TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

Durability of compression socks

Master thesis

Study programme: N3106 – Textile Engineering

Study branch: 3106T017 – Clothing and Textile Engineering

Author: **Bc. Radka Laurinová**

Supervisor: Ing. Adnan Ahmed Mazari, Ph.D.

Liberec 2019

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

Trvanlivost kompresních punčoch

Diplomová práce

Studijní program: N3106 – Textilní inženýrství

Studijní obor: 3106T017 – Oděvní a textilní technologie

Autor práce: **Bc. Radka Laurinová**

Vedoucí práce: Ing. Adnan Ahmed Mazari, Ph.D.

Liberec 2019

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

Zadání diplomové práce

Trvanlivost kompresních punčoch

Jméno a příjmení:	**Bc. Radka Laurinová**
Osobní číslo:	T16000475
Studijní program:	N3106 Textilní inženýrství
Studijní obor:	Oděvní a textilní technologie
Zadávající katedra:	Katedra oděvnictví
Akademický rok:	**2018/2019**

Zásady pro vypracování:

1. Proveďte rešerši zaměřenou na vlastnosti zdravotních punčoch z hlediska svěrného účinku na dolní končetiny lidského těla.
2. Na zdravotních punčochách v různých třídách komprese proveďte měření svěrného tlaku pomocí tlakových senzorů.
3. Otestujte trvanlivost zdravotních punčoch a analyzujte životnost a efektivitu po opakovaném použití.
4. Otestujte vlastnosti zdravotních punčoch po pracím procesu.
5. Analyzujte kompresní vlastnosti punčoch před a po použití.
6. Experimentální výsledky vyhodnoťte a formulujte závěry a doporučení pro další vývoj.

14.4.2019

Rozsah grafických prací:	dle rozsahu dokumentace
Rozsah pracovní zprávy:	cca 60 stran
Forma zpracování práce:	tištěná

Seznam odborné literatury:

- Flaud, P., Bassez, S., & COUNORD, J. (2010). Comparative in vitro study of three interface pressure sensors used to evaluate medical compression hosiery. Dermatologic Surgery, 36(12), 1930-1940.
- Harpa, R., Piroi, C., &DoruRadu, C. (2010). A New Approach for Testing Medical Stockings. Textile Research Journal, 80(8), 683-695 http://doi.org/10.1177/0040517509343781.
- Harpa, R., Piroi, C., &Radu, C. D. (2010). Textile Research Journal. http://doi.org/10.1177/0040517509343781.
- Hui, C. L., & Ng, S. F. (2001). Model to Predict Interfacial Pressures in Multilayer Elastic Fabric Tubes. Textile Research Journal, 71(8), 683-687. http://doi.org/10.1177/004051750107100806.
- Liu, R., Kwok, Y. L., Li, Y., Lao, T. T. H., Zhang, X., & Dai, X. Q. (2005). Objective evaluation of skin pressure distribution of graduated elastic compression stockings. Dermatologic Surgery, 31(6), 615-624.
- Macintyre, L., Baird, M., &Weedall, P. (2004). The study of pressure delivery for hypertrophic scar treatment. International Journal of Clothing Science and Technology, 16(1/2), 173-183.
- Maleki, H., Aghajani, M., Sadeghi, A. H., Asghar, A., &Jeddi, A. (2011). On the Pressure Behavior of Tubular Weft Knitted Fabrics Constructed from Textured Polyester Yarns, 6(2).

Vedoucí práce:	Ing. Adnan Ahmed Mazari, Ph.D. Katedra oděvnictví
Datum zadání práce:	14. prosince 2018
Předpokládaný termín odevzdání:	18. dubna 2019

Ing. Jana Drašarová, Ph.D.
děkanka

L. S.

Technická univerzita v Liberci

-9-

prof. Dr. Ing. Zdeněk Kůs
vedoucí katedry

V Liberci 14. prosince 2018

Prohlášení

Byla jsem seznámena s tím, že na mou diplomovou práci se plně vztahuje zákon č. 121/2000 Sb., o právu autorském, zejména § 60 – školní dílo.

Beru na vědomí, že Technická univerzita v Liberci (TUL) nezasahuje do mých autorských práv užitím mé diplomové práce pro vnitřní potřebu TUL.

Užiji-li diplomovou práci nebo poskytnu-li licenci k jejímu využití, jsem si vědoma povinnosti informovat o této skutečnosti TUL; v tom- to případě má TUL právo ode mne požadovat úhradu nákladů, které vynaložila na vytvoření díla, až do jejich skutečné výše.

Diplomovou práci jsem vypracovala samostatně s použitím uvedené literatury a na základě konzultací s vedoucím mé diplomové práce a konzultantem.

Současně čestně prohlašuji, že texty tištěné verze práce a elektronické verze práce vložené do IS STAG se shodují.

18. 4. 2019

Bc. Radka Laurinová

Prohlášení

Byla jsem seznámena s tím, že na mou diplomovou práci se plně vztahuje zákon č. 121/2000 Sb., o právu autorském, zejména § 60 – školní dílo.

Beru na vědomí, že Technická univerzita v Liberci (TUL) nezasahuje do mých autorských práv užitím mé diplomové práce pro vnitřní potřebu TUL.

Užiji-li diplomovou práci nebo poskytnu-li licenci k jejímu využití, jsem si vědoma povinnosti informovat o této skutečnosti TUL; v tom- to případě má TUL právo ode mne požadovat úhradu nákladů, které vynaložila na vytvoření díla, až do jejich skutečné výše.

Diplomovou práci jsem vypracovala samostatně s použitím uvedené literatury a na základě konzultací s vedoucím mé diplomové práce a konzultantem.

Současně čestně prohlašuji, že texty tištěné verze práce a elektronické verze práce vložené do IS STAG se shodují.

18. 4. 2019 Bc. Radka Laurinová

ANNOTATION

The diploma thesis deals with measurement of compression pressure exerted by medical compression stockings and its durability. The first part is focused on description of mechanical properties of knitted fabrics, properties of compression hosiery used in compression therapy, methods for compression pressure measurement and briefly summarizes durability of knitted fabrics. The second part is focused on the pressure measurement, and the pressure variation during wearing with respect to the time. Then the effect of different types of washing on compression pressure exerted by stockings is analyzed.

KEY WORDS

Medical compression stockings, compression therapy, pressure durability, Kikuhime, washing process

ANOTACE

Tato diplomová práce se zaměřuje na měření tlaku vyvíjeného zdravotními kompresivními punčochami a jeho stálostí. První část práce je zaměřena na popis mechanických vlastností pletenin, vlastností punčochových výrobků používajících se pro kompresivní terapii, způsoby měření kompresivního tlaku a stručně shrnuje stálosti pletenin. Druhá část práce je zaměřena na samotné měření svěrného tlaku a jeho kolísáním během nošení. Dále je analyzován efekt různých způsobů praní na svěrný tlak vyvíjený punčochami.

KLÍČOVÁ SLOVA

Zdravotní kompresní punčochy, kompresivní terapie, trvanlivost tlaku, Kikuhime, prací cyklus

Content

List of symbols and abbreviations

cB	limb circumference at the narrowest point
CCL	compression class
CI	confidence interval
cm	centimeter
ČSN	Czech technical standards
D_{AHW}	dimensions after HW
D_{AWM1}	dimensions after WM1
D_{AWM2}	dimensions after WM2
D_{NW}	dimensions before washing
D_o	original dimensions
D_{R24}	dimensions after 24 hours of relaxation
D_{RO}	dimensions immediately after releasing tension
g	gram
HW	hand wash
kPa	kilopascal
m	meter
MCS	medical compression stockings
mmHg	millimeter of mercury
MST	medical stocking tester
N	Newton
NW	no washing

Pa	pascal
R	air permeability
SD	standard deviation
T	tension
WM1	washing in washing machine (30ºC, 38 min)
WM2	washing in washing machine (50ºC, 72 min)
ε	extensibility

Introduction

Although the benefits of compression therapy are known for centuries, only over the last few decades the utilization of compression products increased extensively, due to a large number of the population, especially in older age, suffering from a form of chronic venous disease. Nowadays medical compression stockings are widely used to treat various types of lymphatic and venous diseases, as a short-term treatment or as a maintenance treatment. They apply graduated pressure to the limbs to help improve venous return. A unit of this applied pressure and its variability during the use is a crucial factor for the efficacy of compression therapy. Due to this fact, measurement and knowledge of compression pressure durability are important to provide patients with the best possible treatment.

The first part of the master thesis is devoted to research related to the given topic and suitable for understanding the problematics. Therefore the general theory of knitted fabrics, their geometry, utility and mechanical properties are described here. The theoretical research is further focused on compression therapy, its benefits for blood circulation disorders and medical compression products used in this therapy. The main attention is paid to the medical compression stockings, their production and specification of major characteristics determining the behavior and working mechanism. The information about measurement of interface pressure exerted by compression stockings and commonly used devices are also provided. On the end, the research part deals with several factors influencing textile durability, mainly for knitted fabric and compression stockings.

Main factors significantly influencing the interface pressure of compression stockings is washing process and the frequency with time they are used. Aim of the thesis is to analyze these influences on compression pressure of different types of stockings. Because of the stockings should be subjected to washing process after each use, the experimental part deals with analysis of three different types of laundering on overall efficiency of compression stockings, including hand washing recommended by manufacturer and use of washing machine. In order to analyze the effect of long term wearing an experiment focused on measuring the interface pressure after application of compression stocking and its variation during 48 hours in the static mode was performed.In all, ten different types of commercially available medical compression stockings (MCS) were used to analyze. All medical compression stockings were from four various manufacturers (Aries, Maxis, Varitex and Sigvaris) and none of them was aware that their products were being tested. Tested stockings were also in three different compression classes, with different material composition, but all of them were made for the same size of leg circumference 23 cm.

1. Knitted Fabrics

Knitted fabrics are structures produced by inter-looping a single yarn or assembly of yarns. This complicated interlocked structure causes that knitted fabric can be highly extensible. Needle loops are the basic elements in knitted structure formed by interlocking new loops through the previously formed ones. Then a knitted fabric is created by continuous addition of new loops. If the new loop passes through the old one from the back to the face side, during loop formation, it is called a face loop or weft knitted loop. When the loop passes through the previous loop oppositely, from the face side to the back side, it is called a back loop or purl loop. Figure 1 shows face and back loop with its described parts. Two directions are distinguished in knitting, courses and wales: a course is defined as the row of knit loops while a wale is defined as the column of the loops. [1]

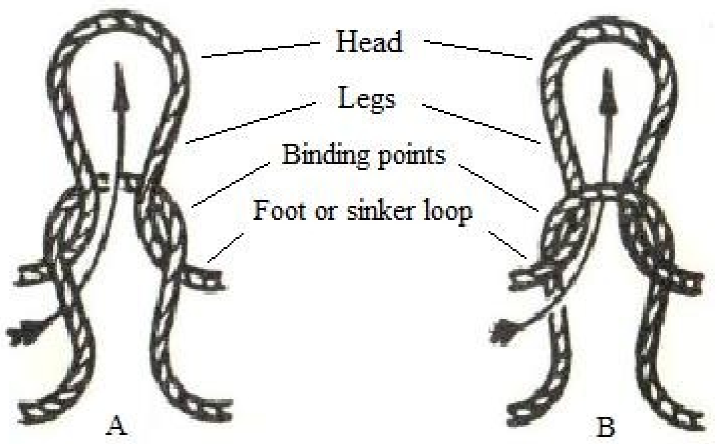

Figure1: Face loop (A), back loop (B)[1]

According the method of production, knitted fabrics are categorized as weft knitted fabrics and warp knitted fabrics:

Weft knitted fabrics

Weft knitted fabrics shown in the Figure 2 are constructed from a single yarn with the loops made horizontally from side to side across the width of the fabric. Besides the hand knitting, weft knitted fabrics can be made by flat bed knitting machines or as tubular fabrics on circular knitting machines. This type of knit is able to unravel very easily, when the yarn is broken. [1]

Depending on the interlacing, weft knitted fabric can be [2]:

- Single Jersey Knit Fabric - there are only face or back loops on the one side of fabric, this type of knit is used the most for hosiery
- Rib Stitch Knit Fabric - have stitches drawn to both sides of the fabric, which produces columns of face loops or columns of back loops
- Purl Knit Fabric - contains both, face and back loops in the same column
- Interlock Stitch Knit Fabric - variation of rib knit constructions, the front and back of interlock fabric are the same, looking like a Jersey knit

Warp knitted fabrics

Warp knitted fabrics, shown in Figure 2, are structures from vertical loops formed by one or more sets of warp. The principle is in forming a vertical loop in one course and then moving diagonally to the next wale to make a loop in the following course to connect the stitches. It means the yarns are zigzag along the all length of the fabric and each loop in the row has its own yarn. Those types of knitted fabric are difficult to unravel. [1]

Warp knitted fabrics are divided [30]:

- Trickot Knit Fabric - the front side of the fabric has vertical wales, and the back side has crosswise courses, mostly plain or have a simple geometric design
- Raschel Knit Fabric - produced from spun or filament yarns of different weights and types, characteristic is their intricate designs, the open-space look of crochet or lace

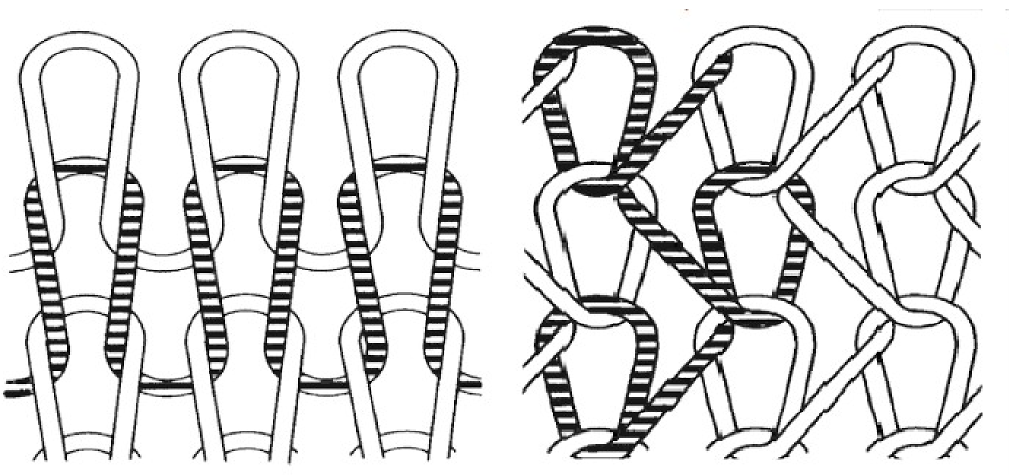

Figure 2: Weft knitted fabric (left), warp knitted fabric (right) [23]

Knitted fabrics can be further divided into subgroups according the used patterning. Apart from the basic knitted loop stitch, two most commonly produce stitches are the tuck stitch and the miss stitch (float stitch). Other patterning can be achieved by changing the yarn color in the courses or wales of the knit. [2]

1.1. Geometry of Knitted Fabrics

Normally, the basic geometry parameters of knits are determined although they do not have an importance for the final customer. These include an independent input parameters like loop length and yarn diameter affecting the values of output parameters. Output parameters are stitch density and the thickness of a knit. [3]

1.1.1. Stitch Density

Stitch density indicates the total number of loops in a measured area of fabric, usually 10 x 10 cm. The value of stitch density is obtained by counting the number of wales in 10 cm (SD_W) and the number of courses in 10 cm (SD_C). While the density of wales is dependent on the needle gauge (number of needles per unit of needle bed width) of the knitting machine, the density of courses depends on the length of loops. Therefore, knitted fabrics with different course density can be made on the same machine. According the fabric density the size of loops, strength and stiffness changed. Knitted fabric with low density is characterized with large loops and bad elasticity. On the other way, with increasing density decreases size of loop and knits are more toughness. Total number of needle loops (i.e. stitch density, SD) is calculated by the following equation [2]:

$$SD = SD_C * SD_W, \tag{1}$$

Where: SD = Stitch density [loops/10 cm^2]

SD_C = Course density [loops/10 cm]

SD_W = Wale density [loops/10 cm]

1.1.2. Loop Length

Loop length is a parameter influencing structure of knitted fabric and its financial cost for manufacturing (yarn consumption). It can be determined experimentally by unravelling the yarn from an already made knit or using a geometrical model. However, in the practice knitted loops are really often sloppy due to the several causes. The most serious of them is an influence of torsional moment (twist), the direction of knitting and the effect of strains that are imparted to the fabric when comes off the knitting machine. Since an each loop in real knitted fabric has its own complicated geometry, it is not easy to describe overall geometry of knitted fabrics. For these purposes, geometry models which are still very simplified are used. In the literature, a couple of geometrical models were proposed for knitted fabrics, mainly aiming at plain weft knitted fabrics. As a classic one can be considered the model from professor Dalidovič (Figure 3). This model is based on the assumption that diameter of yarn is static, feet and head parts of loop are defined as semicircles and loop legs as abscissas. [2], [3]

From the model results that loop length is [2]:

$$l = \pi \left(\frac{1}{2} w + d\right) + 2c \tag{2}$$

Where: l = loop length [mm]

d = yarn diameter [mm]

w = loop width (wale spacing) [mm]

c = loop height (course spacing) [mm]

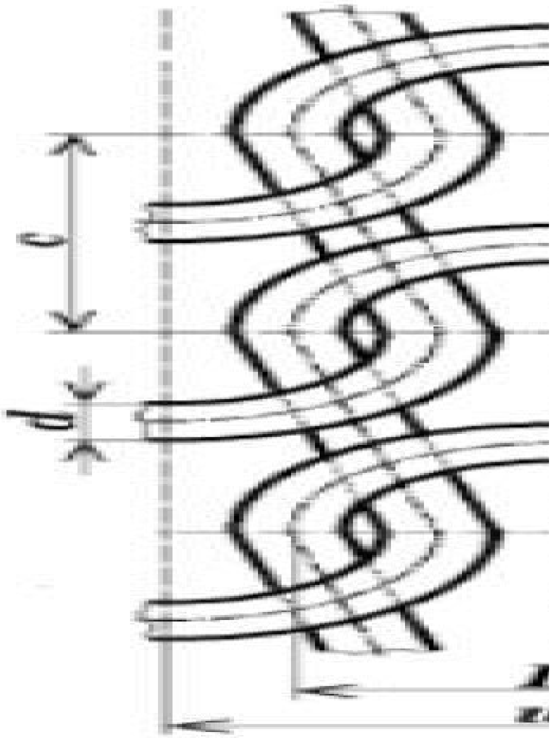

Figure 3: Dalidovič's geometry model [2]

1.2. Properties of Knitted Fabrics

Knitted fabrics are characterized by variety of features which are defined especially by the material used in manufacturing and a knit structure that includes shape and size of loops, linear density of yarns and the type of pattern. Due to the shapes of knitted loops, fabrics have a high extensibility and with their elasticity and softness provide the wearer with comfortable wearing and freedom in motion. Other favorable properties are air permeability, absorption and with certain thickness even good warmth, which is caused especially due to the porosity of knitted fabric. Individual fabric properties are analyzed by measurements performed according relevant standards so their properties can be compared and the utility value is determined. [1]

1.2.1. Utility Properties

Utility properties of knitted fabrics are important particularly for the final customer, because they are asserted in their using. Those properties may be divided as: durability, aesthetic properties and physiological properties.

Garments are normally stretched, scraped and exposed to impacts of heat, sweat, sun and many other influences in their use. Therefore, one of the most important properties is durability. It can be characterized as a resistance to damage and wear and tear. Durability is influenced by other properties of textiles, such as strength, extensibility or unravelling, understood as a spontaneous release of loops from knitted fabric, mostly caused by yarn breakage. [4]

Other important properties for customer are aesthetic properties of textiles, especially those which affect their appearance. These properties include drapeability or ability to resist creasing, in particular influenced by material composition. The appearance of textiles can be also unfavourably influenced by low snag resistance, when a yarn or part of a yarn is pulled or plucked from the surface usually by exposing to pointed or rough surfaces. [4]

Physiological properties of knitted garments, like air permeability and breathability, absorbent ability or thermal insulation, may be also found substantive for the customer. Those properties ensure comfortable wearing and all of them may have a high importance from the health point of view. Breathability is fabric ability to transmit moisture vapor through the material, while air permeability is the ability to allow air to pass through the material. Fabrics with high air permeability tend to have high moisture vapor transmission, but it is not necessary to be air permeable to be breathable. Factors such as density, structure and material are able to highly influence both of those properties. Other physiological properties are the absorbency, understood as the ability of a fabric to take in moisture, and thermal insulation, the reduction of heat transfer from colder object or environment to warmer ones and conversely. This ability is dependent on the amount of air in the knitted structure, material and also density. However thermal insulation is to the detriment of air permeability, with increasing thermal insulation decreases air permeability. [4]

1.2.2. Mechanical Properties of Knitted Fabrics

Mechanical properties of any materials are in general the physical properties which describes its behavior upon the application of external forces. In the practice types of stresses to which materials can be subjected occur mostly in a combination, but in laboratory are tested separately from each other, while standardized is just the tensile test. Mechanical stresses of garments from flat textiles are during wearing and using within small deformations. It means, rarely occurs such a huge mechanical stresses that would be able to cause the textile breakage. However knitted fabrics tend to the yarn move at binding points, due to their interlocked structure, therefore can be very easily deformed even with a low stress. [2], [6]

1.2.2.1. Deformation

Changes in dimensions, known as deformation, occur when a knitted fabric is exposed to a mechanical stress. This deformation depends on the amount of loading, speed and the duration length of loading.

Different types of stress [5]:

1. Tension
   - Uniaxial stress
   - Biaxial stress
2. Bending
   - Bending moment
   - Buckling
3. Shear stress
4. Compression

If a knitted fabric, with dimensions A_x and A_y, is exposed to just uniaxial tensile stress, both dimensions of knit will be changed. It means, if the dimension A_x will be extended by value Δ_x due to the tensile stress, a perpendicular dimension A_y is shorten by value Δ_y. The relative change in dimensions can be defined by the following formula [5]:

$$\varepsilon_X = \frac{A_x + \Delta_x}{A_x} \quad a\, \varepsilon_y = \frac{A_Y + \Delta_Y}{A_Y}$$

(3)

In the practice, technical and clothing textiles are very often exposed to a biaxial stresses, which means that the load acts on them in two directions. It happens already during knitting or wearing, most often at the knee or elbow area. In the case of steel and similar materials, Hook's Law can be used for calculation of deformation but textiles are for those calculations much more complicated because of the fact, not all textiles behave the same. A special case may be (with a certain tension) stretching a textile in one direction while the second one keeps its original dimensions. [5]

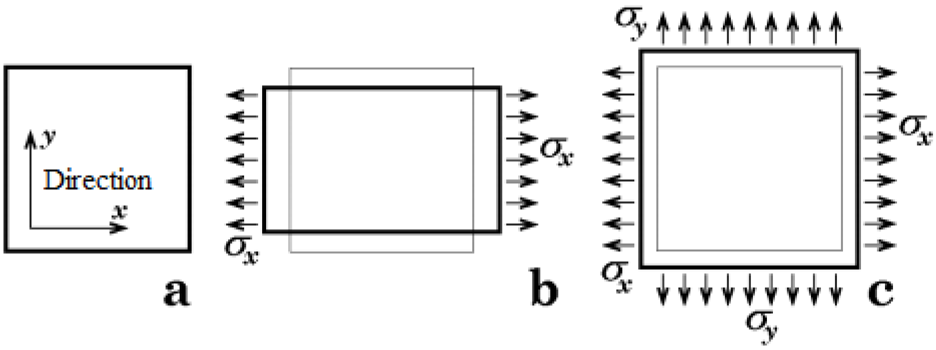

Figure 4: Forms of deformation (a, b – uniaxial stress, c – biaxial stress) [5]

1.2.2.2. Tensile Strength

Tensile strength can be expressed as the force necessary to break the measured specimen. In other words, it is an amount of tensile stress that the specimen of fabric can withstand before damage occurs. The unit of fabric breaking strength used for evaluating is Newton [N]. In normal practice, textiles made for clothing purposes are usually not exposed to such a high tensile force to cause the damage. It means strength does not have a crucial importance for those textiles, but in the case of technical textiles the tensile strength is important information to assess the quality. [4]

Model determination of strength is relatively easy, but there is one coefficient difficult to detect, that represents unevenness of yarn strength and textile structure. For calculation the force F_p [N] necessary to break the textile in the width of 1m may be used formula [5]:

$$F_p = SD_{C,W} \cdot F_N \cdot K_{VZ} \cdot K_{VP} \tag{4}$$

Where: $SD_{C,W}$ = stitch density of courses or wales, depending on the stress direction

F_N = yarn strength

K_{VZ} = structure coefficient, number of yarns in row or column participating in fabrics strength

K_{VP} = strength utilization coefficient (knitted fabrics usually $K_{VP}<1$)

Strength of knitted fabric may be influenced by structure. For example in purl knit fabric, where the rows of face and back loops are changed, can be certainly predicted that failure occurs sooner at face loop rows. Rows of face loops are less extensible than rows of back loops that transfer just insignificant amount of stress during deformation. [5]

1.1.1.1. Extensibility

Extensibility is one of the most characteristic properties of knitted fabrics, related to the interloped structure, loop shape and to the stitch density. It can be described as the ability to stretch, when external force is applied. This ability secures freedom in motion and comfort in wearing. On the other hand, extensibility may have also negative meaning. Too high extensible fabrics cannot be used for products where stiffness, shape stability, etc. are required. Moreover, the extensibility of courses and wales is considerably divergent, which is also disadvantageous. Possibility of dimensional changes is extremely high especially at weft knitted fabric. For instance, rib stitch knit fabrics are able to achieve huge transverse extensibility and purl knit fabric have on the contrary high longitudinal extensibility. This fabric extension in one direction results in a shortening of the other direction, even in larger proportion, for example to a quarter. Commonly happens that the area of knitted fabrics under tensile stress is reduced. [5]

Deformation properties like strength and extensibility are usually measured simultaneously. As a result of measuring is characteristic deformation curve, shown in the Figure 5 that expresses dependency of stress σ on deformation ε (elongation). This curve is usually non-linear and has four parts. In the first part (1), is visible that knitted fabric even with a low applied stress is considerably deformed. With the deformation the geometry of loops changes and binding points move at the same time. In the second part (2), the curve begins rising upward because as loops in the fabric structure are moving, it requires yarn cross-section deformation. In the third section (3), all geometry changes are done and yarn extensibility is applied now. The fourth part (4) labels breakage of the fabric. [2]

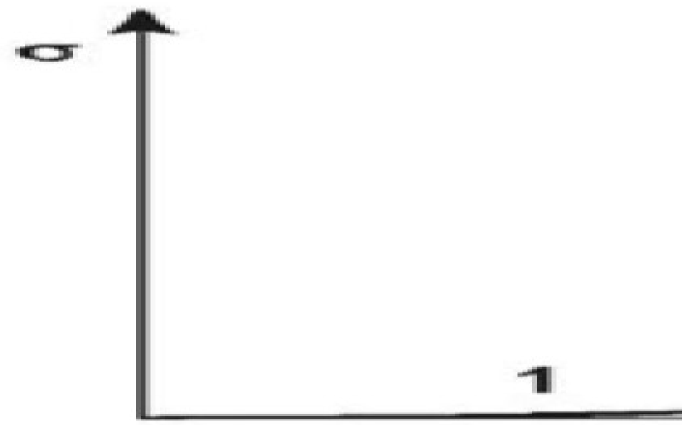

Figure 5: Deformation curve of knitted fabric [2]

Extensibility of material is according V. Kočí [18] determined as an elongation of tested sample at the breaking strength, expressed in percent of gauge length. Directional extensibility (at the wales or courses direction) is:

$$\varepsilon = \frac{l - l_o}{l_o} \; . \; 100 \tag{5}$$

Where: ε = extensibility [%]

l = sample length at breaking strength [mm]

l_o = original (clamping) sample length [mm]

1.1.1.2. Elasticity

Elasticity is understood as an ability of knitted fabric to recover to its original shape with the stress removal. With an applied stress the fabric changes dimension in one direction and after removing the stress a spontaneous change in other direction occurs. It means previous deformation has to be applied to prove elastic properties of material. Elasticity is always advantageous for textiles, especially for those having higher values of extensibility as knitted fabrics. If knitted fabric would not be elastic, each bulging would have a permanent character. [18]

Elastic properties are dependent on the degree of load, time and stress cycles. Because the elasticity is conditioned by loading and unloading (one cycle), for the fabric testing a selected load degree, expressed as a percentage portion of breaking strength, is used. Dependency of load-elongation is determined by hysteresis that can be also a measure of knit elasticity. If the one cycle test is converted into the time dependency (see Figure 6), on the graph curve can be observed three parts: an *elastic deformation* (l'_1-l'_2) that disappears immediately after the stress is removed, *time deformation* (l'_2-l_2), dependent on time and also called relaxation (spontaneous dimensional changes after stress unloading), and *permanent deformation* (l_2-l_0) that stayed after the stress removal and indicates a fabric degradation. If a textile is loaded and unloaded in more cycles, a "fabric fatigue" can be expected. As experiments confirm, knitted fabrics are losing their elastic properties with cyclic loading and become devaluated. [18]

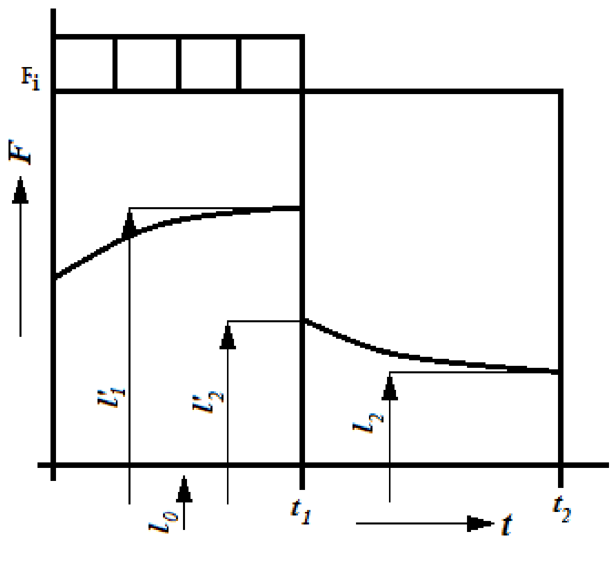

Figure 6: Force-time curve [18]

1.1.1.3. Air Permeability

Due to the characteristic structure, knitted fabrics contain relatively large amount of air. This fact significantly influences air permeability, an important property for physiological comfort. Geometrical parameters of the material, like thickness, density, cross-sectional shape of yarn, loop length etc. may highly influence this property. The air permeability of textile fabrics is determined by the rate of air flow which passes through material. Closely related to air permeability is as well moisture permeability, because, as the general relationship suggests, material that is permeable to air is also permeable to water, in either vapour or liquid from. Another closely related property is the thermal resistance of fabric, which is strongly dependent on the enclosed air affected by fabric structure as well as air permeability. [18]

According the standard ČSN EN ISO 9237 (800817) [27], the air permeability R is received by the equation:

$$R = \frac{\bar{q}_v}{A} \,.\, 167 \;\; [mm/s] \tag{6}$$

Where: $\bar{q}_v$ = arithmetic mean of air flow speed [dm^3/min or l/min]

A = tested textile area [cm^2]

167 = conversion factor from cubic decimeters (or liters) per minute on square centimeter to millimeters per second

2. Compression Therapy

Compression therapy can be defined as a medical treatment exerting pressure by elastic or non-elastic material to a certain part of the human body. This therapy is known since the ancient times where was used in the form of bandaging to treat venous leg ulcers. Currently is considered as a cornerstone of the treatment for chronic venous and lymphatic diseases and conditions of the human body. The prescription of medical compression stockings as an important part of phlebological practice has to be taken seriously because there are many diseases which require treatment for a whole patient life. In order for compression therapy to be effective a certain pressure must be applied by compression hosiery, bandages or less common intermittent pneumatic compression (IPC) devices, to the body and this exerted pressure is transmitted to the underlying tissue. [7], [8]

2.1. Blood Circulation Disorders

Problems of blood circulation very often concern limbs, especially lower limbs due to the Acceleration of Gravity which blood returning to the heart need to overcome. The source of the pressure needed to return blood back to the heart is primary a rest of the arterial pressure after passage through vascular capillaries and muscle activity. The rest of the arterial pressure may not be sufficient and also pulsates, so the level of residual pressure can be lower than 12 kPa (the pressure necessary just to overcome the gravitation), which leads to the undesirable blood backflow. Therefore, veins are provided with valves releasing blood only toward the heart, but damaged veins lose this ability which leads to accumulation of blood respectively other body fluids in limbs and to the danger of occurrence other diseases. Muscle activity (muscle pump) also contributes a proper backflow. During walking or running, blood is pressed up from veins by muscle contractions and therefore the problems are smaller than during standing. [9]

Systemic veins are classified as being either: deep veins, superficial veins and connecting veins. In the case of deep veins disorders the operative treatment is difficult and priority is given to conservative methods, including compression therapies. The effect of compression therapy is founded in increasing pressure at the limb on the level that support blood return, but does not prevent blood supply through the arterial system. Due to the pressure exerted on venous walls, enlarged veins are tapered, blood flow is accelerated and that accordingly results in better blood circulation. Because of smaller veins diameter the degree of valvular insufficiency in reduced. [9]

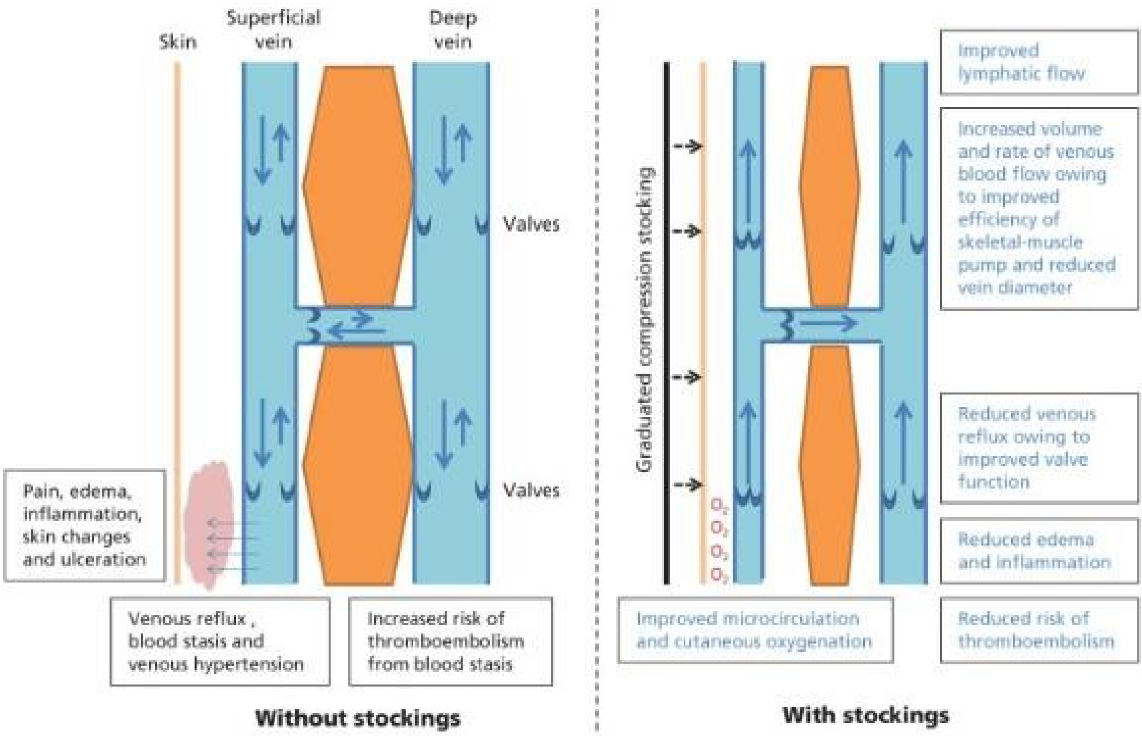

Figure 7: The mechanisms of action of graduated compression stockings [10]

2.2. Indications for Compression Therapy

Compression therapy is one of the oldest methods recommended to treat various venous and lymphatic diseases, which belong to the world's most common health disorder affecting mainly the population of western civilization. Over the last hundred years the number of patients with these diseases has been increasing excessively. This increasing is apparently caused not just by heredity but also by overweight, age and the lifestyle of civilized countries, where people have lack of movement and spend more time sitting at computer or in the work. [11], [8] Compression therapy may be implemented either as short-term treatment in addition to surgery or sclerotherapy or as a main therapy requiring long term treatment. It can be distinguished venous and non-venous indications. The most common indication for medical compression garment is chronic venous insufficiency. However, among the venous indications also belongs leg ulcer treatment, deep venous thrombosis, superficial thrombophlebitis or addition to sclerotherapy. In the case of non-venous, included can be for example erysipelas, vasculitis, edema cruris, posttraumatic conditions and lymphedema. But compression therapy is not used only to promote healing and aid in prevention for these types of diseases, it can be also implemented to prevent leg swelling in pregnant women, during long traveling or improve athletic performance and as a preventative way against injuries in the sport medical therapy for athletes. [12], [8]

Although compression garments are safe to use, with poorly fitting garments a discomfort may occur and in the worst case, pressure necrosis. However there are also contraindications for which compression therapy cannot be used. The most important is arterial insufficiency, acute deep vein thrombosis without sufficient collaterals, severe congestive heart disease, bacterial infection of the skin and subcutaneous tissue or contact allergies to components of the materials contained in hosiery. [12]

2.3. Medical Compression Products

Compression system can be either elastic (bandages or stockings) or non-elastic (bandages) or a combination of both. Elastic materials (long-stretch) can be stretched to increase the overall length of the material by over than 100%, due to content of elastic fibers, and when the tension is released the elastic fibers return almost to their original length. While inelastic materials (short - stretch) do not contain elastic fibers or just few of them so increase in length is often considerably less than 100% when stretched. [14]

In the current healthcare industry there are few commonly used systems and devices to administer compression therapy. To deliver compression, bandages, stockings and pneumatic compression (IPC) devices can be used. From these, bandages and stockings are the most widely used. [12]

2.3.1. Compression Bandages

Compression bandages are long strips of fabric which are wrapped around the leg as a single layer or multilayered system to form a continuous covering. Today many different types of compression bandages are available on market, depending on conditions that required treatment. They are mainly divided according their extensibility or pressure, also referred as a subbandage pressure. Bandages use pressure categories in order to determine a prescribed pressure - described as being "inelastic" or "short-stretch" to "elastic" or "long- stretch". The stretch of the compression bandage is according to the percent extensibility of the bandage when pulled, with the maximal elasticity percent characterizing the bandage as short or long. [13]

Compared to hosiery, bandages have several advantages, for example they are destined for all types of humans body, the pressure can be regulated directly on the leg and better perform its healing function. On the other side, most often compression bandage warp system require a skilled health practitioner for application due to the multilayers and the steady amount of tension required while being applied on a patient. This demanding application and the aesthetic look are main lacks for long-term solutions. [8], [14]

2.3.2. Medical compression stockings (MCS)

MCS can be easily described as knitted socks or stockings that can either apply graduated or constant pressure on the leg. Depending on the length, there are available many types of MCS from below knee and thigh length to pantyhose and with an option of closed or open toe.

Graduated MCS works by exerting the greatest degree of compression at the ankle with the level of compression gradually decreasing up the garment (see Figure 8). This system is used because the highest pressure at the ankle level ensures that blood flows upward the heart instead downward to the feet or into the superficial veins. Utilization of guarded pressure reduces the diameter of major veins, so velocity and volume of blood flow in legs increase. [2]

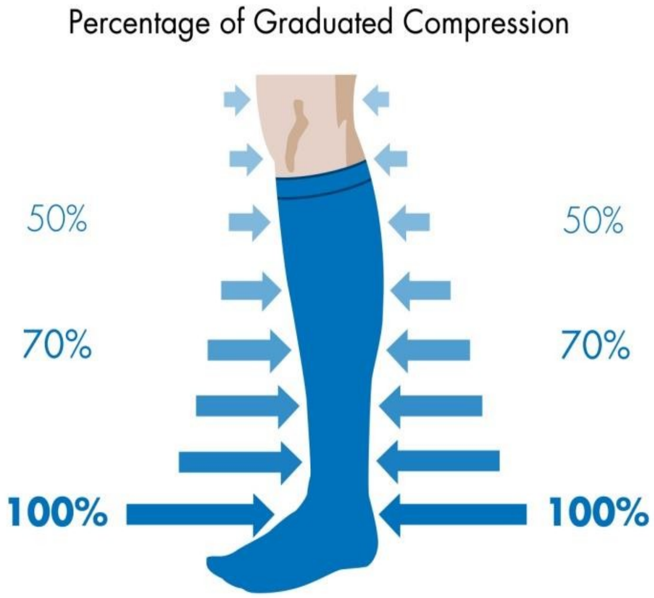

Figure 8: Percentage representation of compression intensity [10]

Over the years, a range of different medical compression stockings used for compression therapy has been developed. Stockings on the current market are available in various leg lengths, sizes and with variety of pressure ranges to address different patient's needs. Compression hosiery is generally characterized by the pressure exerted on the leg at the ankle level where is minimum girth. According those pressure values is hosiery divided into compression classes. To date this, is the only way for distinguishing one pair of socks from another, although compression classes may be varied and have different standards depends on the country. In the Europe individual pressure values are determined by widely used RAL-GZ 387 standard. Those pressure values are shown on the Table 1. But it is known from the literature that to guarantee the best possible treatment for patient the information about compression class is not sufficient. The material used for manufacturing and the knitting method contribute highly to its characteristics and its behavior, it means each hosiery has its own characteristics that are fundamental to their working mechanism. [12], [2]

Table 1: Compression classes according RAL GZ 387

Compression class	Compression intensity	Compression in kPa[1)]	Compression in mmHg[2)]
I	Low	2.4 to 2.8	18 to 21
II	Moderate	3.1 to 4.3	23 to 32
III	High	4.5 to 6.1	34 to 46
IV	Very high	6.5 and higher	49 and higher
[1)] 1 kPa = 7.5 mmHg			
[2)] 1 mmHg = 0.133 kPa			

The norm RAL GZ 387 defines 4 compression classes: class I is used as a prevention, while class II and III are prescribed by doctors and used for treatment respectively for clinical prevention, and class IV is rarely used. [9]

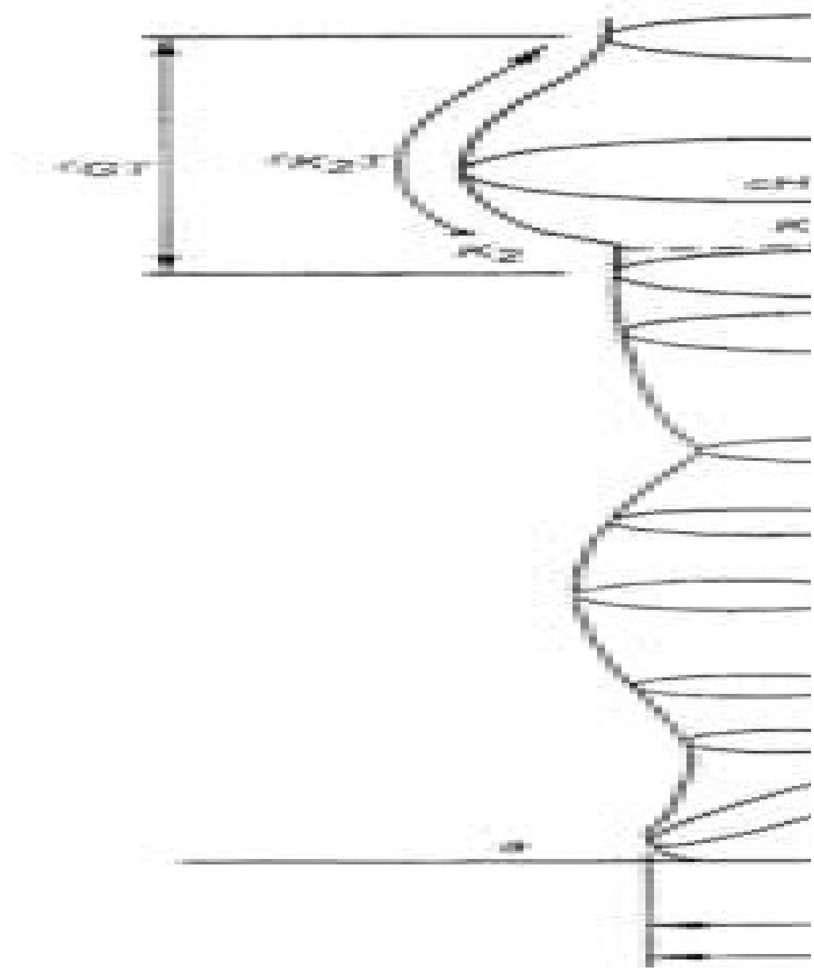

Figure 9: Measurement point on a human leg according RAL GZ 387 [16]

This norm also specifies dimensions and points where should be the leg measured (see Figure 9). There are defined only dimensions for the functional shape of stockings (leg dimensions), because dimensions before deformation are not important, the applied pressure of the sock is decisive. [9]

2.4. Production of Medical Compression Hosiery (MCS)

2.4.1. Fibers and Yarns

The most significant feature of MCS is its elastic properties that make the hosiery effective during wearing. Elastic fibers and yarns which exhibit good extensibility and elastic recovery are used in knitting production to achieve elastic properties of fabrics. Depending on the extensibility of fibers, they can be classified as a low elastic fibers (elongation range from 20% - 150%), medium elastic fibers (elongation from 150% - 390%) and the high elastic fibers (elongation from 400% - 800%). For manufacturing of compression garments are generally used fibers or a mixture of fibers with en extension over 200% and exhibiting rapid recovery when tension is released. But apart from elastic fibers, other fibers such as nylon, polyamide or cotton are added into a mixture. Commonly utilized in the compression garments are also core-spun yarns composed of an elastic core wrapped by cotton or polyester yarn. Those core-sheath yarns are applied as inlay threads to the knit or weave with ground yarns to ensure medical compression function. The different levels of elasticity and strength of the material will provide varying degrees of fabric tension. [17]

Manufacturers always try to adapt to patient's needs so there are many different finishings on current market provide with a special function. For example, microcapsules fixed between fibers with the active substance inside or antimicrobial finish able to provide protection against the emergence and multiplication of microorganisms and helps to prevent unpleasant odors. [19]

2.4.2. Medical Compression Hosiery

Two approaches to fabricate medical compression hosiery exist: flat-knitting (with seam) and round-knitting (seamless). Both of them can be ready-made or custom-made. Flat-knitted stockings are usually custom-made because the precise tension and circumference can be achieved in production against to round-knitted stockings, and that is appropriate especially for patients with bigger or atypical circumferences who cannot find their ideal ready-made size. All knitted compression stockings must be smaller than circumference of the leg to provide their function, so a certain tension is required to elongate the stockings to the correct fitting size. Due to the low stiffness and high elasticity is tolerance to different leg sizes high and that enables manufacturer to produce a few sizes of stockings fitting all patients. Generally round-knitted, ready-made stockings are most frequently prescribed to patients worldwide. [12]

Compression hosiery is commonly produced by small-diameter knitting machine with fine machine gauge. Most of MCS are constructed as plain knitted fabrics with an inlay elastic yarn so usually there are at least two types of yarns in the knitted structure: a ground yarn to ensure the thickness and stiffness of MCS fabric and an inlay-yarn to generate compression. The length of inlayed yarn in round-knitted MCS is very important during manufacturing, because it secures circumference and proper pressure. Knitting machines are equipped with controlled feeder of inlayed yarn to comply the dimensions and reproducibility of production. Higher classes of MCS are usually achieved by increasing the thickness of the elastic core of inlay yarn, but knitting process adjustments such as varying loop size, stitch density and cylinder diameters can also change the range of compression. [17]

2.5. Properties of Medical Compression Hosiery

The essential function of MCS is to deliver externally a controlled compression and compensate malfunction or insufficiency of the specific parts of human body, thus achieving prophylaxis, treatment or rehabilitation purposes. The behavior and the working mechanism of MCS determinate three characteristics: elasticity, stiffness and hysteresis. Two different MCS with the same compression class may have different levels of stiffness, elasticity and hysteresis which can affect pressure performance, durability, comfortability and medical efficacy of MCS. The currently available MCS do not have adequate descriptions on these characteristics to assist medical professionals and end users to choose proper MCS. [20]

2.5.1. Elasticity

MCS are made of either natural or synthetic rubber yarns. The most important aspects of those materials are their elasticity and elastic recovery. Elasticity is defined as the ability of material to return to its original length after being extended or stretched. Because of the elasticity, MCS are able to exert continuous pressure on the human body. This pressure exerted by a stocking or bandage is called as the interface pressure. If the pressure is measured under static conditions, it is labeled as resting pressure, and when it is measured during movement it is labeled as working pressure. The unit of pressure or the amount of force of the compression material per surface area is expressed as mmHg or as Pa ($1N/m^2$). [12], [17]

The elasticity in MCS is significantly dependent on the fibers or elastomeric yarns inserted lengthwise in the structure. It has been done many research studies regarding extensibility and elastic recovery of elastomeric materials, which prove that elastomeric yarns and knitting construction all influence the elasticity of the fabric. For example, in the study conducted by Cooper [33] were tested the stretch and recovery properties of different fabrics (with all-cotton, nylon, and polyester/spandex core yarns) and was indicate that yarn type and inter fiber friction may play a significant part in the stretch and recovery properties. Research studies also indicated that elastic recovery depends on the compression force provided, the length of time that the force is applied for, and the length of time that the fabric is allowed to recover. [17]

2.5.2. Stiffness

In the MCS, stiffness is also a significant mechanical property of fabric that affects the compression performance. According to the European Committee of Normalization (CEN), stiffness is defined as the increase in the pressure at the cB level (i.e. the smallest circumference of the ankle) if the circumference increases by 1 cm. Easily, it is a measure of how the pressure underneath a stocking changes during walking or exercise. [12]

In the Figure 10 is shown a relation between size (circumference) and pressure. There are two different types of MCS, stocking I has a high stiffness and stocking II has lower stiffness. The higher and steeper the stiffness curve is, the better the edemapreventive effect can be expected. On the other side, the higher the stiffness, the more difficult it is for patients to put on MCS, and the more it resembles non-elastic material. A properly chosen MCS should have good balance between comfort and effectiveness. [12], [17]

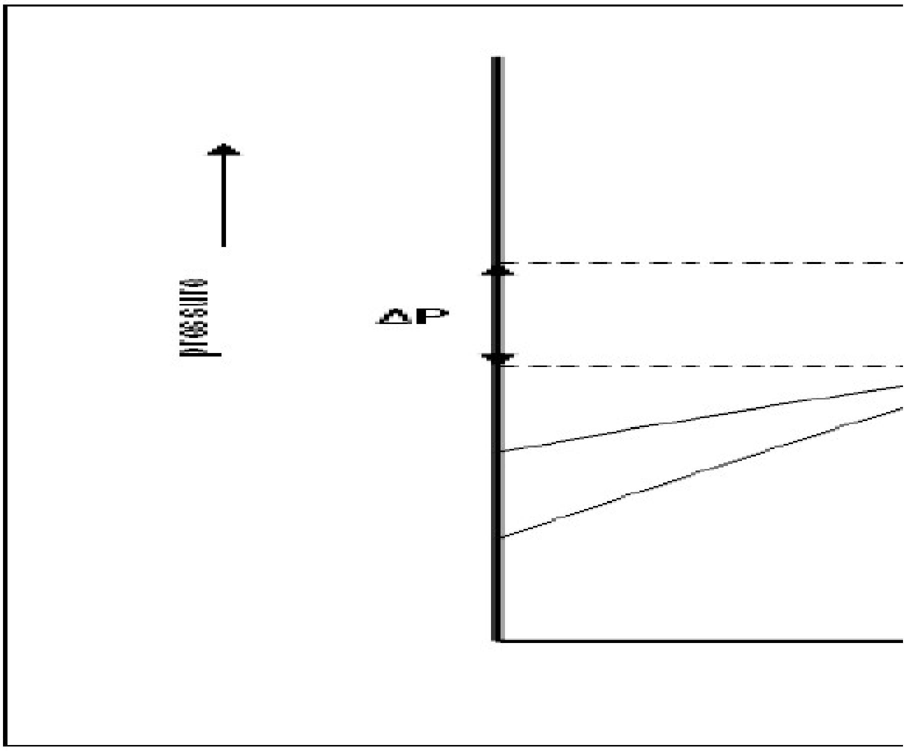

Figure 10: Pressure-circumference relation [12]

2.5.3. Hysteresis

Hysteresis also plays an important role in working mechanism of MCS and elastic fabrics generally. It is a characteristic of elastic material and a result of internal friction between different knitted loops that reflects the stress relaxation of fabric when it has been exposed to repeated stretching and recovery. Studies regarding hysteresis found, that fabrics containing elastomeric yarns had relaxed their stress significantly under stretching and the degree of stress relaxation would increase with prolonged time under deformation. [17]

During walking the circumference of the leg is constantly changing with every step, therefore MCS are still under stretching and releasing and elastic material has to be adapted to these changes. Many of MCS are necessary to wear even 23 hours per day, which means stretching the knitted material for a long and continuous time. It is known that pressure of elastic knitted fabric is dependent on time. It means stress relaxation causes the pressure degradation in long-term wearing and compression therapy provided by MCS may be influenced. [12]

Figure 11 illustrates the way how to determine hysteresis of elastic materials by force-elongation curve. To elongate elastic material a force is necessary, but then material is released and comes to its almost original shape. This tensile curve is shown on the graph. Area in the middle of tensile curve illustrates the hysteresis phenomenon and shows that a high percentage of deformation energy was converted into heat during deformation and relaxation. Due to the structure of knitwear and its internal friction (friction between the different knitted loops, frictions in yarns, fibers, etc.), is caused that even with a perfectly elastic yarn cannot be excluded a significant percentage deformation of knitwear. [12], [9]

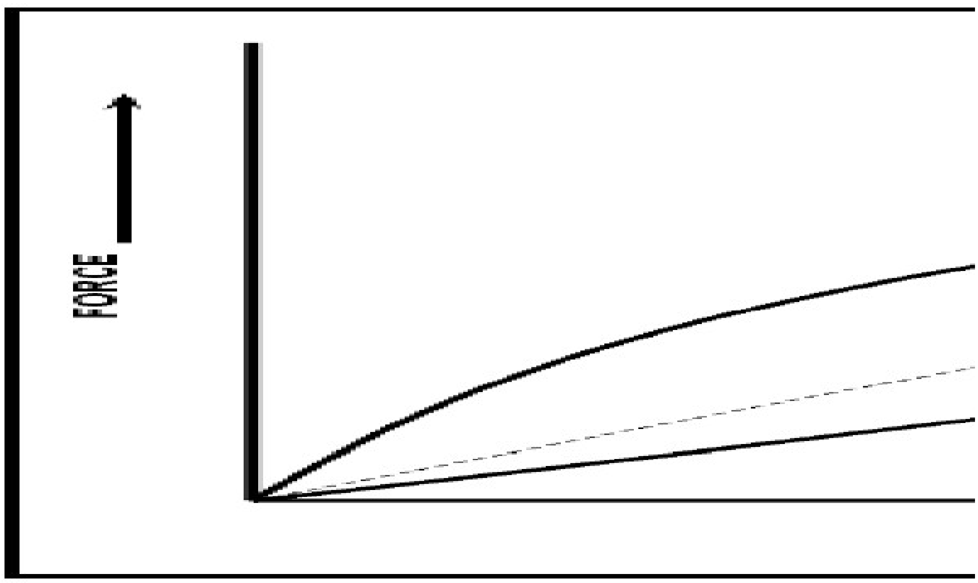

Figure 11: Force-elongation curve [12]

2.6. Measurement of Interface Pressure

MCS are divided into several compression classes according pressure exerted at the ankle level (cB), where is the minimum girth. Determining the compression pressure is necessary for evaluating compression garments. Many devices and methods for pressure measurement exist, based on direct measuring and indirect measuring. With direct measuring is necessary to simulate conditions of wearing compression garments, while at indirect measuring can be measured a tension in knitwear stretched to the dimensions corresponding with the circumferences of the leg and then calculate compression pressure using Laplace law. [9]

2.6.1. Factors Affecting Interface Pressure

The efficacy of the compression therapy provided by MCS highly depends on the pressure generated at the interface between the stocking and the human skin. This pressure is called interface pressure, and usually is expressed in medical compression units mmHg (1 mmHg = 133.3 Pa). The interface pressure of each MCS has to be within its prescribed certain limits and should not be below or above, otherwise it would lead to an inaccurate treatment. [34]

The performance of MCS depends upon the level of applied interface pressure and the sustenance of this pressure over time. Several studies have been done, regarding variation of interface pressure over time. For example, it has been pointed out by Mukhopadhyay and Ghosh [34], that the presence of higher percentage of elastane and a highly close construction (higher stitch density) causes better holding capacity and a more homogeneous interface pressure distribution. On the other way, poor elastic behavior of different fibrous material in the MCS may cause the pressure reduction over time. Other factors affecting the interface pressure of MCS include the reduction of limb circumference during wearing, physical and structural properties of the MCS, physical activities taken by the patient and also the way of putting on compression stockings, because improperly application technique may influence the pressure. [34]

2.6.2. Prediction of Interface Pressure

One of the indirect methods for measuring the interface pressure is mentioned by Vladimir Nikolajevič Filatov [25]. This method consists of cutting out cylindrical strips from compression stockings, and then determining fabric tensions by performing Instron test to get the tensile force when the tested strips are stretched to the same dimensions as should have on the leg. Based on obtained values, a compression pressure of stockings can be indirectly determined by using the law of Laplace.

The Laplace's law can be easily expressed as [12]:

$$P = \frac{T}{r} \tag{7}$$

Where: T = Tension [N]
r = radius [mm]

The Laplace's law is widely used to predict the interface pressure, generated by elastic bandages and MCS, on the limb with known circumference and known tension of elastic material. As is shown in the equation (7) external pressure (P) is directly proportional to the tension (T) of the elastic material and is inversely proportional to the radius (r) of the leg. In practise this means that at constant tension and decreasing radius, pressure increases. By this can be explained why patients wearing MCS may feel uncomfortable at sites with a small radius such as the Achilles tendon. [12], [25]

2.6.3. Devices Used for Measuring Interface Pressure

The most used devices for measuring compression pressure in industry is HATRA, which is required for measuring MCS by British standards, and HOSY device, required by German standard RAL GZ 387. [21]

HATRA

This device, with two metal bars, simulates a simplified leg shape onto the stockings are stretched. Moveable is just the top bar while the lower bar is fixed and has two curved attachments that are used to simulate calf and thigh. Holders for the top edge of stockings are also available in different sizes (i.e. thigh-high length, knee-high length, etc.). After the garment is placed on the leg form, a measurement is made by simultaneously stretching the stocking both length and width ways on the dimensions which simulate its wearing. The measurement head force element is brought into contact with the stocking at the place marked for measuring. When pressed against the material, the device counts pressure acting on the sensor. [21]

HOSY

The HOSY utilizes system of twenty tensile tester devices, where each is 5 cm wide. The measured stocking of any shape is clamped in these tester devices and measure without destroying. Upper gripping system is fixed, while the lower gripping system is moveable, and stretches clamped stocking at the specified length to the specified width, simulating its wearing. When it is stretched to the destined dimension, the force needed to stretch the stocking in the circumferential direction is measured. Based on these values an amount of applied pressure on the body is determined. In addition to interface pressure, it can measure elongation, tensile force, and residual pressure. [21]

MST (Medical stocking tester)

The MST consists of a flat, air-filled sleeve, connected to the pressure sensor. This sleeve is inserted between measured stocking and the leg or a leg form. Due to its low profile, there are no bulges on the stocking which would result in an inaccurate measurement, and the pressure can be registered at different height levels. The MST has been developed over the years, and while the earlier versions used a wooden leg form required to be changed to test different sized stockings, the current version can be used for quality control in production or laboratory environments, as well as on patients in the hospital environment. [21], [22]

Kikuhime

Kikuhime device represents one of the most easiest method to measure compression pressure of MCS directly on the body. It is a portable monitoring device, consists of an oval polyurethane balloon sensor containing a 3 mm thick foam sheet, and this is connected to a syringe and a measuring unit. When the sensor is placed between the leg and the compression stockings, the transducer monitors the pressure experienced by the balloon and the pressure value is converted to mmHg and shown on the digital display. [22]

3. Durability of Textile

Textile durability is the measure of textile ability to resist mechanical and chemical influences they are exposed during their manufacturing and subsequent using. It is determined by the length of time that a textile is able to maintain its innate characteristic, like strength, dimension and appearance, in use. This time may vary depending on the environment, the amount of use and also on the user's judgment about the durability. Interpretation of textile durability has considerably changed over years. For example, hundred years ago, textiles were relatively expensive, so they were intensively used and repaired. Nowadays, textiles are much cheaper and customer more often prefers a buy of a new product than a repair of old one, which substantially influences the durability. [23]

Performance and characteristics of textile materials are determined by their manufacture, i.e. the type of fibers, yarn, fabric structure and finishing treatments. Generally, knitted textiles are less stable in use than woven textiles. This is caused by the fact they are produced from low twist yarns, and have a slack construction. So, knitted fabrics tend to deform easily under a low degree of tension. [23]

Below, there are stated several selected factors influencing the durability of knitted fabrics.

3.1. Strength

Strength is generally not that important factor for clothing textiles, as it is for textiles designed for upholstery, beddings or technical textiles. However strength parameters are deciding factors in ensuring the durability and serviceability of the final product. In normal use, the garment is exposed to multi-directional stresses with every movement of the body forcing garment to change shape or extend in new directions. Any other properties such as air permeability, crease recovery etc. are essential physical attributes of fabric, but all of them are useless if the fabric is not enough strong to face abrasion and stress occur in everyday 'wear and tear'. In general, three tests are done to determine the strength of material: tensile strength, tearing strength and bursting strength. Tests are done according the material type and its final use. [23], [26]

Tensile Strength

Tensile strength is the breaking strength of a material under exertion of a force capable of breaking many threads simultaneously, at a constant rate of extension/load. Tensile strength quantifies the force needed to stretch a fabric to the stage where it breaks. Whereas compression stockings contain a high proportion of elastic fibres so in practice, is extremely unlikely to experience situations as those used during testing. It means that the instrumentally predicted breaking strength of a fabric does not hold a direct relationship with its serviceability. Tensile strength tests are used in laboratories to determine the extensibility of material and its maximal force in breaking. [23]

Tearing Strength

Whilst the tensile strength of a fabric provides a potential parameter for basic strength judgment, the tearing strength predicts the actual serviceability, as well as durability, of a fabric. Tearing is a natural, undesired and destructive phenomenon which is much more common than breaking, and does not have any match with laboratory practices because cannot be predicted. During use, a hole or slit developed as a result of an accident or carelessness may occur. This hole gradually develops into a tear and the stresses of normal use are quite capable of causing an extension of such damage. [23]

In the case of knitted fabric tearing does not occurs, but this damage is called unravelling, a specific phenomenon for knitted fabric given by the structure. Unravelling occurs when there is a spot in the knitted structure that is not protected against unravelling, like broken yarn, and if the energy able to unravel loops is given to the fabric (usually is enough to stretch the knitted fabric). Unravelling can be reduced by fixation, type of used material or structural parameters - knitted fabric with higher stitch density is more difficult to unravel. [29]

Bursting Strength

Movements of the body create multi-directional stresses forcing garment to change shape. When measuring the bursting strength the textile is exposed to multiaxial loading that simulates the garment wearing and influence of environment on mechanical properties of textile. Measurement of bursting strength in laboratory is performed by the application of force on the specimen from an enclosed container of air or water. For knitted fabrics is the bursting strength a measure of its resistance to rupture, depends largely on the tensile strength and extensibility of a fabric. [23], [26]

3.2. Dimensional Stability

The dimensional stability of textiles is the ability to keep its original dimensions during and after the manufacturing process and when it is in use by the customer. Knitted textiles can exhibit either reversible or irreversible shrinkage (i.e. dimensional decrease) or, growth (i.e. dimensional increase). Several factors affecting the change in dimensions of a knitted fabric exist: fiber characteristics, stitch length, machine gauge, yarn twist, yarn count, knitting tension, type of machine, type of needle, type of fabric, the method of relaxation procedure, the method of washing, finishing, drying, etc. Not all of those factors have such a major influence on fabric shrinkage, but the most responsible is the relaxation of internal stress imposed on the yarn during the knitting process. [23]

Knitted fabrics have more than any other textiles tendency to dimensional instability and spontaneous changes. Already, in the knitting process is a fabric in unstable shape. When knitted textile is drawn-off, it shrinks in wales direction and the geometrical parameters are changed. After taking-off from the machine and removing strain, a fabric gets into a dry relaxation (relatively stable shape). Higher dimensional stability gets a fabric after wet relaxation. After laundering, especially after multiple laundering is a fabric most approaching the state of complete relaxation (state with minimum of internal deformation energy and with the lowest tendency to change dimensions). Subsequent drying process must be without any mechanical stresses, it means lying, because when a knit is hanging, there is a tension leads again to the deformation and dimensional changes. [29]

Leigh [35] has studied the problem of knitted fabrics shrinkage and divided the yarn into three groups:

1) Hydrophilic Yarns (eg. cotton, silk and rayon)
   There is significant effect on the dimensional stability when are first wetted out, but during subsequent washing only small changes in area shrinkage occur. For fabrics made of those yarns, fabric relaxation cannot be achieved by dry relaxation.
2) Wool
   When first wetted out, there is the same area change as for hydrophilic yarns, but with further washing cycles the shrinkage continue. As the fabric decreases in area it becomes thicker, stiffer and loses its extensibility, which is known as felting.
3) Hydrophobic Yarns (eg. polyamide and polyester)
   Also exhibit greatest dimensional changes when are first wetted out. However, changes are less than for hydrophilic and wool yarns. Fabric from those yarns may return to almost full relaxation in the dry relaxation state (on condition they are given enough time to relax).

Relaxation Treatments Causing Dimensional Changes

There are three categories of dimensional changes that occur when mechanical strains are released during wetting out and washing. Those changes may be either reversible or irreversible. Munden [35] has divided fabric shrinkage into three categories as follows:

1) Relaxation Shrinkage:
   This is an irreversible dimensional change observed when fabrics, made from any type of textile fibres, are first wetted out in water. During manufacturing, fibres are subjected to extension, twisting and bending forces. These forces leave significant stresses in the fibres which are released by the combined effect of time, finishing treatments and laundering. The largest stress reduction, show up as shrinkage or change of shape, occurs when first wetted out and each time of washing decrease the extent of dimensional changes.
2) Consolidation Shrinkage:

This type of shrinkage occurs after relaxation shrinkage. It describes the further dimensional changes of cotton and man-made fabrics during washing and after standard wet relaxation treatment.

3) Felting Shrinkage:
   This type of shrinkage occurs only in fabrics composed partly or completely of animal hair, like wool. These fibres have scales along their surface and when exposed to washing (moisture and high temperatures), scales are tightened and squeezed together.

Dimensional stability can be determined experimentally by marking or embroidering perpendicular dimensions on the tested textile sample before it is going to be subjected to laundering, ironing or any other processes. The size of sample is usually 300 x 300 mm. By re-measuring dimensions a shape change, like shrinkage, growth or bevelling, can be determined. [6]

3.3. Effect of Laundering

Garments are during their wearing exposed to human body movements, friction effects, abrasion and also many types of dirt, which needs to be, for hygienic or aesthetic reason, removed before its subsequent use. Garments should therefore be able to withstand repeated washing and drying processes, when they are exposed to higher temperatures, detergents and mechanical actions to remove soil. The damage caused by washing may be higher than that caused by wear and use. Laundering, in addition to keep the garment hygienic and aesthetically acceptable, can at the same time cause a deterioration in the appearance, dimensions and other desirable and performance-related properties of a garment. For this reason, garments have a care labels, informing the user how to treat a product without adverse effect to ensure maximum garment durability.
By not keeping the instructions on care label, regarding washing, drying and ironing, can lead to fabric shrinkage, loss in color or function, etc. The overall impact of laundering on textiles is influenced by many factors such as the water temperature, water quality, composition and action of detergents. [26]

The biggest impact have laundering and especially drying treatments on weft knitted fabrics that tend to undergo large changes in dimensions and are often prone to distortion. In the study of S.C. Anand and others [31], a weft knitted fabrics containing cotton, were tested in laundering and drying treatments with keeping the correct conditions appropriate to the cotton fibre type. As the study shown, dimensional changes, of the fabric, that occurred during those processes were caused due to changes in loop shape rather than yarn or loop length shrinkage. According this theory, it is possible to stretch the knitted fabric to reorient the loops and restore the original dimensions. The exceptions are materials containing wool, that is not resistant to higher temperatures and shrinkage is largely irreversible. The study also proves that knitted fabrics with higher density have better dimensional stability in laundering, than fabrics with low density.

3.4. Durability of Medical Compression Hosiery

There are a variety of MCS on the current market, from which customers can choose according their needs. Instructions informing the end user about proper putting on or recommended washing and care are attached to ensure the life time of MCS as long as possible. Those informations may slightly vary, depending on the manufacturer. For example, the company Varitex [32] recommends washing of MCS by hand after each use in soap water, without using a bleaching agent or stain remover. In the case of washing machine set up the program on gentle washing with the temperature maximally 30ºC. Manufacturers recommend washing after each use, so the wet relaxation can occur and MCS are able to keep its compression pressure for a longer time. For subsequent drying, MCS should be lying on a towel without exposure to the sun or central heating. Generally MCS are recommended to be replaced after three to six months.

It is known from the literature that if a knitted fabric is exposed to a constant deformation, then stress relaxation occurs. This decrease of stress is the highest at the beginning and the rate of decrease becomes smaller with time. It means the pressure of elastic fabric is time-dependent. Most of MCS have to be worn even about 23 hours per day, so the fabric is under tension over a long period of time. As a result, some of the stresses in it are relieved when patients wear them for a long time and this pressure decay affects the effectiveness of compression therapy. [17], [36]

MCS are designed to be worn during the daytime and especially during walking, because in combination with motion are most effective. The pressure exerted by MCS is dependent on the shape of the leg. This shape is irregular and changes during walking. The knowleage about stiffness and dynamic behavior of the hosiery during walking is very essential for effective compression therapy, because they are responsible for pressure changes. The higher the stiffness of MCS, the higher the pressure-amplitude (so-called massaging effect). In the study of Catharina van der Wegen-Franken [12], a MCS pressure during eight hours was measured with the dynamic leg-segment model simulates the walking speed and walking pattern of the real leg during walking. The obtained values of pressure decrease of twelve different MCS are shown in the Figure 12. It can be seen that interface pressure of all MCS significantly decreased during walking.

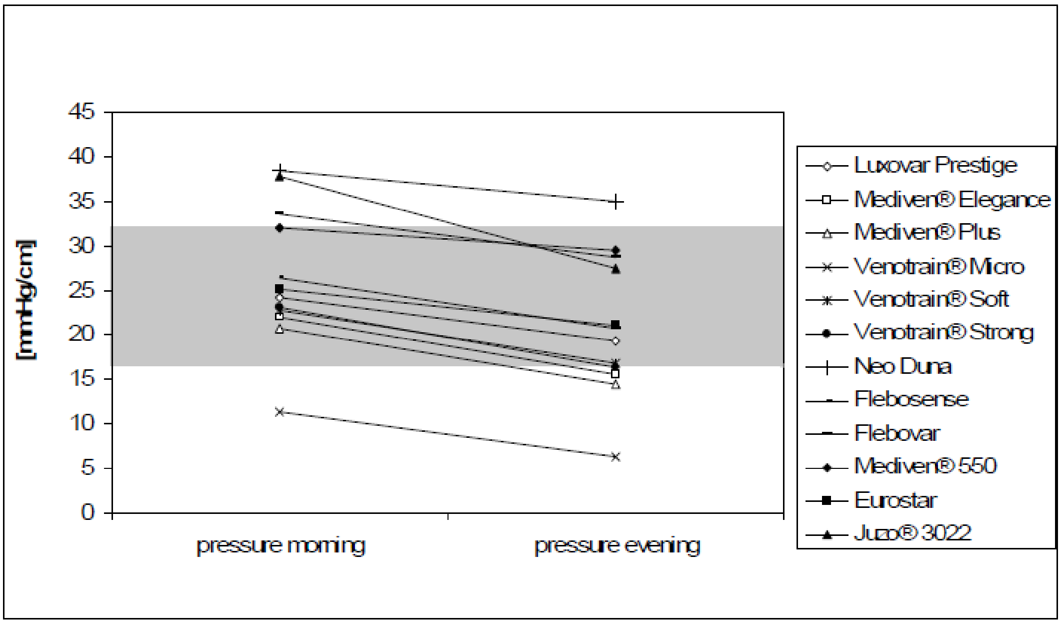

Figure 12: Change in pressure of 12 different brands of MCS after simulation of eight hours long walking [12]

4. Experimental Part

Following part of this master thesis is focused on description of used MCS, devices, data evaluation and analysis of washing processes and long term wearing on the performance of MCS.

4.1. Experiment Procedure

In all, ten different types of MCS made for the same circumference of the leg were tested. Firstly, MSC were divided into four separate groups according the subsequent testing (see Figure 13). The groups 1, 2 and 3 contain one stocking from each type of MCS, and the 4th group contains three identical stockings from each type of MCS. The 4th Group was used to determine the air permeability, thickness, compression pressure, stitch density and the effect of long term wearing on compression pressure. Other groups were separately subjected to different laundry processes (HW, WM1, WM2), described below. Then all MCS were tested for compression pressure and air permeability to evaluate the effect of different laundry processes.

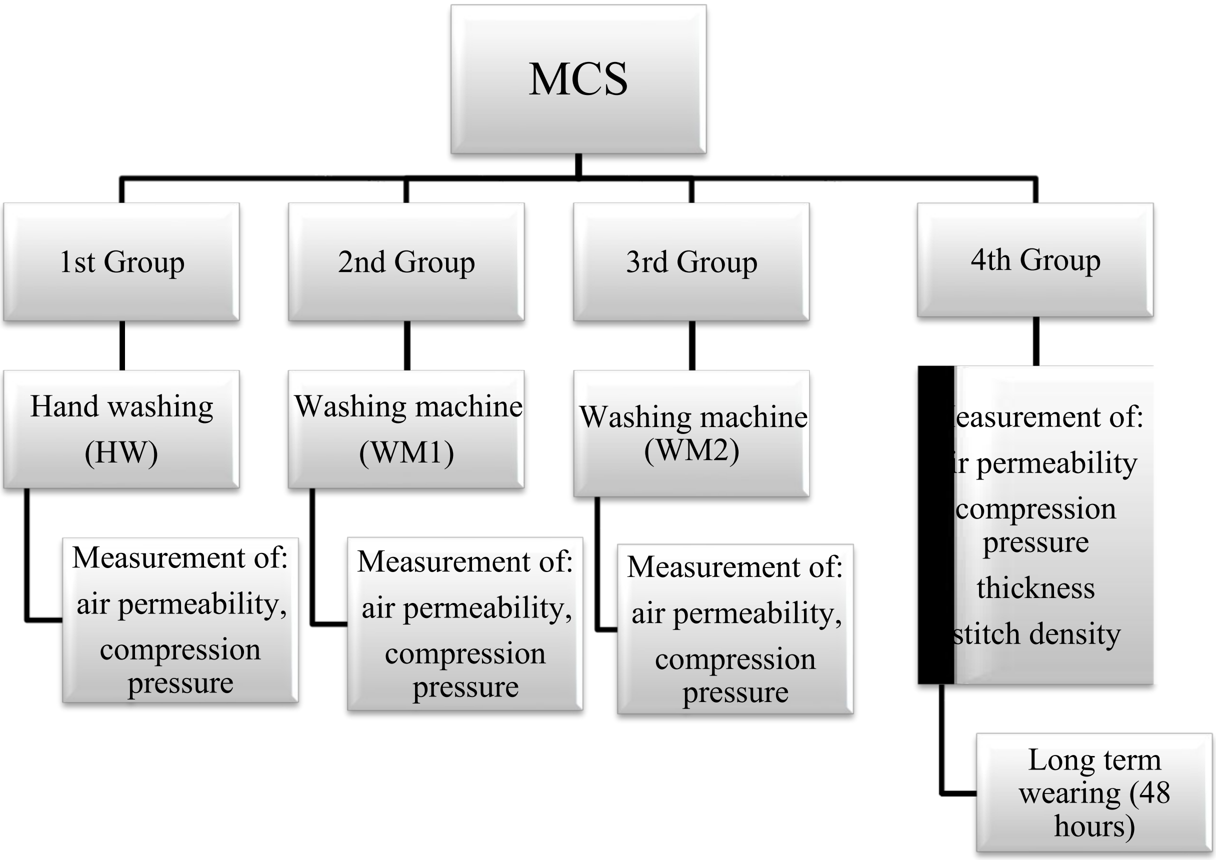

Figure 13: Diagram of the experiment

4.1.1. Statistical Processing of Measured Values

Measured values were processed by statistical methods with using Microsoft Excel. The **mean**, or the average of a data set, is counted by following formula:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (8)$$

Then **dispersion** was determined by formula:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

(9)

Standard deviation by formula:

$$s = \sqrt{s^2}$$

(10)

Coefficient of variation expressed in [%] by formula:

$$v = \frac{s}{\bar{x}} . 100$$

(11)

and **95% confidence interval** according following formula:

$$95\%CI = \bar{x} \pm t_{(n-1)} \cdot \frac{s}{\sqrt{n}}$$

(12)

Statistical significance between two groups of measured values was determined according 95% confidence intervals. If the confidence intervals overlap, it means the difference is not statistically significant, and on the contrary, non-overlapping confidence intervals indicate statistical significance. For comparing the effect of multiple levels of two factors with multiple observations at each level an Excel ANOVA was used. ANOVA uses a Null hypothesis and an Alternate hypothesis. The Null hypothesis in ANOVA H_0: $\mu_1=\mu_2$ is valid when all the sample means are equal, or they do not have any significant difference. Whereas, the Alternate hypothesis H_1: $\mu 1 \neq \mu 2$ is valid when at least one of the sample means is different from the rest.

4.2. Characteristics of Tested MCS

As shown in Table 2, ten different commercially available medical compression stockings (MCS) were used for testing. From the chosen MCS, three of them belonging to compression class I, four belonging to compression class II, and three belonging to class III. There was no specific reason for choosing given number of MCS in those compression classes. All MCS are from four various manufacturers and none of them was aware that their products were being tested. For the experiments just round-knitted MCS with leg-size (cB) of 23 cm were used. All socks of the same type of MCS were identically marked (AI, BII, CIII, DI, EII, FII, GIII, HCI, HCII, HCIII) to avoid confusions in subsequent testing. Where the first letter indicates the sample and I, II, III indicates compression class of the sample. Socks HCI, HCII and HCIII have the similar designation due to the same composition, structure and manufacturer.

Table 2: Specifications of MCS samples

Sample identification	CCL	Structure	Composition	Manufacturer (Country)	Circumference [cm]
AI	CCLI /Light	Rib	60% Polyamide, 40% Elastane	Varitex (Netherlands)	23 - 26
BII	CCLII /Medium	Plain/Single Jersey		Varitex (Netherlands)	23 - 26
CIII	CCLIII /High		60% Tactel/Polyamide, 40% Lycra/Elastane	Aries (Czech Republic)	23 - 26
DI	CCLI /Light		69% Polyamide, 31% Elastane	Varitex (Netherlands)	23 - 26
EII	CCLII /Medium		60% Cotton, 35% Elastane Lycra, 5% Nylon	Aries (Czech Republic)	23 - 26
FII	CCLII /Normal		31% Elastane, 41% Polyamide, 28% Cotton	Maxis (Czech Republic)	23 - 25
GIII	CCLIII /High		32% Elastane, 68% Polyamide	Maxis (Czech Republic)	23 - 25
HCI	CCLI /Light	Rib	52% Polyamide, 34% eEastane, 14% Cotton	Sigvaris (Switzerland)	22 - 24
HCII	CCLII /Medium			Sigvaris (Switzerland)	22 - 24
HCIII	CCLIII /High			Sigvaris (Switzerland)	22 - 24

Basic geometry parameters of MCS material, which are not provided by manufacturer, were determined (see Table 3). Those parameters were thickness and stitch density.

4.2.1. Measurement of Stitch Density

The stitch density, indicating the total number of loops in a measured area, was calculated per 1 cm ^{2} of MCS at the cB level. Stitch density was obtained by counting the number of wales in 1 cm (SD_w) and the number of courses in 1 cm (SD_c), than multiplying those two values (see formula 1) the value for 1cm^2 was calculated.

Each measurement of the number of loops in wales or courses per 1 cm was repeated five times, always in a different area of MCS at cB level. Measurements were performed with the help of magnifying glass. Results from individual measurements are given in Annex No. 1.

4.2.2. Measurement of Material Thickness

Fabric thickness is measured as the perpendicular distance between the two fabric surfaces under a specified applied pressure. For fabric thickness determination SDL M034A device was used. The measuring was done according the standard ČSN EN ISO 5084 (80 0844): Textilie - Zjišťovánítloušťkytextilnií a textilníchvýrobků. The standard specifies applied pressure 1 000 Pa, size of the pressure head 20 cm ^{2} and sample load 200 g. Measurement, the same as results, are recorded by computer. Ten measurements of material thickness were performed on each MCS, always in the different area. Results from individual measurements are given in Annex No. 1.

Table 3: List of stitch density and thickness of MCS

Sample identification	Wale density [Loops/cm]	Course density [Loops/cm]	Stitch density [Loops/cm^2]	Thickness [mm]
AI	28	22	616	0.94
BII	23.8	21.8	518.84	0.76
CIII	26.6	21	558.6	0.63
DI	27	13.2	356.4	0.69
EII	27.2	20.2	549.44	0.95
FII	26	22	572	0.78
GIII	27.2	17.8	484.16	0.95
HCI	26	25	650	0.87
HCII	23.8	23	547.4	0.86
HCIII	27.6	22.2	612.72	0.79

4.3. Compression Pressure Measurement

Pressure measurement of MCS was performed at the cB level, the point where the Achilles tendon changes into the calf muscles. As literature shows, this is the area of MCS that has to keep the biggest pressure and has to withstand largest differences in the circumference during its wearing. Also measuring at this cB level is recommended and published by the international compression club (ICC) [12].

Pressure measurements were performed with using a standardized leg model with circumference 23 cm at cB level. For measuring the pressure exerted by stocking on the surface of wooden leg a Kikuhime device was used. This device was chosen, due to its availability on the Department of Clothing Technology and its easy and portable using.
A general view of the Kikuhime device is presented in Figure 14. To measure with Kikuhime, it needs to be calibrated after turning on, and then insert sensor between the surface of leg model and stocking. The resultant pressure is displayed on the device display immediately. Mean pressure values of ten tested MCS at the cB level are provided in Table 4. Results from individual measurements are given in annex No. 2.

Figure 14: The Kikuhime pressure measuring device

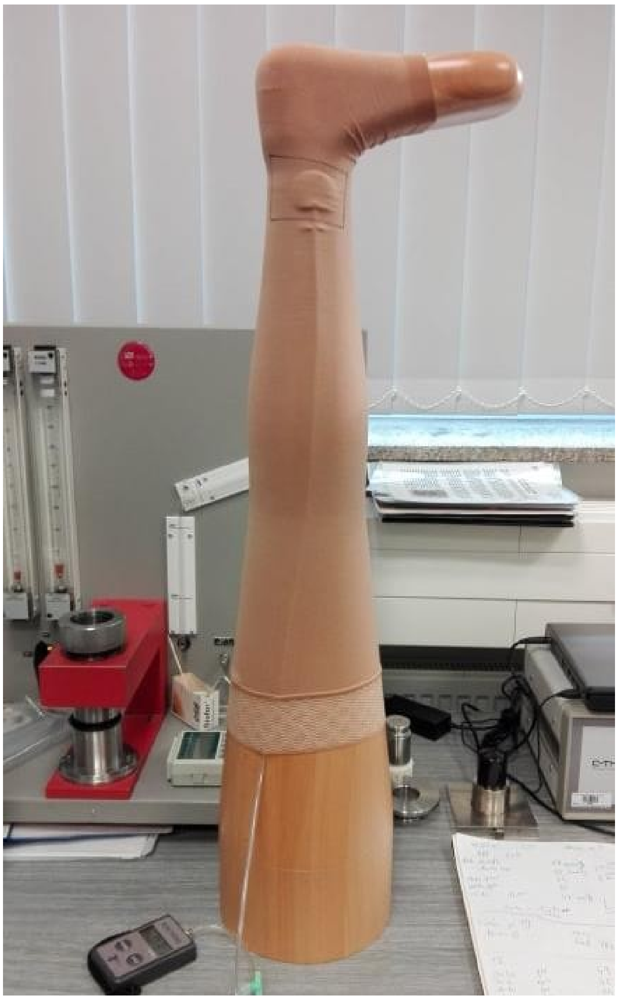

Figure 15: compression pressure measuring at cB level

For patients are MCS effective only when correct application is complied. To prevent different or wrong compression pressures of the same MCS due to various ways of applications, the same technique for donning MCS on the leg was used. Firstly the stocking was turned inside out with the part from the heel to the toe tucked into the stocking. Then, the stocking was stretched with the fingers or thumbs of both hands and pulled over the wooden foot up to the instep and drawn upward over the heel. With inserting a pressure sensor between the leg and stocking at the cB level, the stocking was pulled up in sections. Any folds formed on the surface had to be removed. [37]

All tested stockings were before pressure measurement conditioned for 24 hours under standard atmospheric condition (relative humidity 65±5%, temperature 20±2 °C). Each stocking was measured ten times and there was at least 4 hours interval between individual measurements for the knitted fabric relaxation. The interfacial pressure was recorded after 2 minutes from application on the leg model, so the stocking was allowed to relax sufficiently before measuring.

Table 4: Mean pressure values at cB level

Pressure	**Sample identification**									
	AI	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
	CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
mmHg	26.60	40.50	54.60	21.70	40.60	37.60	55.30	33.50	39.90	56.10
kPa	3.54	5.39	7.26	2.89	5.40	5.00	7.35	4.46	5.31	7.46

Table 4 provides with mean values of interfacial pressure in mmHg and kPa. Further, in the thesis are listed just medical pressure units mmHg.

It should be noted that measuring compression pressure on hard surfaces, as the wooden leg, fails to simulate the compressional characteristics of the human skin. Due to this fact, the measurement leads to the higher pressure values, especially for thicker and more textured samples which exhibit higher stiffness. The thickness and size of pressure sensor may also influence the measurements. [18]

4.4. Effect of Long Term Wearing

Medical compression stockings are effectively used to treat many lymphatic and venous diseases, but it has been observed that as soon as the pressure is removed the body fluid returns back to the tissues, undoing the effect. Therefore the compression pressure exerted on limb must be maintained continuously. It is known from the literature that knitted fabrics under a constant tension over a long time relieve some of the stresses in it. Therefore, the measurement of pressure exerted by MCS and its variation with time becomes very important for the therapy efficacy. [34]

The aim of this experiment was to measure the pressure after the application of the MCS and the pressure variation during 48 hours in the static mode. Ten commercially available MCS were chosen for the analysis, see Table 2. Three repeated measurements were conducted per one kind of MCS. The interface pressure applied by MCS was measured using Kikuhime device and standardized wooden leg. A pressure sensor was held continuously under the stocking at cB level, and the pressure values were recorded immediately after the application and after 4, 24, 28 and 48 hours. Averages of 3 measurements per each type of MCS are provided in Table 5. Individual measurements are provided in Annex No. 3.

Table 5: Pressure at cB level of ten different types of MCS measured in 48 hours

Sample identification	**Pressure at cB level [mmHg]**					**Total of pressure drop [mmHg]**
	After application	**After 4 hours**	**After 24 hours**	**After 28 hours**	**After 48 hours**	
AI	26.67	23.00	18.00	17.00	13.67	13.00
BII	40.67	38.67	32.00	30.33	26.33	14.33
CIII	54.00	48.67	37.67	36.33	29.67	24.33
DI	22.67	20.00	16.33	16.00	14.33	8.33
EII	41.33	37.67	26.67	25.00	18.00	23.33
FII	37.67	34.00	22.00	21.33	18.00	19.67
GIII	54.33	51.67	39.67	39.00	31.33	23.00
HCI	32.67	27.67	20.67	20.00	14.67	18.00
HCII	39.67	37.00	26.00	25.33	19.33	20.33
HCIII	55.67	47.67	34.33	32.33	23.67	32.00

Before the application of MCS on wooden leg, on each sample was marked a square by textile marker at the location of cB level, to determine the fabric relaxation after long term extension from wearing. The exact original dimensions (D_O) of square were 50x50 millimeters. After the MCS have been worn for 48 hours, the dimensions were re-measured. First measurement was taken immediately after taking off the stocking from the wooden leg (D_{R0}) and the second one after being relaxed for 24 hours (D_{R24}). The mean dimensional values are provided in Table 6.

Table 6: Long term wearing effect on dimensions of marked square

Sample identification	**D_O [mm]**	**D_{RO} [mm]**	**D_{R24} [mm]**
	course x wale	**course x wale**	**course x wale**
AI	50 x 50	51.17 x 50.17	50 x 50
BII	50 x 50	52.83 x 50.17	50.67 x 50
CIII	50 x 50	52.17 x 50.17	50.33 x 50
DI	50 x 50	51.67 x 50	50.50 x 50
EII	50 x 50	52.50 x 50.67	50.50 x 50
FII	50 x 50	53.17 x 51.33	50.83 x 50.67
GIII	50 x 50	53.17 x 50.17	51 x 50
HCI	50 x 50	52.17 x 50.83	51 x 50
HCII	50 x 50	53.17 x 51.17	51.17 x 50
HCIII	50 x 50	53.17 x 50.33	51 x 50

From the Table 6 is visible that even 24 hours after elongation all MCS, except the AI sample, did not recover initial dimensions. This dimensional extension is related mainly to the course direction, where the highest tension was applied so the amount of loading with the duration length of loading caused higher dimensional deformations in the coursewise directions than in the walewise directions. All MCS have also knitted elastic inlayed yarns in the course directions so they are naturally more elastic in the transversal directions. Those inlayed yarns should increase the fabric recovery after extension due to the higher potential energy in the structure which permits better dimensional recovery. This partial recovery of the course dimensions after extension can be explained by the hysteresis phenomenon of inlayed elastic yarns.

As those results showing, even with enough time to relax the fabric of MCS is not able to return initial dimensions in the dry relaxation state so wet relaxation is necessary.

4.4.1. Evaluation of Long Term Wearing Effect

Compression garments are generally made as a stretchable structure containing higher percent of elastic yarns to achieve appropriate compression. It is known, that fabrics having a high percentage of elastic yarns have also a higher stress relaxation under constant elongation. This stress relaxation is a viscoelastic property of material which refers to the behavior of internal stress reaching a peak and then reducing the stress over the time with constant deformation. Due to this fact, a higher percentage of pressure degradation over the time was expected.

The results from measurement coincide with the study of Ng. [38], who observed the stress relaxation phenomenon. All test specimens of the MCS have relaxed their stress significantly under extended state on the leg model, and the degree of stress relaxation increase with prolonging the time that MCS are under stretching. This stress relaxation resulted in pressure degradation. The decrease of interface pressure in 48 hours of MCS from compression class I (CCLI) is shown in Chart 1. MCS from compression class II (CCLII) are shown in Chart 2, and pressure degradation of MCS from compression class III (CCLIII) is given in Chart 3.

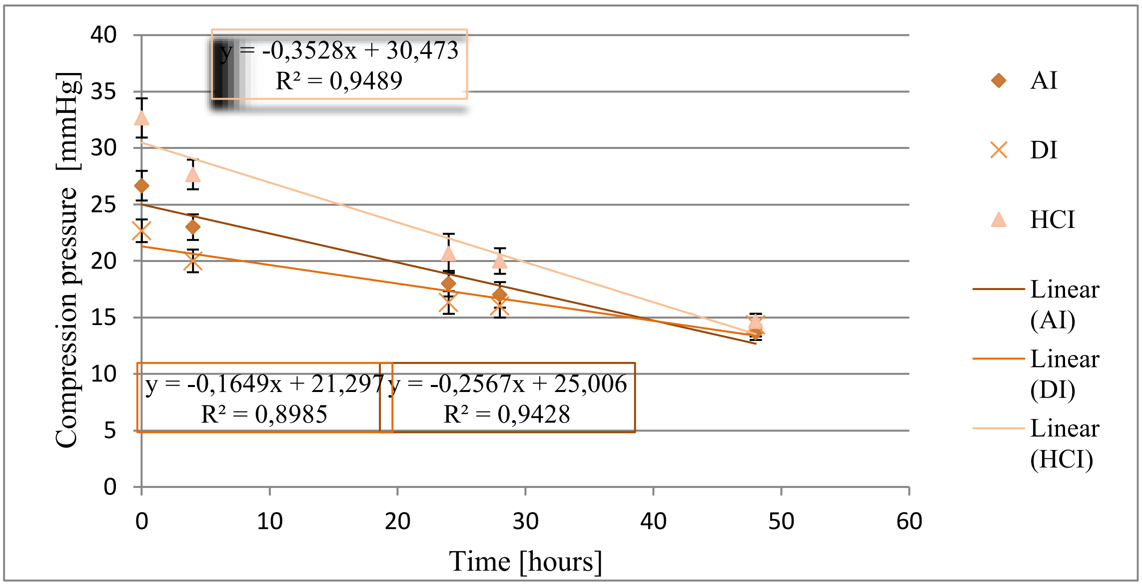

Chart 1: Compression pressure generated in 48 hours by MCS from CCLI

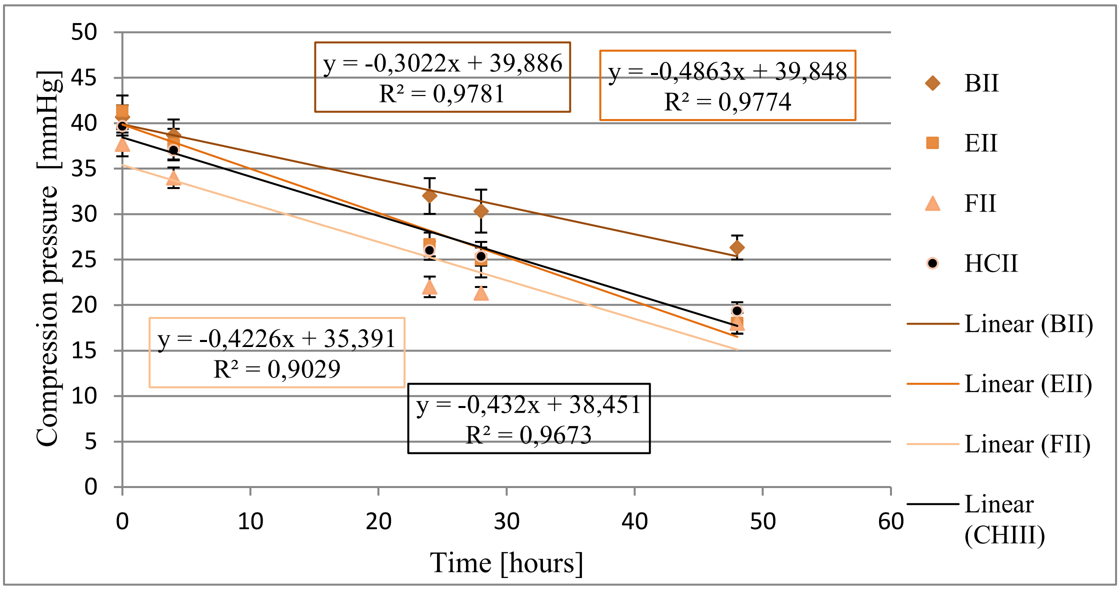

Chart 2: Compression pressure generated in 48 hours by MCS from CCLII

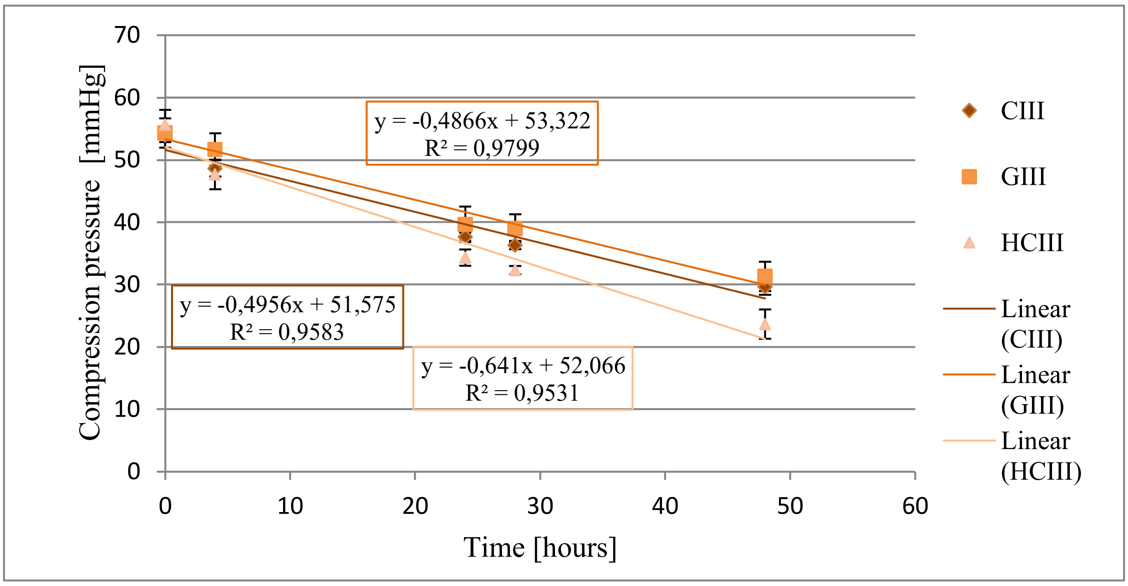

Chart 3: Compression pressure generated in 48 hours by MCS from CCLIII

A percentage drop of compression pressure was calculated (see Table 7) to compare each MCS. Table 8-10 provide the ANOVA results for each compression class to check the significant difference in the mean values of the pressure drop at various levels of the factors.

Table 7: Percentage pressure degradation in 48 hours

Sample identification	Pressure decrease at cB [%]			
	After 4 hours	After 24 hours	After 28 hours	After 48 hours
AI	13.75	32.50	36.25	48.75
BII	4.92	21.31	25.41	35.25
CIII	9.88	30.25	32.72	45.06
DI	11.76	27.94	29.41	36.76
EII	8.87	35.48	39.52	56.45
FII	9.73	41.59	43.36	52.21
GIII	4.91	26.99	28.22	42.33
HCI	15.31	36.73	38.78	55.10
HCII	6.72	34.45	36.13	51.26
HCIII	14.37	38.32	41.92	57.49

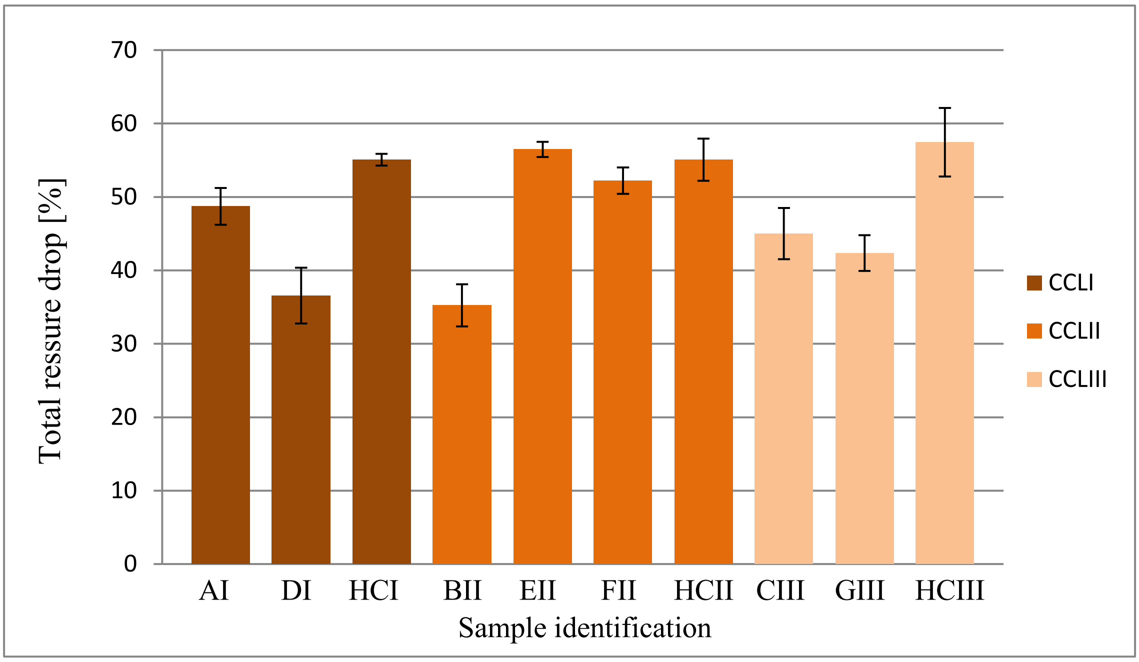

Chart 4: Total percentage pressure degradation in 48 hours

The results show, there is no significant relationship between compression class (interface pressure) and the total pressure decrease. So it does not mean that MCS from one compression class has significantly higher or lower total pressure decrease than other compression classes.

Table 8: ANOVA results for three MCS (AI, DI, HCI) from CCLI to check the significant difference in the mean values of the pressure drop

Source	*Sum of square*	*Degree of freedom*	*Mean square*	*F*	*p value*	*F krit*
Type of MCS	638.4966	2	319.2483	25.6227	1.11E-06	3.402826
Time	5090.819	3	1696.94	136.1955	3.34E-15	3.008787
Interactions	183.4289	6	30.57149	2.453652	0.054116	2.508189
Residuals	299.0301	24	12.45959			
Total	6211.774	35				

The ANOVA results from the Table 8 shows that percentage pressure drop of one MCS is significantly different from the others in the same compression class (Null hypothesis is rejected $p = 1.11^{-6} < 0.05$). Results also confirm a significant influence of time on interfacial pressure drop ($p = 3.34^{-15} < 0.05$). The factor of interactions shows that the interface pressure values of each MCS at the same measured time vary with the same trend (parallel). Changing the "time" factor would cause essentially the same change of pressure for all three MCS types (Null hypothesis is not rejected $p = 0.054 > 0.05$).

Table 9: ANOVA results for four MCS (BII, EII, FII,HCII) from CCLII to check the significant difference in the mean values of the pressure drop

Source	*Sum of square*	*Degree of freedom*	*Mean square*	*F*	*p value*	*F krit*
Type of MCS	1626.278	3	542.0926	53.67482	1.38E-12	2.90112
Time	10774.7	3	3591.566	355.6158	1.22E-24	2.90112
Interactions	380.7512	9	42.30569	4.188861	0.001206	2.188766
Residuals	323.1862	32	10.09957			
Total	13104.91	47				

Table 9 with the ANOVA results for MCS from compression class II confirms significant difference in percentage pressure drop between individual MCS in the same compression class ($p = 1.38^{-12} < 0.05$). Significant difference is also between the values of pressure for individual MCS in different times of being extended ($p = 1.22^{-24} < 0.05$). As the results of interactions show, there is a significant difference, meaning that the interface pressure values of individual MCS within the same time do not change with the same trend, so changing the "time" factor does not cause the same pressure change for all MCS types from CCLII ($p = 0.0012 < 0.05$, Null hypothesis is rejected).

Table 10: ANOVA results for three MCS (CIII, GIII, HCIII) from CCLIII to check the significant difference in the mean values of the pressure drop

Source	*Sum of square*	*Degree of freedom*	*Mean square*	*F*	*p value*	*F krit*
Type of MCS	962.4119	2	481.2059	88.4017	8.5E-12	3.402826
Time	6861.42	3	2287.14	420.1674	7.23E-21	3.008787
Interactions	54.11815	6	9.019692	1.656996	0.175058	2.508189
Residuals	130.6416	24	5.443401			
Total	8008.591	35				

The ANOVA results from Table 10 show, as the previous results, that there is also significant difference between individual MCS and their percentage of pressure drop ($p = 8.5^{-12} < 0.05$) and the time of being extended significantly influences the interface pressure ($p = 7.23^{-21} < 0.05$). The same as the MCS from compression class I, show also MCS from compression class III that the pressure of each sample vary with the same trend ($p = 0.17 > 0.05$).

It can be observed that the rate of pressure degradation is the highest for the first 24 hours for all MCS and with time is the speed of decrease lower. The results infer that the decrease of compression pressure is primarily caused by the stress reduction in the stocking. The faster and higher pressure decrease, especially in first four hours, may be explained by rearranging the fibers and yarns in the structure of stocking to attain a new relaxed position of having low internal stress in the structure.

The most significant reduction in compression behavior due to the time can be found at samples EII, FII, HCI, HCII and HCIII, where the compression pressure was reduced by over 50% of the original pressure. It cannot be unnoticed that all those MCS partly contain cotton in its composition. In the literature [34], an influence of different composition on stress relaxation was tested. It was observed that higher and faster pressure drop had samples contain cotton and viscose, because of their poor ability to sustain internal stress in the structure .With increasing portion of elastomeric material in the composition, decrease the total pressure drop of samples. Based on this knowledge and measured data can be confirmed the importance of material composition on stress relaxation and related compression pressure behavior over the time. Material composition with cotton has been found to have the highest stress relaxation compared to others MCS (AI, BII, CIII, DI, GIII) contain just polyamide and elastane in the different ratio.

4.5. Effect of Laundering

As all manufacturers recommend, MCS should be washed after each use, because of the wet relaxation that helps fabrics to come back to its original dimensions and retain the pressure for a longer time.

Overall three different laundry processes were performed to analyze their effect on MCS and compression pressure. Those processes include hand washing and washing in washing machine with two different settings. Identification and specification of all laundry processes are provided in Table11. Each time, ten MCS samples (Table 2) were used for individual laundry process.

Table 11: Specifications of laundry processes

Washing type	Water temperature	Washing time	Spin speed
NW (no washing)	-	-	-
HW (hand washing)	20±2°C	5 min	-
WM1 (washing machine)	30°	38 min	400
WM2 (washing machine)	50°	72 min	400

The main purpose of these washing processes was to simulated laundry conditions that can occur in regular household. Hand washing (HW) recommended by manufacturers was realized according attached care instructions. MCS were dip into warm water bath (20°) and left for five minutes, then water was gently squeezed out and MCS were laid flat on a towel to air-dry. Other two washing processes (WM1 and WM2) were performed using washing machine (Miele W1) available on Department of Clothing Technology. Washing MCS at WM1 process was done with a program for wool, due to its possibility to set up the lowest temperature 30 °C and time 38 minutes. For the WM2 process was set up a delicate washing program with temperature 50 ° and washing time 72 minutes. As well as after HW, all stockings were laid on the towel and left to air-dry. Before washing all MCS samples were carefully labeled to avoid confusions. Because the experiment does not take into consideration the effect of detergents, there was not use any of them.

4.5.1. Compression Pressure Measurement

In order to determining the interfacial pressure of MCS after laundry process, the measurements were repeated in the same way as above (see subchapter 4.3). The samples were put on the wooden leg model and measurements were performed at the cB level with using the Kikuhime device. Each stocking was measured ten times with at least 4 hours interval between individual measurements for the fabric relaxation.

Measured pressure values were processed by statistical methods, see subchapter 4.1.1. Mean values, dispersion, standard deviation, coefficient of variation and 95% confidence interval were calculated from all measured values. Statistic results of compression pressure before washing (NW) are shown in Table 12, after HW in Table 13, after MW1 in Table 14, and after HW2 in Table 15. Results from individual measurements are provided in Annex No. 4.

Table 12: Pressure at cB level on MCS without washing

NW											
Sample Identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		**26.60**	**40.50**	**54.60**	**21.70**	**40.60**	**37.60**	**55.30**	**33.50**	**39.90**	**56.10**
Dispersion [$mmHg^2$]		1.60	1.39	1.38	1.79	6.27	0.71	6.78	2.06	1.88	1.66
SD [mmHg]		1.26	1.18	1.17	1.34	2.50	0.84	2.60	1.43	1.37	1.29
Coefficient of variation [%]		4.76	2.91	2.15	6.16	6.17	2.24	4.71	4.28	3.43	2.29
95% CI	lower limit [mmHg]	25.82	39.77	53.87	20.87	39.05	37.08	53.69	32.61	39.05	55.30
	upper limit [mmHg]	27.38	41.23	55.33	22.53	42.15	38.12	56.91	34.39	40.75	56.90

Table 13: Pressure at cB level after hand washing

HW											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		**35.60**	**44.60**	**71.20**	**27.70**	**49.10**	**49.00**	**65.10**	**36.40**	**40.50**	**58.80**
Dispersion [mmHg^2]		0.93	3.38	1.51	1.12	1.21	1.11	5.61	1.16	4.94	3.07
SD [mmHg]		0.97	1.84	1.23	1.06	1.10	1.05	2.37	1.07	2.22	1.75
Coefficient of variation [%]		2.71	4.12	1.73	3.82	2.24	2.15	3.64	2.95	5.49	2.98
95% CI	lower limit [mmHg]	35.00	43.46	70.44	27.04	48.42	48.35	63.63	35.73	39.12	57.71
	upper limit [mmHg]	36.20	45.74	71.96	28.36	49.78	49.65	66.57	37.07	41.88	59.89

Table 14: Pressure at cB level after washing in washing machine (30^o, 38 min)

WM1											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		**35.20**	**46.80**	**74.00**	**30.80**	**53.50**	**50.90**	**72.70**	**40.80**	**44.90**	**60.20**
Dispersion [mmHg^2]		2.62	7.29	0.89	9.07	3.39	2.99	2.03	1.29	1.66	3.51
SD [mmHg]		1.62	2.70	0.94	3.01	1.84	1.73	1.42	1.14	1.29	1.87
Coefficient of variation [%]		4.60	5.77	1.27	9.78	3.44	3.40	1.96	2.78	2.87	3.11
95% CI	lower limit [mmHg]	34.20	45.13	73.42	28.93	52.36	49.83	71.82	40.10	44.10	59.04
	upper limit [mmHg]	36.20	48.47	74.58	32.67	54.64	51.97	73.58	41.50	45.70	61.36

Table 15: Pressure at cB level after washing in washing machine (50°, 72 min)

WM2											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		**38.80**	**48.40**	**77.40**	**30.80**	**54.00**	**52.10**	**72.50**	**40.90**	**46.60**	**62.10**
Dispersion [$mmHg^2$]		0.62	2.93	3.16	1.29	5.11	2.54	14.69	3.66	3.82	2.77
SD [mmHg]		0.79	1.71	1.78	1.14	2.26	1.60	3.83	1.91	1.96	1.66
Coefficient of variation [%]		2.03	3.54	2.30	3.69	4.19	3.06	5.29	4.67	4.20	2.68
95% CI	lower limit [mmHg]	38.31	47.34	76.30	30.10	52.60	51.11	70.12	39.71	45.39	61.07
	upper limit [mmHg]	39.29	49.46	78.50	31.50	55.40	53.09	74.88	42.09	47.81	63.13

Mean values of interface pressure after three different types of laundering were plotted into following bar Charts 5-7.

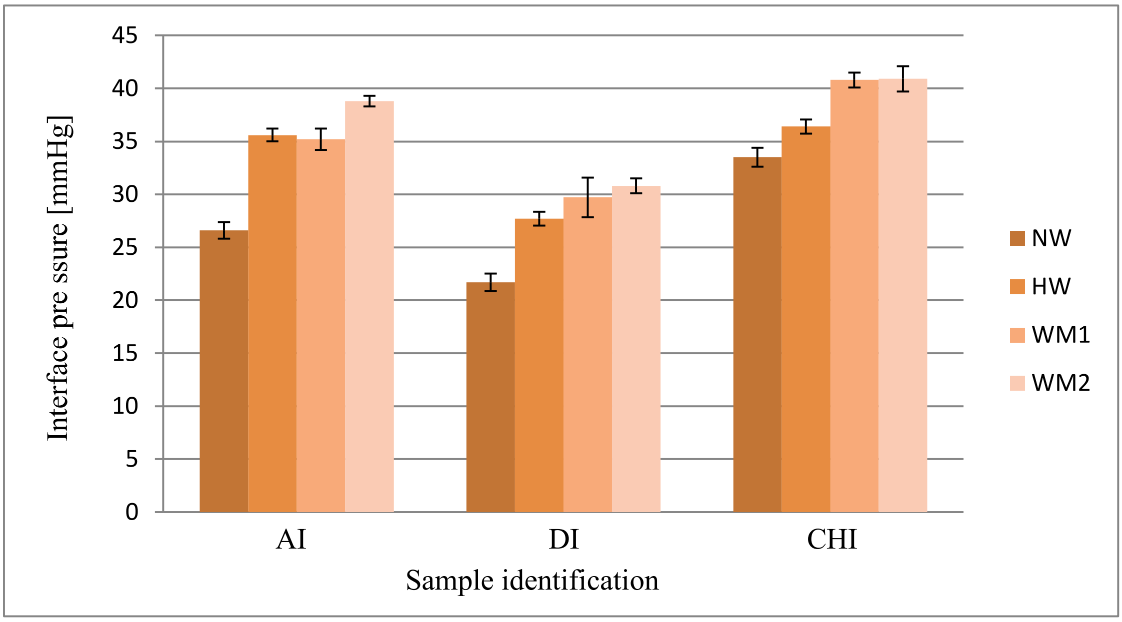

Chart 5: Interface pressure of MCS from CCLI after three different types of laundering

The chart 5 provides with results of interface pressure of MCS from compression class I. The AI sample had the highest pressure change after each washing process with no significant difference between HW and WM1, and just a low difference between HW2. Interface pressure of the DI sample was also significantly increased due to washing processes, but without any differences between WM1 and WM2, having the same mean pressure values. In the case of HCI sample, the HW had very low influence on compression pressure and the same as sample DI there was not proved the significant difference between WM1 and WM2.

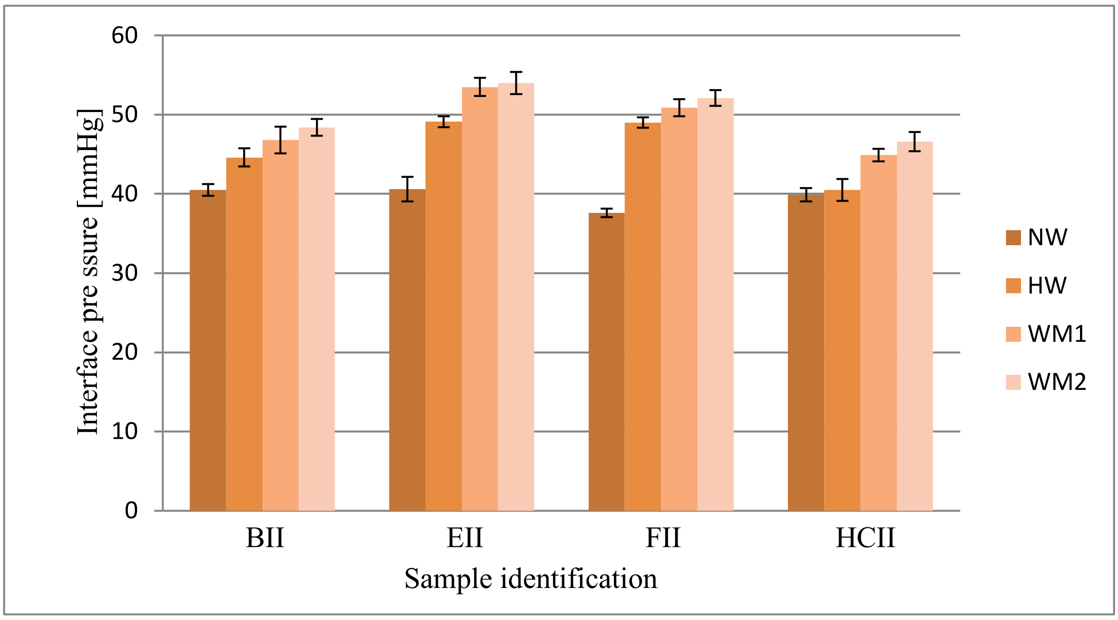

Chart 6: Interface pressure of MCS from CCLII after three different types of laundering

Mean pressure values of MCS from compression class II provided in Chart 6 show that already HW, except the sample HCII, had significant influence on interface pressure, and there was no difference between WM1 and WM2 for all MCS from CCLII. But compared to unwashed samples, the pressure after washing in washing machine significantly increased.

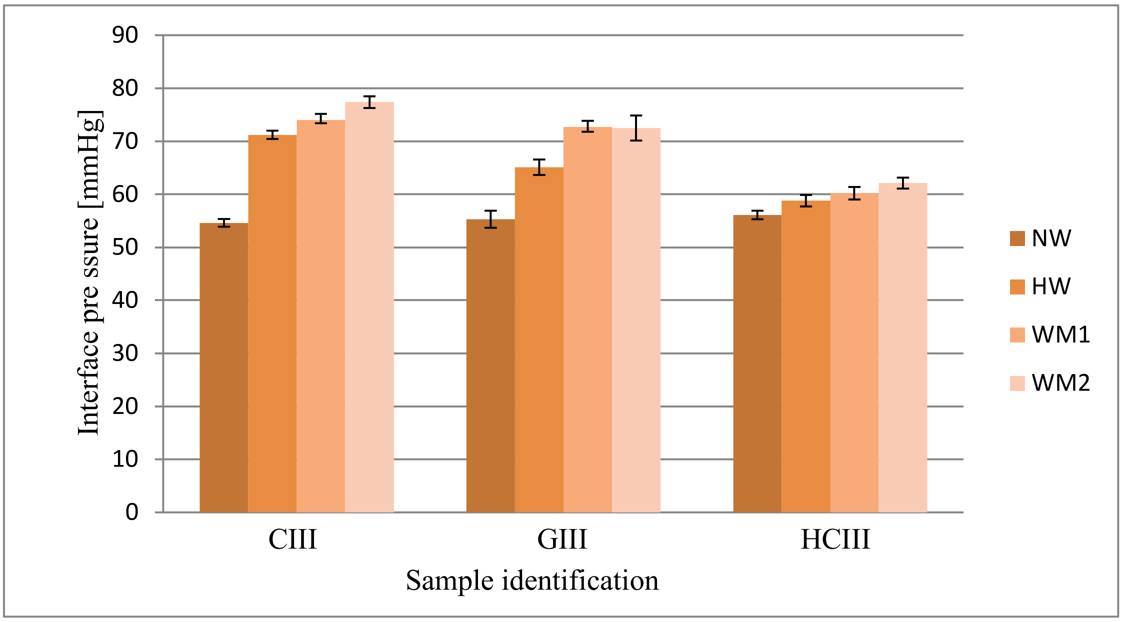

Chart 7:Interface pressure of MCS from CCLII after three different types of laundering

Chart 7 provides with mean values of interface pressure measured on MCS from compression class III. As the previous charts show, these pressure values are also considerably higher after washing in washing machine without any significant difference between WM1 and WM2. From all MCS the HCIII sample may be found to have the best pressure stability in laundering with maximal pressure increase 6 mmHg after WM2.

4.5.2. Dimensional Change

The exact original dimensions in a square form were indicated by textile marker pen on each sample of MCS at the location of cB level. The size of marked square was 50x50 millimeters. After the samples were washed and air-dried, the dimensions of the marked square were measured again to determine the change in MCS dimensions after wet relaxation in different types of laundering. Table 16 shows the dimensions in course and wale directions before and after the MCS samples were washed, where D_{NW} are dimensions of marked square before washing, D_{AHW} are dimensions after HW, D_{AWM1} after WM1 and D_{AWM2} are dimensions after WM2. Measurements were taken to the nearest 0.5 millimeter of the lines that were marked off.

Table 16: Dimensional change after different types of laundering

Sample identification	D_{NW} course x wale [mm]	D_{AHW} course x wale [mm]	D_{AWM1} course x wale [mm]	D_{AWM2} course x wale [mm]
AI	50 x 50	50 x 48.5	50 x 47	49 x 47
BII	50 x 50	49 x 50	48 x 46	48 x 48.5
CIII	50 x 50	49 x 49.5	47.5 x 47.5	48 x 48.5
DI	50 x 50	50 x 49	49.5 x 48.5	49 x 47.5
EII	50 x 50	49.5 x 49	49 x 48.5	49 x 48.5
FII	50 x 50	49.5 x 49.5	48.5 x 49	48.5 x 49
GIII	50 x 50	49 x 49.5	47 x 49	48 x 48
HCI	50 x 50	49.5 x 50	48.5 x 49.5	48 x 49
HCII	50 x 50	48.5 x 50	49 x 49.5	49 x 48
HCIII	50 x 50	49.5 x 50	49 x 50	49 x 49

Dimensional changes expressed in [%], were calculated according the literature [6] as follows:

$$s = \frac{l_1 - l_2}{l_1} . 100 \tag{13}$$

Where: s = shrinkage [%]

l_1 = is the initial dimension of the sample [mm]

l_2 = is the dimension of the sample after washing [mm]

Change in dimensions is indicated (+) if shrinkage occurs or (-) when fabric is extended. The higher the dimensional change value, the more shrinkage or extension occurred. Table 17 shows the total dimensional change for course and wale in [%] for the marked square at cB level of each MCS after being washed by three different types of laundering.

Table 17: Dimensional change in percent after different types of laundering

Sample identification	D_{AHW} course x wale [%]	D_{AWM1} course x wale [%]	D_{AWM2} course x wale [%]
AI	0 x 3	0 x 6	2 x 6
BII	2 x 0	4 x 8	4 x 3
CIII	2 x 1	5 x 5	4 x 3
DI	0 x 2	1 x 3	2 x 5
EII	1 x 2	2 x 3	2 x 3
FII	1 x 1	3 x 2	3 x 2
GIII	2 x 1	6 x 2	4 x 4
HCI	1 x 0	3 x 1	4 x 2
HCII	3 x 0	2 x 1	2 x 4
HCIII	1 x 0	2 x 0	2 x 2

From the results of percentage dimensional changes is obvious that no fabric extension happened, but shrinkage occurs for all types of MCS mainly after laundering in washing machine. Wale direction can be labeled as a less stable direction due to the higher values for shrinkage than occur in course direction.

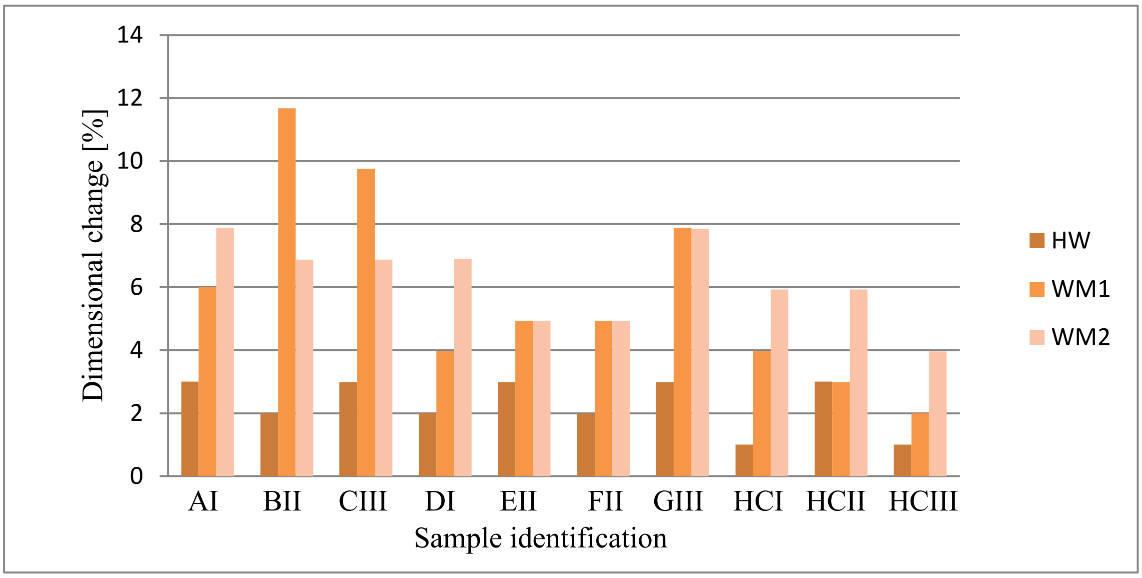

Chart 8: Percent area shrinkage after three different types of laundering

The results from Chart 8 demonstrate that shrinkage occurs during each type of washing, but the amount of dimensional changes after individual washing processes does not occur with the same trend. The lowest shrinkage have all MCS after HW while

the amount of shrinkage after WM1 and WM2 differs from the type of MCS to another.
It cannot be determined which washing process had significantly higher influence on dimensional stability. Also, MCS samples with the same or similar stitch density or composition do not behave in laundering with the same trend, so influence of those factors on overall performance of MCS cannot be confirmed.

4.5.3. Air Permeability

Air permeability is defined as the rate of air flow passing perpendicularly through a known area under a prescribed air pressure differential between the two fabric surfaces. [27]

The measurement of air permeability can be used as an independent method for testing the shrinkage of fabric. As the general relationship suggests when the air space available in the fabric decreases, due to the shrinkage, then the air permeability also decreases.

Measurements were performed on the device SDL M021S Air Penetration. All tested stockings were before air permeability measurement conditioned for 24 hours under standard atmospheric condition (relative humidity 65±2%, temperature 20±2°C). For comparison of results was the measurement performed with the same test area 20 cm^2 and pressure drop 30 Pa. Ten readings were obtained, in different parts of each sample at cB level. The result of measuring is the air permeability R [mm/s], which is according the standard ČSN EN ISO 9237 (800817) [27] calculated by the equation:

$$R = \frac{\bar{\bar{\bar{q}}}_v}{A}\,.\,167[\mathrm{mm/s}] \tag{14}$$

Where: $\bar{q}_v$ = arithmetic mean of air flow speed [dm^3/min or l/min]

A = tested textile area [20 cm^2]

167 = conversion factor from cubic decimeters (or liters) per minute on square centimeter to millimeters per second

The obtained average results for air permeability after each washing process are provided in Table 18-21. The results from individual measurements are recorded in Annex No. 5.

Table18: Air permeability of MCS before washing

NW											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		198.90	9.72	13.70	167.08	19.09	25.55	15.41	47.85	52.86	46.09
Dispersion [$mmHg^2$]		11.43	0.79	0.08	47.48	0.81	1.34	0.16	11.78	24.33	25.38
SD [mmHg]		3.38	0.89	0.29	6.89	0.90	1.16	0.40	3.43	4.93	5.04
Coefficient of variation [%]		1.70	9.16	2.12	4.12	4.70	4.53	2.57	7.17	9.33	10.93
95% CI	lower limit [mmHg]	196.80	9.17	13.52	162.81	18.53	24.83	15.16	45.72	49.80	42.97
	upper limit [mmHg]	200.99	10.27	13.88	162.81	19.64	26.27	15.65	49.97	55.91	49.21

Table19: Air permeability of MCS after hand washing

HW											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		182.61	9.67	12.68	166.33	15.03	23.45	12.88	43.24	48.64	42.38
Dispersion [$mmHg^2$]		80.11	0.50	0.48	26.77	0.70	6.79	1.34	8.15	7.62	3.80
SD [mmHg]		8.95	0.71	0.69	5.17	0.84	2.61	1.16	2.85	2.76	1.95
Coefficient of variation [%]		4.90	7.35	5.45	3.11	5.56	11.12	9.00	6.60	5.68	4.60
95% CI	lower limit [mmHg]	177.07	9.23	12.25	163.12	14.51	21.83	12.16	41.47	46.93	41.18
	upper limit [mmHg]	188.16	10.11	13.10	163.12	15.55	25.06	13.59	45.01	50.35	43.59

Table20: Air permeability of MCS after washing in washing machine (30º, 38 min)

WM1											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		181.61	6.29	11.62	165.58	13.68	21.04	12.88	36.22	44.49	37.73
Dispersion [$mmHg^2$]		70.07	0.17	0.37	20.15	0.66	2.06	1.22	1.23	7.24	5.52
SD [mmHg]		8.37	0.42	0.60	4.49	0.81	1.44	1.10	1.11	2.69	2.35
Coefficient of variation [%]		4.61	6.63	5.20	2.71	5.93	6.83	8.56	3.06	6.05	6.23
95% CI	lower limit [mmHg]	176.42	6.03	11.25	162.80	13.17	20.15	12.19	35.53	42.82	36.27
	upper limit [mmHg]	186.80	6.55	12.00	162.80	14.18	21.93	13.56	36.91	46.16	39.18

Table21:Air permeability of MCS after washing in washing machine (50º, 72 min)

WM2											
Sample identification		**AI**	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
Compression class		CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
Mean [mmHg]		179.86	5.04	8.87	159.07	13.65	21.09	11.64	36.82	39.58	37.22
Dispersion [mmHg2]		42.95	0.13	0.56	31.03	0.87	1.59	1.18	7.04	2.34	9.04
SD [mmHg]		6.55	0.36	0.75	5.57	0.93	1.26	1.09	2.65	1.53	3.01
Coefficient of variation [%]		3.64	7.21	8.44	3.50	6.82	5.97	9.35	7.21	3.87	8.08
95% CI	lower limit [mmHg]	175.80	4.81	8.40	155.62	13.07	20.31	10.96	35.18	38.63	35.36
	upper limit [mmHg]	183.92	5.26	9.33	155.62	14.23	21.87	12.31	38.47	40.53	39.09

The mean values of air permeability were plotted against interface pressure in the Chart 9-11. As to be expected, with increasing interfacial pressure the air permeability decreased. It means, after washing the shrinkage occurs with a consequent decrease in air permeability, because if the fabric structure became closer and tighter due to the shrinkage the air flow through the fabric is smaller.

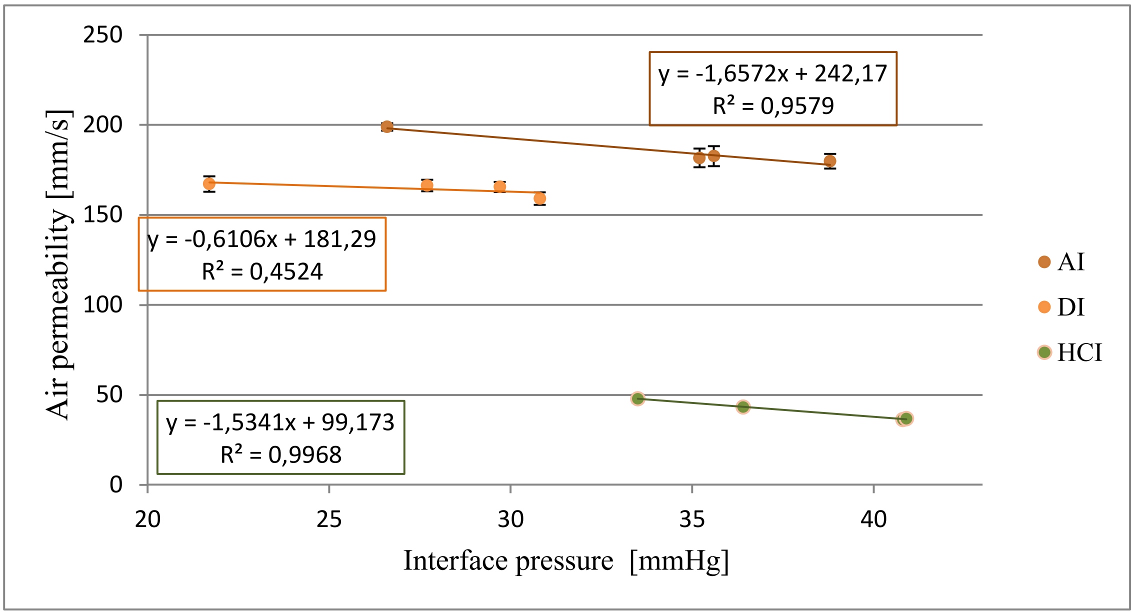

Chart 9: Dependence of interface pressure on air permeability for CCLI

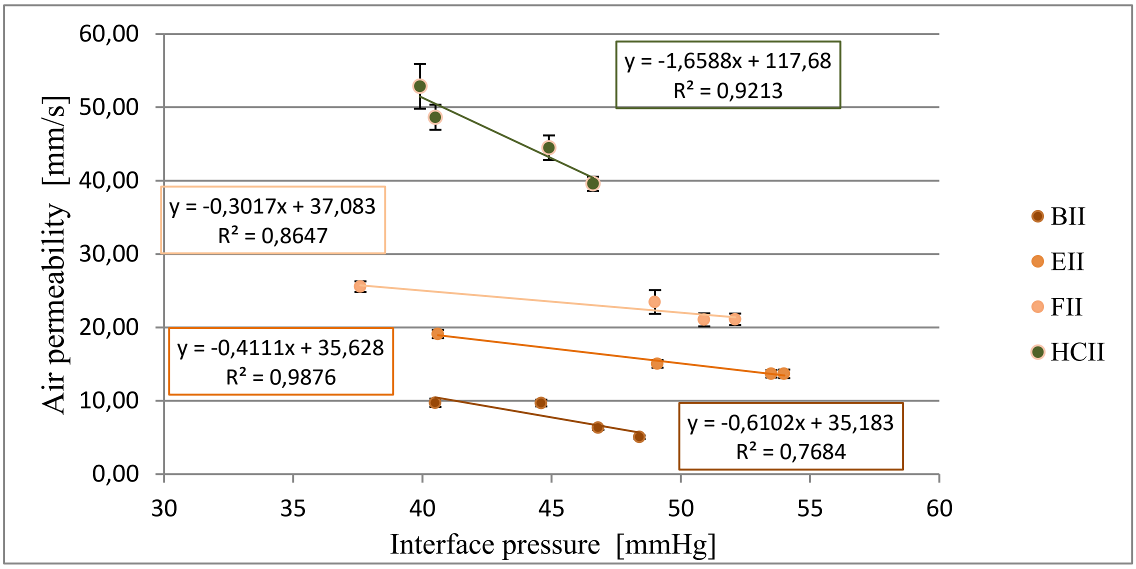

Chart 10: Dependence of interface pressure on air permeability for CCLII

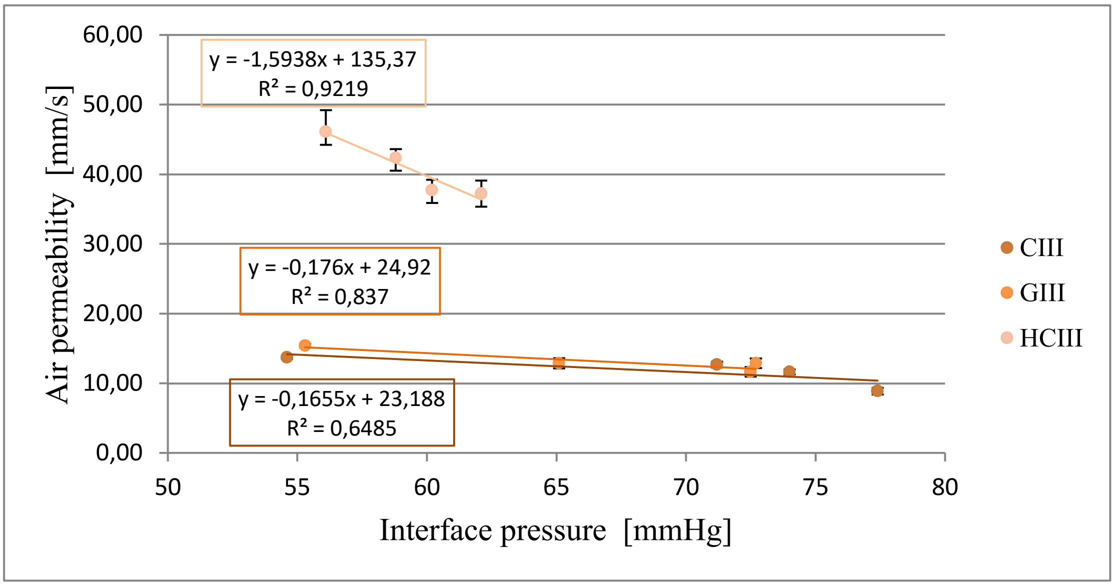

Chart 11: Dependence of interface pressure on air permeability for CCLIII

4.5.4. Evaluation of Laundering Effect

MCS as knitted fabrics are highly stretchable structures that are able to shrink and relax. Wet treatments create ideal conditions for this inherent tendency of fabric to shrink. As the results shown, each washing process caused the shrinkage of MCS fabric and due to this phenomenon the interfacial pressure exerted on the leg increased.

The minimal dimensional changes and related interfacial pressure changes were obtained after HW for all MCS. Those low values of changes can be explained by low temperature of water bath and minimum mechanical stresses on fabric in wet state. The increasing measured values are caused mainly as a result of the wet relaxation treatment.

Compared to HW, washing in washing machine had significantly higher influence on dimensional stability. The results also suggest there were none or very low significant differences between interfacial pressures of individual MCS that were subjected to WM1 and WM2. Though it cannot be confirmed the influence of two different laundry processes in washing machine on interfacial pressure, both of those washings significantly influenced interface pressure compared to unwashed samples. The mean pressure values of samples washed in washing machine are much higher than pressure values of samples before washing. This increased of interface pressure is related to the fabric shrinkage and can be explained as a consolidation shrinkage which occurs as a combination of temperature, moisture and mechanical stresses (agitation during washing in washing machine).

The measurements of air permeability prove the dimensional change of fabric, with increasing shrinkage decrease the air space and the air permeability decreases.

Conclusion

In this research work 10 different medical compression stockings (MCS) with 3 different compression classes for standard 22-26 cm circumference are tested for compression pressure, effect of washing and performance with respect to time.

The effect of long term wearing on compression pressure exerted by ten different MCS and its variation during 48 hours. Measurements were performed at static mode using Kikuhime device and standardized wooden leg model. From the results, it has been observed that the interface pressure generated by MCS significantly depends on time. All tested samples of MCS have relaxed or stretched significantly under extension which leaded to the pressure degradation. The efficacy of different types of MCS varies because of the different structures and used material in manufacturing. It has been found that compression stockings having cotton in its composition have a poor stability of compression pressure due to the higher stress relaxation. From 34 - 41% of total pressure decrease was observed for those MCS in first 24 hours, after 48 hours the pressure decrease was over 50%. Many MCS have to be worn at least 23 hours per day and this pressure degradation may significantly influence the compression therapy especially to the patients who are unable to walk.

Three different types of laundering were performed to analyze the influence of washing on interfacial pressure exerted by MCS. Washing processes included hand washing, performed according the manufacturer recommendation, and two washings using washing machine with two different settings. The main purpose of these washing processes was to simulated laundry conditions that can occur in regular household. Though it could not be confirmed the trend of the material composition or stitch density in the experiment, it was founded that major changes in the dimensions and related compression pressure increase occur with the washing in washing machine. This increase was apparently caused by combination of higher temperature and mechanical stresses in the form of agitation during washing in washing machine.

It can be finally concluded form research that medical compression socks loses the compression pressure even after wearing for few hours and nearly 20 – 55 % decrease in pressure is observed after 20-48 hour. The washing increases the compression pressure and one of the reasons is the shrinkage of the structure.

Durability of compression socks is a comprehensive topic due to the variability of factors which could influence the compression durability of socks. Overall understanding would need more time and another testing, which would be beyond this work. But assumptions from this thesis might be addressed in future studies.

References

[1] ŠTOČKOVÁ, Hana. *Textilní zbožíznalství: pleteniny*. Liberec: Technická univerzita v Liberci, 2006. ISBN 80-7372-114-7.

[2] KOVÁŘ, Radko. *Pletení*. Liberec: Technická univerzita, 1997. ISBN isbn80-7083-244-4.

[3] KOVÁŘ, Radko. *Struktura a vlastnosti textilií 2: struktura a vlastnosti pletenin*. Liberec: Technická univerzita v Liberci, 1998. ISBN isbn80-7083-266-5.

[4] MENCÁKOVÁ, Michaela. *Uplatnění metody konečných prvků v konstrukci kompresních oděvů*. Liberec, 2016. Diplomová práce. Technická univerzita v Liberci.

[5] KOVÁŘ, Radko. *Struktura a vlastnosti plošných textilií*. V Liberci: Technická univerzita, 2003. ISBN isbn80-7083-676-8.

[6] KOVAČIČ, Vladimír. *Textilní zkušebnictví*. Liberec: Technická univerzita, 2004. ISBN isbn80-7083-825-6.

[7] MOEIN, Hadi, Ulises SCHMILL, Mojtaba KOMEILI, Shahram POURAZADI a Carlo MENON. Effect of the Leg Volume Change on the Performance of an Active Compression Brace Based on Shape Memory Alloys. *Journal of Medical and Biological Engineering* [online]. 2017, **37**(2), 248-261 [cit. 2018-09-16]. DOI: 10.1007/s40846-017-0218-4. ISSN 1609-0985. Dostupné z: http://link.springer.com/10.1007/s40846-017-0218-4

[8] KWON, Cassandra Hyun. *Characterizing the Relationship of Tensile Properties and Pressure Profiles of Compression Bandages and Fabrics*. Raleigh, 2014. Disertační práce. North Carolina State University.

[9] KOVÁŘ, Radko. *Pletení*. Liberec: Technická univerzita, 1997. ISBN isbn80-7083-244-4.

[10] LIM, Chung Sim a Alun H. Graduated compression stockings. *NCBI* [online]. 2014 [cit. 2018-09-18]. Dostupné z: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4081237/

[11] BROULÍKOVÁ, Alena. *Chronické žilní onemocnění – současný pohled* [online]. 2010, , 3 [cit. 2018-09-18]. Dostupné z: https://www.internimedicina.cz/pdfs/int/2010/09/04.pdf

[12] VAN DER WEGEN-FRANKEN, Catharina. *Medical Elastic Compression Stockings*. Helmond, 2009. Disertační práce. Erasmus Universiteit Rotterdam.

[13] ŠVESTKOVÁ, Sabina. *Kompresivní terapie u chronického žilního onemocnění* [online]. 3.9.2009, , 2 [cit. 2018-09-18]. Dostupné z: https://www.dermatologiepropraxi.cz/pdfs/der/2009/05/05.pdf

[14] *Principles of compression in venous disease: a practitioner's guide to treatment and prevention of venous leg ulcers* [online]. 10. 5. 2013, , 24 [cit. 2018-09-18]. Dostupné z: https://www.woundsinternational.com/resources/details/principles-compression-venous-disease-practitioners-guide-treatment-and-prevention-venous-leg-ulcers

[15] Compression Stockings. *VenaCure-EVLT* [online]. [cit. 2018-09-18]. Dostupné z: http://venacure-evlt.com/endovenous-laser-vein-treatment/alternatives/compression-stocking/

[16] *RAL-GZ 387/1: Medical Compression Hosiery - Quality Assurance*. Sankt Augustin: RAL Deutsches Institut für Gütesicherung und Kennzeichnung e.V., 2008.

[17] XIONG, Ying a Tao XIAOMING. *Compression Garments for Medical Therapy and Sports* [online]. 14.6.2018, , 19 [cit. 2018-09-18]. Dostupné z: http://www.mdpi.com/2073-4360/10/6/663

[18] KOČÍ, Vladimír. *Vazby pletenin*. Praha: Státní nakladatelství technické literatury, 1980.

[19] Materiály. *Aries* [online]. [cit. 2018-09-24]. Dostupné z: http://cz.aries.eu/materialy-a-vyroba/materialy

[20] LIU, Rong, Xia GUO, Terence T LAO a Trevor LITTLE. A critical review on compression textiles for compression therapy: Textile-based compression interventions for chronic venous insufficiency. *Textile Research Journal* [online]. 2016, **87**(9), 1121-1141 [cit. 2018-09-24]. DOI: 10.1177/0040517516646041. ISSN 0040-5175. Dostupné z: http://journals.sagepub.com/doi/10.1177/0040517516646041

[21] HEGARTY-CRAVER, Meghan, Cassandra KWON, William OXENHAM, Edward GRANT a Lawrence REID. Towards characterizing the pressure profiles of medical compression hosiery: an investigation of current measurement devices and techniques. *The Journal of The Textile Institute* [online]. 2014, **106**(7), 757-767 [cit. 2018-09-24]. DOI: 10.1080/00405000.2014.941535. ISSN 0040-5000. Dostupné z:http://www.tandfonline.com/doi/full/10.1080/00405000.2014.941535

[22] TYLER, David. Application of pressure sensors in monitoring pressure. HAYES, Steven G. a Praburaj VENKATRAMAN. *Materials and technology for sportswear and performance apparel* [online]. Boca Raton : CRC Press, 2015, s. 289–310 [cit. 2018-09-24]. ISBN 9781482220506. Dostupné z: https://e-space.mmu.ac.uk/532/1/Tyler_Ch%2012%20Monitoring%20pressure%20GreenOA.pdf

[23] ANNIS, Patricia A. *Understanding and improving the durability of textiles*. Philadelphia, Pa.: Woodhead Pub., 2012. Woodhead publishing in textiles, no. 132. ISBN isbn9780857090874.

[24] ODĚRY A ŽMOLKOVÁNÍ. *Textilní zkušební ústav* [online]. [cit. 2018-09-24]. Dostupné z: https://www.tzu.cz/odery-a-zmolkovani

[25] FILATOV, Vladimir Nikolajevič. *Navrhování pružných textilních výrobků: studijní pomůcka pro studenty středních i vysokých škol textilního zaměření*. Praha: Státní nakladatelství technické literatury, 1984

[26] HUNTER, Lawrance a Jintu FAN. *Engineering apparel fabrics and garments*. Cambridge (Massachuttes): Woodhead Publishing Limited, 2009. ISBN 978-1-84569-134-9.

[27] ČSN ISO 9237. *Textilie - Zjišťování prodyšnosti plošných textilií*. Praha: Český normalizační institut, 1996, 12 s. Třídící znak 80 0817.

[28] *Textilní zkušební ústav: PEVNOST V DALŠÍM TRHÁNÍ* [online]. [cit. 2018-09-29]. Dostupné z: https://www.tzu.cz/pevnost-v-dalsim-trhani

[29] KOVÁŘ Radko, Teorie pletení, Vysoká škola strojní a textilní v Liberci, 1986. 55-819-86

[30] Knitted fabrics and types – list of knitted fabrics. *TextileSchool* [online]. 2018 [cit. 2019-03-23]. Dostupné z: https://www.textileschool.com/251/knitted-fabrics-and-types/

[31] ANAND, S.C., K.S.M. BROWN, L.G. HIGGINS, M.E. HALL a D. CONRAD. Effect of laundering on the dimensional stability and distortion of knitted fabricss. *AUTEX Research Journal* [online]. 2002, (2.), 16 [cit. 2018-09-29]

[32] Co byste měli vědět. *VARITEX* [online]. [cit. 2018-09-29]. Dostupné z: https://www.varitex.cz/co-byste-meli-vedet

[33] COOPER, A.S., Helen M. ROBINSON, Wilson A. REEVES a William G. SLOAN. Mechanism for Stretch and Recovery Properties of Certain Stretch Fabrics1. *Textile Research Journal* [online]. 2016, **35**(5), 452-458 [cit. 2019-03-01]. DOI: 10.1177/004051756503500512. ISSN 0040-5175. Dostupné z: http://journals.sagepub.com/doi/10.1177/004051756503500512

[34] KUMAR, Bipin, Apurba DAS a R. ALAGIRUSAMY. *Science of Compression Bandage*. New Delhi: Woodhead Publishing India Pvt., 2014. ISBN 978-93-80308-41-8.

[35] JEDDI, Asgharian. *The study of dimensional and geometrical properties of weft knitted fabrics constructed from cotton yarns* [online]. 1985 [cit. 2019-03-23]. Dostupné z: https://www.dora.dmu.ac.uk/handle/2086/13251. Disertace. De Montfort University.

[36] HASHEMI, Nasrin, Azita ASAYESH, Ali Asghar Asgharian JEDDI a Toba ARDAKANI. The influence of two bar warp-knitted structure on the fabric tensile

stress relaxation Part I: (reverse locknit, sharkskin, queens' cord). *The Journal of The Textile Institute* [online]. 2015, **107**(4), 512-524 [cit. 2019-03-23]. DOI: 10.1080/00405000.2015.1046288. ISSN 0040-5000. Dostupné z: http://www.tandfonline.com/doi/full/10.1080/00405000.2015.1046288

[37] GOLDMAN, Mitchel, Robert WEISS, Jean-Jérome GUEX, et al. *Sclerotherapy: Treatment of Varicose and Telangiectatic Leg Veins*. 6th ed. China: Elsevier, 2017. ISBN 978-0-323-37726-3.

[38] HUI, C.L. a S.F. NG. Theoretical Analysis of Tension and Pressure Decay of a Tubular Elastic Fabric. *Textile Research Journal* [online]. 2016, 73(3), 268-272 [cit. 2019-04-12]. DOI: 10.1177/004051750307300312. ISSN 0040-5175. Dostupné z: http://journals.sagepub.com/doi/10.1177/004051750307300312

List of Figures

List of Charts

List of Tables

List of Annexes

Annex No. 1: *Measurement of basic geometry parameters*

Annex No. 2: *Pressure measurement*

Annex No. 3: *Measurements of the long time wearing effect*

Annex No. 4: *Pressure measurements after laundering*

Annex No. 5: *Air permeability measurements*

Annexes

Annex No. 1: *Measurement of basic geometry parameters*

Stitch density measurement

Table 22: Stitch density measuring (AI, BII, CIII, DI, EII)

Measurements	Sample identification									
	AI		BII		CIII		DI		EII	
	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]
1	28	22	24	22	27	21	27	13	27	20
2	28	22	24	22	27	21	27	13	27	20
3	28	22	24	21	26	21	27	14	27	20
4	28	22	23	22	27	21	27	13	28	20
5	28	22	24	22	26	21	27	13	27	21
Mean [Loops/cm]	28	22	23,8	21,8	26,6	21	27	13,2	27,2	20,2
Dispersion [Loops/cm]^2	0	0	0,20	0,20	0,30	0	0	0,20	0,20	0,20
SD [Loops/cm]	0	0	0,45	0,45	0,55	0	0	0,45	0,45	0,45
Coefficient of variation [%]	0	0	1,88	2,05	2,06	0	0	3,39	1,64	2,21
95% CI lower limit [Loops/cm]	0	0	23,41	21,41	26,12	0	0	12,81	26,81	19,81
95% CI upper limit [Loops/cm]	0	0	24,19	22,19	27,08	0	0	13,59	27,59	20,59
Stitch density [Loops/cm^2]	**616**		**518,84**		**558,6**		**356,4**		**549,44**	

Table 23: Stitch density measuring (FII, GIII, HCI, HCII, CHIII)

Measurements		FII		GIII		HCI		HCII		HCIII	
		Sample identifications									
		SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]	SD_W [Loops/cm]	SD_C [Loops/cm]
1		26	22	27	18	26	25	24	23	28	22
2		26	22	27	18	26	25	23	23	28	22
3		26	22	27	17	26	25	24	23	27	22
4		26	22	27	18	26	25	24	23	28	23
5		26	22	28	18	26	25	24	23	27	22
Mean [Loops/cm]		26	22	27,2	17,8	26	25	23,8	23	27,6	22,2
Dispersion [Loops/cm]^2		0	0	0,2	0,2	0	0	0,2	0	0,3	0,2
SD [Loops/cm]		0	0	0,45	0,45	0	0	0,45	0	0,55	0,45
Coefficient of variation [%]		0	0	1,64	2,51	0	0	1,88	0	1,98	2,01
95% CI	lower limit [Loops/cm]	0	0	26,81	17,41	0	0	23,41	0	27,12	21,81
	upper limit [Loops/cm]	0	0	27,59	18,19	0	0	24,19	0	28,08	22,59
Stitch density [Loops/cm^2]		**572**		**484,16**		**650**		**547,40**		**612,72**	

Material thickness measurement

Figure 16: Digital SDL M034A device

Table 24: Thickness measuring

Measurements		**Sample identification**									
		AI	BII	CIII	DI	EII	FII	GIII	HCI	HCII	HCIII
1		0,92	0,76	0,56	0,73	1,05	0,79	0,99	0,79	0,81	0,74
2		1,01	0,76	0,71	0,7	1,01	0,76	0,97	0,83	0,87	0,78
3		0,96	0,77	0,59	0,69	0,97	0,78	0,95	0,86	0,91	0,83
4		0,93	0,76	0,71	0,68	0,93	0,78	0,93	0,9	0,94	0,83
5		0,91	0,77	0,69	0,65	0,88	0,79	0,91	1,02	0,91	0,82
6		0,9	0,74	0,58	0,69	0,95	0,8	0,94	0,82	0,79	0,72
7		0,95	0,76	0,57	0,66	1	0,78	0,99	0,8	0,88	0,79
8		0,94	0,76	0,6	0,68	0,93	0,76	0,98	0,95	0,82	0,76
9		0,98	0,78	0,72	0,69	0,9	0,78	0,92	0,93	0,84	0,84
10		0,92	0,76	0,63	0,72	0,98	0,78	0,93	0,89	0,92	0,85
Mean [mm]		0,942	0,762	0,636	0,690	0,950	0,780	0,951	0,879	0,869	0,796
Dispersion [mm]		0,0012	0,0001	0,0042	0,0852	0,0920	0,0002	0,0009	0,005	0,003	0,002
SD $[mm]^2$		0,034	0,010	0,065	0,292	0,303	0,012	0,030	0,073	0,052	0,045
Coefficient of variation [%]		3,602	1,355	10,168	42,307	31,925	1,599	3,113	8,351	5,954	5,656
95% CI	lower limit [mm]	0,921	0,756	0,596	0,509	0,762	0,772	0,933	0,834	0,837	0,768
	upper limit [mm]	0,963	0,768	0,676	0,871	1,138	0,788	0,969	0,924	0,901	0,824

Annex No. 2: *Pressure measurement*

Table 25: Individual pressure measurements at cB level

Measurements		Sample identification									
		AI	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
		CCL I	CC L II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
1		27	42	54	20	37	37	59	35	40	58
2		25	41	56	23	41	37	53	32	39	56
3		26	40	55	20	38	37	54	34	42	56
4		28	39	55	21	42	39	56	31	40	55
5		27	39	53	24	44	37	55	35	38	54
6		26	42	54	21	39	38	54	34	41	57
7		25	40	54	22	44	38	59	33	41	56
8		29	40	56	23	38	37	52	34	38	58
9		27	40	56	21	41	37	58	32	41	55
10		26	42	53	22	42	39	53	35	39	56
Mean [mmHg]		26,60	40,5	54,60	21,70	40,60	37,60	55,30	33,50	39,90	56,10
Dispersion [$mmHg^2$]		1,60	1,39	1,38	1,79	6,27	0,71	6,78	2,06	1,88	1,66
SD [mmHg]		1,26	1,18	1,17	1,34	2,50	0,84	2,60	1,43	1,37	1,29
Coefficient of variation [%]		4,76	2,91	2,15	6,16	6,17	2,24	4,71	4,28	3,43	2,29
95% CI	lower limit [mmHg]	25,82	39,7	53,87	20,87	39,05	37,08	53,69	32,61	39,05	55,30
	upper limit [mmHg]	27,38	41,2	55,33	22,53	42,15	38,12	56,91	34,39	40,75	56,90

Annex No. 3: *Measurements of the long time wearing effect*

Individual measurements of compression pressure in 48 hours

Table 26: Pressure decrease of AI sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
AI	1	26	23	18	18	14
	2	28	24	19	17	14
	3	26	22	17	16	13
Mean [mmHg]		26,67	23,00	18,00	17,00	13,67
Dispersion [$mmHg^2$]		1,33	1,00	1,00	1,00	0,33
SD [mmHg]		1,15	1,00	1,00	1,00	0,58
Coefficient of variation [%]		4,33	4,35	5,56	5,88	4,22
95% - CI	lower limit [mmHg]	25,36	21,87	16,87	15,87	13,01
	upper limit [mmHg]	27,97	24,13	19,13	18,13	14,32

Table 27: Pressure decrease of BII sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
BII	1	40	37	30	28	25
	2	42	40	33	32	27
	3	40	39	33	31	27
Mean [mmHg]		40,67	38,67	32,00	30,33	26,33
Dispersion [$mmHg^2$]		1,33	2,33	3,00	4,33	1,33
SD [mmHg]		1,15	1,53	1,73	2,08	1,15
Coefficient of variation [%]		2,84	3,95	5,41	6,86	4,38
95% - CI	lower limit [mmHg]	39,36	36,94	30,04	27,98	25,03
	upper limit [mmHg]	41,97	40,40	33,96	32,69	27,64

Table 28: Pressure decrease of CIII sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
CIII	1	54	48	37	36	29
	2	53	48	38	37	31
	3	55	50	38	36	29
Mean [mmHg]		54,00	48,67	37,67	36,33	29,67
Dispersion [$mmHg^2$]		1,00	1,33	0,33	0,33	1,33
SD [mmHg]		1,00	1,15	0,58	0,58	1,15
Coefficient of variation [%]		1,85	2,37	1,53	1,59	3,89
95% - CI	lower limit [mmHg]	52,87	47,36	37,01	35,68	28,36
	upper limit [mmHg]	55,13	49,97	38,32	36,99	30,97

Table 29: Pressure decrease of DI sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
DI	1	25	22	17	17	15
	2	21	19	17	16	14
	3	22	19	15	15	14
Mean [mmHg]		22,67	20,00	16,33	16,00	14,33
Dispersion [$mmHg^2$]		4,33	3,00	1,33	1,00	0,33
SD [mmHg]		2,08	1,73	1,15	1,00	0,58
Coefficient of variation [%]		9,18	8,66	7,07	6,25	4,03
95% - CI	lower limit [mmHg]	20,31	18,04	15,03	14,87	13,68
	upper limit [mmHg]	25,02	21,96	17,64	17,13	14,99

Table 30: Pressure decrease of EII sample in 48 hours

Sample identification	**Measurements**	**After application [mmHg]**	**After 4 hours [mmHg]**	**After 24 hours [mmHg]**	**After 28 hours [mmHg]**	**After 48 hours [mmHg]**
EII	1	43	39	28	26	19
	2	40	38	26	26	17
	3	41	36	26	23	18
Mean [mmHg]		41,33	37,67	26,67	25,00	18,00
Dispersion [mmHg^2]		2,33	2,33	1,33	3,00	1,00
SD [mmHg]		1,53	1,53	1,15	1,73	1,00
Coefficient of variation [%]		3,70	4,06	4,33	6,93	5,56
95% - CI	lower limit [mmHg]	39,60	35,94	25,36	23,04	16,87
	upper limit [mmHg]	43,06	39,40	27,97	26,96	19,13

Table 31: Pressure decrease of FII sample in 48 hours

Sample identification	**Measurements**	**After application [mmHg]**	**After 4 hours [mmHg]**	**After 24 hours [mmHg]**	**After 28 hours [mmHg]**	**After 48 hours [mmHg]**
FII	1	37	33	22	21	17
	2	39	34	21	21	19
	3	37	35	23	22	18
Mean [mmHg]		37,67	34,00	22,00	21,33	18,00
Dispersion [mmHg^2]		1,33	1,00	1,00	0,33	1,00
SD [mmHg]		1,15	1,00	1,00	0,58	1,00
Coefficient of variation [%]		3,07	2,94	4,55	2,71	5,56
95% - CI	lower limit [mmHg]	36,36	32,87	20,87	20,68	16,87
	upper limit [mmHg]	38,97	35,13	23,13	21,99	19,13

Table 32: Pressure decrease of GIII sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
GIII	1	52	49	37	37	29
	2	55	53	42	41	33
	3	56	53	40	39	32
Mean [mmHg]		54,33	51,67	39,67	39,00	31,33
Dispersion [$mmHg^2$]		4,33	5,33	6,33	4,00	4,33
SD [mmHg]		2,08	2,31	2,52	2,00	2,08
Coefficient of variation [%]		3,83	4,47	6,34	5,13	6,64
95% - CI	lower limit [mmHg]	51,98	49,05	36,82	36,74	28,98
	upper limit [mmHg]	56,69	54,28	42,51	41,26	33,69

Table 33: Pressure decrease of HCI sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
HCI	1	34	29	21	20	15
	2	31	27	19	19	14
	3	33	27	22	21	15
Mean [mmHg]		32,67	27,67	20,67	20,00	14,67
Dispersion [$mmHg^2$]		2,33	1,33	2,33	1,00	0,33
SD [mmHg]		1,53	1,15	1,53	1,00	0,58
Coefficient of variation [%]		4,68	4,17	7,39	5,00	3,94
95% - CI	lower limit [mmHg]	30,94	26,36	18,94	18,87	14,01
	upper limit [mmHg]	34,40	28,97	22,40	21,13	15,32

Table 34: Pressure decrease of HCII sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
HCII	1	41	38	27	27	21
	2	39	37	24	23	18
	3	39	36	27	26	19
Mean [mmHg]		39,67	37,00	26,00	25,33	19,33
Dispersion [$mmHg^2$]		1,33	1,00	3,00	4,33	2,33
SD [mmHg]		1,15	1,00	1,73	2,08	1,53
Coefficient of variation [%]		2,91	2,70	6,66	8,22	7,90
95% - CI	lower limit [mmHg]	38,36	35,87	24,04	22,98	17,60
	upper limit [mmHg]	40,97	38,13	27,96	27,69	21,06

Table 35: Pressure decrease of HCIII sample in 48 hours

Sample identification	Measurements	After application [mmHg]	After 4 hours [mmHg]	After 24 hours [mmHg]	After 28 hours [mmHg]	After 48 hours [mmHg]
HCIII	1	58	50	35	33	23
	2	55	47	33	32	26
	3	54	46	35	32	22
Mean [mmHg]		55,67	47,67	34,33	32,33	23,67
Dispersion [$mmHg^2$]		4,33	4,33	1,33	0,33	4,33
SD [mmHg]		2,08	2,08	1,15	0,58	2,08
Coefficient of variation [%]		3,74	4,37	3,36	1,79	8,80
95% - CI	lower limit [mmHg]	53,31	45,31	33,03	31,68	21,31
	upper limit [mmHg]	58,02	50,02	35,64	32,99	26,02

Annex No. 4: *Pressure measurements after laundering*

Table 36: Individual pressure measurements at cB level after hand washing

HW										
Measurements	**Sample identification**									
	AI	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
	CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
1	35	45	71	27	48	48	62	38	37	56
2	37	47	73	29	48	50	68	36	38	61
3	36	42	70	29	50	49	67	37	43	58
4	35	44	72	27	49	49	65	36	41	57
5	36	45	71	28	50	48	63	35	39	60
6	37	47	70	27	49	50	62	38	42	59
7	35	42	72	27	48	49	68	36	43	61
8	35	43	70	29	51	51	66	37	40	59
9	36	46	73	26	50	48	65	35	39	60
10	34	45	70	28	48	48	65	36	43	57

Table 37: Individual pressure measurements at cB level after washing in washing machine (WM1)

WM1										
Measurements	**Sample identification**									
	AI	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
	CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
1	32	42	74	30	53	51	72	40	45	62
2	37	47	73	30	55	54	73	42	45	57
3	35	50	74	29	51	49	75	42	46	63
4	36	49	74	30	56	49	71	39	43	61
5	37	46	74	31	54	51	72	40	47	60
6	33	44	75	39	51	50	71	42	44	58
7	36	49	73	30	54	49	73	42	43	60
8	35	48	76	30	53	52	74	40	45	60
9	36	44	74	31	52	51	71	40	46	62
10	35	49	73	28	56	53	75	41	45	59

Table 38: Individual pressure measurements at cB level after washing in washing machine (WM2)

WM2										
Measurements	**Sample identification**									
	AI	**BII**	**CIII**	**DI**	**EII**	**FII**	**GIII**	**HCI**	**HCII**	**HCIII**
	CCL I	CCL II	CCL III	CCL I	CCL II	CCL II	CCL III	CCL I	CCL II	CCL III
1	38	50	78	32	57	50	76	43	47	64
2	39	51	78	30	51	54	67	42	49	62
3	38	46	79	31	56	51	79	39	45	59
4	40	48	79	31	56	53	69	37	44	62
5	39	49	74	30	53	52	73	41	48	63
6	38	46	78	29	55	50	69	40	48	61
7	40	50	79	31	52	54	74	42	49	64
8	38	48	75	31	56	51	70	42	45	63
9	39	49	78	30	51	54	73	40	44	63
10	39	47	76	33	53	52	75	43	47	60

Annex No. 6: *Air permeability measurements*

Table 39: Individual air permeability measurements for AI sample

AI				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	200,40	190,38	172,85	182,87
2	200,40	175,35	170,34	165,33
3	190,38	190,38	182,87	185,37
4	200,40	170,34	190,38	177,86
5	200,40	190,38	187,88	175,35
6	200,40	192,89	172,85	185,37
7	200,40	172,85	187,88	177,86
8	195,39	190,38	172,85	187,88
9	200,40	177,86	190,38	177,86
10	200,40	175,35	187,88	182,87

Table 40: Individual air permeability measurements for BII sample

BII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	10,02	9,02	5,76	4,76
2	8,52	8,02	6,01	5,51
3	9,52	10,02	7,01	5,01
4	11,02	10,02	6,26	4,76
5	9,02	10,02	6,51	5,51
6	9,52	10,52	6,26	4,76
7	8,52	9,52	6,76	5,01
8	10,02	10,02	6,01	4,51
9	11,02	10,02	5,76	5,51
10	10,02	9,52	6,51	5,01

Table 41: Individual air permeability measurements for CIII sample

CIII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	13,78	12,78	11,02	8,02
2	14,03	11,27	12,02	8,52
3	13,53	13,03	12,53	9,52
4	13,78	12,78	11,27	8,52
5	13,03	13,53	11,02	10,02
6	13,53	13,03	12,02	9,52
7	13,78	12,02	11,27	8,02
8	13,78	13,53	11,52	9,02
9	14,03	12,53	11,02	8,02
10	13,78	12,27	12,53	9,52

Table 42: Individual air permeability measurements for DI sample

DI				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	160,32	165,33	160,32	160,32
2	175,35	167,84	162,83	147,80
3	165,33	165,33	160,32	162,83
4	170,34	157,82	167,84	162,83
5	155,31	165,33	170,34	160,32
6	165,33	172,85	172,85	150,30
7	160,32	165,33	165,33	160,32
8	175,35	175,35	167,84	160,32
9	170,34	167,84	160,32	160,32
10	172,85	160,32	167,84	165,33

Table 43: Individual air permeability measurements for EII sample

EII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	20,04	14,28	13,03	14,03
2	18,04	14,03	12,78	12,78
3	19,04	15,53	14,53	14,53
4	18,04	16,53	14,53	13,03
5	19,04	15,28	12,78	15,53
6	20,04	14,78	14,03	12,78
7	18,04	15,03	13,03	14,03
8	20,04	16,03	14,53	13,03
9	18,54	14,78	14,53	14,03
10	20,04	14,03	13,03	12,78

Table 44: Individual air permeability measurements for FII sample

FII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	25,05	25,05	21,54	21,04
2	25,05	27,56	22,55	19,04
3	24,05	20,04	19,54	22,55
4	27,56	20,04	20,04	22,55
5	25,05	23,05	20,04	20,04
6	27,56	24,55	22,55	21,54
7	25,05	24,05	19,04	19,54
8	25,05	20,04	22,55	21,04
9	26,05	25,05	22,55	21,04
10	25,05	25,05	20,04	22,55

Table 45: Individual air permeability measurements for GIII sample

GIII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	15,28	11,27	13,53	11,17
2	15,03	11,02	14,53	12,27
3	15,53	12,53	12,02	12,02
4	15,03	14,03	12,27	13,53
5	16,03	14,78	15,03	11,02
6	15,03	13,78	12,02	10,02
7	15,03	13,03	12,53	12,02
8	16,03	12,78	12,27	10,02
9	15,53	12,53	12,02	12,27
10	15,53	13,03	12,53	12,02

Table 46: Individual air permeability measurements for HCI sample

HCI				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	55,11	45,09	36,57	35,07
2	42,59	47,60	37,58	42,59
3	47,60	42,59	35,07	35,07
4	47,60	42,59	36,07	35,07
5	45,09	40,08	37,58	35,07
6	50,10	40,08	35,07	37,58
7	47,60	47,60	35,07	40,08
8	47,60	40,08	37,58	37,58
9	50,10	44,09	35,07	35,07
10	45,09	42,59	36,57	35,07

Table 47: Individual air permeability measurements for HCII sample

HCII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	47,60	45,09	42,59	39,58
2	55,11	50,10	47,60	41,58
3	47,60	45,09	40,08	40,08
4	60,12	53,00	41,58	40,08
5	60,12	50,10	45,09	37,58
6	50,10	50,10	47,60	37,58
7	55,11	45,09	45,09	40,08
8	47,60	50,10	42,59	41,58
9	50,10	47,60	47,60	40,08
10	55,11	50,10	45,09	37,58

Table 48: Individual air permeability measurements for HCIII sample

HCIII				
Measurements	**NW [mm/s]**	**HW [mm/s]**	**WM1 [mm/s]**	**WM2 [mm/s]**
1	52,61	45,09	40,08	36,57
2	40,08	42,59	40,08	37,58
3	45,09	40,08	37,58	42,59
4	40,08	40,08	35,07	32,57
5	50,10	41,58	37,58	37,58
6	45,09	42,59	34,07	40,08
7	52,61	45,09	40,08	37,58
8	50,10	44,09	40,08	37,58
9	45,09	42,59	37,58	32,57
10	40,08	40,08	35,07	37,58

Obrázek 17: SDL M021S Air Penetration device