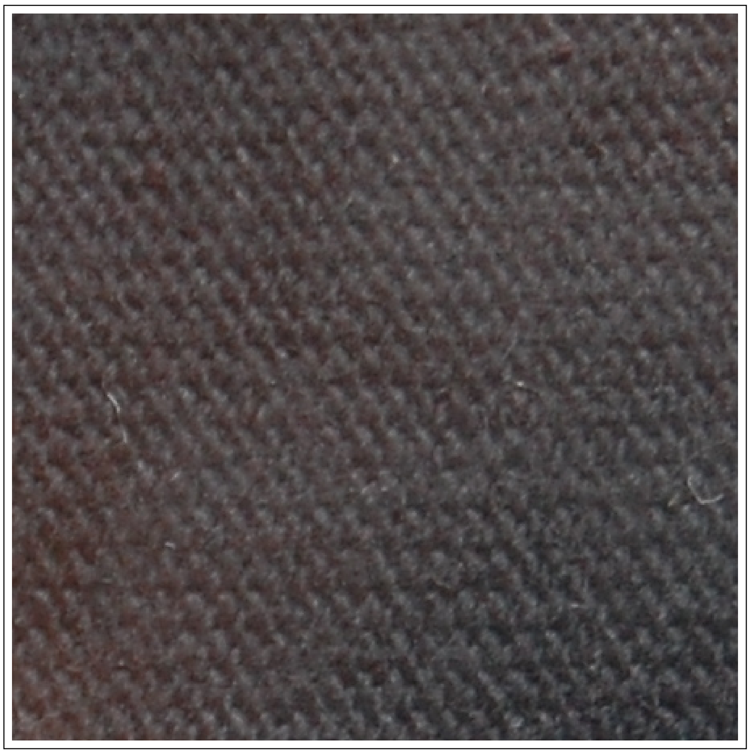
Figure A.1: Pictures of FCO - 100% cotton woven fabric

(a) Technical front

(b) Technical back

Figure A.2: Pictures of ECV - 100% viscose woven fabric

(a) Technical front



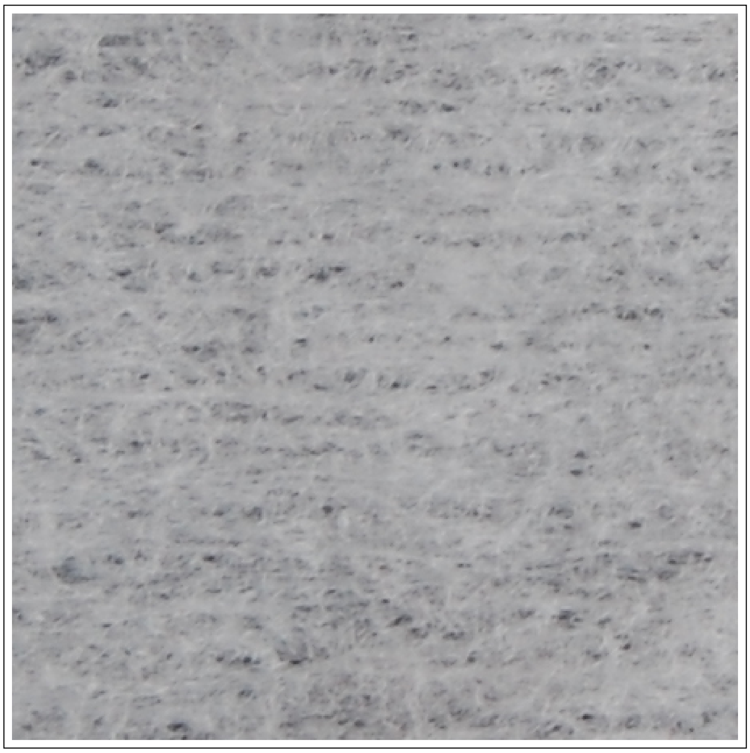
(b) Technical back

Figure A.3: Pictures of OCO - 100% cotton knit fabric

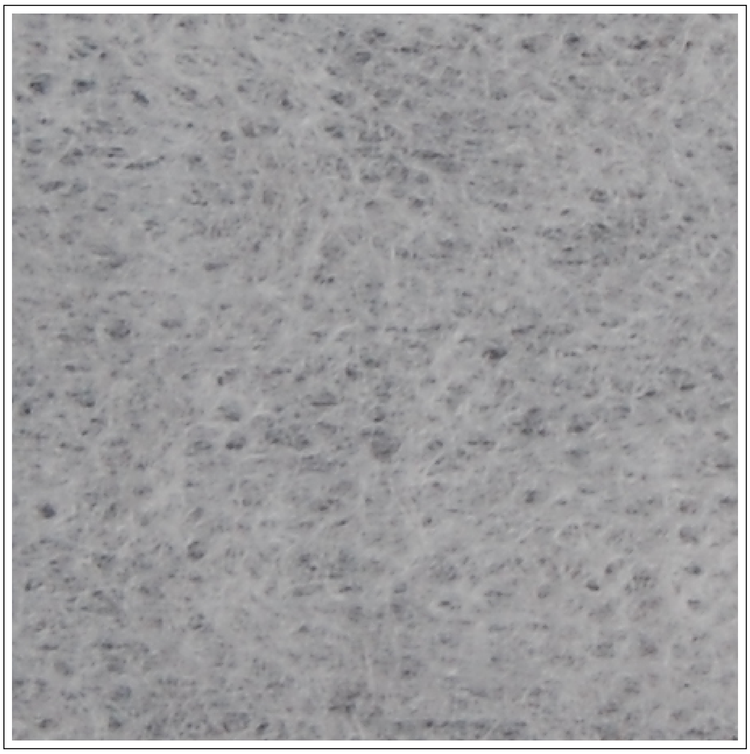
(a) Technical front

(b) Technical back

Figure A.4: Pictures of OCV - 100% viscose knit fabric

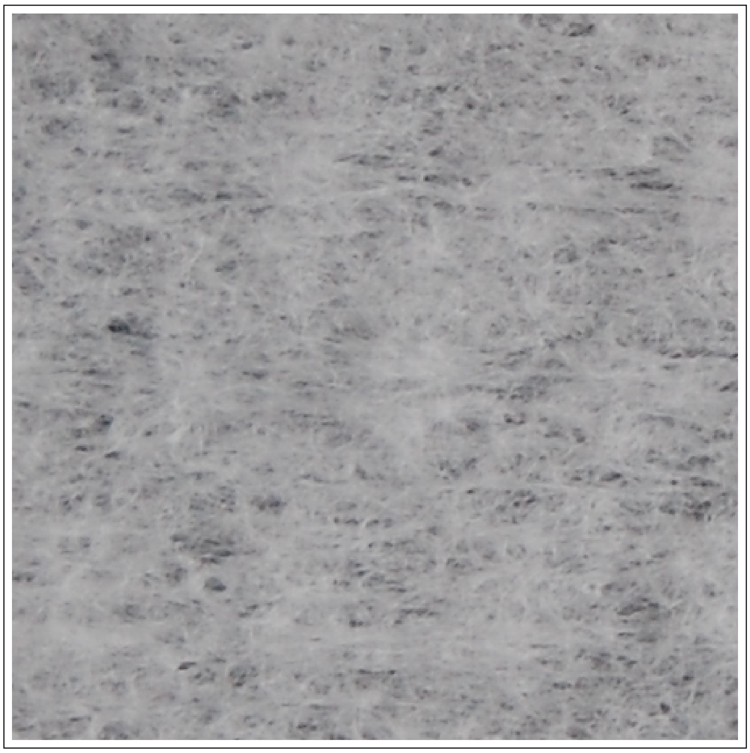


(a) Technical front

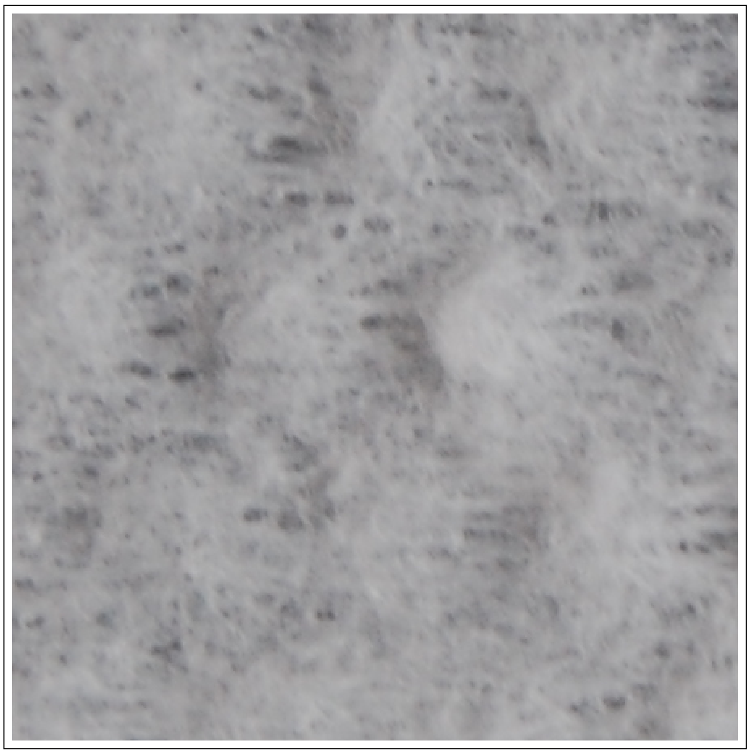


(b) Technical back

Figure A.5: Pictures of BCP - mixed viscose-PLA non-woven fabric

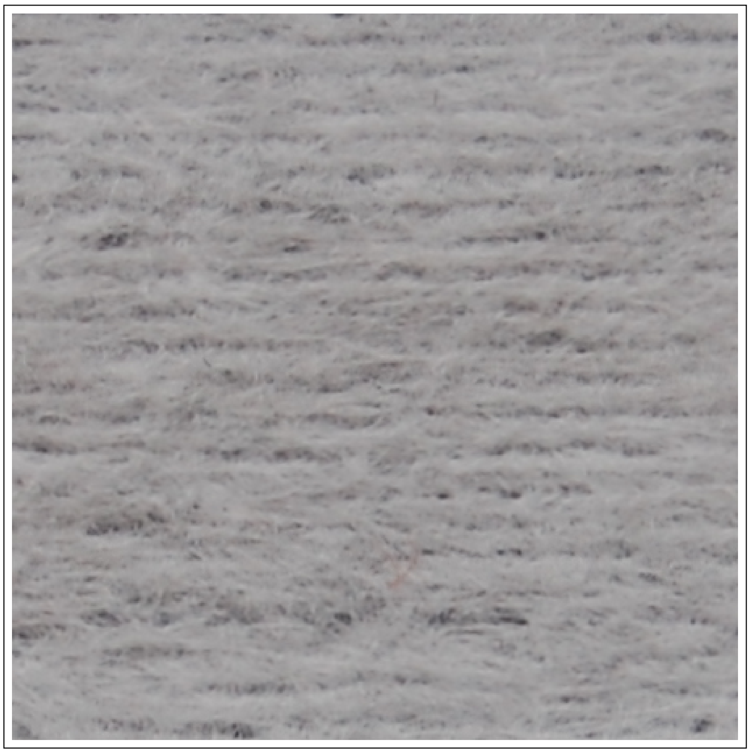


(a) Technical front



(b) Technical back

Figure A.6: Pictures of BPCC - mixed viscose-PLA-cotton non-woven fabric



(a) Technical front

(b) Technical back

Figure A.7: Pictures of BCV - 100% viscose non-woven fabric

A.2 Funnel nozzle and extraction beam

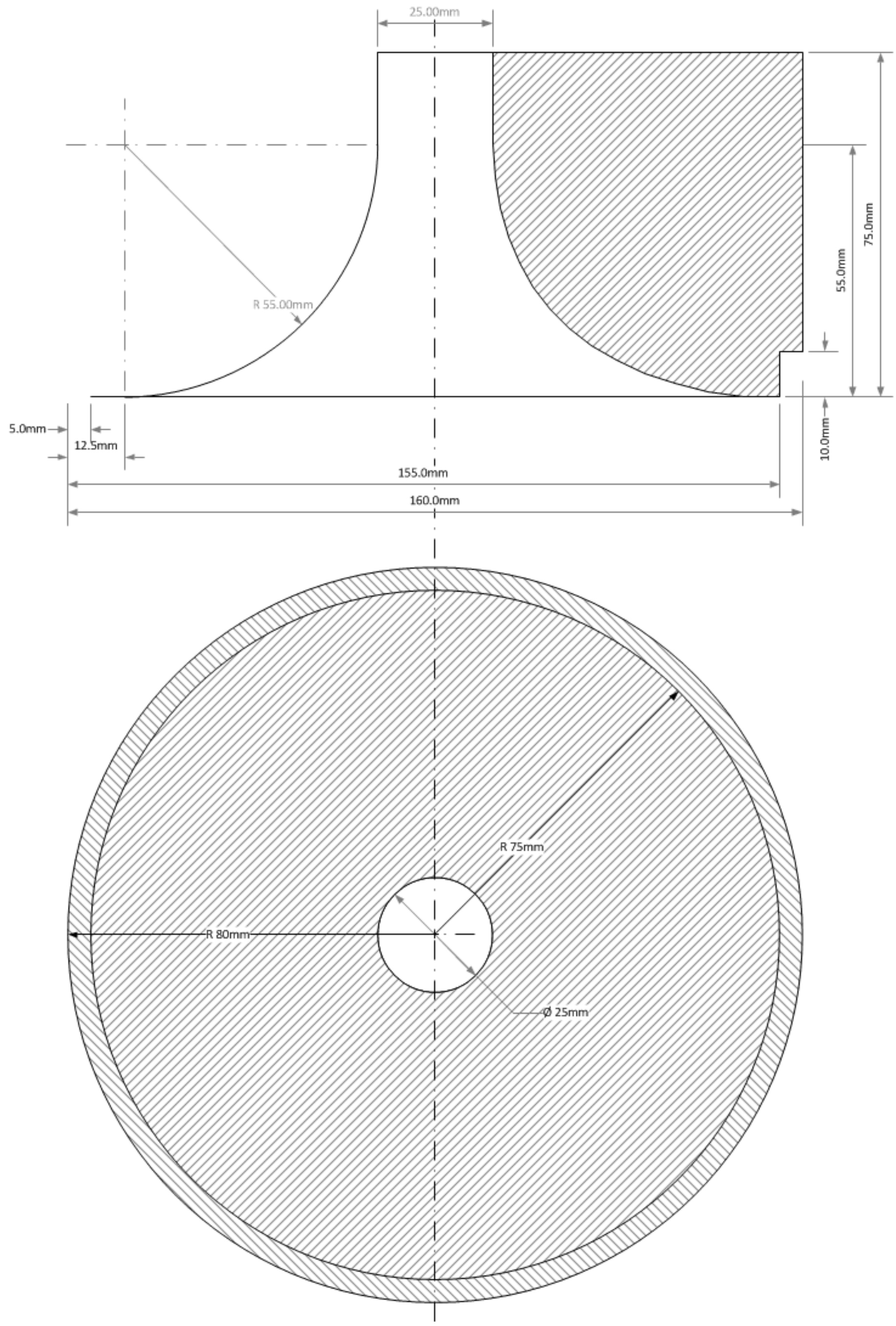


Figure A.8: Technical drawing of a funnel nozzle

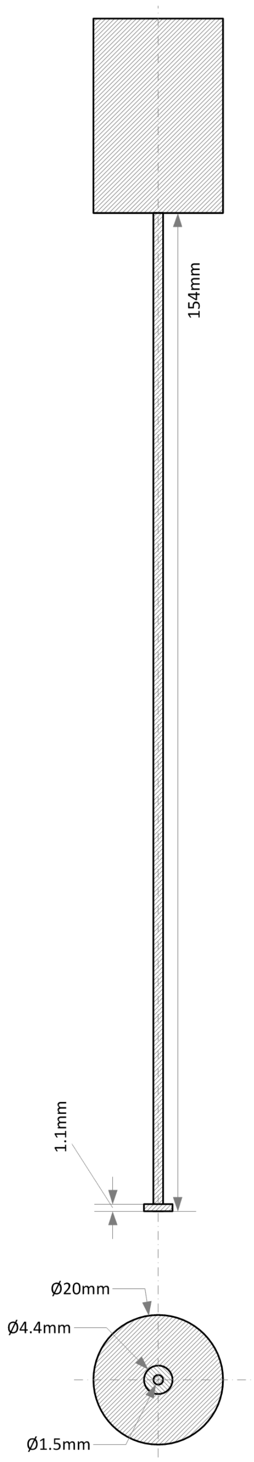


Figure A.9: Technical drawing of an extraction beam

A.3 Matlab code for drape coefficient calculation

```
function areaInPixels = processImage(fName, fMask, showPhases)

    axesXsize = 2; % CONSTANT
    axesYsize = 1; % CONSTANT
    imgNo = 1;

    if (showPhases)
        axesXsize = 3;
        axesYsize = 3;
    end
    fontSize = 16;
    smallestAcceptableArea = 7000; % Keep areas only if they're bigger than this.

    hold on;
    % Open and show the image
    [I, map] = imread(fName);

    % Use a mask file to crop image
    if (isequal(exist(fMask),2)) % variable refers to a file
        M = imread(fMask);
        M = im2bw(M); % Convert to binary-image
        rp = regionprops(M, 'BoundingBox'); % Find region properties
        mask = rp.BoundingBox; % Just interested in the bounding box
        I = imcrop(I, mask);
        clear M;
        clear mask;
    end

    subplot(axesYsize, axesXsize, imgNo);
    imgNo=imgNo+1;
    imshow(I, map)
    title('Original', 'FontSize', fontSize);

    % Treshold ja inversion
    thr = graythresh(I);
    BW = im2bw(I, thr); % Tai itsearvioitu arvo
    BW = ~BW;

    if (showPhases)
        subplot(axesYsize, axesXsize, imgNo);
        imgNo=imgNo+1;
        imshow(BW, map);
        title('Treshold & Invert', 'FontSize', fontSize);
    end

    % Get rid of small objects.  Note: bwareaopen returns a logical.
    cBW = uint8(bwareaopen(BW, smallestAcceptableArea));
    if (showPhases)
        subplot(axesYsize, axesXsize, imgNo);
        imgNo=imgNo+1;
        imshow(cBW, map);
        title('Small objects removed', 'FontSize', fontSize);
    end
    BW = cBW;


    % Clear borders
    cBW = imclearborder(BW);
    if (showPhases)
        subplot(axesYsize, axesXsize, imgNo);
        imgNo=imgNo+1;
        imshow(cBW, map);
        title('Clear Borders', 'FontSize', fontSize);
    end
    % If we removed too much
    if (sum(sum(cBW)) < smallestAcceptableArea)
        cBW = BW;
    end
    BW = cBW;

    % Fill in any holes in the regions
    fBW = uint8(imfill(BW, 'holes'));
    if (showPhases)
        subplot(axesYsize, axesXsize, imgNo);
        imgNo=imgNo+1;
        imshow(fBW, map);
        title('Filled', 'FontSize', fontSize);
    end
```

```
    BW=fBW;

    % Smooth the border using a morphological closing operation, imclose().
    structuringElement = strel('disk', 4);
    sBW = imclose(BW, structuringElement);
    if (showPhases)
        subplot(axesYsize, axesXsize, imgNo);
        imgNo=imgNo+1;
        imshow(sBW, map);
        title('Smoothed␣(ignored)', 'FontSize', fontSize);
    end
    BW=sBW;

    % Find the centroid of the image
    Ilabel = logical(BW);
    stat = regionprops(Ilabel,'centroid');
    subplot(axesYsize, axesXsize, imgNo);
    imgNo=imgNo+1;

    imshow(BW, map);
    hold on;
    for x = 1: numel(stat)
        plot(stat(x).Centroid(1),stat(x).Centroid(2),'r*');
    end
    title('Processed', 'FontSize', fontSize);

    % Calculate the drape area (sum of the white pixels (1) on a b/w-pic)
    areaInPixels = sum(sum(BW));

    hold off;
end %from processImage
```