DOCTORAL THESIS

Effect of Fibre Content, Structural Parameters, and Laser Fading on Durability and Aesthetic Properties of Multicomponent Denim Fabric

Nele Mandre

TALLINNA TEHNIKAÜLIKOOL
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NELE MANDRE

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TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Material and Environmental Technology
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Supervisor:	Senior Lecturer Tiia Plamus School of Engineering Tallinn University of Technology Tallinn, Estonia
Co-supervisor:	Professor Andres Krumme School of Engineering Tallinn University of Technology Tallinn, Estonia
Opponents:	Professor Eugenija Strazdiene Faculty of Arts and Creative Technologies Vilnius University of Applied Sciences Vilnius, Lithuania
	Senior Researcher Milda Juciene Institute of Architecture and Construction Kaunas University of Technology Kaunas, Lithuania

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Nele Mandre

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Kiulise koostise, struktuuri parameetrite ja laserkulutuse mõju mitmekomponentse teksakanga vastupidavusele ja esteetilistele omadustele

NELE MANDRE

TALTECH KIRJASTUS

Contents

List of publications

The list of author’s publications, on the basis of which the thesis has been prepared:

I **Mandre, N.**; Plamus, T.; Krumme, A. (2021). Impact of weft yarn density and core-yarn fibre composition on tensile properties, abrasion resistance, and air permeability of denim fabrics. Materials Science, 27 (4). 483–491. DOI: 10.5755/j02.ms.27532.

II **Mandre, N.**; Plamus, T.; Linder, A.; Varjas, T.; Majak, J.; Krumme, A. (2023). Design of performance characteristics on laser treated denim fabric. Materials Science, 29 (4). DOI: 10.5755/j02.ms.33259.

III **Mandre, N.**; Plamus, T.; Linder, A.; Krumme, A. (2023). Impact of laser fading on physico-mechanical properties and fibre morphology of multicomponent denim fabrics. Proceedings of the Estonian Academy of Sciences, 72(2). 145–153. DOI: 10.3176/proc.2023.2.05.

Author’s contribution to the publications

Contribution to the papers in this thesis are:

I The author prepared the specimens for the test; performed a majority of the physico-mechanical experiments; measured and analysed the experimental results; and authored the article with the help of co-authors.

II The author prepared the specimens for the test; performed physico-mechanical experiments; gathered the experimental results; analysed the obtained data; and authored the article with the help of co-authors.

III The author prepared the specimens for the test; performed physico-mechanical experiments; gathered the experimental results; analysed the obtained data; and authored the article with the help of co-authors.

Introduction

Denim is a sturdy and durable cotton fabric. Denim's history dates back to the 16th century. The word "denim" comes from a fabric named serge de Nimes, which was made in the city of Nîmes in France. It is made of warp and weft yarns, wherein the warp yarns are usually dyed with indigo and weft yarns are remain white. Denim fabric is used to make different types of clothing, such as jeans, jackets, dresses, and skirts (Muthu, 2017; Paul, 2015). Nowadays, as denim is used in everyday garments, the fabric should provide comfort, have a good breathability, and be durable, tailorable, and easy to care for. Additionally, the aesthetic properties are also important for its customers (Gandhi, 2020).

Historically, denim fabrics were typically made of cotton. To provide different levels of fitting and comfort, nowadays cotton is blended with other fibres to enhance the fabric properties. Blended yarns are made of two or more types of fibres combined into one yarn. The cultivation of cotton and production of yarn raise different sustainability issues (Paul, 2015). Khan *et.al* have stated in their study that denim fabric production, worldwide, is a highly polluting textile industry and has raised sustainability issues owing to the large amounts of water, chemicals, and energy used during denim fabric production (Khan & Jintun, 2021). It has been stated that 11,000 litres of water are needed to make a single pair of jeans, approximately 70% of consumed water is used for cotton cultivation and 70 litres for finishing. Denim dyeing, washing, and finishing are the most water-intensive processes in the denim garment production cycle (Muthu, 2017). Thus, sustainability is a key concern for the textile industry. Therefore, manufacturers implement new production techniques to reduce the negative impact of denim production on the environment. In addition to sustainable production processes, clothing longevity is also an important factor to be considered.

Finishing is an essential treatment for ready-made denim garments. It provides a final look and adds unique value to the garments so that customers are attracted to the product. Different dry and wet processes are used to obtain the desired looks (Nilsson & Lindstam, 2012). Laser fading technology is an innovative solution for finishing of denim garments and giving the final product a fashionable or vintage look. This technique is environment-friendly because it can save up to 67% water, 85% chemicals, and 62% energy compared to the conventional processes. Moreover, it reduces labour and production costs (Khan & Jintun, 2021). A key element of this research involves laser fading of denim fabrics and testing their durability after laser fading.

Previous studies in this field were focused more on testing the properties of denim fabrics containing cotton or cotton and elastane. The properties of three- and four-component denim fabrics have not been thoroughly reported in scientific literature. Moreover, there are no available scientific data on how laser fading affects the physico-mechanical properties and colour of four-component denim fabrics. The current work tackles the problem of producing a durable multi-component denim fabric that can withstand the laser fading process, and ensuring long-lasting denim products. The physico-mechanical properties of both the raw and laser faded denim fabrics were tested, and a design optimisation of the denim fabric in terms of its tear force, abrasion resistance, and colour difference after laser fading was conducted.

The fabrics prepared for this study also consisted of cotton and elastane, and these were compared with multicomponent fabrics containing cotton, polyester, polybutylene terephthalate, elastane, viscose, modal, and Lycra T400® fibres. Multicomponent fabrics are widely used in the textile industry. Polyester and elastane are used in denim fabrics because they provide durability and enhance the stretchability of the fabric. Viscose provides a soft feel and lustrous finish (Paul, 2015).

This research was conducted for a clothing manufacturing company, Põldma Kaubanduse AS, which can benefit from the knowledge acquired during the research.

In addition, the results of this research have been represented at various scientific fora through the following submissions:

- Mandre, N; Plamus, T; Krumme, A. Structure, characteristics, and impact of treatment on durability of denim fabric containing elastomeric fibre. GSFMT Scientific Conference 04–05.02.2020.
- Mandre, N; Plamus, T; Krumme, A. Impact of weft yarn density and core-yarn fibre composition on tensile properties, abrasion resistance, and air permeability of denim fabrics. GSFMT Scientific Conference 15–16.06.2021.
- Mandre, N; Plamus, T; Linder A; Varjas, T; Majak, J; Krumme, A. Design of performance characteristics on laser treated denim fabric. GSFMT Scientific Conference 17–18.05.2022 (20 min oral presentation).
- Mandre, N; Plamus, T; Linder A; Rohumaa, A., Krumme, A. Impact of laser fading on physico-mechanical properties and fibre morphology of multicomponent denim fabrics. Baltic Polymer Symposium 21–23.09.2022.

Abbreviations and symbols

ANN	Artificial neural network
Approx.	Approximately
CMD	Modal
CNN	Convolutional neural network
CO	Cotton
CO_2 laser	Carbon-dioxide laser
CTH:YAG laser	Yttrium aluminium garnet laser crystals doped with chromium, thulium and holmium ions laser
CV	Viscose
dpi	Dots per inch
dtex	Deci-tex-grams per 10,000 m of fibre or yarn
EL	Elastane
EME	Elastomultiester
FLES	Fuzzy logic expert system
HOHWM	Higher order Haar wavelet method
HWM	Haar wavelet method
ISO	International Organisation for Standardisation
LR	Linear regression
MJS	Murata jet spinning
Nd:YAG laser	Neodymium yttrium-aluminium-garnet laser
OVAM	Public Waste Agency of Flanders
oz	Ounce
PBT	Polybutylene terephthalate
PES	Polyester
PET	Polyethylene terephthalate
ppi	Pulses per inch
PTT	Polytrimethylene terephthalate
SEM	Scanning electron microscopy
T400	Lycra T400®

Terms

Abrasion resistance	A material's ability to resist its surface being worn away by rubbing or friction (Scott & Safiuddin, 2015).
Air permeability	Velocity of air flow passing perpendicularly through a test specimen under specified conditions of test area, pressure drop, and time (EVS EN ISO 9237:2000, 2000).
CM800	Bi-component elastic filament extruded from two polymers with different viscosities (Textile Focus, n.d.).
Colourfastness	A fabric's ability to maintain its original colour. High colour fastness means that the fabric retains its colour; poor colour fastness means that the fabric fades or changes its colour (Hatch, 1993).
Core-spun yarn	Two-layered structure yarn, which consists of a core and sheath. A yarn is formed by twisting the sheath yarn around the core yarn (Gandhi, 2020).
Cotton	The seed fibre obtained from the boll of a cotton plant (Hatch, 1993).
Denim	A hard-wearing cotton twill fabric, traditionally woven with an indigo dyed warp and white filling yarns (Paul, 2015).
Drafting	A yarn drawing process, wherein several individual slivers are doubled or drafted into one sliver (strand). Typically, six or eight to produce one sliver (Kozłowski & Mackiewicz-Talarczyk, 2020).
Elastane	A synthetic fibre, made up of linear macro-molecules of high molecular weight. Elastane is characterised by high elasticity and ability to recover rapidly when tension is released (Uyanik & Kaynak, 2019).
Elastomultiester	A fibre formed by the interaction of two or more chemically distinct linear macromolecules in two or more distinct phases (of which none exceeds 85% by mass), which contains ester groups as the dominant functional unit (at least 85%), and which, after suitable treatment, when stretched to one and half times its original length and released, recovers its initial length rapidly and substantially (EP & EUCO, 2011).
Fabric	A structure consisting of fibres and yarns. Other major components of a fabric include fabric construction, chemicals, colourants, and intersticks (Hatch, 1993).
Fibre	A unit of matter or a particle, whose length is at least 1000 times its diameter. It can be spun into a yarn and subsequently into a fabric (Hatch, 1993).
Laser	Light amplification by stimulated emission of radiation (Silfvast, 2004).
LYCRA®	The trademarked brand name of a class of synthetic elastic fibres. Only the LYCRA Company produces authentic LYCRA® fibres (LYCRA, n.d.).
Mass per unit area	Mass of a known area of fabric divided by that area, expressed in g/m^2 (EVS EN 12127:2000, 2000).

Multicomponent fabric	A fabric that contains several different types of textile fibres.
Number of threads per unit length	The number of threads per cm^2 is given by the sum of the mean warp (ends) and weft (picks) per cm (EVS EN 1049-2:2000, 2000).
Tear force	Force required to propagate a tear initiated under specified conditions (ISO 13937-2: 2000, 2000).
Tensile property	A material mechanical property, that is a measure of the resistance to tensile stress. This is the force per unit area required to break the material (Schaschke, 2014).
Woven fabric	A textile, which is formed by the interlacing of warp and weft yarns (Kozłowski & Mackiewicz-Talarczyk, 2020).
Yarn	A continuous strand of textile staple or filament fibres that are suitable for intertwining to form a textile fabric (Hatch, 1993).
Yarn twist	The number of turns around the yarn axis per unit length. It is expressed in turns per inch (tpi), turns per meter (tpm) or turns per centimetre (tpcm) (Hatch, 1993).
Yellowness	The attribute, by which an object colour is judged to be departing from a preferred white towards yellow. The Yellowness Index is a number calculated from spectral data that describes the change in the colour of a test sample from clear or white toward yellow (X-Rite, 2012).

1 Literature review

1.1 Introduction

This chapter presents an overview of how denim fabric is manufactured and introduces its characteristic properties. Additionally, it introduces fibres, yarns, and weave constructions, which are used in the production of a denim fabric. Next, it describes the peculiar features of dyeing and fading of the denim fabric. This chapter also addresses the environmental issues related to the textile industry and explains the concept of CO_2 (10.6 µm) laser fading, which is a promising technology used for the fading of denim fabric. Mathematical modelling approaches (ANN and the HWM), which provide opportunities to optimise the laser fading parameters that would have minimal impact on fabric durability after laser fading are also described.

1.2 Denim fabric construction

Denim was first used as workwear, where durability was the most important consideration. Currently, denim clothing is mainly used as leisure wear; however, it has been gaining acceptance for different formal occasions. Denim clothing is popular among consumers of different genders and ages, for whom comfort, style, and fit are important parameters. The logistics solutions provider Maersk stated that according to Statista (provider of market and consumer data) 4.5 billion pairs of jeans were sold in 2020. Approximately 2.2 billion m of denim fabric is produced every year. The market value of denim was 90 billion US dollars (90.32 billion euros) in 2019, and is expected to increase to 105 billion U.S dollars (105.34 billion euros) by 2023. Approximately 50% of denim fabrics worldwide are produced in Asia (Paul, 2015; Infographic, 2021).

The traditional denim fabrics are woven into a warp-faced twill weave (Figure 1a). The 3/1 weave is the most widely used denim twill construction. This numerical notation indicates that the twill weave is formed by passing the warp yarns (ends) over three weft yarns (picks) and then under one weft yarn. Denim fabrics are also woven into a 2/1 or 2/2 twill weave. The warp yarns are indigo-dyed, while the weft yarns retain a white colour. Classical denim fabrics have a high mass per unit area. However, nowadays, lightweight denim fabrics are also available. The weight of a fabric is influenced by the yarn linear density, fabric tightness, and weave type. The weight of the denim fabric is traditionally measured in oz per yard. For example, a weight of 3.5–8 oz per square yard (130–270 g/m^2) is used for blouses, shirts, and tops, while 8.0–16.5 oz per square yard (270–560 g/m^2) is used for trousers, jeans, and jackets (Paul, 2015).

The satin weave is similar to the twill weave (Figure 1b). It is warp-faced, but with a 1-yarn longer float than the other. The satin weave has less interlacing than the twill weave, which enables the weaving of more threads per cm (Hatch, 1993). Similar to the twill weave, the satin weave has a greater number of warps per cm than the weft yarns. The most commonly used weave numbers are five and eight, where the warp yarns go over four wefts and then under one warp yarn. Because of their lustrous weave appearance, satin weaves are used for silk fabrics; however, nowadays, it is also used in uniforms, industrial and protective clothing, and denim fabrics (Adanur, 2000; Paul, 2015; Miao & Xin, 2018; Csanák, 2015).

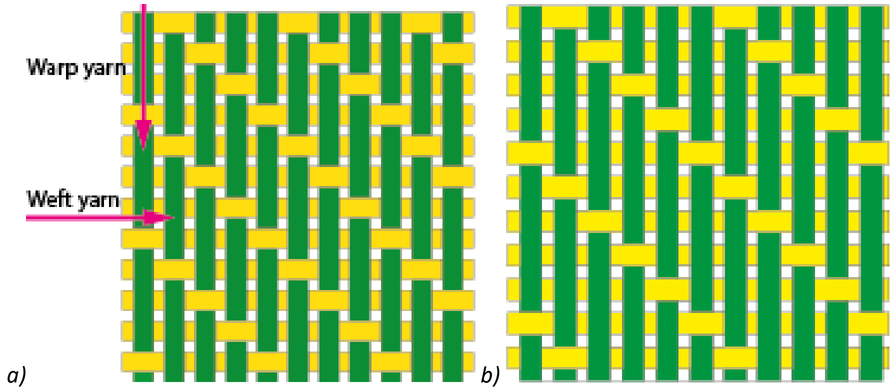


Figure 1. a) 3/1 twill weave construction and b) 4/1 satin weave construction.

1.3 Textile fibres used in denim fabrics

Denim fabrics are conventionally produced using 100% cotton. As denim garments are highly popular in all age groups, many improvements have been made to provide not only durability, but also comfort to the wearer. Denim garments should fit the body closely, without restricting the body movement. Comfort is considered to be a psychological, sensorial, and thermo-physiological property. Modal, viscose, and Tencel are mainly used as regenerated fibres in denim fabrics to provide a soft feel, smooth handling, and bright appearance. However, these fibres provide denim adequate abrasion resistance and tensile properties. Regenerated fibres are produced from natural raw materials, such as wood pulp; they serve as a good alternative to cotton and from an environmental perspective (Gokarneshan, Velumani, Sandipkumar, Malathi, & Aathira, 2018).

In addition to regenerated fibres, synthetic fibres are added in denim fabrics to improve their durability. Synthetic fibres, such as polyester and polypropylene fibres, are also commonly used. Furthermore, cotton blended with polyamide 6.6 provides higher abrasion resistance than 100% cotton denim. Elastic fibres, such as elastane are widely used in denim fabrics to improve their stretchability and recovery (Gokarneshan, Velumani, Sandipkumar, Malathi, & Aathira, 2018).

In the 19th century, Levi Strauss used the same rough canvas for trousers as that used for sewing tents. Their primary intension was that workwear should be durable and last longer. However, the abrasion and tear resistance of these trousers were low. To eliminate this problem, cotton fabric was introduced. These improved pants are today known as jeans. Rivets were used to reinforce the parts that could tear easily. Since then, denim fabrics have been usually made of cotton. The crystalline structure of cotton (tenacity~3.0–5.0 g/den) provides moderate strength and its surface structure comprising hemispherical (broad, blunt tips) tapered (narrow, pointed tips), or convolutionary (a twist of the fibre through 180° about its axis) provides comfort characteristics (Figure 2) (Elmogahzy, 2020; Kozłowski R. M., 2012; Paul, 2015; Han, Cho, & Lambert, 1996; Graham & Haigler, 2021).

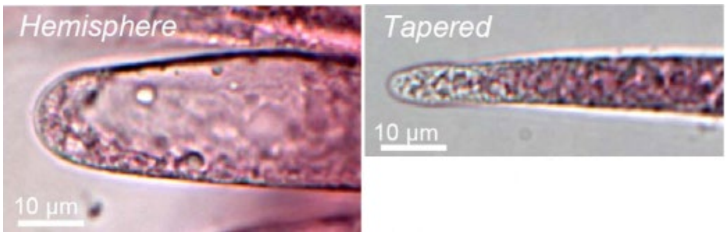


Figure 2. Hemispherical (left) and tapered tip (right) morphologies of cotton (Stiff & Haigler, 2016).

Cotton is a natural fibre, and its quality depends on the climate and length of the total growing period. The longer the cotton fibre, the higher the technical quality of the fabric (Hatch, 1993). Cotton elongation at break is low. According to literature, cotton recovery is 75% at 2% extension. However, at a 5% extension, cotton provides less than 50% elastic recovery. Abrasive actions damage the cotton fibre cell wall and break the fibre tips, resulting in a thinner fabric. Cotton is considered a moderately rigid and stiff fibre; a larger diameter implies a stiffer fibre. Cotton is hydrophilic, and it has better moisture-absorption properties than polyester and dries slowly. However, in dry conditions it absorbs water vapour, providing comfort for the human body (Hatch, 1993).

Nevertheless, this natural fibre has some disadvantages; For example, depending on the region it is grown in, local climate, irrigation methods, variety of seeds used, etc., it can have inconsistent characteristics. Additionally, cotton fibres tend to wrinkle and are prone to shrinkage after washing. To overcome these shortcomings, cotton fibres are blended with synthetic and regenerated fibres. Mixing fibres ensures a uniform and consistent yarn, as well as a whole fabric. Blending different types of fibres leads to improvements in the fibre characteristics of the final yarn, as well as the fabric itself (Shabbir, Ahmed, & Sheikh, 2020; Gandhi, 2020; Kozłowski R. M., 2012; Miao & Xin, 2018).

Core spinning process is used to blend different fibres into one yarn, which is called a core-spun yarn. These yarns are formed by twisting or wrapping sheath fibres around a central core fibre (Figure 3) (Lawrence, 2010; Paul, 2015).

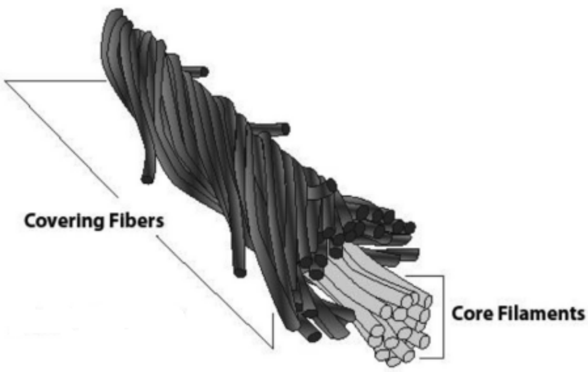


Figure 3. Typical core-spun yarn (Akter et al., 2021).

Elastomeric fibre elastane is widely used as a core yarn in the weft direction of denim to improve the crease and bagging properties of the cotton fabric (Miao & Xin, 2018). Elastane can be stretched repeatedly by approximately 400%–800%. After being stressed, the garment returns to its original length without any undesirable deformation during its lifespan. Additionally, the increased elasticity provides comfort for the wearer. An elastane content of 1%–5% would be sufficient to provide stretchability and recovery properties to denim fabrics (Miao & Xin, 2018; Elmogahzy, 2020). Many studies have evaluated the durability of denim fabrics containing elastane fibres. As the elastane content increases, the mechanical strength of the fabric decreases (Almetwally & Mourad, 2014; Choudhary & Bansal, 2018; Mourad, Elshakankery, & Almetwally, 2012; Akankwasa, Jun, Yuze, & Mushtaq, 2014; Qadir, Hussain, & Malik, 2014; Su & Liu, 2020; Türksoy, Kılıç, Üstüntağ, & Yılmaz, 2019; Dhouib, El-Ghezal, & Cheikhrouhou, 2006).

Polyester is a synthetic, man-made fibre; it is known as a "workhorse" and "big mixer", as it is one of the most used fibres in the world, and can be blended with a majority of other types of fibres. The polyester fibre has high consistency of quality, high breaking tenacity, and abrasion resistance. Polyester is often blended with cotton to improve its durability and abrasion resistance. In addition, polyester is highly resilient, which means that garments made of polyester do not require ironing. The elasticity of polyester is higher than that of cotton. However, its elastic recovery is high only under a low stress. For example, at 2% elongation, the polyester recovery is approximately 97%; however, at high stress levels, its stress recovery is poor. Similarly, polyester shows good results under small repeated stresses but cannot withstand high repeated stresses. Polyester is highly hydrophobic, even in very high-humidity environments, and has a low moisture absorption capability (Hatch, 1993; Miao & Xin, 2018).

Regenerated cellulosic fibre viscose was invented as a cheaper alternative to silk. It is used in denim fabrics to provide wearing comfort; viscose provides a soft and silk-like feel, and has higher elasticity and water retention capability than cotton. Viscose structure is more uniform; however, it becomes weaker in wet conditions than cotton, and loses approximately half of its tenacity. The abrasion resistance and elastic recovery of viscose are also lower than those of cotton (Hatch, 1993; Rouette, 2000; Kumari & Khurana, 2016).

Various bast fibres, such as kenaf, jute, ramie, and hemp have also been blended with cotton in denim fabrics. However, processing and blending problems typically occur in their production. Jute fibres are shorter and weaker than other bast fibres, which makes them difficult to spin into a yarn. In addition, other issues such as fibre dye-affinity, fabric surface texture, and comfort of the wearer present challenges in product development. Furthermore, high costs are a major factor limiting their development (Shishoo, 2015; Markova, 2019; Elmogahzy, 2020).

1.4 Yarn structure of denim fabrics

As previously mentioned, core-spun yarns are often used in denim fabrics. A two-layered core-spun yarn consists of a sheath (outer layer) and a core (inner layer). The main aim of blending fibres into one yarn is to improve individual yarn properties and produce better performance. The outer layer provides a good hand-feel and aesthetics. The inner layer contains various synthetic or regenerated fibres. Usually, a continuous filament yarn is used as the core and staple fibres are used as sheath fibres. Traditionally, cotton has been used as a sheath fibre in denim fabric. The core is responsible for the mechanical properties of the yarn. Thus, a core filament is used to improve the durability, abrasion resistance, and wash and wear performance of the denim fabric; elastic fibres are used to add more elasticity to the yarn (Paul, 2015; Gandhi, 2020; Elrys, El-Habiby, Elkhalek, Eldeeb, & El-Hossiny, 2022). Core-spun yarns were introduced to improve fabric durability by extending the garment-wearing period. In addition, the use of manmade fibres makes the yarn cheaper. Core-spun yarns can be classified into hard-core and soft-core yarns. A hard-core yarn provides durability. While a soft-core yarn, such as elastane, imparts elasticity (Gazi, Kılıç, Üstüntağ, & Yılmaz, 2018; Babaarslan, Sarioğlu, Çelik, & Avci, 2018).

According to some existing literature, dyeing and finishing processes damage elastane fibres; elastane can break owning to its high processing temperature. To improve the elastane durability, additional fibres can be spun into the yarn. This type of multicomponent yarn that contains two different fibres in the core is called a dual core-, double core-, or twin core-spun yarn. Multicomponent yarns contain two or more polymers with different chemical composition, physical properties, and/or morphology. The production of double core-spun yarn is similar to that of the core-spun yarn. Yarns are placed at the core of the weft yarn and covered with cotton fibres. This type of denim fabric warp yarn is also made of cotton (Türksoy, Kılıç, Üstüntağ, & Yılmaz, 2019).

Ute, in a study conducted in 2018, compared double core- and core-spun yarns, and concluded that fibre content and ratio influence the mechanical and dimensional properties of the fabric. He considered three fabrics, one containing polybutylene terephthalate, the second one containing polyester, and the third containing elastomultiester fibres, all spun together with elastane. The core-spun yarns contained a single fibre in the core. He concluded that by increasing the weft yarn number per cm, the fabric stiffness was also increased. He also observed that the stiffness of the fabrics woven with core-spun yarn was lower than that of fabrics containing double core-spun weft yarns. The elongation and elasticity of the fabrics woven with double core-spun yarns were higher than those of the fabrics woven with core-spun yarns. The tear force of denim fabrics in the warp and weft directions, tensile force in the warp direction, breaking elongation, elasticity, and growth were decreased with an increase in the number of weft yarns (Ute, 2018).

In another study, four double core-spun yarn fabrics were tested. Yarns containing synthetic fibres, namely polyester, polybutylene terephthalate, new polytrimethylene terephthalate (PTT)/polyethylene terephthalate (PET) fibres, Lycra T400, and CM800, together with elastane in the core of the weft yarn were prepared. The test results showed that when compared with the cotton-elastane core-spun yarn, the breaking force and elongation were improved in the double core-spun yarn (Su & Liu, 2020).

There is very little information and analysis available that evaluates how multicomponent yarns in a denim fabric structure affect the physico-mechanical properties of the fabric.

1.5 Dyeing of denim fabrics

Dyeing is the process, in which a colour is applied to a fabric, yarn, or fibre. This process helps impart a certain visual appearance to the garment. Ever since the denim fabric was invented natural indigo dye has been used to colour this fabric. Natural indigo is a dye derived from natural resources; it is extracted from the plant named Indigofera tinctoria (Paul, 2015). Indigo is a type of vat dye, which has remained the most commonly used dye for denim fabrics. In the 19th century, the industrial revolution paved way for the mass production of goods, and the amount of naturally derived indigo was insufficient for the mass production of clothing. Moreover, the natural indigo dyeing process is expensive. This led to the development of synthetic indigo (Paul, 2015; Chakraborty & Chavan, 2004).

Cellulosic fibres are suitable for dyeing with direct, sulphur, vat, reactive, or azoic colourants. These dyes are used in the colouration of cotton, which is the main component of denim fabric. Despite its high cost and difficulties in applying, indigo blue vat dye is the most widely used dye in denim fabrics. Vat dyes are insoluble in water, and before the application they are reduced to a water-soluble substance, called “leuco” by using sodium sulfide or sodium hydrosulphite. After the application, the denim fabric is exposed to air to return the vat dye to its insoluble form. At the end of dyeing, the fabric is washed to remove the unfixed dye (Blackburn, 2015; Cassidy & Goswami, 2017).

Usually, vat-dyed fabrics exhibit good colour fastness to washing and light irradiation. Vat dyes are classified into indigo and anthraquinonoid derivatives. The colour fastness of indigo-based dyes is lower than that of the anthraquinonoid-based dyes. However, owing to its low affinity, it enables the creation of different shades of denim garments (Hussain, 2016).

1.5.1 Denim dyeing techniques

Three major continuous dyeing techniques are used to dye denim fabric cotton yarns with indigo, namely rope, slasher, and loop dyeing methods; these provide a ring-dyeing effect. This implies that only the warp yarn surface is dyed with indigo dye, leaving the fibres in the core uncoloured. Owing to the low affinity of indigo dye to cotton fibres, the dye particles get dislodged during abrasion (Elmogahzy, 2020; Paul, 2015).

It is known that pH value in the dye bath is a crucial factor when dyeing denim yarns. This is because the pH value influences the dye uptake. Indigo dye shows the highest affinity to cotton yarn when pH value remains approximately 10.5–11.5. In an acidic environment, the dye will not get permanently fixed on the cellulosic fibre. When pH is more than 12.5, the dye uptake decreases, and the yarn will acquire a poor colour fastness. Figure 4 shows that upon increasing the pH value, the dye penetration into the yarn also increases; In contrast, the ring dyeing effect decreases, thus making stone washing difficult because the colour shade on the fabric becomes redder and brighter. When pH decreases, the shade after the stone washing becomes greener and duller (Paul, 2015; Chakraborty & Chavan, 2004).

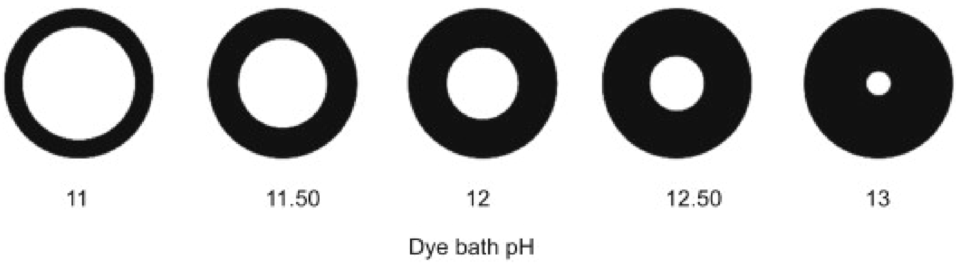


Figure 4. Effect of dye bath pH on ring dyeing (Paul, 2015).

Similar results were reported by Uddin *et al*., who found the optimal ring-dyed cotton yarn dye ratio. The thinner dye layer around the cotton yarn had a dye ratio of approximately 20%, while this ratio for the undyed core was 80%. For deeper ring-dyed yarn, the dye ratio was approximately 40%, and that for the undyed cotton core was 60% (Uddin, 2014).

Other than the pH, the dye effect also depends on the form and amount of the dye, immersion time, and the number of dips. The longer the immersion time and larger the number of dips, the better the dye penetration and colour yield.

In addition to indigo, sulphur and reactive dyes are also used to dye denim fabrics. The shade palette of sulphur dyes contains mostly dull colours, such as brown, blue, olive, and green. The most important and frequently used colour is sulphur black because there is no other colour that provides a more attractive black shade on denim fabric. Its low price has contributed to its widespread use in large-scale production. Sulphur dyeing can be divided into causticised (mercerised) and non-causticised processes with two options, ring and solid dyeing, as shown in figure 5 (Paul, 2015; Cassidy & Goswami, 2017).

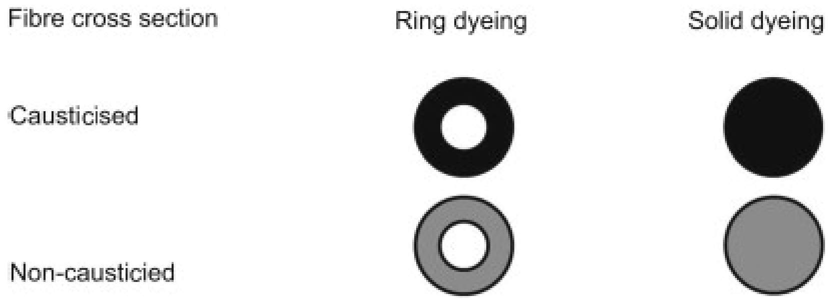


Figure 5. Fibre cross-sections with different dyeing methods (Paul, 2015).

Reactive dyes are rarely used to dye denim fabrics. As this dyeing method is completely solid, denim fabrics dyed with reactive dyes exhibit excellent colour fastness; however, the faded effect is difficult to achieve. Moreover, reactive dyes require special equipment for their application in denim yarns and the preparation of cotton yarns for dyeing sets limits the amount of dye that can be applied to the yarn (Paul, 2015).

1.6 Finishing methods of denim fabrics

Originally, denim was a rigid dark blue cotton fabric. Different dry and wet processes and their combinations are applied to denim fabrics to change their colour, provide a soft feel, and create different visual appearances. The finishing processes for denim fabric can be divided into mechanical (dry) and chemical (wet) processes. For example, sanding, brushing, sand blasting, and laser fading are considered dry processes. The wet processes include stone washing, enzyme washing, bleaching, and acid washing (Paul, 2015).

Traditionally, textile-finishing techniques require large amounts of electricity and water, thereby producing wastewater and chemical waste. To reduce its negative impacts on the environment, more sustainable techniques have been developed for denim fabric finishing. The following sub-section describes stone and enzyme washing, and an innovative laser fading technique, which are very widely used.

1.6.1 Stone and enzyme finishing

Stone washing is a widely used finishing method as it gives the desired "used" look. However, this method also has several disadvantages. Pumice stones, which are typically used in this process, can cause physical damage to the washing machines and garments. Stone washing has a high environmental footprint because it produces large amounts of sludge, and consumes water and energy (Islam & Asaduzzaman, 2019; Chowdhury, 2014).

Enzyme washing is as an alternative method to alleviate the drawbacks of stone washing. Enzyme washing is considered environmentally friendly. Cellulase enzymes are used to remove fabric hairiness, thereby improving the softness and comfort. In this process cellulase enzymes are added in the bath instead of pumice stones. During the washing, the enzyme abrades the fibre surface and dye particles. Enzymes degrade cellulose chains into shorter-chain polymers, which reduces the mechanical strength of the fabric (Mondal & Khan, 2014; Card, Moore, & Ankey, 2006; Partra & Bala, 2018). In the enzyme treatment, natural enzymes are used to degrade the dye from the fabric surface and this process consumes less water than stone washing. Nevertheless, these methods still have an environmental footprint considering the amount of water and energy used in washing.

Temperature, time, and pH are significant parameters that determine the intensity of enzyme washing of garments. Cellulases can be divided into acidic (pH = 4.5), neutral (pH = 6.6–7), and alkaline (pH = 9–10). Several studies have found that neutral cellulase enzyme treatment is the most suitable for denim washing because acidic cellulase may cause degradation of the cotton yarn (Kan, Yuen, & Wong, 2011; Islam & Asaduzzaman, 2019; Elmogahzy, 2020; Partra & Bala, 2018; Card, Moore, & Ankey, 2006).

1.6.2 Laser fading

Laser technology has been used in the textile industry since the 20th century. Used mostly in garment cutting and engraving initially, nowadays it is also widely used for fading denim fabrics. This provides an attractive visual appearance for the ready-made product (Figure 6). The intensity of denim fabric discolouration depends on current trends and customer preferences. Laser fading offers several advantages over other mechanical and chemical finishing methods. This is a more environment-friendly finishing method as it consumes less water, energy, and harmful chemicals. In addition, laser technology is an automated process that is easy to control; lasers have a high processing speed and accuracy, and provide high throughput (Nayak & Padhye, 2016; Gandhi, 2020; Vilumsone-Nemes, 2018). This technology enables the application of various shades of fading, patterns, lines, dots, and images (Elmogahzy, 2020). Laser process parameters, such as the speed of the laser cutter head, input power, and focal distance are manipulated to apply various shades and patterns to the garment. The duration and intensity of the laser beam exposure are important factors that determine the final appearance of the garment. During the laser processing indigo dye is burned and removed (Paul, 2015; Vilumsone-Nemes, 2018). Therefore, it is important to set the correct laser fading parameters. When the laser beam intensity is low, the effect of laser fading on the denim garment is minimal or invisible. However, a high intensity may destroy the fabric (Khan & Jintun, 2021). When a laser beam is applied to the fabric surface, the laser energy is absorbed by the yarn, and the dye particles evaporate into the atmosphere. Consequently, colour-fading effect is obtained (Figure 7) (Juciene, Urbelis, Juchneviciene, Saceviciene, & Dobilaite, 2018).

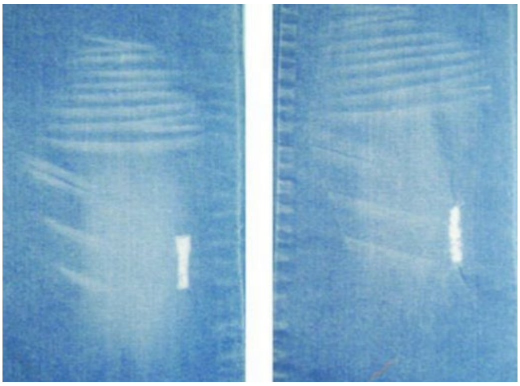


Figure 6. Effect of laser fading on the visual appearance of denim fabric (Sarkar & Rashaduzzaman, 2014).

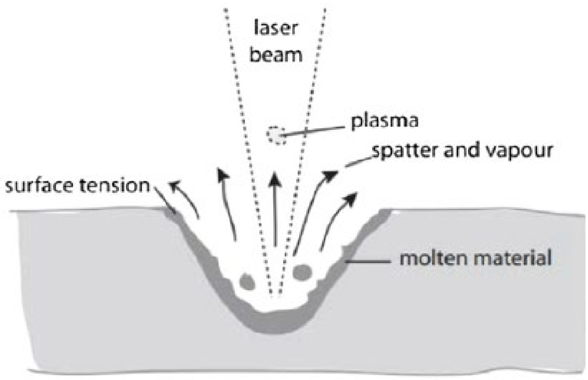


Figure 7. Mechanism of laser fading (Dalbaşıa, Kayseri, & İlleez, 2019).

Various types of lasers are available, including carbon dioxide (CO_2), neodymium (Nd), and neodymium yttrium-aluminum-garnet (Nd-YAG) lasers. Ortiz-Morales *et al.* applied laser fading on denim fabric by using three different lasers, Nd:YAG laser (1064 nm and a second harmonic of 532 nm), CTH:YAG laser (2.09 µm), and CO_2 laser (10.6 µm). CO_2 lasers were found to be the most suitable for denim fabrics as they demand lower amounts of energy and water, and smaller and cheaper cooling systems than the other lasers. In addition, CO_2 lasers have lower investment and maintenance costs than other lasers (Ortiz-Morales, Poterasu, Acosta-Ortiz, Compean, & Hernandez-Alvarado, 2003). A few other studies have also observed that CO_2 laser is suitable in textile industry for fading of denim fabric, because of its high accuracy, efficiency, and simplicity (Nayak & Padhye, 2016; Dalbaşıa, Kayseri, & İlleez, 2019).

1.7 Main properties of denim fabrics

An important mechanical property of denim fabrics is their response to an applied load, in other words, their ability to recover or change their shape after the external force is removed. The mechanical properties of denim fabrics depend on the material properties, applied load, and tension (Jahan, 2017).

A quality denim fabric possesses adequate strength, resilience, moderate drape, and elasticity. Additionally, higher levels of thermal conductivity, air permeability, absorbency, fabric dimensional stability, and colour fastness also indicate the quality of the denim fabric. Fabric durability is an important indicator because it determines the product's wearing period. The longer the wearing period, the less is the waste generated. Moreover, the lifespan of denim products influences the manufacturer's reputation. It has been stated that the breaking and tear properties of high-quality denim fabrics should be at their maximum levels (Annis, 2012).

The physical properties of materials depend primarily on the fibre structure (degree of orientation and crystallinity), yarn (spinning method, fibre content, yarn linear density, etc.), and fabric properties (weave type, number of warp and weft yarns per cm). In addition, the mechanical properties are influenced by the weaving parameters (speed, tension, number of yarns in the reed, etc.) (Zupin & Dimitrovski, 2010; Hatch, 1993).

1.7.1 Fibre and yarn properties

According to literature, abrasion resistance is one of the most important factors that define the durability of denim fabrics. Fibre elongation and elasticity influence the abrasion resistance. In addition, fabrics containing synthetic fibres, such as polyester or elastane exhibit higher abrasion resistance (Annis, 2012).

Yarn geometry properties, such as yarn twist, yarn diameter, length, yarn ply, and creep influence fabric durability. Fibres with larger diameters and longer fibres incorporated into a fabric increase the fabric abrasion resistance because short fibres are more easily removed from the yarn. Yarns with lower number of twists have lesser durability, as such yarns would be loosely intertwined with each other. A higher level of yarn twisting increases the resistance to abrasion; A higher yarn linear density also increases the abrasion resistance because a larger number of fibres must be abraded before the yarn failure. In addition, coarser yarns show better resistance to abrasion than finer yarns. The colour depth increases with decreasing yarn twist. The fabrics made of two-ply yarns exhibit a higher colour difference than those made of one-ply yarns (Annis, 2012; Ashraf, Hussain, & Jabbar, 2014).

1.7.2 Fabric properties

Fabric abrasion is an important property because during an abrasion the fabric demonstrates its ability to withstand repetitive mechanical friction. The fibres used in the fabric significantly influence the fabric resistance to abrasion. In addition, the yarn size, structure, and the entire fabric mass determine the durability of the fabric against abrasion. In addition, lubricants and sizing agents used in finishing stage affect the fabric's resistance to abrasion (Gandhi, 2020).

For example, the number of threads per cm influences the fabric abrasion resistance, breaking strength, tear, and tensile properties. In tight constructions, yarns are placed very close together, which leads to a lower tear force. The difference between the tensile and tear force tests is that in the latter, only one or at least a few yarns in the direction of loading bear the load, whereas in the former, all the yarns bear the load (Eryuruk & Kalaoglu, 2015). In another study, Triki *et al.* revealed that increasing the number of longitudinal yarns per cm in the fabric decreased the tear force. This was because of the decrease in mobility of the yarn, which led to a crowding of the yarns. However, increasing the transverse yarn mobility decreased the tear force because of the slippage of the transverse yarns' (Triki, Dolez, & Vu-Khanh, 2011). On the other hand, a higher thread number per cm increased the fabric tensile force because all the yarns shared the load, which implied that each yarn bore a small fraction of the total load. In addition, the orthogonal yarns supported yarns that are in the direction of the pulling forces. Yarn crimp is another factor to consider because a higher force and longer time are required to break the yarns. Generally, there are more warp yarns than weft yarns in denim fabrics. Thus, the fabric tensile force is higher in the warp direction (Annis, 2012; Hung, Chan, Kan, & Yuen, 2017).

1.7.3 Fabric comfort

Fabric comfort is a subjective assessment. Briefly, the comfort of a fabric can be described in terms of its physical properties and the psychological as well as physiological responses of the human body. Fabric comfort is assessed based on its mechanical and thermal attributes. The mechanical attributes are evaluated using visual and tactile means. The fibres used in the fabric, thread number per cm, yarn linear density, yarn twist, and weave type determine the appearance and touch of the fabric. The yarn diameter, cross-section, and yarn crimp determine the smoothness of the fabric. The thermal properties include fabric air permeability, thermal insulation capacity, water repellency, and water vapour transmission (Gandhi, 2020).

Comfort is an important aspect; however, usually, increasing the elastane content decreases the fabric durability. Therefore, many researchers have studied the optimum elastic fibre content in the fabric, and determined the effect of elastic fibres on the durability of denim fabrics.

Qadir *et al.* studied the effects of the elastane draft ratio and linear density on the physical and mechanical properties of core-spun weft yarns. It was concluded that the optimum yarn tenacity, elongation percentage, and hairiness were affected by the draft ratio, overall yarn linear density, and elastane linear density. The most suitable elastane linear densities for the 10/1 Ne and 16/Ne yarns were 70D and 40D respectively (Qadir M. B., Hussain, Malik, Ahmad, & Jeong, 2014).

Babaarslan *et al.* compared the breaking force, breaking elongation, static tear force, elastic recovery, and moisture management of denim fabrics containing dual core-spun yarns. Elastane and polyester were used as weft yarns cores. They concluded that the denim fabric provided the highest elastic recovery when the elastane draft ratio was 2.9 with polyester filament finesses of 3.05, 1.15, and 0.57 dtex (Babaarslan, Sarioğlu, Çelik, & Avci, 2018).

Özdil tested the tensile, tear, and bagging properties of cotton-elastane by changing the elastane content in the fabric. Their tests showed that when the elastane ratio was varied from 0.5% to 1.5%, the tensile force decreased by almost 100 N. Additionally, the tear force decreased by more than 5 N (Özdil, 2008).

Regenerated cellulose fibres, mainly made of wood pulp are considered as promising alternatives to cotton. They are used in the denim fabric to provide a soft feel. In addition, some studies have used regenerated fibres, such as modal, viscose, and Tencel in denim fabrics. For example, Basit *et al.* blended viscose with other regenerated or natural fibres, such as modal, Tencel, Tencel-bamboo, and cotton. Mechanical properties, such as tear and tensile forces, abrasion resistance, and pilling and comfort properties, such as air permeability, moisture management, and thermal resistance, were evaluated. They found that increasing the yarn twist, decreased yarn diameter, and it led to a higher air permeability. Tencel-viscose and Tencel-bamboo showed higher mechanical and comfort properties than 100% cotton. Viscose exhibited the highest tear force; however, after blending with cotton, it provided the lowest tear resistance (Basit et al., 2018).

In another study, Basit *et al.* focused on Tencel fibre and blended it with modal, viscose, or bamboo at a ratio of 50:50 in each fabric. The tensile and tear forces, pilling, abrasion resistance, and comfort properties, such as moisture management, thermal resistance, and air permeability, were tested. They concluded that the Tencel-modal blended fabric exhibited the best mechanical and comfort properties. Furthermore, Tencel-viscose and Tencel-bamboo yielded better test results than 100% cotton fabrics (Basit et al., 2019).

Tyagi *et al.* observed the relationship between the fibre cross-section and thermal comfort characteristics of polyester-viscose, polyester-cotton ring, and Murata jet spinning (MJS) fabrics. The air permeability decreased as the polyester content in the fabric increased because of the increased yarn diameter. The ring-spun fabrics had higher wickability, but lower moisture absorbency, air permeability, and water vapour transmission properties than the MJS yarn fabrics (Tyagi, Krishna, Bhatlacharya, & Kumar, 2009).

1.7.4 Impact of laser fading on physico-mechanical properties of denim fabric

The laser beam intensity, energy density, and the speed of the laser cutter head influence physical properties of the fabric, such as the thickness, stiffness, strength, and extensibility (Juciene, Urbelis, Juchneviciene, Saceviciene, & Dobilaite, 2018).

According to the literature, a laser beam influences fabric warp and weft yarns differently. In a twill weave, the warp yarns lie predominantly on the face of the fabric; for this reason, the warp yarns are affected more (Juciene, Urbelis, Juchneviciene, Saceviciene, & Dobilaite, 2018). Hung *et al.* found that after laser fading, cotton fibres absorbed thermal energy, which caused the fibres to swell and burst. Consequently, the cotton fibre degraded, resulting in pits on the fibre surface (Figure 8). Increased laser resolution and pixel time increased the number of pits; however, they were randomly formed on the cotton fibre surface (Hung, Chan, Kan, & Yuen, 2017).

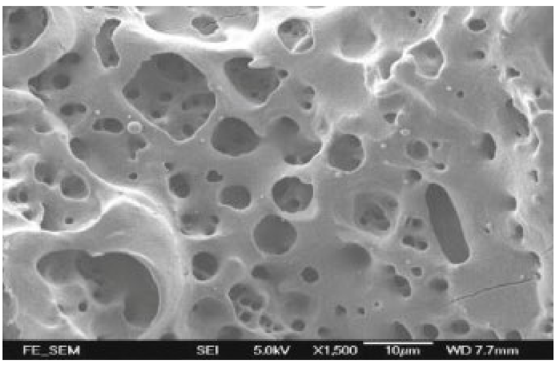


Figure 8. SEM image of cotton fibre surface after being modified by laser fading (×1500; 68dpi, 120μs) (Hung, Chan, Kan, & Yuen, 2017).

In a cotton-polyester blended laser faded fabric, the polyester fibre melts. Fibre ends coagulate into small polyester grains and the melted polyester fibres fill the cotton pores. The weight and thickness of the laser faded fabric decreases because the surface cotton fibres are removed and the water vapour inside the fibre evaporates during the laser treatment. Compared with a cotton denim fabric the weight loss in a cotton–polyester blended fabric is less because only the cotton fibre is removed after the laser fading. It can be seen from Figure 9 that the polyester fibre melts, but remains in the yarn. A higher laser beam intensity reduces the strength of the fabric, as more pores would be formed, which weaken the fibres. Hung *et al.* also stated that, with a resolution of 58–68 dpi/140 µs, the cotton fabric weight loss was 6%–12%; however, in the cotton–polyester blended fabric, the weight loss was 3%–9% (Hung, Chan, Kan, & Yuen, 2017).

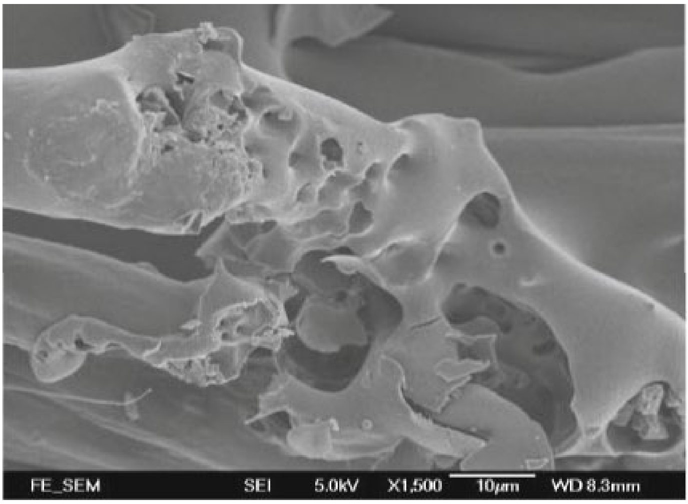


Figure 9. SEM image of cotton-polyester fibre surface after being modified by laser fading (×1500; 60dpi, 120µs) (Hung, Chan, Kan, & Yuen, 2017).

Denim fabric is usually made of a 3/1 twill weave, which means that warp yarns are more dominant on the face side of the fabric, and consequently, they are more affected during laser fading. More pores are created, and the spaces between the fibres would also be larger. This causes the warp yarns to move more easily, resulting in a higher elongation at the break point (Hung, Chan, Kan, & Yuen, 2017). In cotton–polyester blended fabrics, after laser fading, the polyester is melted and re-solidified, which results in the fibres becoming brittle and sticking to one another. Thus, the yarn movement is restricted, and as a result, the fabric tensile force decreases (Hung, Chan, Kan, & Yuen, 2017).

Many studies have observed the effect of laser fading on fabric properties. For example, Tarhan *et al.* studied the tensile force, weight loss, back staining, and colour change of a 100%-cotton denim fabric after laser fading and sandblasting. Their test results showed that when laser faded with the highest intensity (250 W/cm^2), the fabric lost approximately 60% and 50% of its strength after the laser fading and sandblasting, respectively. The colour loss increased with an increase in the laser intensity and fabric washing time (Tarhan & Sariisik, 2009).

Venkatraman *et al.* determined the optimum set of laser fading parameters for the decolourisation of indigo dyes. They observed the impact of laser fading parameters on the density and thickness of 100%-cotton denim fabrics. The fabrics were prepared with three different weights. The laser fading parameters used were 23 and 46 W, and the laser pulse irritation was set at 500 pulses per inch (ppi). The colour brightness of the fabrics treated with a laser power of 23 W was higher than that of the fabrics treated with the power of 46 W. Moreover, the fabric colour changed from blue to greenish yellow. This is because of cellulose fibre oxidation after the laser irritation. A grayscale of 0%–100% was used to assess the colour shade differences. They concluded that a laser power of 24 W was more suitable for retaining the fabric structure and performance. The optimum laser set parameters were set at 20%–30% grayscale for light- and medium-weight fabrics, and 40%–50% for large-weight fabrics (Venkatramana & Liauw, 2019).

Štěpánková *et al*. compared the impact of dye removal and tensile force of 100%-cotton denim fabric after laser fading with an energy density between 3.1–15.6 mJ/mm^2. They tested both dyed and non-dyed cotton yarns. Their test results showed that a low energy density has a minimum impact on the tensile force of the yarns in the weft direction; a medium energy density (7.8 mJ/mm^2) decreased the tensile force by 15%, while a high laser density (15.6 mJ/mm^2) decreased the tensile force 45%. In the case of the undyed cotton yarn, the tensile force reductions in the weft direction with different applied energy densities are as follows: 35% with medium and 70% with high laser energy density. On the other hand, in the warp direction in the non-dyed yarn, the tensile force reductions in the warp direction are as follows: 56% with medium and 100% with high laser energy densities. The dyed yarns showed a higher tensile force because the dye protected the cotton yarns from infrared laser light. Scanning electron microscope (SEM) analysis showed that increased laser energy density increased the craters on the fibre surface and caused carbonisation of the fibres owing to the thermal effect (Štepankova, Wiener, & Rusinova, 2011). Juciene *et al.* studied the impact of the laser speed, energy, and beam density on the tensile properties of a denim fabric. The highest laser energy density (9.89 mJ/cm^2) decreased the strength in the warp direction of a cotton-elastane denim fabric by approximately 91%, while the lowest density (6.18 mJ/cm^2) reduced the same by 22%. In weft direction the highest energy density decreased the fabric tensile force by 81% compared to an untreated denim (Juciene, Urbelis, Juchneviciene, Saceviciene, & Dobilaite, 2018).

Sakib *et al.* determined the effect of a laser beam on the tensile and tear strengths, and the colour difference of a denim fabric after laser fading. They found that in the warp direction the tensile force decreased by 7%–8%; on the other hand, the weft yarns were less affected, and the tensile force after laser fading decreased by only 1%–3%. The tear force also decreased more in the warp (7%–13%) than in the weft (3%–9%) direction (Sakib, Islam, Islam, Dr Ahmed, & Ali, 2019).

Kan & C.W faded a 100%-denim fabric by using different laser resolutions (30, 60, and 80 dpi) and pixel times (110, 160, 220, and 300 µs). They suggested an optimum laser power of 13 W/cm^2 (Kan & C.W, 2014).

1.7.5 Minimum requirements

Usually, countries or manufacturers have established legislations or minimum requirements for ready-made garments to provide more durable products and increase their wearing periods of the product. According to the Estonian Consumer Protection and Technical Regulatory Authority, consumers have the right to file a complaint with the trader within two years of purchase if a defect occurs in the goods (TTJA, 2019). According to this requirement, the wearing period of faded denim garments must be at least two years.

Based on this knowledge, the minimum criteria were defined for every physico-mechanical test performed in this study. These requirements were based on those of the Public Waste Agency of Flanders, Belgium (OVAM), which is an internally independent agency and a part of the Environment, Nature and Energy policy domain of the Flemish government. Their main objectives include sustainable waste and material management, clean and healthy soil, and transition to a circular economy (OVAM, 2021).

The colour difference was measured in this research after laser fading. The colour difference can be assessed visually and it has no fixed minimum requirement. Therefore, the optimum colour difference was evaluated visually. The following minimum requirements were set.

- Abrasion resistance: 20,000 rubs
- Tear force: 15 N
- Tensile force: 250 N

1.8 Mathematical modelling in textile industry

Some previously studies have used ANN or HWM in the textile industry. However, only a limited number of studies have mathematically predicted denim fabric durability or colour difference after laser fading. The colour difference was measured using CIE2000, which was developed to improve the correlation between the visually observed degree of colour difference and numerical values (chapter 2.2.8). The human eye can view the visible light region between 380–780 nm (extending from the infrared region at longer wavelengths to the ultraviolet region at shorter wavelengths).

ANN is a more established approach than the HWM, and is therefore, the primary method used in the textile sector. For example, Hung *et al.* used an ANN to predict the colour properties after laser fading of a 100% cotton denim fabric. The laser beam resolution, pixel time, and greyscale were used as input layers. The output layers were the colour yield (K/S) CIE L*, CIE a*, CIE b*, and yellowness index. These values are described in Section 2.3.8. A linear regression (LR) approach was used to estimate the colour shade of the faded denim fabric with minimum faults. The results were compared with those of the ANN. The relative error was distributed mainly in the range of 10%–50% for K/S, CIE a*, CIE b*, and yellowness index; for CIE L* it was distributed mostly in the range of 15%–10%. They concluded that the predictive power of ANN was better than that of the LR approach (Hung O. N., Chan, Kan, Yuen, & Song, 2014).

Tong *et al.* used a convolutional neural network (CNN) and compared it with ANN to evaluate the colour fading effect on a denim garment by changing the laser processing parameters. The mathematical modelling test results were consistent with the actual fading appearance (Tong et al., 2023). Sarkar *et al.* used Fuzzy logic expert system (FLES) to predict the tear strength of laser faded denim fabric. Their test results yielded a coefficient of determination (R^2) of 0.98 (R = 0.99). This implies that the predicted value was similar to that of the actual tests (Sarkar, Faruque, & Khalil, 2022). HWM, a more recent approach was introduced for function approximation in the first few years since its birth (Majak et al., 2020); it is not yet used for modelling denim fabrics.

1.8.1 Artificial neural networks (ANNs)

ANN belong to a group of Artificial Intelligence algorithms, along with fuzzy logic, expert systems, support vector machines, and evolutionary optimisation algorithms. ANNs are used in various applications, including pattern and handwriting/face recognition, weather prediction, robotics, and autopilots. ANNs are finding application in the textile industry, for example in fabric engineering and garment production. They enable the prediction of yarn or fabric durability, colour difference, seam strength, and seam consumption as well as detection of fabric faults and wrinkles in the fabric. ANNs can be used in widely diverse fields, unique and unambiguous mathematical explanations of ANNs are not available in the literature. In general, an ANN is a computational model inspired by networks of biological neurons, wherein neurons compute the output values from a given set of inputs (Puri et al., 2016; Chauhan, Yadav, & Arya, 2018).

ANN is inspired by and is essentially an imitation of the human brain (Figure 10). The human brain contains a network of neurons. Neurons consist of a cell body (also called soma), axons, and dendrites. Axons carry signals among the neurons, which receive these signals through synapses, which in turn, are connections between the dendrites of two neurones. When the signals are sufficiently strong, the neuron is activated and the axon carries the signal to another synapse, and activates another neuron. An ANN is based on the behaviour of natural and biological neurons. It has inputs (dendrites) and outputs (synapses via the axons). Although, there are many inputs, the goal is to receive a single output (Kukreja, Bharath, Siddesh, & Kuldeep, 2016).

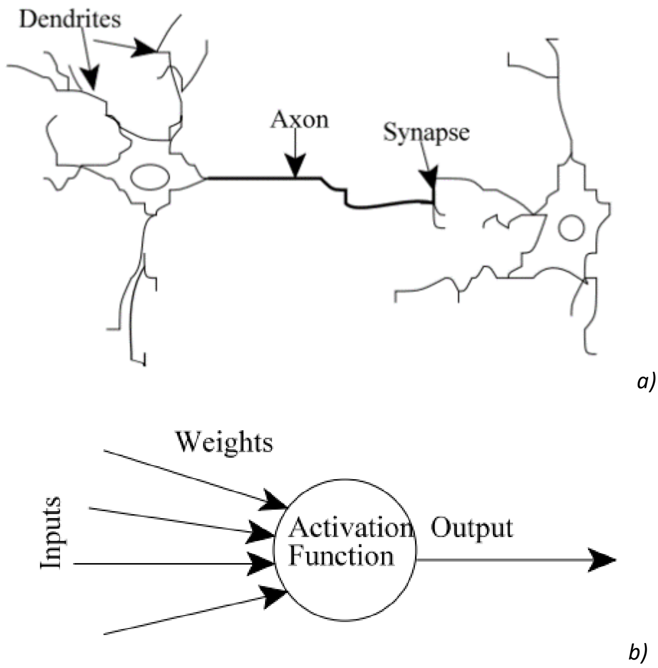


Figure 10. (a) Natural and (b) artificial neurons (Gershenson, 2003).

The working principle of artificial neurons is relatively simple. All the inputs are multiplied by their corresponding weights (i.e. the strengths of the corresponding signals) and summed. The value of the bias is multiplied by the weight w_0 and added to the sum. An activation function is applied to the sum and the output value is obtained (Figure 11) (Sheela & Deepa, 2013).

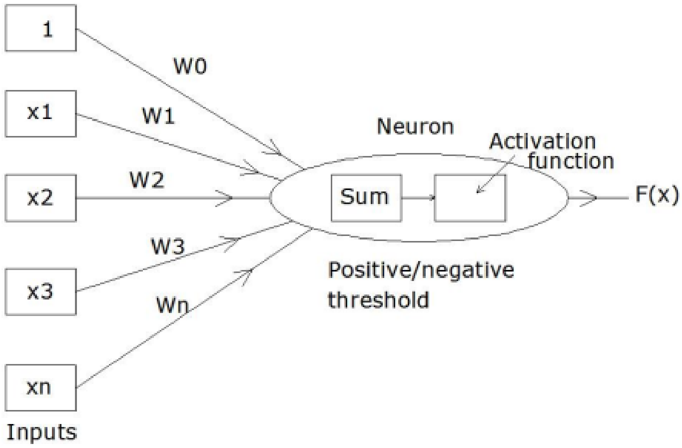


Figure 11. Model of an artificial neuron.

In the current study, an ANN was used for mathematical modelling, in other words to approximate a set of objective functions. The ANN consists of input, hidden, and output layers (Figure 11). It is well known that in the case of a function approximation (Sheela & Deepa, 2013),

- it is adequate to consider a feedforward ANN (without loops) with one or two hidden layers;
- it is justified to use a nonlinear function (e.g sigmoid) in the hidden layer(s) and a linear function in the output layer (to obtain accurate results).

When the dataset available for the function approximation is not large, the use of one hidden layer is preferred (Figure 12).

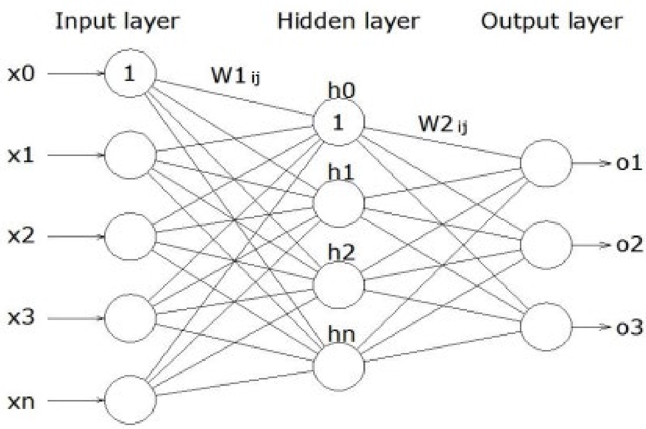


Figure 12. Neural network architecture (Shiruru, 2015).

The working principle of the feedforward ANN with one hidden layer, as depicted in (Figure 11), is outlined as follows (Kukreja, Bharath, Siddesh, & Kuldeep, 2016; Sheela & Deepa, 2013):

- The initial configuration of the ANN uses sigmoid and linear activation functions in the hidden and output layers, respectively. The initial number of neurons in the hidden layers can be estimated as:

$$N_h = \frac{(N_{in}+\sqrt{N_{tr}})}{L}, \tag{1.1}$$

where N_h is the initial number of neurons in the hidden layer;
N_{in} is the number of inputs; and N_{tr} is the capacity of the training dataset;
and L is the number of hidden layers.

- Initialisation of the weights in all the layers is done using random values.
- Computation of the output values using the ANN:
  - the input values are multiplied by weights and summed, and a bias is added (for each neuron in the hidden layer);
  - the sigmoid activation function of the hidden layer is applied to the sum (for each neuron in the hidden layer);
  - the output values of the hidden layer are treated as input values for the output layer;
  - input values of the output layer are multiplied by the corresponding weights and summed, and the bias is added to the sum;
  - the activation function of the output layer is applied to the sum and the final output value(s) is/are obtained.
- The error of the ANN model is computed for the given dataset (i.e., the difference between the dataset and output values, commonly estimated in terms of a root mean squared error).
- An error correction algorithm is utilised to adjust the weights such that errors are minimal (among different algorithms available for this purpose, the one widely used is the Levenberg–Marquardt algorithm).
- The weights are adjusted, and the iteration is applied (computing new output using ANN), until the error is below a prescribed limit, or the prescribed maximum number of iterations is exceeded.
- If the achieved accuracy is unsatisfactory, the entire process can be repeated with a reconfigured network, typically by the increasing number of neurons in the hidden layer.

Note that ANN needs a certain degree of tuning for each individual problem; that is the number of hidden layers, number of neurons in the hidden layer, and activation functions used should be customised.

Unfortunately, ANN models have accuracy problems for limited datasets. The dataset available in the current work was limited and will be extended in a future study. Therefore, HWM was introduced in this study as an alternative approach. HWM provides accurate and trustworthy results even with a limited dataset, and does not suffer from uncertainty (Tšukrejev, Karjust, & Majak, 2021).

1.8.2 Haar wavelet method (HWM)

HWM is based on the simplest type of wavelets. This system comprises a sequence of square waves. These wavelets contain pairs of piecewise constant functions. The name “wavelet” indicates that waves function above and below the x-axis; however, the result should integrate to zero (Hariharan & Kannan, 2013). Haar wavelets were first introduced by Haar in 1910 as square waves:

$$h_i(x) = \begin{cases} 1 & for \quad x \in [\xi_1(i), \xi_2(i)) \\ -1 & for \quad x \in [\xi_2(i), \xi_3(i)) \\ 0 & elsewhere \end{cases} \tag{1.2}$$

where

$$\xi_1(i) = A + 2k\mu\Delta x,\ \xi_2(i) = A + (2k+1)\mu\Delta x,\ \xi_3(i) = A + 2(k+1)\mu\Delta x, \tag{1.3}$$

$$\mu = \frac{M}{m},\ \Delta x = \frac{B-A}{2M},\ M = 2^J \tag{1.4}$$

where h_i and h_j are Haar functions defined as square waves; $m = 2^j$ is a resolution parameter with a maximum value of $M = 2^J$; and k is a translation parameter.
Any 2D square integrable function in a given domain can expanded into a Haar wavelet as (Lepik & Hein, 2014):

$$f(x,y) = \Sigma_{i=1}^{2M}\Sigma_{j=1}^{2M} a_{ij}h_i(x)h_j(y) \tag{1.5}$$

In (1.5), a_{ij} represent unknown coefficients determined at the collocation points, where the above formulas are satisfied.

However, an approach based on direct expansion of the function into Haar wavelets leads to low accuracy. Therefore, a modified approach for function approximation based on HOHWM was used, introduced by Majak *et.al* in 2018 for solution of differential equations and as (Majak, et al., 2020)

$$\frac{\partial^{p+q}f}{\partial x^p \partial y^q}(x,y) = \sum_{i=1}^{2M}\sum_{j=1}^{2M} a_{il}h_i(x)h_l(y) \tag{1.6}$$

where p and q denote orders of the derivatives with respect to x and y, respectively. The accuracy of HOHWM and the widely used HWM are compared in Table 1, where the function approximation results are given for a simple 1D exponential function. Here 2M represents the mesh used (or number of collocation points).

Table 1. Absolute errors of HWM and HOHWM (based on (Majak et al., 2020)).

	HWM		HOHWM, p=1		HOHWM, p=2	
2M	Fn. value at point x=0.5	Absolute error	Fn. value at point x=0.5	Absolute error	Fn. value at point x=0.5	Absolute error
8	1.75505	1.06E-01	1.64746	1.26E-03	1.64871813	3.13E-06
16	1.70106	5.23E-02	1.64840	3.21E-04	1.64872107	1.97E-07
32	1.67468	2.60E-02	1.64864	8.13E-05	1.64872125	1.23E-08
64	1.66165	1.29E-02	1.64870	2.13E-05	1.64872126	8.00E-10
128	1.65517	6.45E-03	1.64872	1.27E-06	1.64872127	1.28E-13

It can be observed from Table 1 that, in the case of the widely used HWM, the highest accuracy was achieved with a mesh size of 128, for which the absolute error was 6.45E–03. In the case of HOHWM with p = 1, at similar accuracy was achieved using a mesh size of 8 (absolute error = 1.26E03) and in the case of HOHWM with p = 2, even mesh size 8 lead to much higher accuracy (absolute error 3.13E–06). Note that in the case of HOHWM, with p = 1 and 2; the wavelet expansion included first- and second-order polynomials, respectively, for each element. In the case of classical regression with first- and second-order polynomials, the absolute errors for the same function approximation were 6.51E–2 and 1.52E–04, respectively. Thus, in the case of the sample considered, HOHWM achieved higher accuracy than the classical linear or nonlinear regression. HWM and HOHWM are known to be capable of covering local effects of functions (local rapid changes).

1.9 Environmental issues and sustainability

Although denim is often blended with synthetic or regenerated fibres, cotton remain the most commonly used fibre in denim fabric production. The entire denim fabric production process, from cotton cultivation to finished garment production, negatively impacts the environment. Large quantities of water and pesticides are used to grow cotton crops. World Wildlife Fund (WWF) has stated that approximately 8%–10% of world's pesticides are used for cotton cultivation. Approximately 1 kg of cotton lint is used to produce a pair of jeans. To grow this quantity of cotton, approximately 8500 L of water is required. In addition to cotton cultivation, fabric production, dyeing, washing, and finishing consume large amounts of energy and water.

The final stage of garment production is finishing. This is a very important stage in the manufacturing process, because finishing gives the product its appearance. Aesthetics, attractiveness, while fashion influences customers' choices. Unfortunately, washing is considered as one of the most environmentally damaging phases in denim production. For example, Khan *et al.* (2021) stated that using traditional washing recipes to fade one pair of denim jeans consumes 150 g of chemicals, 70 L of water, and 1 kWh of power (Csanák, 2021; World Wildlife Fund, 2007; Khan & Jintun, 2021). Moreover, after a large amount of water is used, the resulting waste must be treated before it is discharged into the ecosystem.

To reduce the water consumption during the finishing stage, a sustainable laser technology was developed for fading of denim fabrics. Lasers are managed by computers that imitate the same fading appearance as that obtained through conventional processes. In addition, patterns, dots, abrasions, and whiskers can be created. Laser technology reduces the use of chemicals by 85%, water by 67%, and energy by 62%. This fading process saves time, and reduces labour and production costs. In addition, it allows easier maintenance and service (Khan & Jintun, 2021).

1.10 Summary of literature review and aim of current study

Denim fabric is widely used worldwide. Conventional denim fabric is made of a twill weave, where warp yarns are dyed with indigo blue and weft yarns are undyed. Cotton is the main fibre used to weave yarns in denim fabrics. Denim garments were originally used as rigid workwear; nowadays, they are used for everyday wear. Durability and comfort are two of the most important requirements of customers. To improve cotton fabric properties, mainly synthetic but also regenerated fibres are added to the core of weft yarns, while cotton is still used as a sheath fibre.

Dyeing the denim fabric is complicated because the dye does not penetrate the yarns completely. This ring dye effect results in denim fabrics with low washing fastness; however, it is considered more advantageous because it enables the creation of a worn-out or faded effect on the denim garment.

Numerous finishing methods are applied to denim fabrics and garments to enhance their visual appearance and feel. However, an undesirable feature of the denim finishing methods is that they significantly reduce the fabric durability. Laser fading is innovative, and its water and energy consumption are significantly lower than those of other conventional finishing methods. Despite its lower environmental impact, laser fading reduces fabric durability. Based on the Estonian Consumer Protection and Technical Regulatory Authority regulation denim garments, after laser fading, need to withstand everyday stress without tearing or otherwise sustaining damage for at least two years (TTJA, 2019).

Previous studies have mainly focused on the properties of cotton or cotton–elastane fabrics. Few studies have examined denim fabrics containing widely used polyesters or regenerated fibres. However, denim garments currently used for everyday wear contain a mixture of several fibres. A knowledge gap exists in testing the durability of multicomponent raw and laser faded denim fabrics. A limited number of studies have used ANN as a mathematical optimisation approach for the simulation of different denim fabric properties. However, no studies have used HWM to simulate the denim fabric behaviour in terms of tear force, abrasion resistance, and colour difference after laser fading. There have been no research studies that have reported on optimal laser fading parameters that provide denim fabric with durability and an attractive visual appearance.

The main aim of this research was to study the impact of fibre content, structural parameters, and laser fading on multicomponent denim fabric durability and aesthetic properties with a view to prolonging the lifespan of denim clothing. Therefore, denim fabrics containing various synthetic and/or regenerated fibres at the core of weft yarns were studied, and the optimal laser fading parameters were determined. It is extremely important that the improved denim fabric be industrially manufacturable.

To achieve the aim of the study, the following objectives were set:

- Study the impact of fibre composition and structural parameters on the physical properties of the fabric to achieve durable, elastic, and comfortable clothing;
- Understand the effect of laser fading on fabric durability and determine the optimum laser fading parameters that have a minimal impact on the durability of the denim fabric;
- Determine whether the laser fading parameters could be fixed in bulk production of four-component denim fabrics with different weave constructions and fibre ratios.

To achieve these objectives, the following activities were carried out:

- The physico-mechanical properties of two-, three-, and four-component denim fabrics containing various synthetic and regenerated fibres at the core of the weft yarns were tested to evaluate the durability and aesthetic properties of the raw and laser faded denim fabrics.
- ANN and HWM were used to predict the tear force, abrasion resistance, and colour difference of laser faded denim fabrics.
- The effect of laser fading on the morphology of the fibres was studied.

2 Experimental

This section provides an overview of the experimental plan (Figure 13), materials and methods used in this study, and processing and analysis methods applied to assess the mechanical properties of denim fabrics. A number of denim fabrics with different fibre compositions and different numbers of threads per unit area were considered to explore how these parameters affect the fabric strength (Paper I). Additionally, the influence of the applied laser fading on fabric strength was analysed (Paper II). Finally, the optimal laser fading parameters were applied to multicomponent denim fabrics made of satin or twill weaves to determine whether these laser fading parameters were suitable for processing denim fabrics with various weave constructions (Paper III). An overview of the materials and methods used in this research is presented in Table 2.

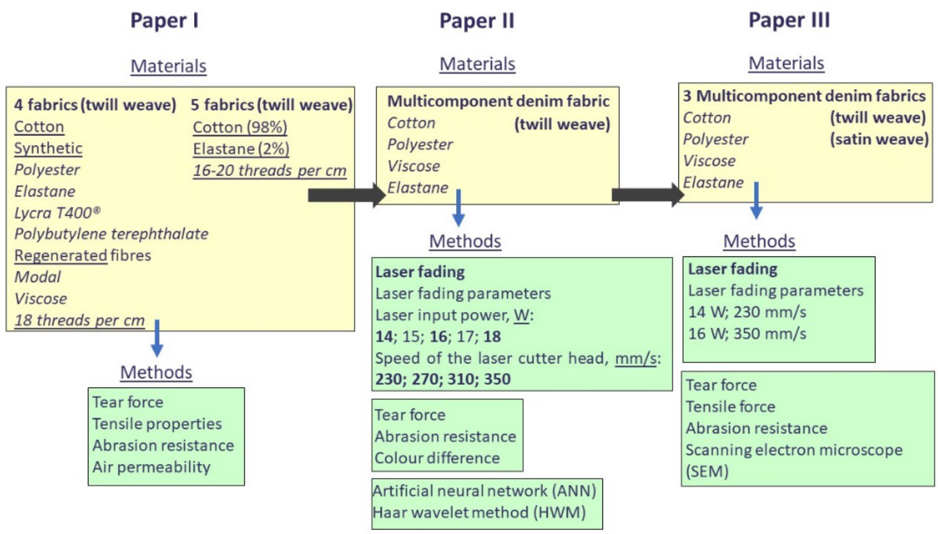


Figure 13. Schematic of the workflow applied in the current research.

Table 2. Materials and methods used in this work and as reported in the papers.

Materials	Methods/parameters	Aim of the work reported in the paper	Paper
9 denim fabrics with different fibre contents and structural parameters	Mass per unit area Thread number per cm Abrasion resistance Specific stress at max load Tear force Air permeability	To find the optimum fibre content for denim fabric and thread number per cm to provide durability and comfort at the same time.	Paper I
Four-component denim fabric	Tear force Abrasion resistance Laser fading, laser wavelength: 10.6 µm Laser parameters: Input power: 14, 16, and 18 W Speed of the laser cutter head: 230, 270, 310, and 350 mm/s Fabric colour difference after laser fading Neural network methodology	To find the optimal speed of the laser cutter head and input power values that have the least effect on denim fabric durability.	Paper II
Three quaternary denim fabrics	Mass per unit area Thread number per cm Abrasion resistance Tensile force Tear force Laser fading, laser wavelength: 10.6 µm Laser parameters: (1) 14 W and 230 mm/s (2) 16 W and 350 mm/s Microscopic analysis	To determine whether the laser fading parameters can be fixed for bulk production when denim fabrics with different weave constructions and different ratios of the same fibres are used.	Paper III

2.1 Materials

To determine the optimum fibre content, nine denim fabrics were prepared by a Turkish company, Kipaş Holding A.S (Table 3). All the fabrics were made of a 3/1 Z-twill weave. Two fabrics were quaternary and contained cotton, elastane, polyester, and viscose or modal. Two fabrics were ternary, containing cotton, elastane, and polybutylene terephthalate or Lycra T400®. The five remaining fabrics contained cotton and elastane, but had different numbers of threads per cm. This work was reported in Paper I. The most durable fabric from the above work was chosen, which contained cotton, polyester, viscose, and elastane (Paper II). Next, denim fabrics containing synthetic and regenerated fibres were prepared by Diraga Home Textiles Ideas & Concepts Private Limited, India (see Table 3). Two fabrics were made of 4/1 satin weave and one denim fabric was made of 3/1 Z-twill weave. These three denim fabrics were quaternary and contained different ratios of cotton, viscose, polyester, and elastane. The study pertaining to these samples was reported in Paper III.

The warp yarns of all the denim fabrics used in this study were made of cotton. The weft yarn contained various synthetic and regenerated fibres in the core, while cotton was used as the sheath fibre.

Table 3. Technical information related to the materials used in the research.

No	Fabric code	Mechanical weft thread number, per/cm	Actual number of weft threads, per/cm	Weave	Fibre content, %	Manufac turer
Reported in Paper I						
1.	CMPE	18	22	Twill	CO[1]/PES[2]/CMD[3]/EL[4] 70/14/14/2	Kipaş Holding A.S
2.	CPVE	18	22	Twill	CO/PES/CV[5]/EL 69/19/10/2	Kipaş Holding A.S
3.	CPE	18	22	Twill	CO/PBT[6]/EL 94/4/2	Kipaş Holding A.S
4.	CT400E	18	22	Twill	CO/T400[7]/EL 94/4/2	Kipaş Holding A.S
5.	CE16	16	19	Twill	CO/EL 98/2	Kipaş Holding A.S
6.	CE17	17	20	Twill	CO/EL 98/2	Kipaş Holding A.S
7.	CE18	18	22	Twill	CO/EL 98/2	Kipaş Holding A.S
8.	CE19	19	23	Twill	CO/EL 98/2	Kipaş Holding A.S
9.	CE20	20	24	Twill	CO/EL 98/2	Kipaş Holding A.S
Reported in Paper II						
1.	CPVE	18	22	Twill	CO/PES/CV/EL 69/19/10/2	Kipas Holding A.S
Reported in Paper III						
1.	Fabric 1	24	23	Satin	CO/PES/CV/EL 67.7/20/10.5/1.8	Diraga Home Textiles Ideas & Concepts Private Limited
2.	Fabric 2	20	18	Satin	CO/PES/CV[5]/EL 75/19/4.5/1.5	Diraga Home Textiles Ideas & Concepts Private Limited

No	Fabric code	Mechanical weft thread number, per/cm	Actual number of weft threads, per/cm	Weave	Fibre content, %	Manufac turer
3.	Fabric 3	20	22	Twill	CO/PES/CV[5]/EL 75/13.5/9.5/2	Diraga Home Textiles Ideas & Concepts Private Limited

[1]CO: Cotton; [2]PES: Polyester; [3]CMD: Modal; [4]EL: Elastane; [5]CV: Viscose;
[6]PBT: Polybutylene terephthalate; [7]T400: Lycra T400®

2.2 Methods

2.2.1 Number of threads per cm

The number of threads per unit length was tested in compliance with the standard EVS-EN 1049-2:2000. According to this standard, method A was used to calculate the number of threads per cm, it is the most used laboratory method and suitable for all fabrics. Five specimens were cut from the warp and five more were cut from the weft direction of the denim fabrics. The width of each sample was 5 cm. A dissecting needle and heavy steel ruler were used to count the number of warp and weft threads per cm. The means of the individual results in the warp and weft directions were considered (EVS EN 1049-2:2000, 2000).

2.2.2 Mass per unit area

Standard EVS-EN 12127:2000 was used to calculate the denim fabric mass per unit area. Five specimens of 100 cm^2 were cut from each fabric using a cutting device (Model 240/100, Schmidt). Each specimen was weighed and the weight was recorded to the nearest 1 mg. The mass per unit area was calculated in g/m^2 using the following equation:

$$M = (m \cdot 1000)/A \quad (1.7)$$

where m is the mass of a conditioned test specimen (g); A is the area of the same test specimen (cm^2); and M is the mass per unit area (g/m^2) (EVS EN 12127:2000, 2000).

2.2.3 Tensile properties

The tensile properties were tested according to ISO standard EVS-ISO 13934-1:2013. As reported in Paper I, the tensile force is expressed in terms of the specific stress at the maximum load. This is the ratio of the maximum load to mass per unit area, and is also known as tenacity (Schwartz, 2019). The specific stress (P_0) was calculated as follows:

$$P_0 = P_t/(B \cdot GS) \quad (1.8)$$

Where P_0 is the specific stress (N·m/g); P_t is the maximum load (N); B is the mass per unit area (g/m^2); GS is the sample width (m) (Ko & Wan, 2014).

As reported in Paper III, the tensile properties were expressed in terms of the load at the break point. Five specimens were cut in the warp direction, and five in the weft direction. The length and width of each specimen were 400 and 50 mm, respectively. The gauge length of the tensile testing machine (Instron 5866) was set to 200 mm.

A pretension of 5 N was used for load cell with a maximum capacity of 10,000 N was used. The extension rate was set to 100 mm/min. The movable clamp extended the test specimen to the point of break (ISO 13934-1: 2013, 2013). The load at break (N) was recorded using BlueHill software.

2.2.4 Tear force

ISO standard EVS-EN ISO 13937-2:2000 was used to determine the tear force of the denim fabric. Five specimens were cut in the warp direction, and five more in the weft direction. The length and width of each specimen were 200 and 50 mm, respectively. A load cell with a maximum capacity of 500 N was used to determine the tear force at a constant test speed of 100 mm/min. A longitudinal slit was cut at 100 mm from each edge. The end of the tear was marked 25 mm from the uncut end of the stripe (Figure 14). An Instron 5866 tensile testing machine was used for testing. The gauge length of the testing machine was set to 100 mm. The tearing was continued to at point marked near the end of the strip and the tear force was recorded (ISO 13937-2: 2000, 2000). Tear force was recorded by using BlueHill software.

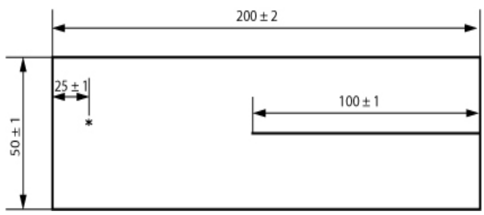


Figure 14. Trouser-shaped test specimen.

2.2.5 Abrasion resistance

The abrasion resistance was tested in accordance with ISO standard EVS-EN ISO 12947-2: 2016, using Martindale abrasion tester (James Heal 1605). Three test samples were cut from each fabric. The diameters of the test specimen and holder foam were both 38 mm. An original Martindale polyurethane foam was used as the foam material. The diameters of the abradant and wool felt underlays were both 140 mm. A Martindale abrasion cloth SM25 was used as the abradant material, and woven felt was used as the felt material. The test was continued until the two yarns were broken (ISO 12947-2: 2016, 2016). A digital microscope (Dino-Lite Digital Microscope AM4113T) was used to examine damaged and broken yarns.

2.2.6 Air permeability

EVS-EN ISO 9237:2000 standard was used to assess the air permeability of the denim fabrics. The test surface area was 20 cm^2 and the pressure drop was 100 Pa. An FX 3340 MinAir was used to test the air permeability of the fabrics. Measurements were made at ten locations on the same surface of each specimen. The air permeability of the tested fabrics was recorded from the face- and back-side of each fabric. However, the analysis was performed using data with the back side on top, as the back side usually is against the human body (EVS EN ISO 9237:2000, 2000).

2.2.7 Laser fading

A laser (10.6 µm; LMP9001300 PIRANHA X) was used. The combinations of the laser input power, the speed of the laser cutter head, and input power density are listed in table 4. The laser spot radius was 0.1 mm. The laser input power density was calculated as follows:

$$Pd = W/(w^2 \cdot \pi) \quad (1.9)$$

where Pd is the laser power density (W/mm^2) and w is the laser spot radius (mm). The focal distance of the laser lens (the distance from the lens to the point, at which the laser beam converges) was 50.8 mm. Thunder Laser RDworks V8 software was used to set the speed of the laser cutter head and input power parameters.

Table 4. Combinations of used laser input power and speed of the laser cutter head.

No.	Laser input power, W/ speed of the laser cutter head, mm/s	Input power density, W/mm^2
1.	14/230	446
2.	14/270	446
3.	14/310	446
4.	14/350	446
5.	16/230	509
6.	16/270	509
7.	16/310	509
8.	16/350	509
9.	18/230	573
10.	18/270	573
11.	18/310	573
12.	18/350	573

2.2.8 Colour measurements

CIE2000 colour-difference formula was used to determine the colour difference of the denim fabrics, in terms of yellowness index (YI) and colour change (ΔE_{00}) after laser fading. A colour assessment cabinet (VeriVide) was used to observe the colour differences after the laser fading under the artificial daylight D65. Yellowness is defined as the degree to which the colour of a surface is shifted from white toward yellow. A spectrophotometer (3NH Technology spectrophotometer YS33060) was used and the laser treated denim fabric's ΔE_{00} were measured. A spectrophotometer program was used to calculate YI according to ASTM 313-00. The spectrophotometer program uses Equation 2.0, given below to calculate ΔE_{00} (Konica Minolta, 2007).

$$\Delta E_{00}=\sqrt{(\frac{\Delta L'}{k_L \cdot S_L})^2+(\frac{\Delta C'}{k_C \cdot S_C})^2+(\frac{\Delta H'}{k_H \cdot S_H})^2+(R_T\left(\frac{\Delta C'}{k_C \cdot S_C}\right)^2\left(\frac{\Delta H'}{k_H \cdot S_H}\right)^2))} \quad (2.0)$$

Where:

$$L' = L^*; a' = a^*(1+G); \text{ where } G=0.5(1-\sqrt{\frac{\bar{C}^*_{ab^7}}{\bar{C}^*_{ab^7}+25^2}} \quad (2.1)$$

$$b' = b^*; C' = \sqrt{(a')^2 + (b)')^2}; \quad (2.2)$$

$$h' = tan^{-1}\left(\frac{b'}{a'}\right) \quad (2.3)$$

C^*; is the Munsell Chroma that indicates saturates; H* is Munsell Hue that indicates the hue; S_L, S_C, $and\ S_H$ are weighing coefficients; and k_L, k_C, k_H are parametric coefficients.

L^* indicates the lightness (white−black);

a^* (red−green) and b^* (yellow−blue) are the chromaticity coordinates; where $+a^*$is the fabric redness; $-a^*$ is the green direction; $+b^*$ is the yellow direction; and $-b^*$ is the blue direction.

ΔL*– Lightness difference;

ΔC*– Saturation difference;

ΔH*– Hue difference.

Weighing coefficients S_L, S_C, S_H are defined:

$$S_L=1+\frac{0.015(\bar{L}'-50)^2}{\sqrt{20+(\bar{L}'-50)^2}} \quad (2.4)$$

$$S_C= 1+0.045\bar{C}' \quad (2.5)$$

$$S_H=1+0.015\bar{C}'T \quad (2.6)$$

$$T=1-0.17\cos(\bar{h}'-30)+0.24\cos(2\bar{h}')+0.32\cos(3\bar{h}'+6)-0.2\cos(4\bar{h}'-63) \quad (2.7)$$

$\bar{h}'$ is the mean hue.

Rotation factor RT is determined as

$$R_T=-\sin(2\Delta\theta)R_C\text{, where} \quad (2.8)$$

$$\Delta\theta=\exp\left(-\left(\frac{\bar{h}'-275}{25}\right)^2\right) \quad (2.9)$$

$$R_C=2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7+25^7}} \quad (3.0)$$

2.2.9 Mathematical modelling

Two mathematical models, one based on ANNs, and the second based on Haar wavelet-based function approximation model were developed and used to analytically predict the tear force, abrasion resistance, and colour difference. The feed forward ANN model was adopted by using Equation 1.1 to calculate the initial number of neurons in the hidden layers. Haar wavelet-based deterministic function approximation techniques were utilised for a preliminary design with a limited dataset using Equations 1.2–1.6. The proposed mathematical models allow a fast evaluation of the objective functions required during the multi-criteria optimisation.

2.2.10 Scanning electron microscopy

A scanning electron microscopy (SEM TMI-1000) was used to examine and compare the fibre and yarn morphology (at 1000x magnification) before and after the laser fading. Prior to the SEM examination, a double-sided conductive tape (16073 Ted Pella Inc. Carbon Tape; 8mm Width x 20m length) was used to attach the specimen to the stub.

3 Results and discussion

3.1 Effect of core-yarn fibre composition and fabric structural parameters on physico-mechanical properties of raw denim fabrics

3.1.1 Number of threads per cm and mass per unit area

Usually, the initial thread number per unit area does not correspond to the actual thread number, owing to the discrepancies in the production conditions and machines. In addition, the actual mass per unit area is influenced by the number of threads per unit area in the fabric. To obtain an adequate fabric thread number per cm and fabric mass, the number of threads per cm and mass per unit area of all the tested fabrics were calculated. Cotton–elastane fabrics were compared with fabrics that contained synthetic and regenerated yarns at the core of the weft yarn (Paper I). The fabrics that contained synthetic fibres and cotton–elastane fabric with a higher number of threads per cm were heavier. The test results showed that the actual weft threads per cm were higher than the mechanical weft thread number by 3 to 4 threads.

3.1.2 Abrasion resistance and air permeability

Fabrics CE16–CE20 contained 16–20 threads per cm (Paper I). The abrasion test clearly showed that an increased thread number per cm also increased the fabric resistance to abrasion (Figure 15). The abrasion resistance of Fabrics CE16, CE17, CE18, CE19, and CE20 were 20,000, 30,000, 35,000, 35,000, 40,000 rubs, respectively. Thus, the abrasion resistance increased by 50% from the lowest to the highest. However, a higher number of threads decreased the air permeability. The highest air permeability was shown by fabric CE16 (41.7±1.2 $l/(m^2{\cdot}s)$) and the lowest by CE20 (27.4±1.2 $l/(m^2{\cdot}s)$) (Figure 16). Thus, the air permeability decreased approximately by 34% from the highest to the lowest. This was attributed to the tight fabric construction, which meant that there was less space between the yarns, and the air flow through the fabric was restricted. On the contrary, the tight fabric structure increased the abrasion resistance. Thus, even one additional thread per cm had a significant effect on the fabric's resistance to abrasion and air permeability.

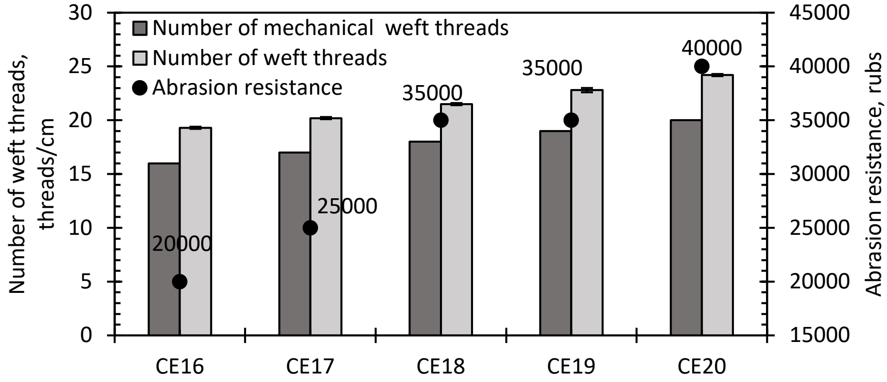


Figure 15. Effect of number of threads per cm on abrasion resistance of fabrics CE16, CE17, CE18, CE19, and CE20 (same graph as in Paper I).

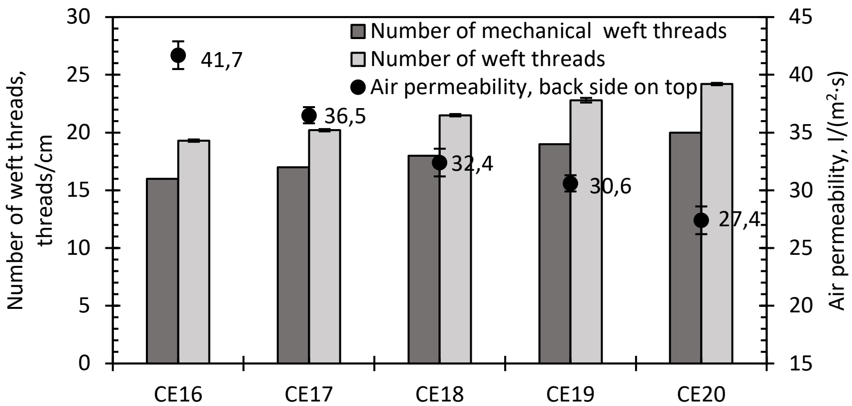


Figure 16. Effect of number of threads per cm on air permeability of fabrics CE16, CE17, CE18, CE19, and CE20 (same graph as in Paper I).

Fibre content was another factor that influenced the abrasion resistance and air permeability. Fabrics CMPE, CPVE, CPE, and CT400E had the same warp and weft threads per cm (18 warp threads and 22 weft threads per cm); however, the abrasion resistance values of the fabrics that contained synthetic fibre polyester at the core of the weft yarn were between 30,000 and 40,000 rubs; this was similar to those of cotton–elastane fabrics, which had higher thread numbers per cm (Fabrics CE18–CE20) (Figures 16 and 17). Polyester typically has a higher tenacity than cotton yarn, which increases its resistance to abrasion.

The air permeability of fabrics that contained synthetic and regenerated fibres at the core of the weft yarn were between (30.3±1.3) and (31.0±1.3) $l/(m^2 \cdot s)$ (Figure 18). On the other hand, cotton–elastane containing fabrics, which contained same number of threads per cm (Fabric CE18) exhibited an air permeability of (32.4±1.2) $l/(m^2 \cdot s)$; this was only 4–6.5% higher. Thus, the synthetic or regenerated fibres, which had a higher yarn diameter possessed lower air permeabilities (Akankwasa, Jun, Yuze, & Mushtaq, 2014). In conclusion, the fabrics that contained 16 or 17 threads/cm of possessed lower abrasion resistance than the other tested fabrics. Synthetic fibres had higher resistance to abrasion, and 18 threads per cm provided the optimal air permeability.

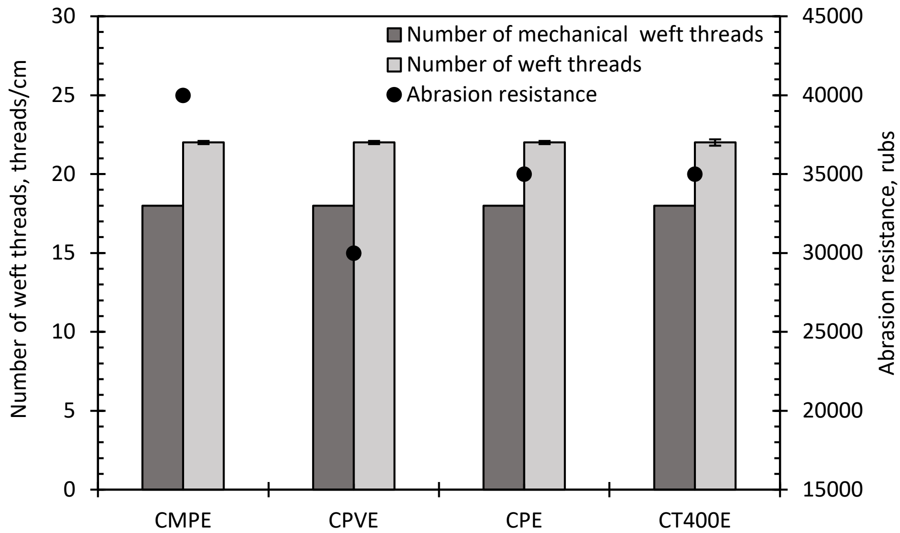


Figure 17. Effect of number of threads per cm on abrasion resistance of raw denim fabrics CMPE, CPVE, CPE, and CT400E (same graph as in Paper I).

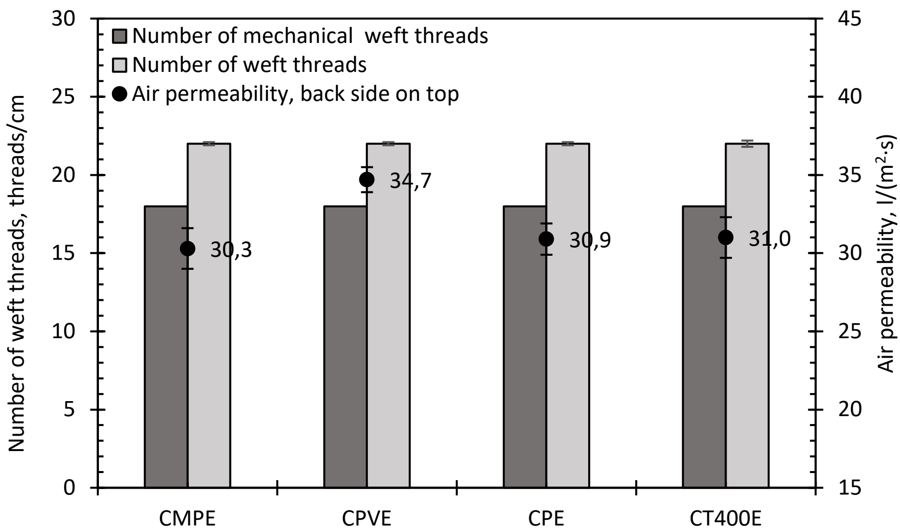


Figure 18. Effect of number of threads per cm and air permeability of raw denim fabrics CMPE, CPVE, CPE, and CT400E (same graph as in Paper I).

3.1.3 Tear force

The tear force of the raw denim fabric was recorded in the warp and weft directions. Only fabrics CMPE, CPVE, CPE, and CT400E produced results in both directions; the other fabrics failed in the weft direction, as the warp yarns were torn in those cases. The specimens broke before the test ended because of the shifted yarns. This was because the elastane yarn was much weaker than the yarns used in the opposite direction. The warp yarns of all the tested fabrics were made of cotton, and consequently, the test results for tearing in the weft direction (warp yarns were torn) were similar (Figure 19). However, in the warp direction (weft yarns were torn) Fabric CPVE showed four times higher tear force (88±4) N than cotton–elastane containing fabrics (between (20±1) – (22±1) N). Polyester which is a synthetic fibre is more resistant to tear than cotton (Islam, Ahmed, Arifuzzaman, Islam, & Akter, 2019).

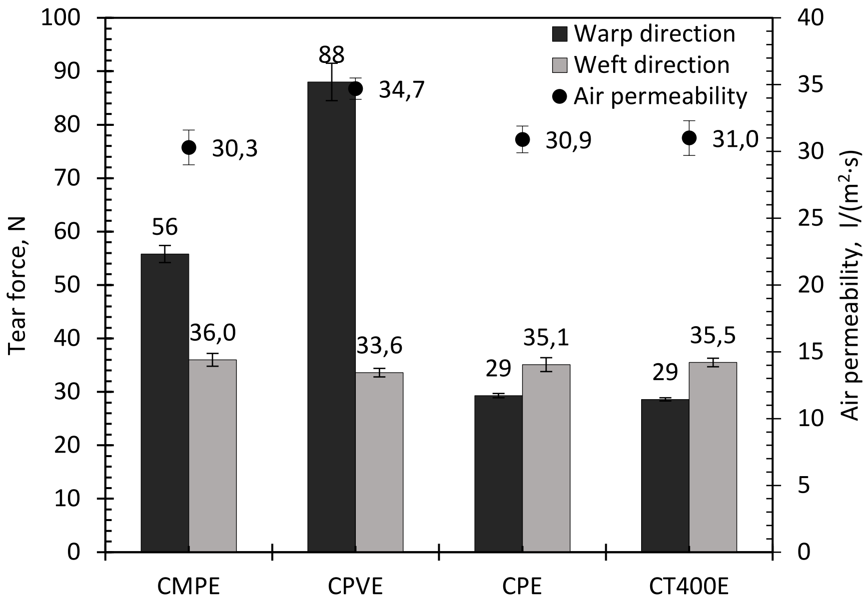


Figure 19. Comparison of mean warp and weft yarn tear force of raw denim fabrics CMPE, CPVE, CPE, and CT400E (same graph as in Paper I).

3.1.4 Tensile force

The tensile properties of the raw denim fabrics were expressed in terms of specific stress at the maximum load (Paper I). The tested fabrics containing synthetic fibre warp yarns had 2–2.5 times higher specific stress values than the weft yarns; The warp yarns of Fabrics CE16–CE20 exhibited specific stress values at the maximum load that were 3–3.5 times higher than those of the weft yarns. This is because elastane has a very high stretchability, which however, decreases the tensile force. Moreover, elastane has a lower tenacity than cotton yarn. It is clearly seen in the weft direction that the fabric that contained a higher percentage of polyester (Fabric CPVE with 19% of polyester) showed approximately 2 times higher specific stress at the maximum load than the cotton–elastane containing fabrics (Figure 20). It can be concluded that the higher polyester content of CPVE had only a minor impact on the fabric's air permeability; however, it significantly increased the tear force.

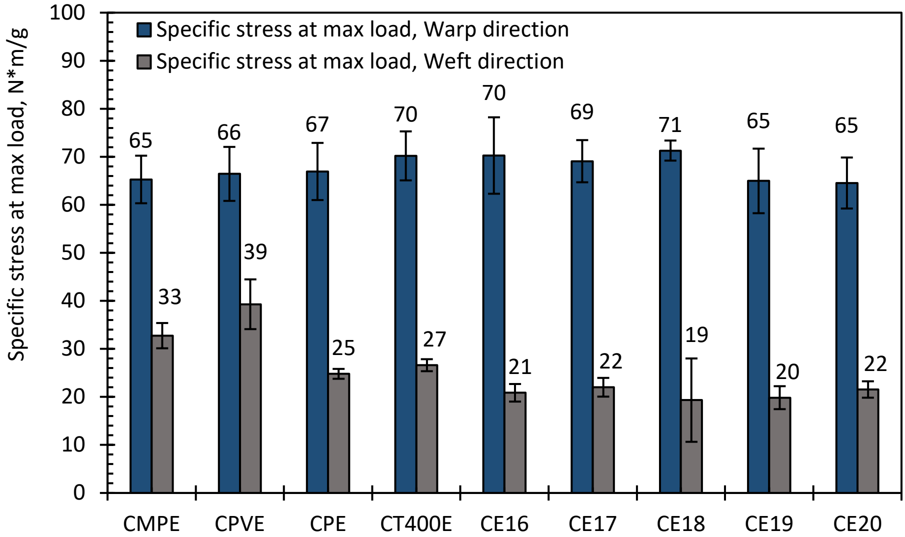


Figure 20. Comparison of specific stress values of raw denim fabrics at maximum load in warp and weft directions (same graph as in Paper I).

3.2 Effect of laser fading on physico-mechanical properties of four component denim fabric

3.2.1 Abrasion resistance of laser faded denim fabric

Fabric CPVE, after laser fading with an input power of 14 W, and laser cutter head speeds of 230, 270, 310, and 350 mm/s, exhibited an abrasion resistance of 25,000 rubs. Thus, the laser cutter head speed had no effect on the fabric's resistance to abrasion. Furthermore, abrasion resistance after laser fading decreased by 17% compared to that of the raw denim (Figure 21).

At a laser input power of 16 W, the speed of the laser cutter head had a greater effect on fabric durability. An input power of 16 W and higher speeds of 310 and 350 mm/s were found suitable for denim fabrics because the abrasion resistance values corresponding to these two sets of parameters were 20,000 and 25,000 rubs, respectively; these meet the minimum requirements for trousers of at least 20,000 rubs, as laid down by the Public Waste Agency of Flanders (OVAM) (Maes et al., 2021). An input power of 18 W burnt the denim fabrics so intensively that at various speeds, the laser fading decreased the fabric's resistance to abrasion by more than 90% compared to that of raw denim; moreover, the test results were below the minimum mandated value.

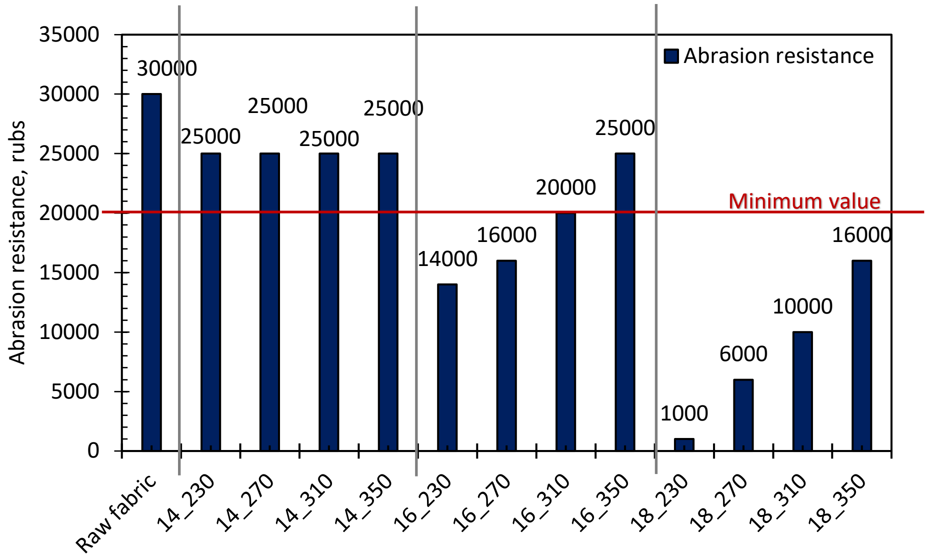


Figure 21. Comparison of abrasion resistance of multicomponent fabrics (containing cotton, polyester, elastane, and viscose) after laser fading (same graph as in Paper II).

3.2.2 Tear force of laser faded denim fabric

To determine the optimum laser input power and speed of the laser cutter head that would have only a negligible effect on the fabric durability and comfort properties, the speed of the laser cutter head was set between 100 and 500 mm/s, while the laser input power was set between 11 and 20 W. However, a laser cutter head speed lower than 230 mm/s and an input power higher than 18 W exhibited a very strong fading effect that broke the fabric. Speeds higher than 350 mm/s and input powers lower than 11 W did not provide visible faded appearance to the fabric. Therefore, physical tests were performed at laser cutter head speeds of 230, 270, 310, and 350 mm/s, and laser input powers were set to 14, 16, and 18 W.

The tear forces of the laser faded denim fabrics were recorded in the warp and weft directions. With an input power of 14 W, when the speed was increased from 230 to 350 mm/s, the fabric tear force increased from (62±9) to (76±6) N. On the other hand, the tear force values of the fabrics that were treated with an input power of 16 W were between (33±2) and (55±4) N in the warp direction. Thus, increasing the input power by 2 W reduced the tear force of the fabrics by approximately 45% (Figure 22). Next, the fabrics treated with an input power of 18 W failed in both warp and weft direction, as their tear force decreased by more than 90%; as a result, they could not withstand the test and gave way before the test ended.

In addition, the tear force values of all the tested fabrics decreased more in warp direction than in the weft direction because the warp yarns were more dominant on the fabrics' surface, and the laser burned more warp than weft yarns. In the weft direction, fabrics faded with an input power of 14 W and with speeds of 270, 310, and 350 mm/s uniformly yielded a tear force of (28±1) N. Only those fabrics that were applied the lowest speed of 230 mm/s exhibited a low tear force of (19±1) N (9 N lower). However, the lowest input power (14 W) with the highest laser cutter head speed (350 mm/s) failed to provide a visual effect on the fabric surface. It was concluded that an input power of 14 W with the speed of the laser cutter head 230 mm/s or an input power of 16 W with a laser cutter head speed of 350 mm/s provided both a satisfactory faded appearance on the fabric and a high tear force.

According to the Public Waste Agency of Flanders (OVAM) minimum requirements for trousers is 15 N. Thus, an input power of 18 W is not suitable for further investigations (Maes et al., 2021).

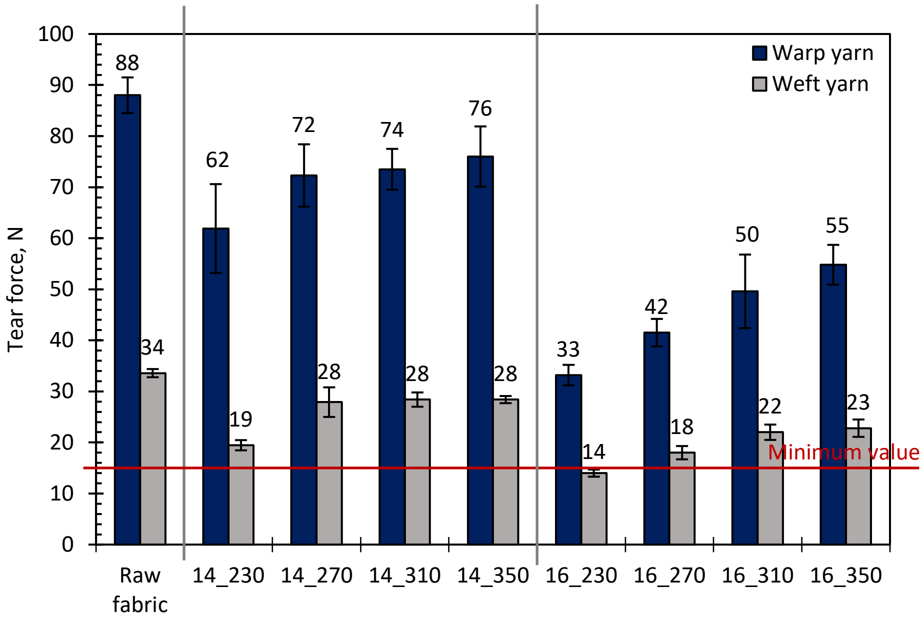


Figure 22. Comparison of tear properties of laser faded multicomponent denim fabrics (containing cotton, polyester, elastane, and viscose) with input powers of 14 and 16 W, and speed of laser cutter head 230–350 mm/s (same graph as in Paper II).

3.3 Effect of laser fading on visual appearance of denim fabric

3.3.1 Colour coordinates

After durability visual appearance is the primary factor that attracts customers' attention. Thus, after the investigations on laser fading, the colour coordinates of the fabrics were measured and analysed to determine the effect of applied laser fading parameters on the fabric colour. These results were reported in Paper II. It is clear that a higher laser input power and lower speed resulted in a higher colour difference. The minimum requirements were determined by visual inspection. Fabrics that were treated with either of the two combinations, namely an input power of 14 W and speed of laser cutter head 230 mm/s, or laser combination 16 W and a speed of laser cutter head 350 mm/s provided a good visual appearance to the fabric surface. Thus, the optimum colour shade difference for the fading of denim fabric should be between ΔE_{00} 15–19 (Figure 23).

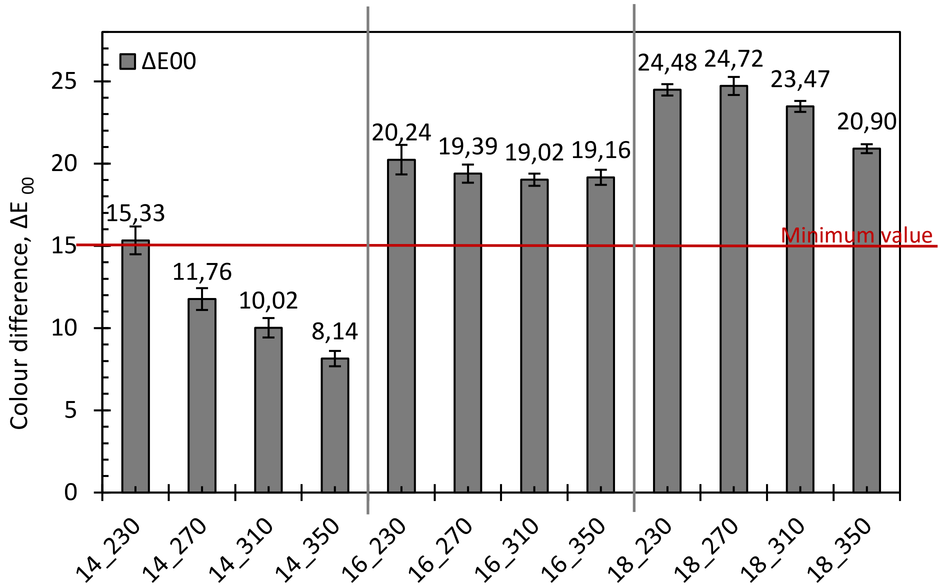


Figure 23. Comparison of colour coordinates of laser faded multicomponent denim fabrics (containing cotton, polyester, elastane, and viscose) with input powers of 14 and 16 W, and speed of laser cutter head of 230–350 mm/s (same graph as in Paper II).

3.4 Multi-criteria design optimisation

With the aim of performing an optimisation, the optimality criteria were introduced, first. Here, the tear force in the warp and weft directions, abrasion resistance, and colour difference were considered as the objectives (i.e., optimality criteria). As optimisation requires the evaluation of a large number of objectives mathematical models were developed for each objective.

For example, the colour difference model was obtained by using configuration L = 1, N_{in} = 2, and N_{tr} = 20, which resulted in N_h = 6. The Levenberg-Marquardt algorithm and a learning rate lr of 0.05 were utilised for error backpropagation (Jena, Chakraverty, Mahesh, & Harursampath, 2022). First, an ANN was developed, and colour differences were compared for laser input powers 14 to 18 W, and speeds of laser cutter head of 230 to 350 mm/s. The weight values were divided between the warp (2/3) and weft (1/3) directions by using the weighted summation technique. The response surface is shown in Figure 24, while the mean squared error is shown in Figure 25.

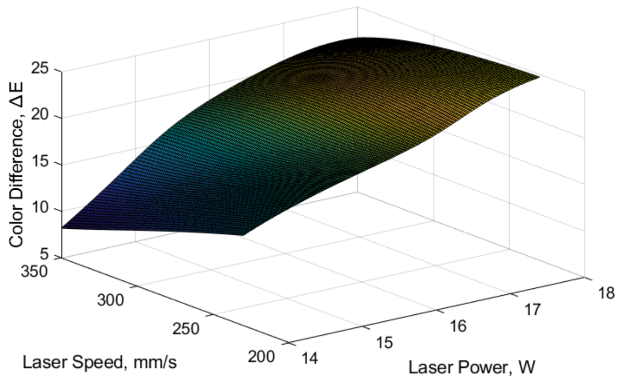


Figure 24. Response surface of colour difference (101x101 points) (same graph as in Paper II).

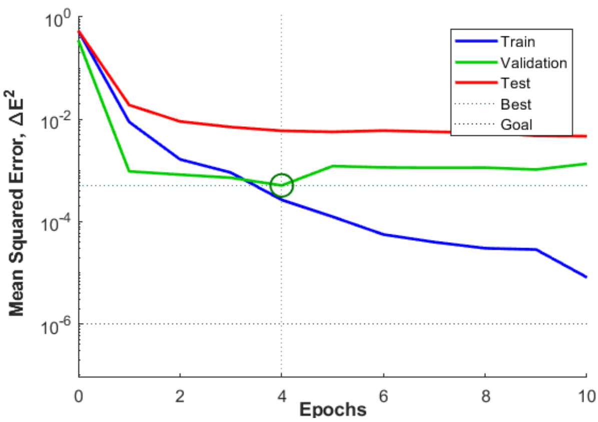


Figure 25. Mean Squared error of ANN model for colour difference (same graph as in Paper II).

Typically, ANN have problems with a limited set of input parameters in obtaining stable and accurate results (the results vary owing to uncertainty). However, it can be seen in Figure 26 that the result was similar with the model developed using the HWM, which is a deterministic method. As shown in Figure 26 the response surface of the colour difference is similar to that of ANN model developed.

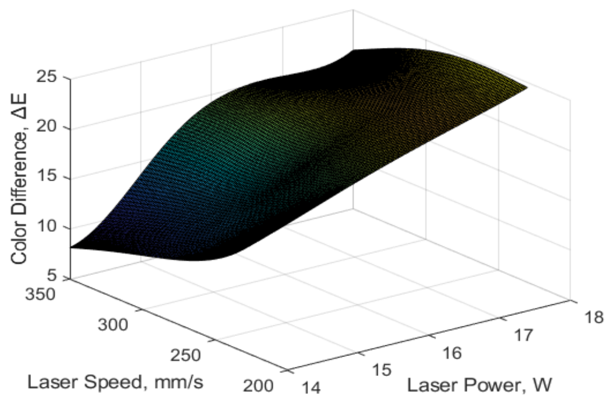


Figure 26. Response surface of colour difference (same graph as in Paper II).

Before performing the optimisation tasks, a pairwise analysis of the optimality criteria was performed. The tear forces in the warp and weft directions were found to be non-conflicting, and hence, criteria are combined using the weighted summation method with weight values of 2/3 and 1/3, respectively. A colour difference is found in the conflicting criteria, and the Pareto concept was applied (Figure 27). On the other hand, the abrasion resistance and colour difference criteria were found to be conflicting, and therefore, the Pareto concept was utilised (Figure 28).

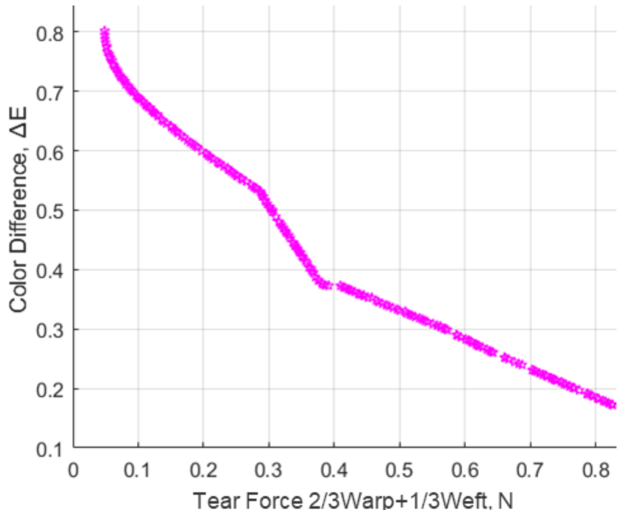


Figure 27. Combined strength vs. colour difference (same graph as in Paper II).

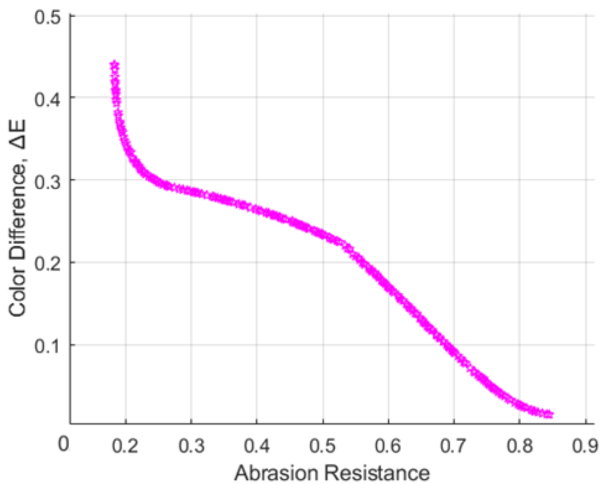


Figure 28. Abrasion resistance vs. colour differences (same graph as in Paper II).

According to the common approach, in the Pareto front, the objective functions are used in a non-dimensional form. The final optimal solution is selected from the Pareto front as the point before the rapid growth of the function on the y-axis. The optimal solutions are converted back to their original values (both functions and parameters).

The rounded values of the laser fading parameters corresponding to the optimal solutions were obtained at a laser input power of 16 W, and the speed of the laser cutter head of 350 mm/s.

Colour difference 20; abrasion resistance 24,016 rubs; tear force in the warp direction 51 N and in the weft direction 23 N. The multi-criteria optimisation problem was formulated and solved using the Pareto concept and weighted summation methods.

3.5 Effect of optimised laser fading parameters on physico-mechanical properties of four-component denim fabrics with varying fibre content and structural parameters

3.5.1 Properties of four-component denim fabric

Optimum durability and faded appearance were obtained in twill weave four-component denim fabrics (containing cotton, elastane, polyester, and viscose) subjected to the following two sets of laser fading parameters: (1) 14 W of input power and 230 mm/s of laser cutter head speed; (2) 16 W of input power and 350 mm/s of laser cutter head speed (reported in Paper II). The same laser fading parameters were also applied to other twill weave fabrics and to two satin weave fabrics that contained the same four fibres as mentioned above, but in different proportions. The aim was to assess whether the same laser fading parameters could be applied for other multicomponent fabrics in bulk production. First, the thread numbers per cm and mass per unit area were measured. Table 3 presents an overview of the fabric parameters used in this study. The differences between the mechanical and actual weft threads per cm were minimal, as can be seen from Table 3.

3.5.2 Comparison of abrasion resistance of laser faded twill and satin weave fabrics

After laser fading two denim fabrics, made of satin weave had 67% (Fabric 1) and 73% (Fabric 2) lower abrasion resistance than the twill weave fabric because of their longer floats and fewer interlacement points. However, the abrasion resistance of twill weave fabric was reduced by 53% compared with that of raw denim fabric. From Figure 29, it can be seen that for Fabric 1 treated with laser fading parameters of 14 W and 230 mm/s, the abrasion resistance was the least, i.e., 20,000 rubs; for higher laser fading parameters of 16 W and 350 mm/s, the abrasion resistance was 10,000 rubs, which was below the minimum requirement. The abrasion resistances of the other satin weave, i.e., Fabric 2 were 16,000 rubs (at 14 W and 230 mm/s), and 14,000 rubs (at 16 W and 350 mm/s), which were also below the minimum requirement. Only Fabric 3, which was made of twill weave exhibited an abrasion resistance 35,000 rubs (at 14 W and 230 mm/s; 16 W and 350 mm/s). Thus, the laser faded satin weave denim fabrics did not meet the minimum requirements. This implies that the denim fabric made of twill weave is more suitable for use in garment production, as it was more resistant to abrasion than the other fabrics tested.

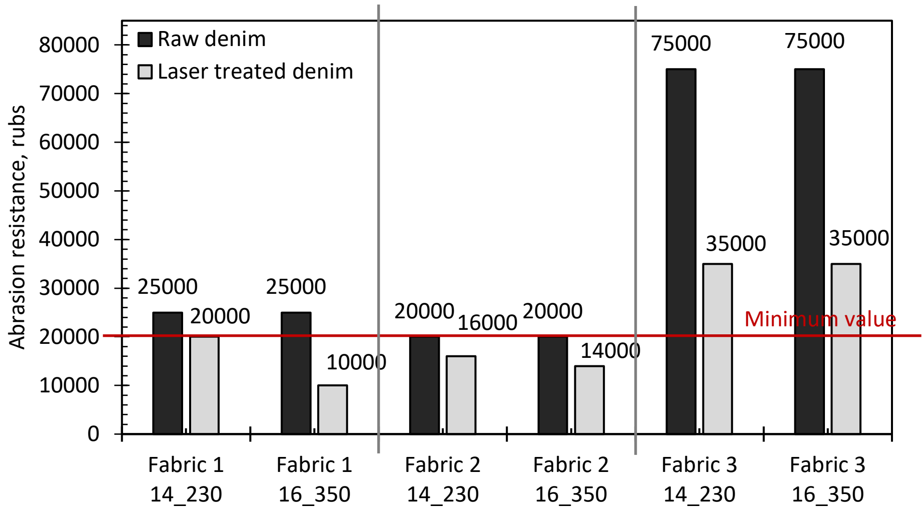


Figure 29. Abrasion resistance of raw and laser treated satin and twill weave fabrics (same graph as in Paper III).

3.5.3 Comparison of tear force of laser faded twill and satin weave fabrics

The tear force test was performed in both warp and weft directions; however, the test failed in the warp direction, as the weft yarns were torn. Thus, the warp yarns (cotton yarns) were sufficiently weak to tear the weft yarns and the test specimens broke before the test ended. The warp yarns were shifted and the results were recorded only in the weft direction.

The test results showed that laser fading had the greatest effect on the tear properties of Fabric 1. Laser fading with laser fading parameters of 14 W and 230 mm/s, 16 W and 350 mm/s decreased the resistance to tear by 39.3% and 39.9%, respectively. Fabric 2 tear force worsened by 20.9% (with 14 W and 230 mm/s), and by 20.1% (with 16 W and 350 mm/s). Fabric 3 tear force decreased by 32.2% (with 14 W and 230 mm/s), and by 35.1% (with 16 W and 350 mm/s). Thus, Fabric 2 yielded the best test results because of its weave construction and thread number per cm. The loose weave construction allowed yarn mobility which reduced the friction between the yarns. Improved yarn mobility implies that the yarns could move and group together, leading to a higher tear force (Figure 30). The thread number also affected the tear force; this is evident in Fabric 1, which was made of a satin weave, but had a higher number of threads per cm; this reduced the fabric durability and hence, Fabric 1 yielded the lowest test performance.

It was also observed that both the applied laser fading parameter combinations yielded the same trend in tear force loss in the satin weave fabrics. The tear force of Fabric 1, after laser fading with laser fading parameters of 14 W and 230 mm/s, and 16 W and 350 mm/s was (16±2) N. The corresponding number for Fabric 2, after laser fading parameters of 14 W and 230 mm/s, and 16 W and 350 mm/s were (43±4) N and (43±5) N, respectively. For Fabric 3 the difference in the tear forces corresponding to the two parameter combinations was 2 N ((32±3) N for 14 W and 230 mm/s; and (30±3) N for 16 W and 350 mm/s).

In conclusion, the two different laser fading parameter combinations influenced the tear force of each fabric by almost the same amount. In addition, all tested fabrics, after laser fading, met the minimum requirements.

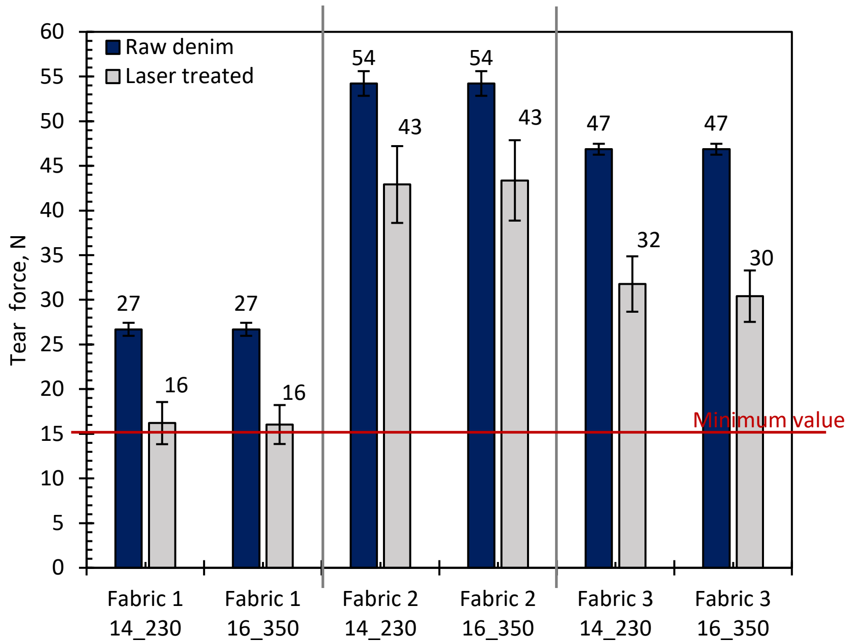


Figure 30. Comparison of tear force of laser faded four-component denim fabrics with (1) input power 14 W and laser cutter head speed of 230 mm/s, and (2) input power of 16 W and laser cutter head speed of 350 mm/s (same graph as in Paper III).

3.5.4 Comparison of laser faded twill and satin weave fabrics tensile force

The warp yarns of a tested fabrics had better tensile properties than the weft yarns (Figure 31). This was owing to the weave construction. In the fabric weaving process, the warp yarns are under higher tension than the weft yarns. When the tension in the warp yarns is increased, the yarn strength also increases, and the crimp decreases.

All the tested fabrics lost more tensile force in the warp direction than in the weft direction compared to raw denim. Laser fading affected more the warp yarns than the weft yarns because in satin and twill weaves, the warp yarns are more dominant on the right side of the fabric. The tensile forces of Fabrics 1 and 2 at rupture in the warp direction were reduced by 38% and 35%, respectively after laser fading with an input power of 14 W and a speed of laser cutter head 230 mm/s. The corresponding figure for Fabric 3 was 30%. A higher laser input power of 16 W and a laser cutter head speed of 350 mm/s burnt the warp yarns more intensively, and the tensile forces of Fabric 1, 2, and 3 were reduced 52%, 36% 41% in the warp direction.

The weft yarns were less affected by the laser beam. Test results also showed that the tensile forces of Fabric 1 and 2 were reduced after laser fading with an input power of 14 W and speed of laser cutter head of 230 mm/s by 19% and 1%, respectively. The tensile force of Fabric 3 weft yarns was reduced by 59%. Laser fading parameters of 16 W and 350 mm/s had a similar effect with respect to yarn damage as that observed at lower input power and lower speed. In terms of values, the tensile forces of Fabric 1 and 2 at rupture were reduced by 19%, and 6%, respectively, while that of Fabric 3 was reduced by a large amount 69%.

According to the minimum requirements, the tensile force of trousers or jeans should be at least 250 N. However, the weft yarn results of Fabric 3 were below the minimum mandated (Maes, et al., 2021). In subsequent microscopic analysis, yarn damage was observed after laser fading (Table 5).

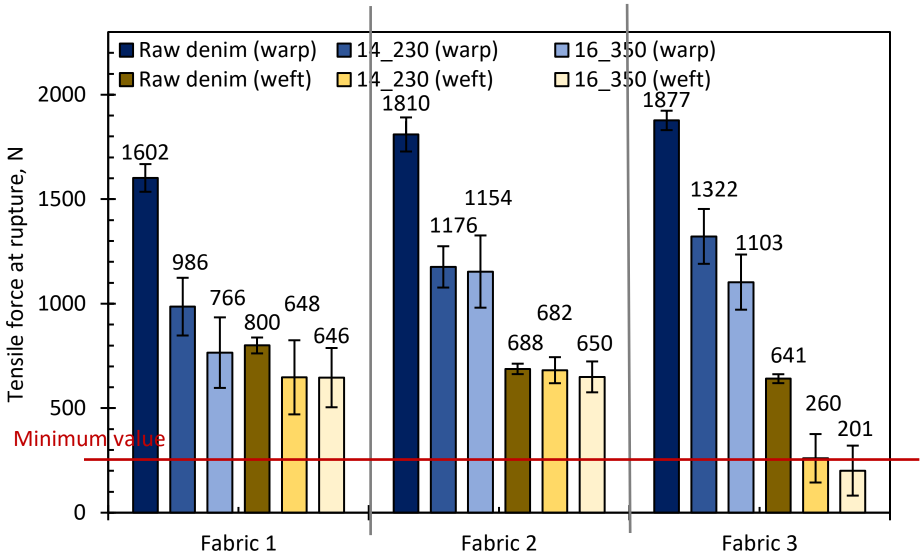


Figure 31. Comparison of tensile forces of laser faded four-component denim fabrics with (1) input power of 14 W and speed of laser cutter head of 230 mm/s, and (2) input power of 16 W and speed of laser cutter head of 350 mm/s (same graph as in Paper III).

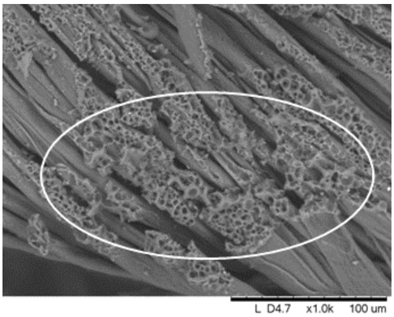
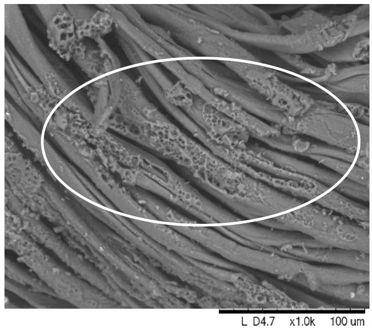
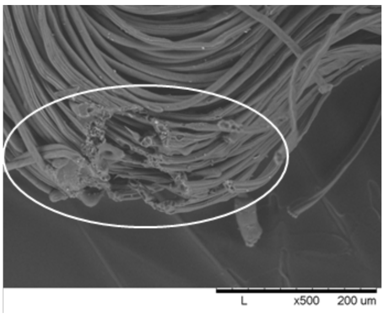
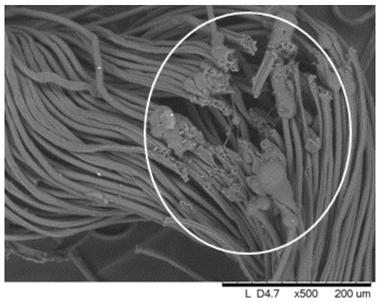
3.6 Effect of laser fading on fibre morphology of multicomponent fabrics

The damage to the yarns subsequent to laser fading with an input power of 14 W and a laser cutter head speed 230 mm/s, and with an input power of 16 W and a laser cutter head speed of 350 mm/s can be seen in Table 5, which presents scanning electron microscopy (SEM) images of the degraded yarns after laser fading. During the laser fading, thermal energy was absorbed and the laser beam burnt the cotton yarn; as a result, pores and cracks formed on the fibre surface, and a sponge-like appearance of the fibres emerged corresponding to both sets of laser fading parameters were similar, except that the lower speed decreased the fabric durability slightly more than the higher speed. Furthermore, the microscopic analysis revealed that more pores formed on the cotton surface at lower speed.

The synthetic fibres at the core of the weft yarn melted to the same extent and grain shapes were observed at the fibre ends. Therefore, faded fabrics have lower durability than raw materials.

Considering that laser fading occurred on the fabric surface only where the beam was applied, the yarns were damaged unevenly, which means that the strength of the denim fabric varied across the fabric surface.

Table 5. SEM images of fibre morphology of Fabric 3.

Laser fading parameters	14 W and 230 mm/s	16 W and 350 mm/s
Fabric 3. Warp yarn (cotton fibres)	a) 	b) 
Fabric 3. Weft yarn (polyester, viscose, and elastane)	c) 	d) 

3.7 Conclusion

The main objective of this study was to develop a denim fabric that satisfies the requirements of durability, comfort, and suitable visual appearance. It is essential that the developed denim fabric be manufacturable on a large scale and is suitable for use in the manufacture of everyday clothing. According to the regulation of Consumer Protection and Technical Regulatory Authority, garments made of denim fabrics should last at least two years. As there have been inadequate research results on three- or four-component denim fabrics, this research adopted the novel path of using advanced mathematical models for the design of denim fabric behaviour in terms of tear force, abrasion resistance, and colour difference after laser fading. A limited number of previous studies have used artificial neural networks, but with different objective functions. However, no studies have reported the use of Haar wavelets to evaluate physico-mechanical properties of denim fabrics.

Based on the result from the current research the following conclusions can be drawn:

1. The number of threads per cm influenced the fabric durability and air permeability. In tight constructions, the pores between the yarns decreased, and air flow through the fabric was restricted. However, an increased thread number per cm also increased the resistance of the denim fabric to abrasion. The cotton-elastane denim fabric had a mechanical thread number per cm of 16 and abrasion resistance of 20,000 rubs; however, the abrasion resistance of the cotton-elastane fabric with 20 threads per cm was twice (40,000 rubs). The optimum number of mechanical threads per cm was found to be 18.
2. Fibre content is another factor that determines fabric durability, as it affects the tensile properties and tear force of the fabric. Raw denim fabric that contained synthetic fibre polyester (19%) at the core of the weft yarn had a tear force of (88±4) N in the warp direction, which was approximately four times higher than the denim fabrics that contained cotton-elastane (tear force between (20±1) N – (22±1) N). This was because elastane has lower tenacity than cotton or polyester. In addition, the tear force of cotton-elastane denim fabrics in the weft direction failed because of the yarn shift. The elastane fibre in the weft was weaker than the cotton fibre in the warp, and weaker yarns could not tear stronger cotton yarns, and hence failure occurred.
3. The raw denim fabric had a higher specific stress at the maximum load in the warp direction than in the weft direction because elastane has a lower tenacity than cotton yarn. Furthermore, the fabrics that contained polyester (Fabric CPVE polyester content of 19%, specific stress at max load of (39±5) N*m/g) had almost twice the specific stress as the cotton-elastane fabrics (specific stress at max load of (20±2) N – (22±2) N*m/g) in the weft direction.
4. Laser fading was applied to the raw denim fabric, which showed a higher durability (CPVE). The optimum laser input power was 14–8 W and the speed of the laser cutter head was 230–350 mm/s. The abrasion test showed that an applied input power of 14 W at four different speeds and an input power of 16 W at a speed of 350 mm/s met the required minimum values of the physico-mechanical properties.

5. Laser treated denim fabrics with an input power of 14 W and with four different speeds had tear forces that were 45% higher than fabrics that were faded with an input power of 16 W and with four different speeds in the warp direction. A laser input power of 18 W burned the denim fabric so extensively that the tear force test failed in the warp and weft directions. In the weft direction, the laser faded denim fabric with an input power of 16 W and laser cutter head speed of 230 mm/s did not meet the minimum requirements. The other applied speeds with an input power of 16 W met the minimum requirements. Additionally, an input power of 14 W and applied speeds of the laser cutter head of 270, 310, and 350 mm/s yielded similar test results. Only a lower speed of 230 mm/s decreased the denim fabric tear force by 9 N compared to other denim fabrics treated with an input power of 14 W. Based on the colour shade difference after laser fading and durability test, it was found that an input power of 14 W with the lowest used laser cutter head speed of 230 mm/s or an input power of 16 W with a laser cutter head speed of 350 mm/s were the most suitable laser fading parameters that provided the optimum faded appearance and durability.
6. Mathematical modelling approaches, such as artificial neural network and Haar wavelet method were used to simulate the fabric durability and colour change after the laser fading with laser input powers between 14 and 18 W, and speed of the laser cutter head between 230 and 350 mm/s. The artificial neural network results were compared with the Haar wavelet method results, and both yielded the same results. The rounded optimum laser input power was 16 W, and the speed of laser cutter head was 350 mm/s. The corresponding optimum colour difference was ΔE_{00} 20; the abrasion resistance was 24,016 rubs; and the tear force was 23 N.
7. The optimum laser fading parameters (14 W, 230 mm/s, and 16 W, 350 mm/s) were applied to four-component denim fabrics made of satin (Fabrics 1 and 2) and twill weave (Fabric 3). Abrasion resistance test showed that the raw denim fabric's resistance to abrasion was 67% higher than that of Fabric 1 and 73% higher than that of Fabric 2. Laser fading decreased the twill weave fabric's abrasion by 53% compared with the same raw denim fabric.
8. The tear force of raw satin weave Fabric 2 was twice that of the twill weave fabric in the warp direction because in the satin weave loose construction allowed yarn mobility; thus, yarns moved and grouped together; this increased the satin weave fabric's tear force. The laser fading decreased the tear force of the satin weave fabric 2 by approximately 10 N.
9. In the twill and satin weave constructions, warp yarns were more dominant on the fabric surface, and it was clearly seen the tensile force at rupture decreased more in the warp direction than in the weft direction. Twill weave raw denim fabric had highest tensile force in the warp direction (1877±46) N, but after laser fading tensile force decreased 30% (14 W, 230 mm/s) and 40% (16 W, 350 mm/s). However, in the weft direction, Fabric 2 exhibited the most uniform test results. The tensile force of the raw denim was (688±25) N. After laser fading, the results decreased slightly to: (682± 62) N (14 W, 230 mm/s) and (650±74) N (16 W, 350 mm/s). Another satin weave fabric (Fabric 1) tensile force at rupture

decreased after laser fading 19% with both sets of laser fading parameters (14 W, 230 mm/s) (16 W, 350 mm/s). This can be explained that satin weave fabrics contain higher percentage of polyester (Fabric 1, 20%; Fabric 2, 19%) than twill weave (Fabric 3, 13.5%). Polyester has a higher tenacity than cotton which increases the entire fabric tensile force at rupture in the weft direction.

10. Microscopic analysis (SEM) revealed that the laser fading degraded the yarns in the fabric. Pores and cracks formed on the surface of the cotton fibres. Synthetic fibres such as polyester and elastane melt. The yarn degradation was greater when the laser input power increased and the speed of the laser cutter head decreased.

This study characterised the advantages of multicomponent denim fabrics (cotton, polyester, elastane, and viscose) advantages. The fibres used significantly increased the durability of the denim fabric, thus prolonging the lifespan of garments and providing comfort and a soft feel. Further research will focus on determining the optimum fibre percentage in denim fabric that satisfies the durability and comfort requirements. Fixed laser fading parameters of 14 W, 230 mm/s, and 16 W, 350 mm/s affect the twill and satin weave fabrics that can be used in bulk production. The results of the current study will find applications in real life, where denim fabric will be manufactured and used in garment production.

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Abstract

Effect of Fibre Content, Structural Parameters, and Laser Fading on Durability and Aesthetic Properties of Multicomponent Denim Fabric

Denim fabric is a 3/1 twill weave textile material used in clothing industry. It is mainly used for everyday wear, and its durability and aesthetic appearance are important considerations for customers. Large amounts of water, chemicals, and energy are used to produce denim fabric. Owing to the high demand for denim clothing, denim fabric production has a significant negative impact on the environment. Therefore, it is essential to develop more durable denim fabrics by using sustainable production processes (Annis, 2012).

The main aim of the research, based on which this thesis was written, was to study the impact of fibre content, structural parameters, and laser fading on multicomponent denim fabric durability and aesthetic properties with a view to prolonging the lifespan of denim clothing**.** The novelty of this study is that it was focused on three- or four-component denim fabrics, and the effect of laser fading on the physico-mechanical and colour properties of four-component denim fabrics. The currently available research on these aspects is inadequate or there is a lack of scientific data. The current study successfully addressed the issue of producing a durable denim fabric that can withstand the laser fading process and ensuring long-lasting denim products. The physico-mechanical properties of both the raw and laser faded denim fabrics were tested, and design optimisation of the denim fabric behaviour in terms of the tear force, abrasion resistance, and colour difference after the laser fading was performed.

The physico-mechanical properties of raw denim fabrics with different fibre compositions and structural parameters were tested to determine the most durable denim fabric that also provided satisfactory comfort to the customer. The chosen denim fabrics contained various synthetic fibres, such as elastane, polyester, Lycra T400, and polybutylene terephthalate, and regenerated fibres, such as modal and viscose. All the tested fabric core yarns were covered with cotton. Next, laser fading, an environment-friendly alternative to conventional fading, was applied to the denim fabric that demonstrated the highest durability and comfort properties, namely the one containing cotton, polyester, viscose, and elastane.

The optimum laser fading parameters were found to have a minimal impact on the durability of the denim fabric. Mathematical modelling via ANNs and HWM was adopted to approximate the objective functions. Four models were developed to describe the behaviour of the tear force in the warp and weft directions, abrasion resistance and, colour difference. A multi-criteria design optimisation problem was formulated and solved by combining the weighted summation technique, Pareto concept, and multi-criteria genetic algorithms. Finally, the optimal values of the design variables (laser input power and speed of the laser cutter head), and the corresponding optimised objective function values were determined.

Based on the previous results obtained, the following laser fading parameters were applied to the denim fabric: laser input power 14–16 W and speed of the laser cutter head: 230–350 mm/s. It was observed that the optimal parameters had a negligible effect on the fabric durability. In the final stage of the study, these optimised laser fading parameters were used for bulk production to reduce the laser adjustment time and

increase the efficiency of the manufacturing process. To this end two sets of laser fading parameters were used (14 W and 230 mm/s; and 16 W and 350 mm/s) on three types of four-component denim fabrics with different weave constructions and textile fibre ratios. Microscopic analysis was performed to assess the effect of laser fading on the denim fabric yarn and fibre morphology.

According to the test results, the raw denim fabric with the highest polyester ratio exhibited the highest physico-mechanical properties. Compared with the cotton-elastane containing fabrics, which exhibited a specific stress of (19±9) – (22±2) N*m/g, the polyester containing fabrics yielded a specific stress of (39±5) N*m/g; this is twice that of the former. Moreover, the fabric that contained 19% of polyester exhibited three to four times higher tear force (88±4) N in the warp direction than the other tested fabrics. This is because polyester had higher tenacity than cotton, thus providing higher tensile and tear force values (Akter et al., 2021).

It was found that laser fading adversely affected the fabric durability. A microscopic study revealed that the laser beam degraded the yarns and fibres in the denim fabric. Laser irritation led to the formation of cracks on the cellulosic fibre surface and melted the synthetic fibres. The laser input power 18 W, and various laser cutter head speeds between 250–350 mm/s burnt the fabric and consequently, the tear force decreased by more than 90% compared with the untreated denims. A laser input power of 14 W, coupled with a low laser cutter speed of 230 mm/s, was found to be more suitable because any higher speed would have a minor impact on the fabric colour change. On the other hand, applied laser input power of 16 W burnt the fabric; therefore, for this power the speed of the laser cutter head should be more than 300 mm/s; otherwise, the fabric would lose more than 50% of its abrasion resistance and tensile force compared with the raw denim fabric. The colour difference was higher when a higher input power and lower speed were used. The highest colour difference was three times (18 W, 230 mm/s, and ΔE_{00} of 24.48) the lowest colour difference (14 W, 350 mm/s, and ΔE_{00} of 8.14). With an input power of 16 W and higher laser cutter head speed, the colour difference was quite uniform (ΔE_{00} of 19.16–20.24). The mathematical modelling was consistent with the physico-mechanical tests. The finalised optimal rounded laser fading parameters were 16 W and 350 mm/s.

In the industry, the use of fixed laser fading parameters is crucial for fast and efficient production. Thus, laser fading parameters of 14 W and 230 mm/s, and 16 W and 350 mm/s were set and applied to three different four-component twill and satin weave denim fabrics. The laser fading damaged more warp yarns than weft yarns, because the warp yarns were more dominant on the fabric surface in both weave constructions (Tarhan & Sariisik, 2009). After the laser fading, the twill fabrics exhibited the highest abrasion resistance of 35,000 rubs. The resistance of the satin weave fabrics to abrasion was between 10,000–20,000 rubs. In both the satin weave fabrics the tear force was reduced by 11 N after the laser fading. In the twill, the tear force was reduced by 15 N (at 14 W and 230 mm/s) and 17 N (at 16 W and 350 mm/s) compared with the raw denim. The satin weave fabrics, which had longer warp yarn floats than in the twill construction on the fabric surface, lost their tensile force by 5%–8% more than the twill fabric warp yarn. The twill weave weft yarns (less affected by the laser beam) that contained 5%–6% less polyester than the satin weave fabrics showed 59% (at 14 W and 230 mm/s) and 69% (at 16 W and 350 mm/s) lower tensile properties compared with the raw denim.

It can be concluded that the gap filled in this study was the knowledge gained on the impact of laser faded multicomponent denim fabric on the physico-mechanical properties and colour with a view to extending the product wearing period. ANN and Haar wavelet mathematical models were developed to simulate the fabric behaviour after laser fading. Multicomponent denim fabrics were found to be the most suitable for everyday wear. These fabrics are approximately three to four times more durable than the traditional cotton-elastane denim fabrics. Thus, multicomponent denim fabrics can prolong the lifetime of garments. However, further research is required to determine the optimal polyester content in the fabric. According to this study the polyester content should be higher than 13%.

In summary, a novel approach was used study the physico-mechanical properties of raw and laser faded three- and four-component denim fabrics. In addition, using mathematical modelling approaches the durability of the denim fabrics after laser fading was accurately determined. It was observed that the optimal laser fading parameters had only a minor effect on fabric durability. It was concluded that laser fading parameters of 14 W and 230 mm/s, and 16 W and 350 mm/s can be used as set parameters for the bulk production of certain types of four-component denim fabrics. Fabrics with tighter weave constructions are more resistant to laser fading. For this reason, the aforementioned parameters would be suitable not only for twill and satin weaves, but also other tighter weave denims.

Lühikokkuvõte

Kiulise koostise, struktuuri parameetrite ja laserkulutuse mõju mitmekomponentse teksakanga vastupidavusele ja esteetilistele omadustele

Teksakangas on 3/1 toimses siduses kootud tekstiilmaterjal, mida kasutatakse enamasti igapäevarõivaste valmistamiseks. Tarbija jaoks on oluline toote vastupidavus ja esteetiline välimus. Paraku kulub teksakanga tootmiseks suurel hulgal vett, kemikaale ja energiat. Aasta-aastalt on suurenenud nõudlus teksakangast valmistatud toodete järele märkimisväärselt suurendanud ka kahjulikku mõju keskkonnale. Sellest tulenevalt püütakse leida lahendusi, vastupidavamate rõivaesemete tootmiseks jätkusuutlike tootmismeetodite abil (Annis, 2012).

Selle doktoritöö peaeesmärk oli teksakanga kiulise koostise, struktuuri ja laserkulutuse mõju uurimine mitmekomponentsete teksakangaste vastupidavusele ja esteetilistele omadustele eesmärgiga pikendada teksakangast valmistatud toodete kandmisiga.

Doktoritöö esimeses etapis katsetati erineva kiulise koostise ja struktuuriga toorteksakangaste füüsikalis-mehaanilisi omadusi, et leida kõige vastupidavam teksakangas, mis pakub ka sobivaid mugavusomadusi. Uurimustöö jaoks valiti teksakangad, mis sisaldasid erinevaid sünteetilisi (elastaan, polüester, Lycra T400, polübutüleentereftalaat) ja tehiskiude (modaal, viskoos). Need kiud lisati koelõnga sisse. Kõikide testitud kangaste koelõngad olid kaetud puuvillaga. Lõimelõngad valmistati puuvillast. Seejärel teostati katsetulemuste põhjal saadud kõrgeimate vastupidavuse ja mugavusomadustega teksakangale laserkulutus (kangas sisaldas puuvilla, polüestrit, viskoosi, elastaani), mida peetakse keskkonnasõbralikumaks alternatiiviks teistele kulutusmeetoditele.

Sihifunktsioonide lähendamiseks kasutati matemaatilist modelleerimist (tehisnärvivõrku, Haari lainikute mudelit). Vastavuse pinnad koostati neljale sihifunktsioonile: hõõrdekindlus, rebimistugevus (koe- ja lõimesuunas), kanga värvi muutumine peale laserkulutust. Vaadeldavate sihifunktsioonide samaaegseks optimeerimiseks formuleeriti multikriteriaalse optimeerimise ülesanne, mis lahendati, rakendades kaalutud summeerimise meetodit, Pareto printsiipi ja geneetilisi algoritme. Lõpptulemusena saadi sisendparameetrite optimaalsed väärtused ja neile vastavad sihifunktsioonide väärtused.

Toetudes eelnevale kogemusele valiti laserkulutuse sisendvõimsus vahemikus 14–18 W ja laserlõikepea kiirus 230–350 mm/s. Laserkulutuse teostamise eesmärk oli leida optimaalsed laserkulutuse parameetrid, millel on minimaalne mõju kanga vastupidavusele. Seejärel uuriti, kui universaalsed on leitud optimaalsed laserkulutuse parameetrid masstootmise jaoks, et vähendada tootmise ettevalmistusaega ja tõsta tootmisprotsessi efektiivsust. Doktoritöö põhjal leiti kaks laserkulutuse parameetrite kombinatsiooni (14 W ja 230 mm/s; 16 W ja 350 mm/s) ning teostati laserkulutus neljakomponentsetele teksakangastele, mis olid valmistatud erinevas siduses ning sisaldasid samu kiude erinevas vahekorras. Mikroskoopilise analüüsi käigus vaadeldi laserkulutuse mõju teksakangas leiduvate kiudude morfoloogiale.

Füüsikalis-mehaaniliste testide tulemuste põhjal selgus, et suurema polüestri sisaldusega toorteksakanga suhteline koormus maksimaalse jõu juures (39 ± 5) N*m/g tõusis kaks korda võrreldes puuvilla ja elastaani sisaldavate kangastega, mille suhtelised

koormused maksimaalse jõu juures olid vahemikus (19 ± 9) N*m/g kuni (22 ± 2) N*m/g. Polüestrit sisaldava teksakanga rebimistugevus oli neli korda suurem (88 ± 4) N, kui teistel testitud kangastel lõimesuunas. See on tingitud asjaolust, et polüestri sitkus on suurem kui puuvillal, seetõttu olid ka tõmbe- ja rebimistugevuse väärtused suuremad kui teistel testitud kangastel (Akter et al., 2021).

Mikroskoopia-uuringu tulemusena selgus, et laserkiir lagundas teksakangas olevaid kiude. Tselluloossete kiudude pinnale tekkisid mitmed praod ja poorid, sünteetilised kiud sulasid. Laserkulutamisel kasutatud sisendvõimsus 18 W ja laserlõikepea kiirused vahemikus 230–350 mm/s kahjustasid kangast sedavõrd, et kanga rebimistugevus vähenes rohkem kui 90%. Sisendvõimsust 14 W oli sobiv kombineerida madalama kiirusega (laserlõikepea kiirus 230 mm/s), sest suurema kiirusega ei saavutatud selgelt eristuvat visuaalset kulutust. Laserkulutuse sisendvõimsust 16 W oli sobilik kasutada kõrgemate laserlõikepea kiirustega (kõrgem kui 300 mm/s). Katsetulemused näitasid, et madalamal kiirusel laserkiir kahjustas kangast selliselt, et see kaotas oma hõõrdekindlusest ja tõmbetugevusest võrreldes toorteksakangaga rohkem kui 50%.

Suurim värvierinevus (18 W; 230 mm/s, ΔE_{00} 24,48) oli kolm korda kõrgem kui madalaim värvierinevus (14 W; 350 mm/s, ΔE_{00} 8,14). Võimsusega 16 W oli värvierinevus erinevate kiiruste juures sarnane, ΔE_{00} oli vahemikus 19,16–20,24. Leiti, et optimaalne laseri sisendvõimsus on 16 W ja kiirus 350 mm/s.

Universaalsete laserkulutuse parameetrite kasutamine on oluline kõrge tootlikkusega masstootmise jaoks. Doktoritöös valiti universaalseteks laserkulutuse parameetriteks kombinatsioonid 14 W ja 230 mm/s ning 16 W ja 350 mm/s ning kulutati nende parameetritega kolme neljakomponentset atlass- ja toimses siduses teksakangast. Laserkulutus nõrgestas rohkem lõime- kui koelõngasid; see oli tingitud kanga sidusest, kuna mõlemas siduses on lõimelõngad domineerivad kanga paremal poolel (Tarhan & Sariisik, 2009). Peale laserkulutust toimse sidusega kootud kangas oli suurema hõõrdekindlusega (35 000 hõõret), atlass-sidusega kangaste hõõrdekindlus jäi vahemikku 10 000–20 000 hõõret. Mõlema atlass-sidusega kanga rebimistugevus vähenes peale laseriga kulutamist koesuunas 11 N. Toimse sidusega laserkulutatud teksakanga rebimistugevus vähenes võrreldes toorteksakangaga 15 N (14 W ja 230 mm/s) ja 17 N (16 W ja 350 mm/s). Atlass-sidusega kangas on lõimkatted pikemad kui toimses siduses ja seetõttu vähenes tõmbetugevus 5–8% enam kui toimse sidusega teksakangal. Toimse sidusega kangas sisaldas 5–6% vähem polüestrit kui atlass-sidusega kangad ja seetõttu vähenes ka tõmbetugevus koesuunas võrreldes toorteksakangaga vastavalt 59% (14 W ja 230 mm/s) ning 69% (16 W ja 350 mm/s).

Kokkuvõtvalt; eelnevate uurimustööde puudujääk, mida doktoritöös lahendati, oli uurida kolme- ja neljakomponentsete toorteksakangaste ning laserkulutatud teksakangaste füüsikalis-mehaanilisi omadusi ning lisaks uurida, milline on kulutuse mõju kanga värvuse muutusele. Teksakangaste omaduste uurimine on oluline teksakangast toodete kandmisea pikendamiseks. Tehisnärvivõrku ja Haari lainikute mudelit kasutati, et simuleerida kanga omaduste muutumist peale laserkulutust. Selle tulemusena selgus, et mitmekomponentsed teksakangad on sobilikud kasutamiseks igapäevarõivaste valmistamisel, kuna nende vastupidavus suurenes võrreldes puuvilla ja elastaani sisaldavate kangastega kolm kuni neli korda. Sellest võib järeldada, et mitmekomponentsetest teksakangastest valmistatud toodete kandmisperiood on pikem. Doktoritöö uudse osana saab välja tuua kolme- ja neljakomponentsete toorteksakangaste ja laserkulutatud teksakangaste füüsikalis-mehaaniliste omaduse uurimise. Samuti on uudne matemaatilise modelleerimise kasutamine, millega simuleeriti täpselt teksakanga vastupidavust pärast laserkulutust ja mis aitas määrata optimaalsed laserkulutuse parameetrid, millel oli minimaalne mõju kanga vastupidavusele. Doktoritöö tulemusena saadi teada, et polüestri sisaldus teksakangas peab olema suurem kui 13%. Täpne protsentuaalne sisaldus kangas on aga teadmata; see vajab edasist uurimist. Doktoritöö tulemusena saab välja tuua, et laserkulutuse parameetrid 14 W ja 230 mm/s ning 16 W ja 350 mm/s on masstootmises kindlat tüüpi neljakomponentsete teksakangaste jaoks universaalsed. Tihedama konstruktsiooniga kootud kangad on suurema vastupidavusega laserkulutusele. Sel põhjusel võime väita, et laserkulutuse parameetrid on sobilikud kasutamiseks lisaks toimse ja atlass-siduse puhul ka teiste tihedama konstruktsioonidega kootud kangaste puhul.

Appendix 1

Paper I

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Impact of Weft Yarn Density and Core-yarn Fibre Composition on Tensile Properties, Abrasion Resistance and Air Permeability of Denim Fabrics

Nele MANDRE *, **Tiia PLAMUS**, **Andres KRUMME**

Department of Material and Environmental Technology, Tallinn University of Technology, Ehitajate tee 5, 12616, Tallinn, Estonia

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Characteristics and serviceability of denim fabrics have undergone major changes. Nowadays denim is commonly used for casual wear. Durability and comfort are important parameters for consumers when choosing a denim garment. Therefore, in this study, abrasion resistance, tear and tensile properties of core–spun yarns and air permeability of denim fabrics with different weft yarns per centimetre and fibre content were analysed. The test results showed that weft yarns per centimetre influences fabric air permeability negatively but abrasion resistance increases. Higher weft yarns per centimetre influences fabric air permeability negatively but abrasion resistance increases. Polyester, elastane, modal, viscose and Lycra T400 were used in the core of weft yarn to analyse the impact of those fibres on the durability and comfort properties. Elastane is used to add stretchability to the fabric, which provides comfort to the wearer. The higher the elastomeric fibre content in the fabric, the greater is its elasticity; however, the tensile properties of the woven fabric decrease. The tear strength of the fabric was increased by the presence of the polyester fibre in the core.

Keywords: denim fabric, specific stress, air permeability, abrasion resistance.

1. INTRODUCTION

Denim fabric has been known as a strong and rigid material. Today the characteristics of the fabric have been improved to provide good performance, durability, comfort and fashion properties for garments. The number of yarns per centimetre and the core–yarn ratio plays an important role in determining physical and performance properties of the fabric. Yarn number per centimetre (weft yarn density) influences fabric strength and air permeability significantly; core–spun yarns are used in the weft yarn to combine strength and stretchability of the fabric [1 – 3].

Core–spun yarn is defined as a sheath–core yarn where sheath yarn is twisted around the core filament. Natural or synthetic fibres can be used as the sheath material, but the core material preferably contains elastomeric filament. For denim, cotton fibre is commonly used as sheath and elastane filament is used in the core of weft yarn. The purpose of the two–layered structure is to improve the properties of the fabric, where the sheath layer provides strength and durability and the core part gives stretch and comfort. This fibre combination provides high elasticity, flexibility and makes denim goods comfortable to wear. There is no one certain definition for comfort. But it has been identified as a combination of physiological, physical and psychological properties that satisfy the requirements of the consumers. Elastic denim garment has a figure shaping function, which provides ease of movement without restricting body movements. 1 – 5 % of elastane provides sufficient stretchability to denim fabric. But on the other hand, elastane affects air permeability which is considered as comfort parameter in this study [4 – 8].

In several studies, the impact of weft yarn count per centimetre on the fabric properties has been tested. For example, the impact of dual-core weft yarns number per centimetre, elastane ratio per unit area on the denim fabrics, also, tensile and tear strength, colour properties and cost per unit were determined. It was concluded that higher elastane content and ratio decreased elasticity value of the fabric because of the increased density that makes the fabric more rigid. Increments in the weft yarns per centimetre were found to decrease the fabric tear strength in the warp and weft direction. But in the weft direction, the decrease was higher [1]. In another study, cotton, polyester/cotton blend and polyester fabrics made in plain and twill weave were tested. The effect of fabric weave, yarn number per centimetre and linear density on the tear resistance was observed. Test results showed that fabrics with plain and twill weave have increased tear strength with the increase of weft yarn count per centimetre and higher linear density. Twill weave fabrics produced with higher number of yarns per/cm showed better resistance to tear than plain weave fabrics because of the higher yarn mobility inside of the fabric structure [9]. In the study by Ute, dimensional and mechanical properties of 3/1 twill weave fabrics produced with double-core and core-spun weft yarns were tested. With the increase of the yarns number per centimetre, the tear strength decreased in the warp and weft direction. Higher weft yarn number per centimetre increased the tensile strength in the weft direction but decreased in the warp direction. In this study, it was observed that tensile strength was higher for the fabrics produced with core-spun yarns compared with double-core spun [10].

* Corresponding author. Tel.: +372 55562824.
E-mail address: *nele.mandre@taltech.ee* (N. Mandre)

In addition, elastane ratio in the weft yarn affects the tensile and tear strength of a fabric significantly. Unfortunately, using elastic fibre in denim fabrics can reduce the lifespan of garments. Polyester or its derivates are added to improve fabric performance properties [6, 11]. Many previous studies have focused on the evaluation of physical properties of cotton and elastane blended denim fabrics. Sarıoğlu and Babaarslan compared 100% cotton and core–spun yarn filament fineness and yarn count on tensile and tear strength [6]. Özdil compared tensile, tear and bagging properties of denim fabrics containing different percentage of elastane. Higher elastane content was found to increase bending rigidity and elastic bagging, but to decrease permanent bagging properties [12]. Bagging is defined as a three-dimensional residual deformation in used garments, which deteriorates in the appearance of the garment. Deformation can be observed on the elbow or on knee area of the garment [13]. In another study, five woven fabrics containing different rates of elastane yarns were prepared. Tear and tensile properties as well as air permeability, fabric growth and permanent stretch of plain weave fabrics were tested [14]. Fabric growth is defined as the difference between the original length of a specimen and its length after the application of a specified tension for a prescribed time and the subsequent removal of the tension. [15]. According to their test results the core yarn ratio is an important parameter that affects tensile and tear strength. Finer yarns increased the core ratio and it led to better tensile strength. At higher elastane ratio, the tensile strength and tear resistance decreased [14].

Core–spun yarn has been developed to eliminate the durability problems caused by elastane filament. Two-layered structure core provides the mechanical properties of the yarn, for example, yarn strength, the sheath improves the aesthetic appearance, and other physical properties like feel and comfort [16]. In addition to elastane in the core of denim fabric, there are several other elastomeric fibres that are suitable for use as core material. In 2002, INVISTA introduced a new elastomultiester fibre Lycra T400. Lycra T400 is the combination of two polyesters to improve the fabric durability and comfort properties. It contains 40% 3-GT type polyester and 60% 2-GT type polyester. 2-GT type is also known as PET (polyethylene terephthalate) and 3-GT type or PTT is poly(trimethylene terephthalate). This bi-component-filament yarn has very good dimensional stability, high stretch and recovery properties but low growth. On averagely, 10 – 25 % of Lycra T400 is needed for jeans to provide high stretch properties [17 – 21]. Polybutylene terephthalate (PBT) is used in denim fabrics because it has better stretch and recovery properties than polyester (PET). PBT is more expensive but even a small amount can contribute enough to elasticity [22, 23].

To improve synthetic fibres and find alternatives to cotton, the use of regenerated fibres is becoming increasingly popular in the manufacturing of the denim fabric. Regenerated fibres are cellulose-based man-made fibres that are mainly produced from wood pulp. These cellulosic fibres are used in the production of denim because of comfort and breathability; also those fibres provide high tensile strength and soft feel. However, studies of synthetic fibres like Lycra T400, or some regenerated fibres like modal, viscose together with elastane or polyester in the core have been reported only in the few research papers [24 – 26]. Yarn and fabric properties have been analysed on the basis of soft-core filaments such as Dorlastan, Lycra and spandex. Also, some new approaches have emerged where polybutylene terephthalate (PBT) or Lycra T400 is used as core filament [27]. The ring spinning system was used to find optimum spinning parameters for Lycra T400 blended with cotton core-spun yarns [28]. Some research papers have analysed the effect of regenerated fibres in a fabric. Air permeability, water vapour transmission, thermal insulation, total absorbency, wickability properties of polyester-viscose, polyester-cotton ring and MJS (Murata Jet Spinning) yarn fabrics were compared. Ring spun fabrics had lower absorbency, air permeability and water vapour transmission properties than MJS yarn fabrics but higher wickability [29]. Basit, Latif, Baig and Rehman blended viscose with cotton, Tencel, modal and bamboo. Mechanical and comfort properties were compared on the basis of air permeability, moisture management, tensile and tear strength. According to their test results, viscose/Tencel and viscose/modal blended yarns showed higher mechanical and comfort properties than viscose/cotton and viscose/bamboo blend [26]. Air permeability is considered an important comfort parameter for a wearer, which is influenced by the thickness, weight and structure of the fabric. Fibre content and the inter-yarn pores (texture, size, shape) between individual yarns have a significant effect on air permeability [30, 31].

There were very few findings based on comparing physical and comfort properties of core–spun yarn containing different elastomeric and regenerated fibres in the core. According to the above-mentioned studies, weft yarn number per centimetre and core components have a substantial influence on the fabric strength and performance characteristics. For this reason, the current study is divided into two parts, five denim fabrics were produced with the same fabric parameters but different number of weft yarns per centimetre and four fabrics contained synthetic and regenerated yarns in the core to demonstrate the influence of weft yarn between the properties of different types of materials. The aim of the study is to evaluate the effect of the fibre composition on tensile properties, abrasion resistance and air permeability of fabrics containing multifilament yarn by the use of new approaches [8]. The focus is on how to achieve durable but elastic fabric that is comfortable to wear. Based on previous studies fabric abrasion resistance, tensile and tear strength indicate denim fabric durability properties the most and air permeability is considered as comfort parameter. For this reason, those parameters were investigated on the basis of fibre composition and weft yarn number per centimetre.

2. MATERIALS AND METHODS

2.1 Materials

Nine woven denim fabrics were prepared by the Turkish company Kipaş Holding A.Ş. All the tested fabrics were made of 3/1 Z twill weave and warp yarns were made of cotton. Five fabrics CE16, CE17, CE18, CE19, CE20 have different weft yarn count per centimetre and fabrics CMPE, CPVE, CPE, CT400E contained multifilament ring core−spun yarns in the weft direction (Table 1).

Table 1. Fabrics parameters

No	Warp yarn, Ne (composition)	Weft yarn (composition)	Reed	Reed width, cm	Mechanical weft yarn number per/cm	Fabric composition, %	Abbreviation [8]
1.	13.5/1 Ne (CO)	18/1 Ne 50/50 + 78dtex (CO [1]/CMD [2]/PES [3]/EL [4])	75/4	210	18	CO/CMD/PES/EL 70/14/14/2	CMPE
2.	13.5/1 Ne (CO)	18/1 Ne 67/33 + 78dtex (CO/PES/CV [5]/EL)	75/4	210	18	CO/PES/CV/EL 69/19/10/2	CPVE
3.	13.5/1 Ne (CO)	18/1 Ne+ 55dtex + 78dtex (CO/PBT [6]/EL)	75/4	210	18	CO/PBT/EL 94/4/2	CPE
4.	13.5/1 Ne (CO)	18/1 Ne+ 55dtex + 78dtex (CO/T400 [7]/EL)	75/4	210	18	CO/T400/EL 94/4/2	CT400E
5.	13.5/1 Ne (CO)	18/1 Ne + 78 dtex (CO/EL)	75/4	210	16	CO/EL 98/2	CE16
6.	13.5/1 Ne (CO)	18/1 Ne + 78 dtex (CO/EL)	75/4	210	17	CO/EL 98/2	CE17
7.	13.5/1 Ne (CO)	18/1 Ne + 78 dtex (CO/EL)	75/4	210	18	CO/EL 98/2	CE18
8.	13.5/1 Ne (CO)	18/1 Ne + 78 dtex (CO/EL)	75/4	210	19	CO/EL 98/2	CE19
9.	13.5/1 Ne (CO)	18/1 Ne + 78 dtex (CO/EL)	75/4	210	20	CO/EL 98/2	CE20

[1] CO-Cotton; [2] CMD-Modal; [3] PES-Polyester; [4] EL-Elastane; [5] CV-Viscose; [6] PBT-Polybutylene terephthalate; [7] T400-Lycra T400®; [8] Abbreviation used in this article to describe the fibre.

Fabrics CE16-CE20 weft yarn contained elastane at the core. Fabric CMPE contained elastane, polyester and modal at the core. Fabric CPVE contained elastane, polyester and viscose. Fabric CPE weft yarn core part consisted of elastane and polybutylene terephthalate. Fabric CT400E contained elastane, polyester and Lycra T400®. Fibres were chosen from different origin. All the tested fabrics core yarns were covered with cotton. To evaluate how fibre composition affects fabric strength and comfort properties elastane was used to give the stretch properties, while polyester and polybutylene terephthalate provide strength to the fabric. Lycra T400® is developed to improve both fabric strength and elasticity. Regenerated fibres viscose and modal are considered as more sustainable than other used fibres. Viscose and modal provide enough strength and comfort to the fabric, which make these regenerated fibres suitable to use in denim fabric. Table 1 gives an overview of the tested fabrics parameters.

2.1 Methods

Fabrics performance and durability properties were measured by the methods covered by the ISO standards. Table 2 gives an overview of the standards used in this study. Before testing, all specimens were conditioned in a standard atmosphere at 20 °C and 65 % relative humidity for 24 hours in accordance with the EN ISO 139:2005/A1:2011 [32].

Abrasion resistance was tested in accordance with the ISO standard EN ISO 12947-2:2016. Martindale abrasion tester James Heal 1605 was used to test the abrasion resistance. Three test specimens were cut from each fabric. The diameter of the test specimen and the holder foam were 38 mm. The original Martindale polyurethane foam was used as foam material. Diameters of the abradant and the wool felt underlay were 140 mm. Martindale abrasion cloth SM25 was used as abradant material and woven felt was used as felt material. Then the number of rubs was set. The test continued until two yarns were broken [33]. Dino-Lite Digital Microscope AM4113T was used to examine damaged and broken yarns.

Tensile strength was tested according to the ISO standard ISO 13934-1:2013, using Instron 5866 testing machine. Specific stress was used to evaluate the tensile properties of the tested fabrics; it is a ratio between the maximum load and the mass per unit area, also known as tenacity [34]. The following Eq. 1 was used to calculate the specific stress (P_0):

$$P_0 = (P_t \cdot 100)/(B \cdot GS), \quad (1)$$

where P_0 is the specific stress (N·m/g); P_t is the average load at break/ max load (N); B is the mass per unit area (g/m^2); GS is the sample width (mm) [35].

Five specimens were cut in the warp and five in the weft direction. The length of each specimen was 400 mm and the width was 50 mm. The gauge length of the tensile testing machine was set at 200 mm and the test specimen was mounted between two jaws. The extension rate was 100 mm/min. Pretension was set at 5 N; load cell was 10 000 N. Movable clamps extended the test specimen to the point of rupture. Maximum load (N), were recorded [36]. Tearing was tested according to the ISO standard EN ISO 13937-2:2000. Instron 5866 testing machine was also used to test the tearing performances of the fabrics. Five specimens were cut in the warp and five in the weft direction. The length of each specimen was 200 mm and width 50 mm. A longitudinal slit was cut 100 mm. The end of tear was marked 25 mm from the uncut end of the stripe. The gauge length of the testing machine was set at 100 mm. Then the test specimen was clamped in the jaws. The moving clamp was put in motion at 100 mm/min. The tear was continued to the point marked near the end of the strip. Tear force was recorded in Newtons (N). Tear trace was recorded using BlueHill software [37]. Air permeability was tested in accordance with the EN ISO 9237:2000. Air permeability is a measure to indicate the air flow through the fabric in one square metre per second. FX 3340 MinAir was used to test air permeability of the fabrics. Test surface area was 20 cm^2 and pressure drop 100 Pa. The measurements were taken at ten locations on the same surface of each specimen [38]. Air permeability of the tested fabrics was recorded on the face side to the back side and on the back to the face side of each fabric. The number of yarns per unit length was tested in compliance with the EN 1049-2:2000. Method A was used to calculate yarns number per centimetre, which is the most used laborious method and suitable for all fabrics. Five specimens were cut from the warp and five from the weft direction of the fabric; minimum measuring distance was 5 cm. Two dissecting needles and a heavy steel ruler were used to count the number of warp and weft yarns per centimetre. Each sample width was 5 cm. The means of individual results in the warp and weft direction were quoted [39]. Mass per unit area was tested according to the ISO standard EN 12127:2000. Five test specimens of 100 cm^2 were cut out from each fabric. Because scissors were used for cutting, three measurements were taken of the warp and three of the weft direction. Results were rounded to the nearest 1 mm. Each of the individual specimen was weighed and the value was recorded to the nearest 1 mg. Mass per unit area M was calculated in grams per square metre using the following Eq. 2 [40]:

$$M = (m \cdot 1000)/A, \qquad (2)$$

where m is the mass of a test specimen conditioned (g); A is the area of the same test specimen (cm^2); M is the mean mass per unit area (g/m^2) [40]. The standard test methods used in this study are listed in Table 2.

Table 2. Standard test methods used

No	Fabric property	Standard test methods
1.	Abrasion resistance	EN ISO 12947-2:2016 Textiles – determination of the abrasion resistance of fabrics by the Martindale method – Part 2: Determination of specimen breakdown
2.	Tensile strength	ISO 13934-1:2013 Textiles – Tensile properties of fabrics – Part 1: Determination of maximum force and elongation at maximum force using the strip method
3.	Tear strength	EN ISO 13937-2:2000 Textiles – Tear properties of fabrics – Part 2: Determination of tear force of trouser-shaped test specimens (Single tear method)
4.	Air permeability	EVS EN ISO 9237:2000 Textiles – Determination of permeability of fabrics to air
5.	Number of threads per unit length	EN 1049-2:2000 Textiles – Woven Fabrics – Construction – Methods of analysis – Part 2: Determination of number of threads per unit length
6.	Mass per unit area	EN 12127:2000 Textiles – Fabrics – Determination of mass per unit area using small samples

3. RESULTS AND DISCUSSION

Fabric mass per unit area and the number of yarns per centimetre in the denim influences air permeability, tensile strength, also, resistance to abrasion. For this reason, tested fabrics mass per unit area, mechanical and actual number of yarns per/cm were measured and presented in Table 3.

Table 3. Fabrics mass per unit area and the number of yarns per centimetre

No	Fabric	Mechanical weft yarn number, per/cm	Actual number of weft yarns, per/cm	Mass per unit area, g/m^2	Mass per unit area, st.dev.*, g/m^2
1.	CMPE	18	22	323	3
2.	CPVE	18	22	330	3
3.	CPE	18	22	323	4
4.	CT400E	18	22	323	2
5.	CE16	16	19	296	5
6.	CE17	17	20	301	3
7.	CE18	18	22	309	2
8.	CE19	19	23	317	4
9.	CE20	20	24	320	4

*st.dev. – standard deviation

3.1. The effect of weft yarn number per centimetre on air permeability and abrasion resistance

Mechanical weft yarn number was compared to the actual number of weft yarns per centimetre. It can be seen in Table 3 and in Fig. 1 and Fig. 2 that actual yarn number was 3 – 4 yarns more than mechanical yarn number per centimetre. Air permeability measurements showed that for all tested fabrics, there was no significant difference between the air permeability whether it was measured from the face side or from the back side of the fabric. So, in this study, the air permeability was measured as follows: air flow was from the back side to the face side of the fabric. These values were lower than the values measured from the opposite direction and usually fabric back side is against the human body. Fabrics CE16–CE20 were all prepared with the same parameters but with different weft yarn densities per centimetre.

According to the test results, higher number of yarns per/cm decreases air permeability. The air permeability of fabric CE20 (27.4 ± 1.2 l/($m^2 \cdot s$)) was one and a half times lower compared with fabric CE16 (41.7 ± 1.2 l/($m^2 \cdot s$)). Fabric weight, and yarns number per/cm were the main structural properties that affected abrasion resistance significantly. Higher mass per unit area of fabric with tight structure were more resistant to abrasion. Tight fabric construction decreased air permeability, because pores between yarns become smaller and the air flow through the fabric is restricted [41, 42]. As it can be seen in Fig. 2, abrasion resistance of fabrics CE18 and CE19 was 35 000 rubs, for fabric CE20, it grew exponentially; but it decreased air permeability. Thus, to find the balance between abrasion resistance, which shows strength of the fabric and air permeability, which indicates fabric comfort properties, the optimum thread number per centimetre should be 18. Because fewer yarns per centimetre showed lower strength properties but higher thread numbers per centimetre decreased air permeability remarkably.

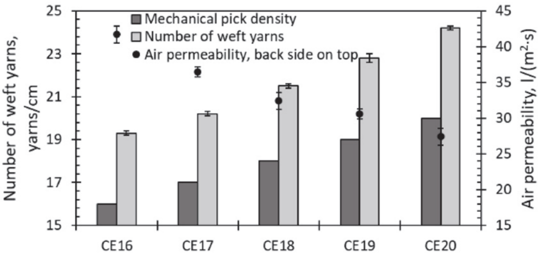


Fig. 1. The effect of weft yarn number per centimetre on air permeability of fabrics CE16–CE20 with different number of weft yarns per centimetre

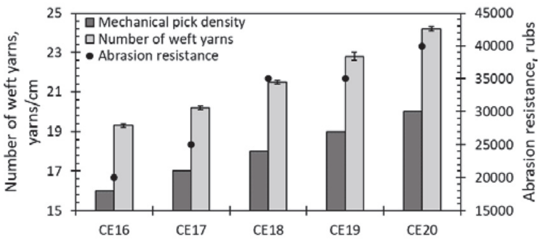


Fig. 2. The effect of weft yarn number per centimetre on abrasion resistance of fabrics CE16–CE20 with different number of weft yarns per centimetre

3.2. The effect of core-yarn on air permeability and abrasion resistance

The test results showed that fabrics CMPE and CE20 had the highest abrasion resistance value, 40 000 rubs (Fig. 2, Fig. 4, Fig. 5), although those fabrics had different number of weft yarns per centimetre, fabric CMPE had mechanical weft yarn number of 18 and fabric CE20 had 20. As can be seen in Fig. 5, the analysis by Dino-Lite microscope revealed that surface warp yarns of fabric CMPE were more damaged than those of fabric CE20. Based on the comparison of those two fabrics, it can be concluded that fabric CE20 provided the highest test results of abrasion resistance. Fabric CE16 showed the lowest abrasion resistance value, 20 000 rubs, which is half less than fabrics CMPE and CE20. (Fig. 2, Fig. 6) It is because fabric CE16 had the lowest number of yarns per centimetre. Fig. 6 shows that many yarns were totally broken and 16 threads per centimetre lacked sufficient fabric strength properties.

In addition, there are other parameters that affect abrasion resistance. Fabric CMPE contained modal, polyester and elastane in the core. Polyester has high abrasion resistance; cotton is considered to have medium resistance to abrasion. The abrasion properties increased by the presence of polyester fibre in the core of cotton covered weft yarn. Usually, polyester is longer fibre than natural staple cotton fibre, which leads to a better abrasion resistance. Longer fibres were more stable, short fibres can be liberated from the fabric more easily. Fabric CPVE showed 10 000 rubs lower test results than fabric CMPE. CPVE abrasion resistance was 30 000 and CMPE was 40 000. Thus, viscose had lower abrasion retention than modal. Fabrics CMPE, CPVE, CPE, CT400E contained various yarns in the core. According to the literature number of yarns per centimetre have a great influence on fabric air permeability. Yarns with higher porosity have better air permeability. It is known that viscose has serrated cross-section but modal has more circular cross–section, this leads to a better air permeability. The test showed different results. Fabric CMPE (30.3 ± 1.3 l/(m^2·s)), which contained modal had lower air permeability than fabric CPVE (34.7 ± 0.8 l/(m^2·s)), that contained viscose. It might be because of the presence of cotton fibre that influenced the air permeability [41 – 44].

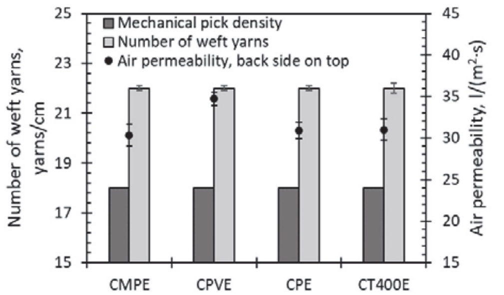


Fig. 3. The effect of weft yarn number per centimetre on air permeability of fabrics CMPE, CPVE, CPE, CT400E with different weft yarn fibre composition.

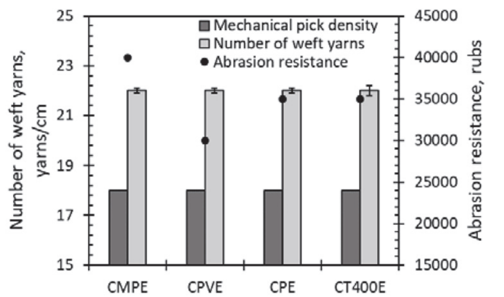
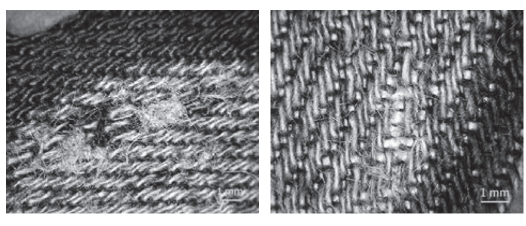


Fig. 4. The effect of weft yarn number per centimetre on abrasion resistance of fabrics CMPE, CPVE, CPE, CT400E with different weft yarn fibre composition



a b

Fig. 5. The highest abrasion resistance of fabrics, specimen's abrasion resistance was 40 000 rubs: a – CMPE; b – CE20

According to the test results higher amount of natural fibre in the yarn led to better air permeability. Fabrics CE16-CE20 contained 2 % of elastane in the core of weft yarns and air permeability was better than with fabrics CMPE, CPVE, CPE, CT400E (Fig. 3, Fig. 4), which additionally contained synthetic or regenerated fibres. This result is similar to the results from the studies of Kadoğlu, Dimitrovski, Marmaralı, Çelik, Bayraktar, Üte, Ertekin, Demšar, Kostanjek, where higher elastane tension exhibited lower air permeability; 100 % cotton showed better air permeability properties than cotton blended with elastane or with PBT [22].

Air permeability test results showed clearly that by increasing the fabrics CE16-CE20 weft yarns per centimetre the air permeability decreases significantly. Fabrics CMPE, CPVE, CPE, CT400E actual weft yarn number per/cm were almost the same. But air permeability test showed different results. Air permeability of the fabrics that contained regenerated fibres were about 10 % better than fabrics CPE and CT400E. Thus, air permeability was more affected by the weft yarn diametre than yarn number per centimetre [29].

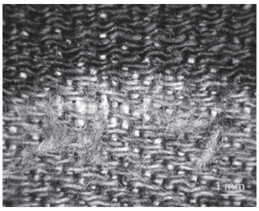


Fig. 6. CE16 showed the lowest abrasion resistance, 20 000 rubs

3.3. Specific stress and air permeability

All the warp yarns of the fabrics showed higher specific stress value than in the weft direction (Fig. 7 and Fig. 8). Fabrics CMPE, CPVE, CPE, CT400E specific stress in the weft direction was about half of the same fabric warp yarns specific stress. And fabrics CE16-CE20 specific stress in the warp direction was 2/3 better than the same fabric weft yarns specific stress. It is because of the elastane yarn in the weft. Elastane provides better stretch properties for denim fabrics but it reduces the tensile properties of the fabric [12, 14].

Differences in the results of the specific stress at the maximum load test were not remarkable (Fig. 7). By increasing the weft yarn count per centimetre, the specific stress values were not influenced significantly. Fabrics CE16-CE20 weft yarn specific stress at max load varied between 19.3 to 22 N·m/g. Higher weft yarn count per centimetre decreases air permeability. Fabric CE16 weft yarn air permeability was about 1/3 better than fabric CE20. Thus, fabrics with tight constructions do not provide as good comfort properties as those with fewer yarns per centimetre. It was expected that higher number of weft yarns increases the specific stress. But specific stress values were similar, it is because warp yarn number was constant, the effect would be greater if the densities in both directions had increased [45].

Regarding the evaluation of the performance and comfort parameters for customers, the air permeability of fabric CE16 showed the highest air permeability result (41.7 ± 1.2 l/(m^2·s)), moderate specific stress value (20.9 N·m/g), but resistance to abrasion was the lowest (20 000 rubs). It was in contrast with the test results of fabric CE20, which showed the highest abrasion resistance (40 000 rubs), as well as a moderate specific stress value (21.5 N·m/g), but the lowest air permeability (27.4 ± 1.2 l/(m^2·s)). Thus, fabrics with 16 and 20 threads per centimetre do not provide sufficient quality to satisfy high strength and comfort characteristics of a fabric.

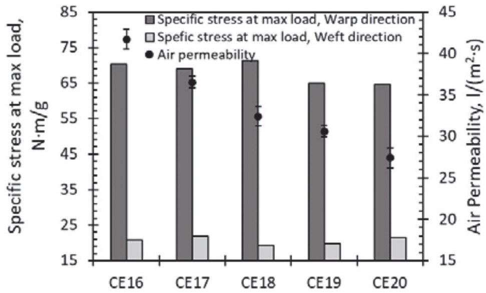


Fig. 7. The effect of specific stress of fabrics CE16-CE20 at maximum load and air permeability

Comparing fabrics CMPE, CPVE, CPE, CT400E specific stress values, fabric CT400E had almost 5% better specific stress properties than the other tested three fabrics in the warp direction (Fig. 8). It might be because it contained Lycra T400 fibre in the weft yarn. This multi–component yarn was made of two kinds of polyesters. In this study, CT400E contained 4 % of Lycra T400. According to the test results, lower percentage of T400 filament also provided good tensile properties. But in the weft direction, fabrics CMPE and CPVE showed higher specific stress values, 32.8 and 39.3 N·m/g accordingly. The tensile properties of the yarn were increased by the presence of the polyester filament at the core, which was the main load carrier when we compared it with cotton yarn [46]. Fabric CMPE contained 14 % of polyester and fabric CPVE contained 19 %. Fabrics containing higher percentage of polyester also showed higher tensile strength, because polyester filament is strong and dimensionally stable fibre. It is used in the core of denim fabrics to add strength and durability. In addition, polyester provides good elasticity [47].

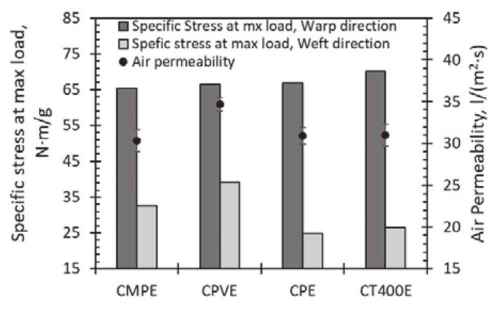


Fig. 8. The effect of specific stress of fabrics CMPE, CPVE, CPE, CT400E at maximum load and air permeability

Viscose and modal are both regenerated cellulose fibres but they have different crystallinity. Usually, viscose crystallinity is lower than modal fibre [48]. Thus, modal provided higher strength than viscose fibre [49].

As can be seen in Fig. 8 fabric CPVE had also the highest air permeability (34.7 ± 0.8 l/(m^2·s)), the other three fabrics showed similar air permeability test results, between

30.3 – 31.0 l/(m²·s). All the tested four fabrics were produced with the same weave and the same yarn count. Thus, the air permeability differences were caused by the blend ratio, different fibre diameter and pore size. Tested fabrics CMPE, CPVE, CPE, CT400E showed lower air permeability than the other five fabrics because of the differences in the yarn cross section. It influenced inter-yarn spaces and the porosity of the denim fabric. Polyester blended with viscose provided better air permeability properties than polyester/cotton blends [50].

3.4. Tear strength

Tear strength of fabrics CMPE, CPVE, CPE, CT400E was recorded in the warp and weft direction (Fig. 9). Tear strength of fabrics CE16-CE20 failed in the weft direction because of the yarn shift (Fig. 10). The failure occurred by tearing across one leg of the specimen. It might be because the tearing direction of the tested fabrics was much stronger than the other direction [51, 52].

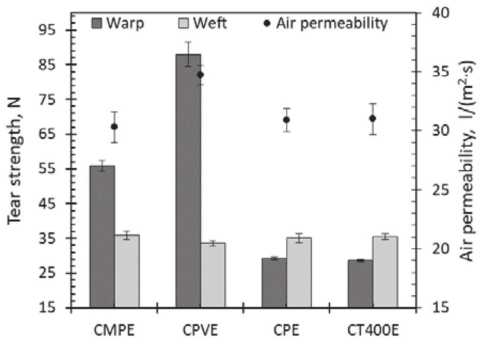


Fig. 9. Average tear strength and air permeability of fabrics CMPE, CPVE, CPE, CT400E in the warp and weft direction

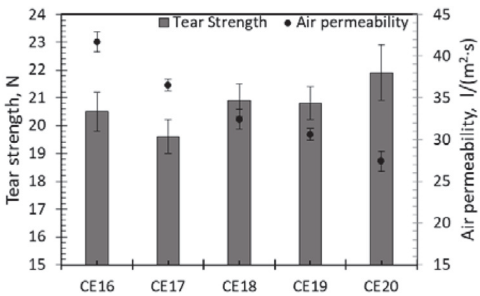


Fig. 10. Average tear strength and air permeability of fabrics CE16-CE20 in the warp direction

Fabrics CMPE, CPVE, CPE, CT400E had similar test results in the weft direction because warp yarns were made of cotton. But there were significantly different results in the warp direction. Tear strength of fabrics CMPE (55.8 ± 1.6 N) and CPVE (88.0 ± 3.5 N) was higher in the warp direction. In the weft direction fabrics CPE (35.1 ± 1.3 N) and CT400E (35.5 ± 0.8 N) showed similar test results as fabric CMPE (36.0 ± 1.2 N). Fabric CPVE had the lowest tear strength in the weft direction (33.6 ± 0.8 N). As mentioned before, polyester influences yarn's tensile strength, as well as tear strength positively. This is consistent with Pramanik and Patil findings. They investigated the energy to break cotton/polyester core spun yarn made of ring and air-jet systems. Polyester filament clearly increased single ring-core yarn strength. The strength was in proportion to the increase in the filament ratio in the core. Single ring core-spun yarn strength increased 15 % to 43 % as compared to 100 % of cotton yarn. Thus, higher filament percentages needed more energy to break the yarn [46].

According to previous research, it was expected that Lycra T400 shows higher tearing properties than the other tested fabrics. Test results might be influenced by the amount of Lycra T400 in the weft or yarns number per unit area. According to Kurtulmuş, Güner, Akkaya and Kayaoğlu, who analysed two fabrics containing Lycra T400, fabric that had lower number of warp yarns per/cm showed the highest tear strength [53]. There might be other reasons; fabric CT400E contained only 4 % of Lycra T400, which is quite an optimal value. To improve comfort and strength properties, the percentage should be higher than the elastane percentage in the fabric [54]. PBT fibre has lower tensile properties than PET fibre; for this reason, fabrics CMPE and CPVE showed higher tearing performance [23]. Both fabrics contained polyester filament, which probably affected the fabric durability properties positively and modal, viscose, which had better air permeability properties than cotton [23].

4. CONCLUSIONS

Abrasion resistance, tear strength and tensile properties are important parameters for characterizing the lifespan of a fabric. Air permeability has high influence on the fabric comfort properties. In current study, elastic fibre was added to provide more stretchy and comfortable wear. Nine denim fabrics with different fibre content and weft yarn densities were produced to evaluate durability and comfort properties.

Fabrics CMPE, CPVE, CPE, CT400E contained various filaments in the core of weft yarn and fabrics CE16–CE20 were produced with the same parameters containing elastane in the core, but with different number of weft yarns per centimetre.

Test results showed that fabrics CMPE, CPVE, CPE, CT400E specific stress in warp direction was about 50 % higher than the same fabrics specific stress in weft direction. And fabrics CE16-CE20 specific stress in weft direction was only 1/3 of the same fabric specific stress value in the warp direction. Using polyester or regenerated fibres (modal, viscose) in the core resulted in better tensile and tear strength. Fabric CMPE tear strength was 55.8 ± 1.6 N, which was two times higher and fabric CPVE tear strength was 88.0 ± 3.5 N, it was three times higher than fabrics CE16-CE20 tear strength.

Tear strength of five fabrics (CE16-CE20) failed in the weft direction because of the direction the force applied was so much stronger than in the other direction. Fabrics CMPE, CPVE, CPE, CT400E tear strength was between 33.6 – 36.0 N in the weft direction. Fabric CMPE showed the highest tear strength value.

Fabric, weight and structure affected air permeability as well. Inter-yarn pores had a substantial influence on air permeability. Fabric CE16 with lower number of yarns per centimetre showed better air permeability (41.7 ± 1.2 l/(m^2·s)) but quite low abrasion resistance (20 000 rubs). Fabric CE20, which had the highest number of yarns per centimetre showed the lowest air permeability (27.4 ± 1.2 l/(m^2·s)) and highest abrasion resistance (40 000 rubs). The aim of this paper was to find the optimum fibre content for denim fabric to provide durability and comfort at the same time. Although all the tested fabrics had some disadvantages it can be concluded that fabric CPVE showed higher specific stress values, also very good resistance to tear and satisfying air permeability than other tested fabrics.

Thus, to satisfy customer needs, prolong the lifespan of denim fabric and depict the shape of body, denim fabric weft yarn core part should contain polyester fibres; which provide strength. Moreover, elastane in the core gives good elasticity and viscose provides both good durability and comfort to the fabric. Those three fibres in the weft yarn should be covered with cotton.

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Appendix 2

Paper II

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Design of Performance Characteristics on Laser Treated Denim Fabric

Nele MANDRE [1] *, Tiia PLAMUS [1], Angelika LINDER[1], Toivo VARJAS[2], Jüri MAJAK[3], Andres KRUMME [1]

[1] *Department of Material and Environmental Technology, Laboratory of Polymers and Textile Technology, Tallinn University of Technology, Ehitajate tee 5, 12616, Tallinn, Estonia*
[2] *Department of Electrical Power Engineering and Mechatronics, Laboratory of Lightning Technology, Tallinn University of Technology, Ehitajate tee 5, 12616, Tallinn, Estonia*
[3] *Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 12616, Tallinn, Estonia*

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The current paper covers an experimental study, mathematical modelling, and design optimization of the laser treatment process of denim fabrics. Laser fading is used in the finishing phase of garment production, unfortunately, it decreases fabric durability. Denim fabric is known as a cotton fabric but nowadays it is blended with other fibres to improve fabric properties. For this reason, the main purpose of this study was to test multicomponent fabric longevity after laser treatment. The knowledge from this study is used by garment production company. The tear force, abrasion resistance, and colour difference are considered as performance characteristics of laser treated denim fabrics subjected to maximization. To achieve the goals, novel, mathematical models were developed. In the preliminary tests, the design space was determined. The full factorial design of experiments was utilized in the experimental study and the values of the performance characteristics are measured. Based on the results of the experimental study the artificial neural network and Haar wavelet based mathematical models were developed to predict the behaviour of the tear force, abrasion resistance, and colour difference. The artificial intelligence-based multicriteria design optimization procedure is developed.
Keywords: laser treated denim fabrics, artificial neural network, multicriteria optimization, wavelet method.

1. INTRODUCTION

Denim fabric finishing is the final process of garment production performed on garment, fabric or yarn to give a fashionable desired appearance to the customer. Denim finishes can be divided into mechanical and chemical. Mechanical processes, are for example, stone washing, sandblasting, machine or hand sanding. The most commonly used chemical washes are bleaching, acid, and enzyme washing. Usually, pumice stones are used in stone washing where about 1 kg of stones are needed for the treatment of 1 kg of denim fabric. Thus, this process produces large amounts of sludge in the water that needs to be filtered. Bleaching is considered a harmful chemical process to human health. Based on previous studies it can cause damage to cotton and corrosion to a washing machine [1 – 3].

According to previous studies, good fitting, comfortable denim jeans with attractive design are important characteristics for customers. In addition, consumer awareness of the negative impact of the textile industry on the environment has led them to more sustainable thinking and choosing clothes that last longer. Manufacturers use different techniques to improve the textile production process and extend the physical longevity of clothing by reducing the waste. A laser technology is an innovative sustainable alternative to common finishing methods for the treatment of denim garments [4 – 8]. Laser is an optical device developed to produce intense and coherent beam of light. Laser beams applied on a fabric surface in the textile industry provide different applications; they are used for engraving, laser welding, laser bonding, and controlled cutting. Spanish company Jeanologia has developed a sustainable laser technology for fading denim fabrics to obtain a special appearance and reduce the use of water, harmful chemicals, and save energy. In addition, it is a more accurate and flexible method than other mentioned methods with high productivity. Also, laser technology helps to reduce time, work, and resourse consumption. CO_2 laser with the wave length of 10 μm is the most widely used laser in the textile industry because of high efficiency. Based on Muthu and Gardetti [9], Gandhi [10], Angelova *et al.* [11], Vilumsone-Neme [12], Juciene *et al.* [13] the laser speed, the laser power, and energy density of laser beam have the greatest impact on fabric properties. For example, Juciene *et al.* [13] determined the impact of laser treatment and industrial washing on the tensile properties of denim fabrics. The fabric was made of 98 % cotton and 2 % elastane. Test results showed that laser treatment and industrial washing increased fabric thickness but decreased mass per unit area and breaking force. It was also noticed in Juciene, that weft yarns were less damaged by the laser beam because warp yarns are more dominant on the surface of the fabric [13].

Kan [14] proved the effectiveness of laser technology. Two laser-treated cotton denim fabrics were prepared. One

* Corresponding author. Tel.: +372 55562824.
E-mail: *nele.mandre@taltech.ee (N. Mandre)*

was manufactured with low-twist yarn spun by torque-free ring-spinning technology, and the other was manufactured with conventional ring-spun yarn. After CO_2 laser treatment colour fastness and dimensional stability of both fabrics were compared with the conventional cellulase treatment. Kan found that laser beam is able to generate a faded look on denim garment within 3 min at room temperature while the stone washing process with enzyme generates the same design for 45 min at 55 °C. Thus, laser technology saves energy, time, and water [14].

Many previous studies have compared laser technology with conventional washing processes. Ozguney *et al.* [15] examined the effect of a CO_2 laser beam on denim fabric tensile and tear properties. Also, abrasion resistance, the static and kinematic friction coefficient, and optimum process conditions were determined. They concluded that a laser beam decreased fabric tear and tensile strength as well as abrasion resistance. Although changes in the warp and weft direction were different, the laser faded process increased the static and dynamic friction coefficients. Dalbaşıa *et al.* [16] compared unwashed and washed laser treated 100 % cotton denim fabrics. Their results showed that the number of washing cycles did not affect the tensile and tear properties significantly, but the laser process affected all the tested fabrics' warp and weft yarn strength properties negatively. Washing cycles and laser process decreased the abrasion resistance of the tested fabrics. In Solman and Saha's [17] research laser fading, hand sand brushing, and potassium permanganate spraying were applied on denim fabric for fading. After testing, the mechanical and aesthetic properties of the fabric were compared with untreated denim. As a result, hand sand brushed fading had the highest negative impact on fabric tear and tensile properties.

Studies on cotton blended with elastane are scarce. No research into the properties of the fabrics containing multicomponent yarns in the core of weft yarn has been reported. Although the multicomponent fabric is widely used in garment production. In addition, knowledge acquired from this study is used by garment producer company. The main purpose of blending fibres is to improve fabric performance properties. Blending different fibres into one yarn helps to compensate one fibre weaknesses or disadvantages. In the current study, 3/1 twill weave fabric was made that consisted of four different fibres to provide comfortable and durable clothing. Abrasion resistance and tear force are considered as durability properties in the current study. Abrasion resistance is the ability of a fabric surface to withstand abrasive stresses. Tear force is the force to begin or continue a tear in a fabric under specified conditions. According to Hutten [18] under tearing load one or at most a few yarns share the load. Denim fabric warp yarn was made of cotton fibre. But the weft yarn core part was ternary, containing elastane, viscose, and polyester covered with cotton. Cotton is a strong but rigid fibre because of its crystalline structure. Polyester-cotton blend was used to improve cotton durability properties. Polyester has higher abrasion resistance and crease recovery properties than cotton. Elastane was blended with cotton to add elasticity and improve the stretchability of denim fabric by providing comfort to the wearer [10, 19]. Viscose is a regenerated fibre made from renewable material cellulose, which makes it a sustainable alternative to cotton. Cotton and viscose have different crystallinity, which also influences fibre properties [20].

The HWM was proposed originally by Chen and Hsiao in 1997 for solving ordinary differential equations [21]. The wavelet expansion introduced in [21] has been utilized by many of authors for function approximation (monograph [22], papers [23 – 25], etc.). The higher order Haar wavelet method (HOHWM) was introduced recently by Majak *et al.* as an improvement of HWM [26]. Utilizing the HOHWM based wavelet expansion approach enables to achieve principal improvement of the absolute error and the rate of convergence in comparison with the widely used HWM (see [27 – 32] for differential equations and [33, 34] for function approximation).

A feedforward artificial neural network is the simplest ANN in which the nodes do not form a cycle [35]. After Rosenblatt perceptron was developed in the 1950s, there was a lack of interest in neural networks for several decades until the backpropagation algorithms for training a multilayer neural network were implemented in parallel by several researchers [36]. Despite its simplicity feedforward ANN forms a powerful tool for function approximation due to its hierarchical structure. The accuracy and configuration of the ANN are studied in detail in [37]. The current work group has long time experience with the adaption of feedforward ANN for a wide range of engineering applications covering the design of composite laminates with structural health monitoring capabilities [38], the design of car frontal protection systems [39], modelling and design of large composite parts [40], modelling reprocessing of the glass fiber reinforced plastic scrap [41], etc.

The mathematical models developed were utilized for evaluations of objective functions. The optimization was performed by applying a multicriteria genetic algorithm (GA). GA was introduced by J.H. Holland in 1992 and is currently well-known and one of the most widely used methods in engineering optimization [42]. The main advantages of the GA over traditional gradient based methods are capabilities to handle integer and discrete variables and avoid local extremes [42]. As it is common for population based evolutionary algorithms, GA does not require that the objective and constraint functions are differentiable. The elitist nondominated sorting based multiobjective genetic algorithm NSGA-II was developed by Deb *et al*. in 2002 [43]. GA together with ANN found wide use in design optimization of composite structures [44 – 47]. In [44] the neural network and the random forest are utilized for determining the delamination of an arbitrary length at a random point of a uniform composite beam using modal properties. In [45] single and multiobjective design is utilized for determining optimal stacking sequences of dimensionally stable symmetric balanced laminated carbon/epoxy composites. In [46] the optimization methodology has been proposed to solve design pultrusion processes for industrial applications employing the design of experiments and the response surface techniques.

The current work group has utilized GA with success for solving a wide class of engineering design problems including the design of composite laminates with structural health monitoring capabilities [38], the design of car frontal protection systems [39], multi-criteria optimization of large composite parts [40], 3D optimal material orientation problems [48], etc.

The main aim of the current study is to find optimal power and the laser cutter head speed values that have a minor effect on denim fabric durability properties. In this study, laser treated denim properties are compared with the properties of raw denim. To determine the damage to the fabric structure due to the laser fading process, the tear strength and abrasion resistance of the fabrics were measured. In addition, colour coordinates were measured to estimate the damage to the fabric as well as the visual effect. Based on the workgroup long-time experience in the area of engineering optimization and the above-mentioned simultaneous goals, the multicriteria optimization problem was formulated and solved by utilizing modern artificial intelligence tools.

In this work, two recent mathematical models were developed for modelling the objective functions: Haar wavelet based model and the feedforward artificial neural network (ANN) model. The deterministic Haar wavelet method (HWM) can be utilized in the case of a limited dataset and the stochastic ANN model in the case of a complete dataset.

2. MATERIALS AND METHODS

2.1. Materials

In this study, 3/1 Z twill weave denim fabric was prepared by the Turkish company Kipaş Holding. Fabric warp yarn was made of cotton; the weft yarn core part contained polyester, viscose, and elastane, covered with cotton yarn. Table 1 gives an overview of the structural properties of the used denim fabric.

Table 1. Structural properties of the denim fabric

Construction		Yarn count, Ne*		No of threads, per/cm		Mass per unit area, g/m^2	Fibre composition, %
		warp	weft	warp	weft		
Denim fabric	3/1 twill weave	13.1/1	18/1	44	22	330	69 % cotton (CO); 19 % polyester (PES); 10 % viscose (CV) 2% elastane (EL)
*Ne (English cotton count) Number of hanks of 840 yards (yd) of yarn weighing 1 lb. (1yd = 0.91 m; 1 lb = 0.45 kg)							

2.2. Methods

The fabric was faded by using LMP9001300 PIRANHA X carbon dioxide (CO_2) laser with a wavelength of 10.6 µm. Laser lens focal distance, i.e. the distance from the lens to the point at which the laser beam converges, was 8 mm. Laser spot radius was 0.1 mm. Laser specification is shown in Table 2. Different powers and the speed of the laser cutter head were applied to the denim fabric to determine the effect of a laser beam on the physical properties of the fabric. The preliminary tests were performed to determine the design space. Based on the authors' previous experience different laser cutter parameters were tested: the speed of the laser cutter head was between 100 to 500 mm/s and power between 11 to 20 W.

Table 2. Specifications of the laser fading machine

Manufacturer model	LMP9001300 PIRANHA X
Laser medium	CO_2
Wavelength	10.6 µm
Maximum laser power	100 W
Maximum speed of the laser cutter head	60 000 mm/min
Laser spot radius	0.1 mm
Energy density with the power of 14 W	446 W/mm^2
Energy density with the power of 16 W	509 W/mm^2

The beam speed lower than 230 mm/s and power higher than 18 W resulted in very strong fading that broke the fabric. The speed of the laser cutter head after 350 mm/s and laser beam power lower than 11 W gave no visually visible faded appearance to the fabric for this reason, laser power for physico-mechanical tests was chosen 14, 16 and 18 W and the speed of the laser cutter head 230, 270, 310, 350 mm/s. The full factorial design of the experiment was performed with five levels for laser power (14, 15, 16, 17, 18 W) and four levels for the speed of the laser cutter head (230, 270, 310, 350 mm/s). Thunder Laser RDworks V8 software was used to set the speed and power parameters.

ISO standard EN ISO 12947-2:2016 Textiles – determination of the abrasion resistance of fabrics by the Martindale method – Part 2: Determination of specimen breakdown was used to test the abrasion resistance of the laser treated fabric. Three test specimens with a diameter of 38 mm were cut from each combination of the laser treated fabric. Martindale abrasion tester James Heal 1605 was used to test the abrasion resistance. Martindale polyurethane foam (with a diameter of 38 mm), Martindale abrasion cloth SM25 (with a diameter of 140 mm) and woven felt (with a diameter of 140 mm) were used as auxiliary materials. The number of rubs was set until two yarns were broken (ISO 12947-2:2016). Damaged and broken yarns were examined using Dino-Lite Digital Microscope AM4113T [49].

Tear force tests were performed following the standard EN ISO 13937-2:2000 Textiles – Tear properties of fabrics – Part 2: Determination of tear force of trouser-shaped test specimens (Single tear method). Tear force tests were carried out using Instron 5866 tensile testing machine and Bluehill software. Five test specimens with the dimensions 200 mm in length and 50 mm in width were cut along the warp and five along the weft direction of laser treated fabrics. A longitudinal slit of 100 mm was cut in the centre of the test specimen. The end of the tear was marked 25 mm from the uncut end of the specimen. A load cell with a maximum capacity of 500 N was used for the tear force tests, the gauge length was set to 100 mm and pulled apart at a rate of 100 mm/min. An average tear force in Newtons (N) was calculated [50].

CIE2000 colour-difference formula was used to measure denim fabrics colour difference after laser treatment. A formula was developed to improve the correlation between the visual degree of colour difference and the numerical values. The colour change of laser treated denim fabrics was measured by 3NH Technology spectrophotometer YS33060. Tested fabrics L^*, a^*, b^* parameters were measured to calculate the surface colour change ΔE_{00}. In MacDougall (2002) the following formulas were utilized to calculate ΔE_{00} [51]:

$$\Delta E_{00}=\sqrt{\left(\frac{\Delta L'}{k_L \cdot S_L}\right)^2+\left(\frac{\Delta C'}{k_C \cdot S_C}\right)^2+\left(\frac{\Delta H'}{k_H \cdot S_H}\right)^2+\left(R_T\left(\frac{\Delta C'}{k_C \cdot S_C}\right)^2\left(\frac{\Delta H'}{k_H \cdot S_H}\right)^2\right)}, \quad (1)$$

where

$$L' = L^*;\ a' = a^*(1+G);\ G=0.5\left(1-\sqrt{\frac{\bar{C}^*_{ab}{}^7}{\bar{C}^*_{ab}{}^7+25^2}}\right.$$

$$b' = b^*;\ C' = \sqrt{(a')^2+(b)')^2};\ h' = tan^{-1}\left(\frac{b'}{a'}\right);$$

C^* is the Munsell Chroma that indicates saturates; H^* is the Munsell Hue that indicates hue: S_L, S_C, S_H are weighing coefficients and k_L, k_C, k_H are parametric coefficients; L^* indicates the lightness (white-black); a^*, (red-green) and b^* (yellow-blue) are the chromaticity coordinates, where $+a^*$ shows the fabric redness, and $-a^*$ is green direction; $+b^*$ is the yellow direction; $-b^*$ is the blue direction: ΔL^* is the lightness difference; ΔC^* is the saturation difference; ΔH^* is the Hue difference.

2.3 Mathematical modelling

In the following, the mathematical models are developed for modelling the laser treatment process of denim fabrics. The treatment parameters, laser power and the speed of the laser cutter head are considered as design variables. Based on our experimental study, the mathematical models were developed for describing the behaviour of the tear and weft strength, abrasion resistance and colour difference.

2.3.1. ANN based function approximation models

The ANN provides powerful tools for function approximation due to its hierarchical structure. The feedforward ANN model with one hidden layer was utilized. The nonlinear sigmoid and linear activation functions were used in hidden and output layers, respectively. The initial number of neurons in the hidden layer N_h was specified as [37, 53].

$$N_h = \frac{(N_{in}+\sqrt{N_{tr}})}{L}. \quad (2)$$

where L is the number of hidden layers, N_{in} and N_{tr} stand for the number of inputs and capacity of the training dataset, respectively.

The normalization is suggested for the ANN model development and is necessary for further optimization. The accuracy of the ANN model is estimated using the mean square error (Fig. 10). The normalized functions are non-dimensional and remain in the same range. The normalization of the design variables is performed as:

$$X = \frac{x-x_{min}}{x_{max}-x_{min}},\ Y = \frac{y-y_{min}}{y_{max}-y_{min}};$$

$$x_{min} = 14,\ x_{max} = 18,\ y_{min} = 230,\ y_{max} = 350. \quad (3)$$

where x and y stand for the laser power and the speed of the laser cutter head, respectively. The normalized variables are denoted by capital letters. Keeping in mind further optimization, the functions are normalized as

$$F_{SWarp}(X,Y) = \frac{f_{SWarpMax}-f_{SW}(x,y)}{f_{SWarpMax}-f_{SWarpMin}};$$

$$F_{SWeft}(X,Y) = \frac{f_{SWeftMax}-f_{SW}(x,y)}{f_{SWeftMax}-f_{SWeftMin}}. \quad (4)$$

$$F_{CDiff}(X,Y) = \frac{f_{CDiffMax}-f_{SW}(x,y)}{f_{CDiffMax}-f_{CDiffMin}};$$

$$F_{AResist}(X,Y) = \frac{f_{AResistMax}-f_{SW}(x,y)}{f_{AResistMax}-f_{AResistMin}}. \quad (5)$$

In Eq. 3 the indexes max and min refers to the estimated maximum and minimum values of the functions obtained from experimental data. The accuracy of the ANN model developed to show the colour difference is satisfactory. However, the results (i.e., models and also MSEs) obtained in repetitive runs may vary remarkably, especially in the case of tear force models, where the dataset is even smaller (12 points). For this reason, in the following the ANN model has been left in reserve for use with a complete dataset. Instead, recent but simple Haar wavelet based deterministic function approximation techniques are utilized for preliminary design with a limited dataset.

2.3.2. Haar wavelets based function approximation models

The Haar wavelet based function approximation approach used herein is based on HOHWM expansion introduced by authors in [26]. The 2D function can be expanded into Haar wavelets as

$$\frac{\partial^{p+q} f}{\partial x^p \partial y^q}(x,y) = \sum_{i=1}^{2M}\sum_{j=1}^{2M} a_{il} h_i(x) h_l(y), \quad (6)$$

where

$$h_i(x) = \begin{cases} 1 & for \quad x \in [\xi_1(i), \xi_2(i)) \\ -1 & for \quad x \in [\xi_2(i), \xi_3(i)) \\ 0 & elsewhere \end{cases}, \quad (7)$$

and

$$\xi_1(i) = A + 2(k+1)\mu\Delta x,$$

$$\xi_2(i) = A + 2(k+1)\mu\Delta x,$$

$$\xi_3(i) = A + 2(k+1)\mu\Delta x,$$

$$\mu = \frac{M}{m},\ \Delta x = \frac{B-A}{2M},\ M = 2^J. \quad (8)$$

The Haar functions $h_i(x)$ and $h_l(y)$ defined by Eq. 7 represent the square waves [30]. The parameters p and q in Eq. 6 stand for the order of derivatives, with respect to the coordinates x and y, respectively. In Eq. 5 $m = 2^j$ is a resolution parameter with a maximum value $M = 2^J$ and k is the translation parameter. The coefficients ail in Eq. 6 can be determined by satisfying the $p + q$-th order integral of Eq. 6 in collocation points. In the case of the uniform grid and collocation points located in the centre of "elements", we obtain

$$x_l = \frac{(l-0.5)}{2M}, y_r = \frac{(r-0.5)}{2M}, l, r = 1,2, \dots, 2M. \quad (9)$$

In the cases where the behavior of the function is critical near boundary, the Chebyshev-Gauss-Lobatto grid can be utilized. The higher order Haar wavelet based function approximation was introduced in 2018 and the results of analytical convergence are not yet available. However, based on the numerical convergence analysis studied in [27 – 32], it can be expected that the values of the method parameters $p = q = 1$ and $p = q = 2$, lead to the second and fourth order convergence, respectively. Direct function approximation with Haar wavelets, i.e., case $p = q = 0$ provides just first order convergence [33, 34]. Note that increasing the values of the parameters of the method will increase the complexity of implementation since the complementary $n + m$ constants/functions of the integration need to be determined. However, the increase in complexity is not substantial for p, $q \leq 2$. The numerical convergence analysis is performed on theoretical samples where the mesh can be simply varied and the exact analytical solution is known. As a rule, the higher values p and q provide higher accuracy in the case of fixed minimum mesh size [33, 34]. The response surfaces developed by Haar wavelet based function approximation models are given in the results section.

2.4. Multicriteria design optimization

In the following, the multicriteria design optimization (MDO) is performed considering tear and weft strengths, abrasion resistance and colour difference as objective functions. Note that in the case of all four objectives considered, a higher value is preferred. However, the normalized objectives (Eq. 5 and Eq. 6) are subjected to minimization, i.e.:

$$F = [F_{SWarp}(X,Y), F_{SWeft}(X,Y), F_{CDiff}(X, Y), F_{AResist}(X, Y)] \rightarrow min, \quad (10)$$

where X and Y stand for the nondimensional design variables (laser power and the speed of the laser cutter head) given by Eq. 4. Based on the preliminary analysis of the objective functions the weighted summation technique and the Pareto concept are utilized. The pairwise analysis of the objectives performed shows that the tear and weft strengths are not contradictive, but both are contradictive with the colour difference function. Thus, the tear and weft strengths as non-conflicting criteria are combined using the weighted summation technique:

$$F_{Strength} = w_1 * F_{SWarp}(X, Y) + w_2 * F_{SWeft}(X, Y); \quad (11)$$

$$w1 + w2 = 1, \quad (12)$$

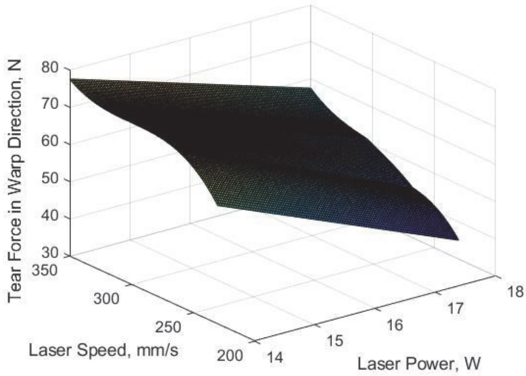
where w_1 and w_2 stand for the weights (importance) of the criteria. Detailed description of the application of optimization techniques is given in results section 3.4.

3. RESULTS

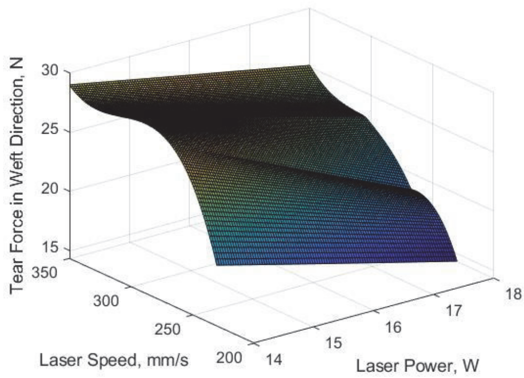
Based on the mathematical models, the multicriteria optimization problem is formulated and solved. As a result, the optimal values of the laser treating parameters and objective functions are determined.

3.1. Tear force

The response surface of tear force in warp and weft directions is depicted in Fig. 1. It can be observed from Fig. 1, that in warp directions, at increasing the laser beam power, the resistance to tear decreases.



a



b

Fig. 1. Response surfaces of tear force: a – warp direction;b – weft direction

Fabrics that were treated with the laser power of 14 W showed higher resistance to tear between (62 – 76) N. But the tear force values of the fabrics that were treated with the power of 16 W were between (33 – 55) N in the warp direction. Thus, the tear force was reduced by approximately half (45 %). Fabrics that were treated with the laser power of 18 W could not withstand the tearing and these tests failed in the warp direction. In twill construction, warp yarns are more predominant on the fabric surface. Laser beam burned warp yarns of denim fabric more intensively and it caused significant difference in tear force value between warp and weft yarns. Thus, during the tearing process, warp yarns could not tear weft yarns and ruptured.

All the tested warp yarns of fabrics were made of cotton. Thus, the strength differences were influenced by the weft yarn strength. In weft directions with a power of 14 W laser treated fabrics, tear forces were more than 40 N and with the power of 16 W tear forces were approximately (20 – 30) N lower than in the warp direction. Tear force values of 18 W laser treated fabrics were very low, between

(1 – 7) N.

Increasing the speed of the laser cutter head, the tear force also increased (Fig. 2). Fabric treated with parameters of 14 W and 230 mm/s showed the tear force (62 ± 9) N and with the speed of the laser cutter head of 350 mm/s the force was (76 ± 6) N in the warp direction. The difference was 14.1 N, which means that the speed decreased the tear force of the denim fabric by 19 %. At the laser beam with the power of 16 W and the lowest speed of the laser cutter head 230 mm/s the tear force was (33 ± 2) N and with the same power but at the highest speed 350 mm/s, the force was (55 ± 4) N. The speed decreased the tear force by 39 %.

The laser beam with the power of 14 W and the speed of the laser cutter head of 350 mm/s decreased the fabric force only by 13.6 % in the warp and 15.5 % in the weft direction as compared with the raw denim fabric. The standard deviation ratio was quite high (standard deviation 6 in the warp and 1 in the weft direction). The reason might be the uneven laser fading throughout the fabric.

According to the test results, laser power beam 16 W appeared most suitable for fading of denim fabric with the speed of the laser cutter head of 350 mm/s. And laser power 14 W is suitable to use with a lower speed of the laser cutter (230 mm/s) to satisfy optimum durability and provide a visually visible fading appearance.

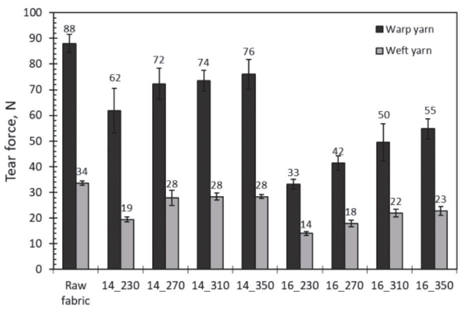


Fig. 2. Comparison of tear force of laser faded denim fabrics

3.2. Abrasion resistance

Laser treatment with different speed of the laser cutter head and power combinations affected the tested fabrics' resistance to abrasion significantly. All the tested fabrics treated with the power of 14 W showed abrasion resistance of 25 000 rubs (Fig. 4). Thus, the speed did not influence denim fabrics' resistance to abrasion. Laser power of 14 W decreased laser treated fabrics' abrasion resistance by approximately 17 % as compared with untreated denim fabrics. Denim fabrics treated with laser power of 16 W and the speed of the laser cutter head of 230 mm/s showed abrasion resistance of 14 000 rubs. By increasing the speed up to 350 mm/s, the resistance to abrasion increased to 11 000 rubs, from 14 000 rubs to 25 000 rubs. Thus, the abrasion resistance of fabric laser treated with the power of 16 W and the speed 350 mm/s was the same as that of fabrics treated with the power of 14 W. The power of 16 W and the slowest speed of the laser cutter head 230 mm/s decreased the abrasion resistance of the fabric by 53 % as compared with the untreated denim fabric. At the power of 18 W and the lowest speed of 230 mm/s, the abrasion resistance of the laser treated fabric was only 1000 rubs. Thus, the abrasion resistance was decreased by approximately 97 % as compared with an untreated denim fabric. Denim fabric treated with the power of 18 W and the speed of the laser cutter head 350 mm/s showed a better test result of 16 000 rubs. This is almost half of the test result of the abrasion resistance of the untreated denim fabric abrasion resistance tests showed that the lowest power had a minor effect on the fabric's resistance to abrasion. The laser power intensity of 16 W decreased the abrasion resistance of the fabric by about 50 % and the laser power intensity of 18 W burned the fabric intensively, and it is unsuitable for further use. The fabric laser treated at 18 W and the speed of 230 mm/s yarn damages after the abrasion test are shown in Fig. 3. Although the speed of the laser cutter head has a lower effect on a fabric's abrasion properties than power, still slower speed decreased a fabric's abrasion resistance. Laser treated fabrics with the power of 16 W speed decreased fabrics' abrasion resistance between the highest and lowest speed by 44 %.

Fabrics laser treated with the power of 18 W speed decreased their abrasion resistance by 15 000 rubs. The difference between the highest and lowest speed was 94 %.

Abrasion tests showed that the power of 14 W has the smallest effect on the reduction of abrasion resistance. Also, the speed of the laser cutter head 350 mm/s and the power 16 W gave the same optimum strength and appearance to the fabric.

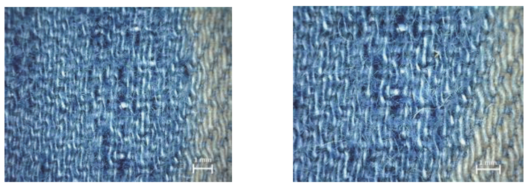


Fig. 3. Fabric laser treated 18 W and 230 mm/s yarn damages after the abrasion test

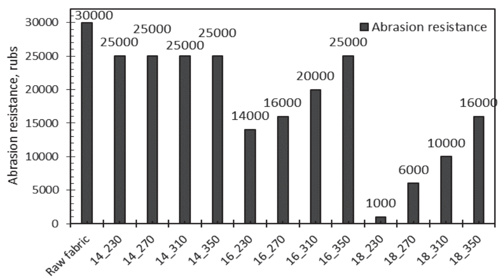


Fig. 4. Comparison of the abrasion test results of laser faded denim fabrics

3.3. Colour measurements

First, the results were obtained ANN described in section 2.3.1. In the case of the colour difference model, the configuration $L = 1$, $N_{in} = 2$, and $N_{tr} = 20$, was used, which results in $N_h = 6$. The Levenberg–Marquardt algorithm and commonly used value of the learning rate $lr = 0.05$ were utilized for error backpropagation [31]. Using the ANN model developed, the response surface for the colour difference was composed (Fig. 5). In Fig. 5 and below the term "laser speed" is used as an abbreviation for the speed of the laser cutter head. The mean square error is depicted in Fig. 6.

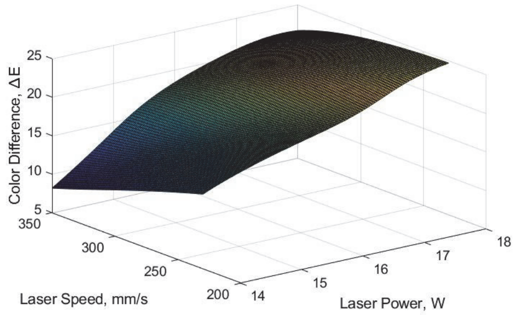


Fig. 5. Response surface for colour difference (101 × 101 points)

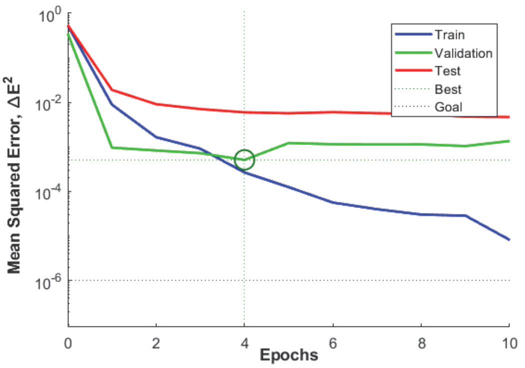


Fig. 6. Mean Squared error of the ANN model for colour difference

In Fig. 5, the values of the design variables and colour difference function are given in terms of original values to get a more realistic picture. Actually, in the model development, both the design variables and the function are used in normalized form.

The response surface of colour differences, using the HWM model described in section 2.3.2, is given in Fig. 7.

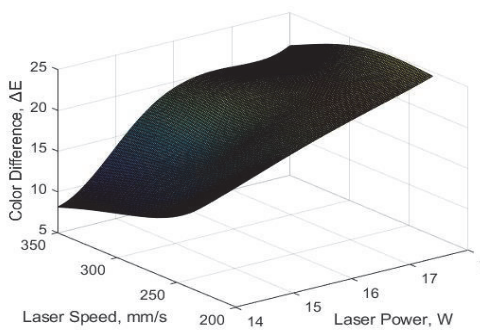


Fig. 7. Response surface of colour differences

Fig. 7 shows that the colour difference of laser treated fabrics was higher when using a lower speed of the laser cutter head and higher power. The highest colour difference value was shown by fabric laser treated 18 W and 230 mm/s ($\Delta E = 24.48 \pm 0.35$) and fabric laser treated 18 W and 270 mm/s ($\Delta E = 24.72 \pm 0.55$). The lowest colour difference was shown by the laser treated denim fabric with the power of 14 W and a speed of 350 mm/s ($\Delta E = 8.14 \pm 0.47$). The test result is three times better as compared to the highest colour difference (Fig. 8).

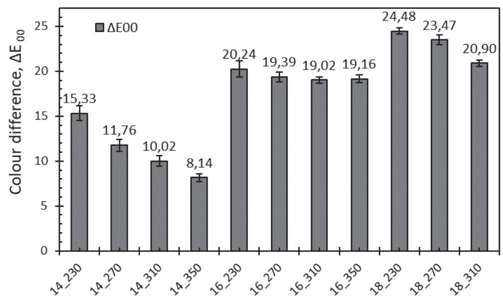


Fig. 8. Comparison of colour difference of laser faded denim fabrics

3.4. Multicriteria design optimization

The multicriteria optimization problem is formulated in section 2. The strategy proposed in section 2 is based on utilizing the weighted summation technique for non-conflicting objectives and the Pareto concept for conflicting objectives.

In the current study, the tear force is considered two times more important than the weft strength, i.e., $w_1 = 2/3$ and $w_2 = 1/3$. The Pareto concept is applied to the combined strength and colour difference criteria (Fig. 9).

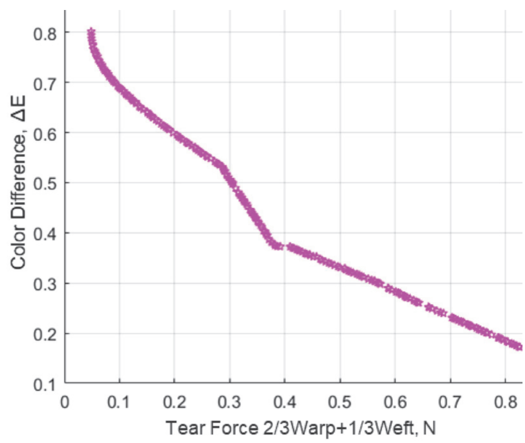


Fig. 9. Combined strength vs. colour difference criteria

Since the objectives are normalized, the smaller value in the Pareto front is better for both criteria with a non-reachable ideal point in (0,0). Near linear behaviour of the compared criteria can be observed from Fig. 9. Any point in the Pareto front is an optimal solution, but the selection of the final solution is not simple in the case of a nearly linear curve since the improvement of strength leads to a decrease of the colour difference in the same range. A separate Pareto front was composed for abrasion resistance and the colour difference criteria, which are contradictive (Fig. 10).

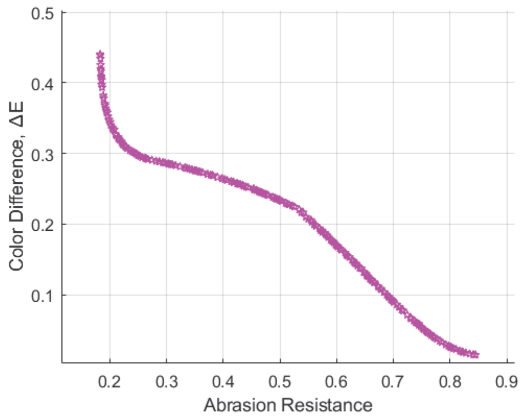


Fig. 10. Abrasion resistance vs. colour difference criteria

The latter Pareto curve is strongly nonlinear and includes rapid growth, i.e., it is suitable for the selection of the final solution. In the current study, the final optimal solution for the whole optimization problem is selected from Fig. 10, since the relation of strength versus colour difference relation does not give clear preferences (near linear behaviour). The detailed values of the design variables, objective functions, etc. are given in the results section. Alternatively, the simplest approach available for solving the posed MDO problem is to combine all three non-conflicting mechanical criteria into one by use of the weighted summation technique and then apply the Pareto concept to the combined and colour difference criteria. This approach is not used in the current study since combining strength criteria with abrasion resistance leads to the loss of direct practical meaning of this combined criterion. As a result, it is complicated to select the final optimal solution in the Pareto front. Additionally, specifying the weights for combining two strength and abrasion resistance criteria is not straightforward.

Due to different datasets available for strength and abrasion resistance criteria (strength measurements failed for fabrics that were treated with the laser power of 18 W), the strength and abrasion resistance criteria were not combined. These criteria have also different meaning. Two Pareto fronts were composed (depicted in Fig. 9 and Fig. 10). First, for the combined strength and colour difference criteria and second, for the abrasion resistance and colour difference criteria. The first Pareto front does not provide a clear preference for the selection final optimal solution since near linear behaviour was observed between the combined strength and the colour difference criteria (Fig. 9). Multicriteria optimization is performed by combining multicriteria genetic algorithm with ANN and HOHWM models. The final optimal solution was determined from the Pareto front given in Fig. 10 as a point before the rapid growth of the colour difference function. Based on the non-dimensional values of the objective functions in the selected point on the Pareto front, the original values of the laser treating parameters and objectives functions can be calculated (determined from normalization Eq. 4 and Eq. 5). The rounded values obtained are: laser power 16 W; the speed of the laser cutter head 350 mm/s; colour difference 20; abrasion resistance 24016 rubs; tear force in the warp direction 51 N; tear force in the weft direction 23 N. These results were obtained on the limited experimental data currently available.

4. CONCLUSIONS

Multicomponent denim fabric was laser treated at different laser beam power and the speed of the laser cutter head to assess the influence of laser treatment on the fabric strength and appearance properties. Tested fabric warp yarn was made of cotton fibre, weft yarn contained elastane, viscose, and polyester at the core; cotton was used as the sheath fibre. Based on the test results, the mathematical models for four optimality criteria were developed. The multicriteria design optimization problem was formulated and solved by combining the weighted summation technique and the Pareto concept, also multicriteria genetic algorithms.

According to the physico-mechanical tests and matemathical modelling two combinations of optimum laser treating parameters were determined that provided optimum durability properties. The speed of the laser cutter head of 350 mm/s with the laser power of 16 W. Also, the combination of the speed 230 mm/s with the power 14 W.

Novelty of the current study is mainly related with HOHWM based model development. The HOHWM was introduced by workgroup for solving differential equations in 2018 and for function approximation in 2020 [33].

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Appendix 3

Paper III
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MATERIAL SCIENCE

Impact of laser fading on physico-mechanical properties and fibre morphology of multicomponent denim fabrics

Nele Mandre[a*], Tiia Plamus[a], Angelika Linder[a], Andres Krumme[a] and Anti Rohumaa[a,b]

[a] Department of Materials and Environmental Technology, Tallinn University of Technology, Ehitajate tee 5, 12616 Tallinn, Estonia
[b] Fiber Laboratory, South-Eastern Finland University of Applied Sciences, 57200 Savonlinna, Finland

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Abstract. Laser fading technology is used to give a unique worn look to a fabric. This finishing technique is environmentally friendly compared to conventional methods because it reduces the use of harmful chemicals and large amounts of water. A carbon dioxide (CO_2) laser with a wavelength of 10.6 µm was used in this study. In bulk production, fixed manufacturing parameters help to reduce production preparation time. Thus, two combinations of laser power and speed of the laser cutter head (14 W and 230 mm/s; 16 W and 350 mm/s) were used to determine how universal the fixed laser parameters are for fading five different types of multicomponent twill and satin weave denim fabrics, which contain cotton, elastane, polyester and viscose. Physico-mechanical properties (tear, tensile properties and abrasion resistance) were tested to evaluate the effect of the selected laser parameters on fabric strength properties. Microscopical analysis was performed to assess the effect of laser fading on the yarn and fibre morphology of denim fabrics.

Keywords: laser fading, sustainable finishing, multicomponent denim fabric, SEM analysis, physico-mechanical properties.

INTRODUCTION

Denim is defined as a 3/1 twill weave cotton fabric made of indigo dyed warp yarns and white filling yarns. Nowadays denim is made of different weave types and the cotton fibre is blended with other fibres to improve fabric properties [1]. The finishing of denim products is an important part of the manufacturing process because it influences the visual appearance and durability of denim fabric. In the 1980s, the denim company Diesel was considered one of the first producers who started to apply the fading effect on garments to make the products attractive to consumers [2].

Many mechanical and chemical finishing techniques are available, such as stone washing, enzyme washing, acid washing, bleaching, sandblasting, mechanical damaging. The growing awareness of today's society about the environmental issues caused by the textile industry makes the industry find new sustainable solutions as well as reduce production time, labour and process costs. Laser fading technology was introduced as a sustainable alternative for the fading of denim garments compared to conventional methods. The laser enables the application of different effects on garment by changing the speed of the laser cutter head, laser power and the size of the focal point. The laser has many advantages over the other processes mentioned. Laser fading technology is eco-friendly because it enables to create various effects on denim garments without using large amounts of water. It is chemical-free, without causing hazards to the workers and has a minimum impact on the environment. Also, it is almost waste-free. In addition, the laser process is precise, easy to control and has high productivity, since it is faster than conventional washing technologies. Laser

* Corresponding author, nele.mandre@denimdream.ee

fading is suitable for mass production because it enables the application of the exact same design for bulk production [3,4,5,6].

Lasers are commonly classified into three types: carbon dioxide (CO_2), neodymium (Nd), and neodymium-doped yttrium aluminium garnet (Nd-YAG) lasers. In the denim industry, a CO_2 laser is considered the most suitable laser for garment colour fading because of lower heat generation, which means lower energy waste and lower investment costs compared to the other lasers [3,7].

Unfortunately, different mechanical and chemical finishing processes, including laser fading, reduce fabric durability. During the laser fading process, the material absorbs laser energy, resulting in dye evaporation. This process affects fabric durability, thickness and other properties [3,5].

In previous studies, various laser parameters have been varied to assess the impact of laser irritation on the physico-mechanical properties of denim fabric. All these studies have shown that the durability of denim fabric decreases with the increase in intensity of different laser parameters. Tarhan and Sariişik [8] examined the effect of laser fading, sandblasting and washing on the tensile properties, weight loss and colour changes of 100% cotton denim fabric. After laser treatment at the highest intensity (250 W/cm^2), the fabric lost about 11% of its weight and about 60% of its strength. In their study, the colour loss increased from approximately 10 to 35% when laser intensity was increased from 100 W/cm^2 to 250 W/cm^2.

Sakib et al. [9] reported that the intensity of fabric fading depends on customers' requirements. However, they found that tensile and tear strength of the fabric decreased more in the warp than in the weft direction. This is because in twill weave, the warp yarns of the fabric are more dominant on the right side of the fabric. Kan [10] treated 100% cotton denim fabrics with a CO_2 laser by varying laser pixel and resolution time. Higher resolution and longer pixel time increased laser power. This resulted in removing more dye from the denim surface, but it also damaged the fabric structure. The optimum laser power was found to be 13 W/cm^2. According to Juciene et al. [11], laser speed, energy and beam density have the greatest impact on the tensile properties of denim fabric. They showed that the highest laser energy density ($E = 9.89$ mJ/cm^2) decreased the strength of cotton-elastane denim fabrics by approximately 91% and the lowest density ($E = 6.18$ mJ/cm^2) reduced the fabric strength by about 22%. Studies by Štěpánková et al. [12] showed, after testing dyed and undyed cotton fabrics, that dye appears to protect cotton yarns from infrared laser light. They applied two laser fluencies to cotton fabrics (7.8 mJ/cm^2 and 15.5 mJ/cm^2). The strength decreased more in the warp than in the weft direction. The undyed cotton fabric lost its strength at higher laser fluency by 100% and the dyed cotton fabric by 71% in the warp direction.

Laser fading technology is used for burning the surface of denim fabric. The energy generated by the laser beam, and absorbed as heat, leads to dye removal and a lighter shade on the fabric surface. The laser creates a beam in a very narrow area. Thus, laser fading technology enables material fading in a certain area where the beam impacts the fabric. The final visual appearance of denim fabric depends not only on the intensity of a laser beam, but also on the fibre content, weave type and colour [3]. A Scanning Electron Microscope (SEM) enables us to observe the laser fading effect on fibre morphology. The results of Hung et al. [13] showed that yarn damage in the fabric increased at higher laser processing variables. The intense beam created by the laser caused dehydration of cotton fibres, which led to the creation of pores on the cotton surface, and the fibre surface was peeled off. This resulted in a sponge-like structure and fibre degradation. It was also noted that higher laser irritation affected not only the fibre surface but caused pores to be formed inside the fibre. Due to the thermoplastic nature of polyester fibres, the heat generated by the laser beam melted the polyester fibre so that individual yarns were less apparent. Laser irritation created grain shapes on the fibre ends, which coagulated into tiny polyester grains. Resolidified polyester covered the pores in the fabric and on the cotton fibre surface.

According to the previous research, there are no distinct optimized laser parameters for the surface treatment of denim fabric. It mostly depends on the final appearance desired. However, for bulk production, certain tested parameters help to reduce laser adjustment time, increasing the efficiency of the manufacturing process. In the current study, two kinds of power and speed of the laser cutter head were applied to three different denim fabrics containing different ratios of cotton, elastane, viscose, and polyester. Fibre composition was selected based on the authors' previous research. The fibre content chosen provides durability and comfort for everyday wear. The aim was to determine whether laser parameters can be fixed for bulk production when denim fabrics are processed with different weave constructions and contain different ratios of the same fibres. To achieve the aim of the study, the effect of laser fading on physico-mechanical properties (abrasion resistance, tensile and tear properties) of denim fabrics was analysed.

In addition, the influence of laser fading on fibre morphology was observed by using the SEM to determine how laser power and speed of the laser cutter head affect multicomponent denim fabric. Two fabrics were satin weaves and one fabric was twill weave. Another purpose of this study was to determine how universal the selected fixed laser parameters are for fading multicomponent denim fabrics containing the same fibres but in different ratios.

MATERIALS AND METHODS

Materials

Three indigo dyed denim fabrics were used in this study. The fabrics were woven in the Diraga Home Textiles Ideas & Concepts Private Limited Company, India. The warp yarn was made of 100% cotton. The weft yarn contained different ratios of viscose, elastane and polyester at the core and were covered with cotton fibres. The structural parameters of the used fabrics are given in Table 1.

Methods

Before testing, all the samples were conditioned at a temperature of 20 ± 2 °C and relative humidity of 65 ± 4% in accordance with the standard EN ISO 139:2005/A1:2011 [14]. In addition, the actual number of yarns per unit length was calculated based on EN ISO 1049-2:2000 [15], using Method A indicated in this standard. Five specimens were cut from the warp and five from the weft direction. Two dissecting needles were used to count the number of threads per centimetre. The mean value of each individual test result was quoted.

A CO_2 laser Bodor BLC-1309XU with a wavelength of 10.6 μm was used for fading denim fabrics. The distance of the laser head from the denim fabric was 8 mm. The radius of the laser spot was 0.1 mm. The variable laser parameters were power (W) and speed of the laser cutter head (mm/s). Laser beams with two types of power (14 W and 16 W) and speed (230 mm/s and 350 mm/s) were applied to three denim fabrics.

A Martindale abrasion tester James Heal 1605 was used to test abrasion resistance. The fabrics were tested in accordance with EN ISO 12947-2:2016 [16]. The test specimen diameter was 38 mm and the abradant material diameter was 140 mm. The abrasion test was continued on individual test specimens until all specimens reached the specified end-point/breakdown. According to the standard EN ISO 12947-2:2016, the quoted result is defined as the lowest individual test result of all the test specimens tested. Damaged and broken yarns were examined by using a Dino-Lite Digital Microscope AM4113T and Dino Capture 2.0 computer software.

Tear properties were tested according to EN ISO 13937-2:2000 [17]. Five specimens were cut from the warp and five from the weft direction with the measurements of 50 × 200 mm^2. Tear force was measured on an Instron 5866 tensile testing machine and BlueHill software was used to record the test results. The gauge length of the testing machine was set to 100 mm and pulled apart at a constant test speed of 100 mm/min. A load cell with a maximum capacity of 500 N was used to test the tear resistance of denim fabric.

Tensile properties were evaluated in accordance with the ISO standard 13934-1:2013 [18]. The tensile properties were expressed in terms of force at rupture. To test the tensile properties, five test specimens were cut from the warp and weft directions with the measurements of 50 × 400 mm. The gauge length of the Instron 5866 tensile testing machine was set to 200 mm and the extension rate was 100 mm/min. The pretension was set at 5 N and a load cell with a maximum capacity of 10 000 N was used [18,19].

Table 1. Structural parameters of the denim fabrics

No.	Fabric name	Weave	No. of threads per cm		Mass per unit area g/m^2	Composition %
			Warp	Weft		
1.	KG 4930 Fabric 1	4/1 Satin	55.5	23	318	67.7% CO 20% PES 10.5% CV 1.8% EL
2.	KG 5264 Fabric 2	4/1 Satin	53	18	347	75% CO 19% PES 4.5% CV 1.5% EL
3.	KG 5716 Fabric 3	3/1 Twill	35	22	340	75% CO 13.5% PES 9.5% CV 2% EL

CO – cotton, PES – polyester, CV – viscose, EL – elastane

A SEM TMI-1000 was used to examine the morphology of the yarn and fabric (1000x magnification) before and after the laser fading process. In the SEM analysis, the fibres were attached to the specimen stub by using a double-sided conductive tape 16073 (Ted Pella Inc.), 8 mm W × 20 m L, prior to SEM examination.

The significance of the differences between the means of the different fabrics was evaluated by the Analysis of Variance (ANOVA). The differences amongst means were compared and segregated by Tukey's test (P\0.05).

RESULTS AND DISCUSSION

Laser faded fabrics were first compared with raw denim to understand the impact of laser treatment on the denim fabrics. Then laser treated fabrics were compared with each other and suitable laser parameter combinations were found.

Abrasion resistance

The results of the abrasion resistance test are shown in Fig. 1. It can be seen that the laser fading process decreased abrasion resistance drastically. The abrasion resistance of twill weave raw fabric (Fabric 3) was 67% higher than that of satin weave Fabric 1 and 73% higher than the abrasion resistance of satin weave Fabric 2. The resistance of laser faded twill of Fabric 3 to abrasion decreased by 53% (decreased by 40 000 rubs and the abrasion resistance was 35 000 rubs) compared to the untreated denim fabric. Figure 2 shows the effect of laser fading on fibre morphology. The damage to the warp and weft yarns of Fabric 3 after laser treatment (14 W and 230 mm/s; 16 W and 350mm/s) was analysed by the SEM. It can be observed that in both power and speed combinations, the warp yarns were severely damaged by the laser beam. Pores were formed on cotton fibres. It is consistent with the findings of Kan et al. [20], Hung et al. [13], Montazer et al. [21]. They have stated that higher laser processing variables, such as laser resolution and pixel time or laser power, increased the number of pores, resulting in higher yarn damage. However, Table 2 demonstrates that by using higher power at a higher speed or lower power at a lower speed, the amount of yarn damage is similar. Broken and melted fibre tips can be observed for weft yarns that contain synthetic fibres.

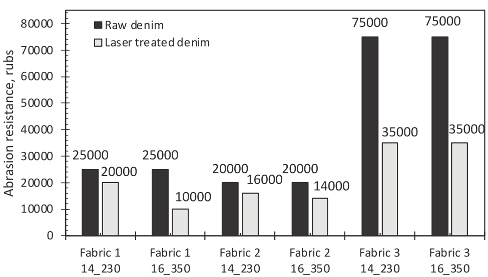


Fig. 1. Comparison of abrasion resistance of raw and laser faded denim fabrics.

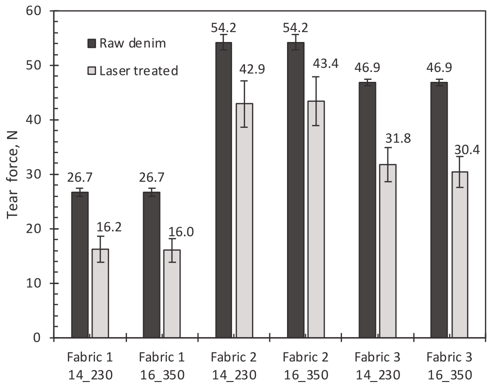
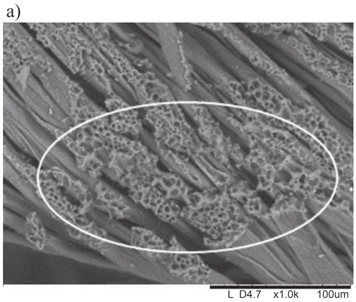
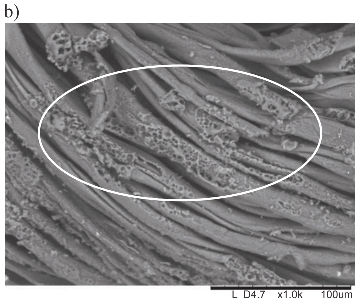
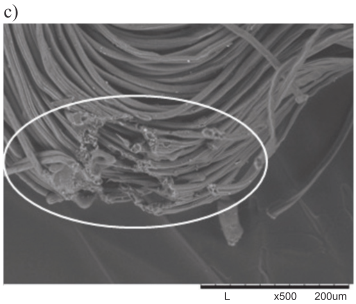
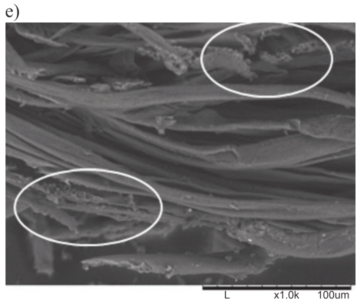


Fig. 2. Comparison of tear properties of raw and laser faded denim fabrics.

The speed of the laser cutter head and the difference in power intensity had a minor effect on fabric durability because for twill weave fabrics faded at different parameters (14 W and 230 mm/s; 16 W and 350 mm/s), the abrasion resistance was the same – 35 000 rubs. The abrasion resistance of laser faded Fabric 2 decreased by 20% (at 14 W and 230 mm/s, the abrasion resistance was 16 000 rubs) and 30% (at 16 W and 350 mm/s, the abrasion resistance was 14 000 rubs) compared to raw denim. The largest difference was observed for Fabric 1. The abrasion resistance decreased by 20% (at 14 W and 230 mm/s, the abrasion resistance was 20 000 rubs) and 60% (at 16 W and 350 mm/s, the abrasion resistance was 10 000 rubs). It can be observed from Fig. 1 that laser fading has intensively damaged cotton fibres in warp yarns. It is because of the weave construction. Warp yarns are more dominant than weft yarns and the laser beam damaged the fabric surface. Twill weave is more tightly woven than satin weave. Arora [22] has found that a higher number of interlacing points and a low number of floats are more durable and resistant to abrasion. In contrast, fabrics woven with longer floats are more prone to abrasion and can cause snagging, which affects negatively the visual appearance of fabric. This might be

Table 2. SEM images of fibre morphology of Fabric 1 and Fabric 3

	Laser fading parameters: 14 W and 230 mm/s	Laser fading parameters: 16 W and 350 mm/s
Fabric 3. Warp yarn (cotton fibres)	a) 	b) 
Fabric 3. Weft yarn (polyester, viscose, elastane)	c) 	d) 
Fabric 1. Warp yarn (cotton fibres)		e) 

the reason why twill fabrics have shown higher test results than satin weave fabrics [22,23].

According to the standard EN ISO 12947-2:2016 [16], abrasion resistance is defined as the lowest individual test result of all the test specimens tested in a certain group.

Denim fabric is mainly used for the production of jeans. For this reason, minimum requirements were established by the Public Waste Agency of Flanders (OVAM) for trousers – abrasion resistance should be at least 20 000 rubs. However, in the current study, the test results showed that after laser fading at both laser parameter combinations (14 W and 230 mm/s; 16 W and 350 mm/s), Fabric 1 and Fabric 2 made of satin weave are not suitable for garment production because this weave construction does not meet the established minimum requirements. Laser parameters cannot be fixed for satin weave denim. Denim garments should be made of twill weave, as it is more resistant to abrasion [24].

Tear strength

Tear force was recorded in the weft direction where the warp yarns were torn. All the warp yarns of the tested fabrics were made of cotton. In the warp direction where weft yarns were torn, the test results could not be recorded because the specimen broke before the test ended. The reason is that the cotton yarns were much weaker than the yarn used in the opposite direction. A yarn shift occurred and the fabric did not tear along the direction of the force applied.

The tear properties test in the weft direction showed that the tear force of laser faded Fabric 1 decreased compared with untreated denim by 39.3% (14 W and 230 mm/s) and 39.9% (16 W and 350 mm/s). The tear force of Fabric 2 decreased by 20.9% (14 W and 230 mm/s) and 20.1% (16 W and 350 mm/s). The tear force of Fabric 3 decreased by 32.2% (14 W and 230 mm/s) and 35.1% (16 W and 350 mm/s). Fabric 2 showed the highest test results. Weave construction and the number of yarns per centimetre affected the tear properties of fabric. Satin weave has fewer interlacings than twill weave. Loose construction allows yarns' mobility and decreases friction between yarns; as a result, yarns move and group together. This leads to higher tear properties. Fabric 1 was also made of satin weave but showed the lowest tear force values. This is due to the higher number of threads per centimetre. Yarn's linear density is another factor that might have reduced the tear properties of Fabric 1 because it contained a higher ratio of synthetic (polyester and elastane) fibres than the other tested fabrics. The strength of the weft yarn influenced the tear properties of the warp yarn. The same effect was observed by Eryuruk et al. [25], Triki et al. [26], Dhamija and Chopra [27] in their studies.

It was also noticed that although different laser power and speeds of the laser cutter head were applied to the denim fabrics, the test results were the same. Figure 2 showed that the results of the satin weave fabrics laser faded at 14 W and 230 mm/s were the same as treated at 16 W and 350 mm/s. In addition, all fabrics showed a similar trend of the loss of tear properties. The satin weave fabrics lost 11 N of their strength after laser fading compared with raw denim. Fabric 3 lost 15 N (14 W and 230 mm/s) and 17 N (16 W and 350 mm/s). It can be concluded that differences in laser power and speed of the laser cutter head had no statistically significant effect on the tear properties of the fabric. Both laser parameter combinations (14 W and 230 mm/s; 16 W and 350 mm/s) were suitable for testing the fabrics because the fabrics met the minimum OVAM requirements and their tear properties were higher than 15 N.

Tensile properties

Tensile properties were expressed in terms of force at rupture. All the tested raw and laser faded fabrics had a higher value of force at rupture in the warp than in the weft direction (Fig. 3). It is related to weaving of a fabric. During weaving, warp yarns are under higher tension compared to weft yarns. Thus, by increasing the tension of warp yarns, the crimp decreases. As a result, it increases the strength of the warp yarn as well as the crimp of the weft yarn. After laser fading, the high standard deviation of denim fabrics is caused by non-uniform fading applied to a fabric [28–30].

The tensile force at rupture of warp yarns was significantly decreased by laser fading for all fabrics (Fig. 3). However, laser fading did not affect the tensile properties of weft yarns, except for Fabric 3, where the laser fading had a statistically significant effect on the tensile properties of the weft yarns. This can be explained by weave construction. Fabric 1 and Fabric 2 were made of satin weave, Fabric 3 was made of twill weave. In both weave constructions, warp yarns are more dominant on the right side of the fabric and the laser beam burnt more warp than weft yarns. Also, satin weave fabrics tend to have lower tensile properties because of lower interlacing points and longer floats than in twill weave. Similar results were reported by Asaduzzaman et al. [31] and Ozguney et al. [32]. For this reason, twill weave fabric showed higher values of tensile force at rupture than satin weave in the warp direction.

Higher tensile force at rupture was shown for satin weave fabric in the weft direction. The highest value of tensile force of raw denim at rupture was shown by Fabric 1, 800 ± 38 N, but after laser fading, the tensile properties decreased by 19% for both fading combinations: 648 ± 177 N (14 W and 230 mm/s), 646 ± 142 N (16 W and 350 mm/s). Satin weave Fabric 2 had slightly

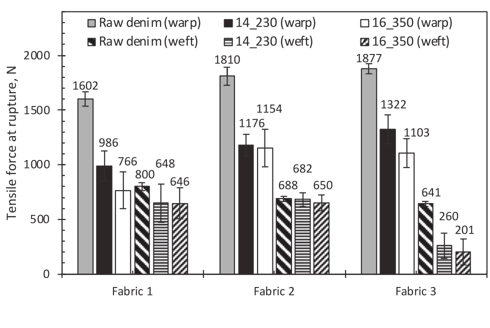


Fig. 3. Comparison of tensile force of raw denim and laser faded fabrics at rupture.

higher tensile force at rupture after laser fading than Fabric 1: 682 ± 62 N (14 W and 230 mm/s), 650 ± 74 N (16 W and 350 mm/s). However, for both fabrics (Fabric 1 and Fabric 2), according to the statistical analysis, the tensile force at rupture was not significantly different. Fabric 3 showed the lowest tensile test results in the weft direction. The tensile force of raw denim at rupture was 641 ± 21 N, which was 6.8% lower than that of Fabric 2 and 19.9% lower than the tensile properties of Fabric 1 in the weft direction. Moreover, all the raw fabrics had statistically different results in the weft direction. Unlike Fabric 1 and Fabric 2, the tensile properties of Fabric 3 decreased remarkably after laser fading. Laser fading at 14 W and 230 mm/s showed a 59.4% decrease and laser fading at 16 W and 350 mm/s showed a 68.6% decrease in the tensile properties of the same fabric compared with raw denim fabric. According to the literature, during the laser fading process, a fabric absorbs thermal energy. It increases the internal volume of the fibre, resulting in expansion and swelling of the fibre and a sponge-like structure forms. In the current study, the SEM analyses revealed pores on the fibre surface. Degradation of the weft yarn was clearly visible after laser fading (Table 2). The weft yarns were broken and melted, grain shapes were formed on the fibre ends. According to the OVAM minimum requirements, the maximum force for clothing should be 250 N. Unfortunately, laser fading of Fabric 3 at the power of 16 W and the speed of 350 mm/s was 201 N, which was below the minimum. This might be because the other fabrics contained a higher ratio of polyester. The laser parameters of 14 W and 230 mm/s were suitable for use for all tested fabrics, but the power of 16 W and the speed of 350 mm/s should be tested before garment production. The reason is that the type of fabric construction and the fibre ratio in the fabric may decrease tensile force at rupture in a different way.

CONCLUSIONS

Resulting from the physico-mechanical testing, it can be concluded that laser fading affected warp yarns more than weft yarns because warp yarns are more dominant on the right side of fabric. Twill weave Fabric 3 of raw denim showed 67% higher abrasion than Fabric 1 and 73% higher than that of Fabric 2. Laser fading decreased the abrasion resistance of Fabric 3 by 53%. Also, laser fading at the parameters of 14 W and 230 mm/s, and 16 W and 350 mm/s decreased the tear properties of Fabric 1 the most (41%). The SEM analyses showed that the laser beam degraded yarns in denim fabric. It generated pores on the cellulosic fibre surface and melted synthetic fibres. The abrasion test showed that twill weave fabric has high abrasion resistance and is suitable for garment production; after laser fading, the tensile properties of Fabric 3 decreased drastically. To increase the tensile properties, the polyester ratio of Fabric 3 could be increased, as in the other tested fabrics. However, further research is needed to find out how much the polyester ratio could be increased. The tear properties of all tested fabrics met the minimum requirements. It can be concluded that the laser parameters of 14 W and 230 mm/s, 16 W and 350 mm/s are more suitable for twill weave fabrics, as generally the test results of twill fabrics showed higher durability than these of satin weave fabrics. Furthermore, the construction type and minor changes in the fibre ratio of fabric can have a major influence on durability properties. For this reason, it is recommended that laser parameters should be tested before garment production.

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Laserkulutuse mõju teksakangaste füüsikalis-mehaanilistele omadustele ja mitmekomponentsete teksakangaste kiumorfoloogia

Nele Mandre, Tiia Plamus, Angelika Linder, Andres Krumme ja Anti Rohumaa

Teksatoodetele esteetilise välimuse andmiseks kangaid viimistletakse, mis sageli on küllaltki keskkonda koormav protsess. Seevastu laserkulutust käsitletakse säästva alternatiivina teksakangast valmistatud rõivaste viimistlemiseks. Selleks pole tarvis ei vett ega kemikaale. Laserkulutuse protsess on täpne ja kergesti kontrollitav, sobilik masstootmise jaoks, vähendades aja ja tööjõu kulusid.

Uuringu eesmärk on leida, kui universaalsed on neljakomponentse kiulise koostisega (puuvill, polüester, viskoos ja elastaan) teksakanga jaoks välja töötatud laserviimistluse meetodid. Uuriti teksakangaste füüsikalis-mehaanilisi omadusi enne ja pärast kulutamist ning analüüsiti kiu morfoloogiat lasertöötluse järel. Töös kasutati kaht laserkulutuse parameetrite komplekti, mis valiti varasemate autorite poolt läbiviidud uuringutest – laseri võimsus ja lõikepea kiirus (võimsus 14 W koos laserlõikepea kiirusega 230 mm/s ja 16 W koos kiirusega 350 mm/s).

Selles töös kasutati kolme teksakangast, mille kõigi lõimelõngad olid valmistatud 100% puuvillast ja koelõngad sisaldasid nii polüestrit, viskoosi kui ka elastaani. (Kangas 1 ja Kangas 2 olid atlass-sidusega, Kangas 3 toimse sidusega). Skaneeriva elektronmikroskoobi (SEM) analüüs näitas, et peale laserkulutust puuvilla kiud kahjustusid oluliselt ning kiudude pinnale tekkisid erineva suurusega poorid, sünteetilised kiud sulasid ning nende otsa tekkisid väikesed kerad. Ka füüsikalis-mehaaniliste testide tulemusel selgus, et hõõrdekindlus laserkulutatud kangastel vähenes oluliselt. Toimse sidusega toorkangal (Kangas 3) oli testituist kõrgeim hõõrdekindlus (75000 hõõret), mis peale laserkulutust vähenes 53%. See juhtus nii parameetrite 14 W, 230 mm/s kui ka 16 W, 350 mm/s kasutamisel. Koesuunas laserkulutatud kangaste rebimistugevus vähenes mõlemal atlass-sidusega kangal üsna sarnaselt: 11 N (Kangas 1 ja Kangas 2) ning Kangas 3 puhul vastavalt 15 N (14 W, 230 mm/s) ja 17 N (16 W, 350 mm/s). Kangas 2 oli vastupidavam tänu oma konstruktsioonile, sest lõdvema sidusega kootud tekstiili puhul on lõngadel võimalik jõu rakendamise ajal liikuda ja grupeeruda, mille tulemuseks on suurem rebimistugevus. Tõmbetugevuse vähenemine rohkem lõime kui koe suunas oli tingitud samuti kanga sidusest, sest lõimelõngad on kanga paremal poolel domineerivad.

Katsetulemuste ja SEM analüüsi põhjal võib väita, et toimse sidusega teksakanga tugevusomadused olid kõrgemad kui atlass-sidusega variandil. Uurimustöös jõuti järeldusele, et siduse ja kiulise koostise suhe mõjutab kanga tugevusomadusi, mistõttu tuleks laseri parameetreid enne tootmist katsetada testkangal.

Curriculum vitae

Personal data

Name:	Nele Mandre
Date of birth:	20.03.1990
Place of birth:	Harju Country, Kiili Parish
Citizenship:	Estonian

Contact data

E-mail:	nele.mandre@mail.ee

Education

2018–2023	Tallinn University of Technology, Department of Materials and Environmental Technology, PhD
2015–2017	Tallinn University of Technology, Technology of Wood, Plastics, and Textiles (specialisation: Technology of Plastics and Textiles, cum laude), Master's degree
2009–2013	Tallinn University of Applied Sciences, Technical Design and Technology (specialisation: Technical Design), Diploma, 4-year study
1997–2009	Kiili Gymnasium, high school education

Language competence

Estonian	Native speaker
English	Fluent

Professional employment

02.09.2019–…	Tallinn University of Technology, Lecturer
12.01.2015–…	Põldma Kaubanduse AS, Chief Patternmaker/CAD Engineer and Team Leader in Product Development Department
23.08.2013–31.12.2014	Calibrato OÜ, Patternmaker/CAD Engineer
18.02–18.03.2013	Baltic Intertex, Product Development Trainee
14.05–14.08.2012	Pumpkin Design Oy in Helsingi, Product Development Trainee
25.07–12.08.2011	BonBon Lingerie, Product Development Trainee
17.05–17.06.2011	Pohjanheimo Fashion House, Product Development Trainee

Defended thesis

Master's thesis: "Development of denim collection inspired by 50's and 60's fashion", Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology
Supervisors: Engineer Kersti Merimaa and Senior Lecturer Tiia Plamus

Supervised dissertations:

Angelika Linder, Bachelor's degree, 2020, (sup) Nele Mandre and Kersti Merimaa, "Improving women figure measurement chart for Denim Dream brand", Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology

Angelika Linder, Master's degree, 2021, (sup) "Impact of laser fading on physico-mechanical properties and fibre morphology of denim fabrics", Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology

Franz Mathias Ints, Bachelor’s degree, 2022, (sup) Tiia Plamus, and Nele Mandre, “The effect of enzyme treatment on the properties of denim fabrics with different fibre content”, Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology

Gretel Brus, Bachelor’s degree, 2023, (sup) Tiia Plamus, and Nele Mandre, “Effect of fibre composition on physico-mechanical properties of denim fabric”, Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology

Elulookirjeldus

Isikuandmed

Nimi:	Nele Mandre
Sünniaeg:	20.03.1990
Sünnikoht:	Harjumaa, Kiili vald
Kodakondsus:	Eesti

Kontaktandmed

E-post:	nele.mandre@mail.ee

Hariduskäik

2018–2023	Tallinna Tehnikaülikool, Materjali- ja keskkonnatehnoloogia instituut, Doktorikraad
2015–2017	Tallinna Tehnikaülikool Puidu- ja plastitehnoloogia (spetsialiseerumine tekstiilitehnoloogiale, cum laude), Magistrikraad
2009–2013	Tallinna Tehnikakõrgkool Tehniline disain ja tehnoloogia (spetsialiseerumine tehnilisele disainile), Diplom, 4 aasta õpe
1997–2009	Kiili, Gümnaasium, keskharidus

Keelteoskus

Eesti Keel	Emakeel
Inglise keel	Kõrgtase

Teenistuskäik

02.09.2019–…	Tallinna Tehnikaülikool, lektor
12.01.2015–…	Põldma Kaubanduse AS, Peakonstruktor/CAD insener ja Tootearenduse osakonna osakonnajuhataja
23.08.2013–31.12.2014	Calibrato OÜ, Konstruktor/CAD insener
18.02–18.03.2013	Baltic Intertex, Tootearenduses praktikant
14.05–14.08.2012	Pumpkin Design Oy Helsingis, Tootearenduses praktikant
25.07–12.08.2011	BonBon Lingerie, Tootearenduses praktikant
17.05–17.06.2011	Pohjanheimo Moemaja, Tootearenduses praktikant

Kaitstud lõputööd

Magisritöö "50-60ndate stiilist inspireeritud teksakollektsiooni mudelite väljatöötamine" Tallinna Tehnikaülikool, Inseneriteaduskond, Materjali- ja keskkonnatehnoloogia instituut

Juhendajad: Insener Kersti Merimaa, Vanemlektor Tiia Plamus

Juhendatud lõputööd:

Angelika Linder, Bakalaureusekraad, 2020, (juh) Nele Mandre, Kersti Merimaa, „Naisfiguuri mõõdutabeli parendamine Denim Dreami brändile", Tallinna Tehnikaülikool, Inseneriteaduskond, Materjali- ja keskkonnatehnoloogia instituut

Angelika Linder, Magistrikraad, 2022, (juh) Tiia Plamus, Nele Mandre, „Laserviimistluse mõju teksakangaste füüsikalis-mehaanilistele omadustele ja kiu morfoloogiale", Tallinna Tehnikaülikool, Inseneriteaduskond, Materjali- ja keskkonnatehnoloogia instituut

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Gretel Brus, Bakalaureusekraad, 2023, (juh) Tiia Plamus, Nele Mandre, „Kiulise koostise mõju teksakanga füüsikalis-mehaanilistele omadustele“, Tallinna Tehnikaülikool, Inseneriteaduskond, Materjali- ja keskkonnatehnoloogia instituut

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