Diana Ališauskienė,
Daiva Mikučionienė,
Laima Milašiūtė

Influence of Inlay-Yarn Properties and Insertion Density on the Compression Properties of Knitted Orthopaedic Supports

Kaunas University of Technology,
Department of Textile Technology
Studentu 56, LT-51424 Kaunas, Lithuania
E-mail: diana.alisauskiene@stud.ktu.lt

Abstract
The aim of this study was to investigate the influence of inlay-yarn linear density and insertion density on the compression properties of knitted orthopaedic supports. Samples were made on a flat double needle-bed knitting machine with a laid-in structure knitted on a rib 1×1 pattern base, differing in the inlay-yarn linear density and their insertion density. It was established that for knitted samples with the same insertion density of inlay-yarn, values of pressure differ in the ranges of error if the linear density of the inlay-yarn differs even twice and less. In the area of low extensions (in our case – 10%), the linear pressure depends on the inlay-yarn's PU core linear density, while the dependence of the elastic inlay-yarn's insertion density on pressure values has an exponential character. However, the influence of inlay-yarn linear density on the compression of the knits investigated is not high. Moreover the raw material and linear density of covering yarns do not have any significant influence on pressure generated by the knit in the area of low extensions. When designing a knitted compressive support, it is necessary to find an optimal ratio between the elastic inlay-yarn's linear density and insertion density, thereby achieving the best compressive, wear comfort and economical result.

Key words: *orthopaedic supports, compressive knits, laid–in structure, inlay-yarn.*

Introduction

Knitted orthopaedic supports are one type of medical textile product assigned to compression garments. Most medical compression garments are individually designed and manufactured for particular parts of the body, such as stockings, gloves, sleeves, face masks and body suits. The level of compression is governed by the garment size as well as the amount of fabric stretching. Fabric for compression garments are usually designed with a stretchable structure and contain elastomeric material to achieve highly stretchable and appropriate compression [1].

The fabric used to make compression garments is produced by knitting two types of yarn together: ground yarn, ensuring thickness and stiffness, and inlay-yarn, generating compression. Inlay-yarns are produced by wrapping polyamide or cotton around a stretchable core such as latex or polyurethane (PU). The wrapping can be adjusted to vary the tensility and strength of the yarn. Tensility is a measure of the elongation of yarn by stretching. High power yarn is less easy to stretch and thus applies greater compression [2]. Polyurethane yarn can be inlayed, floated or plated in the knitted structure. The thickness, texture and appearance of the knitted fabric can also be changed by adapting the wrapping of the yarn. Higher levels of compression are mainly achieved by increasing the thickness of the elastic core of inlay-yarn, although adjustments may also be made to the ground yarn [2].

Fabrics containing elastane yarns have a wide application value, especially because of their increased extensibility, elasticity, high degree of recovery, good dimensional stability and simple care [3, 4]. The tensile property is one of the most important indices for evaluating the properties of yarn because the yarn supports the tension during knitting or weaving.

Weft inlay-yarns can be introduced in each course or in certain courses according to a pattern. The presence of these yarns increases the fabric strength and fabric compactness. Such structures with elastomeric yarns inserted are used for welt stockings and for medical products – orthopaedic stockings and supports. Comandar [5] investigated structural variants where elasticity along the course direction is controlled through weft yarn insertion. It was found that the weft inlay-yarn influences fabric extensibility in both (longitudinal and transverse) directions.

Knitted orthopaedic supports are generally divided into three groups: preventive supports, functional supports, and post-operative/rehabilitative supports. The main differences between these supports are the compression size and consolidation strength. The physician prescribes the compression class for compression stockings corresponding to the pathology of the patient. According to German Standard RAL–GZ–387/1:2008 light compression class 1 (18 ÷ 21 mm Hg) or 2 (23 ÷ 32 mm Hg), strong compression is class 3 (34 ÷ 46 mm Hg) or 4 (>49 mm Hg), depending on the norm used. Unfortunately the compression requirements for orthopaedic supports have not been standardised to date. The level of compression is defined by inlay-yarn properties, which are directly related to the modulus of elastic core yarn and its covering parameters [6]. However, there is a lack of data on the influence of the density of inlay-yarn insertion into the knit at the compression level.

The mechanical behaviour of the covered yarn, which is the main yarn component of elastic knitted fabric of medical compression stockings, has been investigated by several authors. Structure analysis shows that the properties of the inlaid yarns reflect significantly the global behaviour of the fabric. Therefore by characterising the elastic properties of the inlay-yarn, it is possible to predict the mechanical behaviour of all medical compression fabrics [6, 7].

The physical properties of weft knitted fabrics for compressive functional behaviour are influenced by different factors: the material – type and linear density of yarn, the knitting structure – pattern and elastic inlay-yarn insertion density, and the production process – machinery and specific parameters of production. The main knitting structures commonly used in orthopaedic supports are as follows: a) half-Milano rib, b) full two-colour Jacquard (Jacquard pattern is used for logos, edges of supports, etc.), c) combined and tuck stitch patterns (some support places specify special compression or not irritate the skin (e.g. popliteal space of knee support), and d) laid-in structure. The main compression load in knitted support is generated by elastic ground and/or laid-in yarn.

There is limited literature on the properties of elastic covered yarns (with different covering yarn raw material) used for medical application. Usually the dimensional and physical properties of core-spun cotton/spandex yarns are investigated. Several studies were carried out to investigate the properties of core-spun cotton/spandex yarns used in single jersey [8, 9], in interlock [10], and in rib knitted structures [11]. Therefore investigations on the influence of elastic covered yarn's linear density on the compression properties of knits used for orthopaedic supports are essential. Also there is lack of investigations demonstrating the dependence of compression properties on the insertion density of elastic inlay-yarn in the knit.

The aim of this study was to establish the influence of the linear density and insertion density of elastic inlay-yarn on the compression properties of knits used for orthopaedic supports. It could help to find protective and economical aspects of the optimal structure of the compressive knit.

Materials and methods

For inlay-yarns, four types of elastic yarns were used considering the linear density and linear density of their PU core-yarn. The inlay-yarn variants were chosen in accordance with the yarns widely used for knitted orthopaedic supports. Three types of covering of PU core-yarn were used in this work: 1) PU yarns double covered with polyamide 6.6 (PA 6.6) yarns, 2) PU yarns double covered with PA 6.6 and viscose yarns, and 3) PU yarns double covered with PA 6.6 and cotton yarns. Details of the yarns used are presented in ***Table 1***. It should be noted that the linear density of elastic covered yarn is not the arithmetical sum of linear densities of core yarn and covering yarns because the covering yarns are not parallel to the core yarn, but twine around the core yarns with a certain twist level.

Table 1. *Characteristics of tested inlay-yarns.*

Yarn code	Linear density of elastomeric inlay-yarn, tex	Linear density of elastic core - (PU), tex	Linear density and raw material of covering yarn (double covered)
PM2	340	233	PA 6.6 11 tex and Viscose 14.3 tex
P3	230	132	PA 6.6 16 tex and PA 6.6 16 tex
PM1	70	47.5	PA 6.6 2.2 tex and Cotton 4.4 tex
P2	55	47	PA 6.6 2.2 tex and PA 6.6 2.2 tex

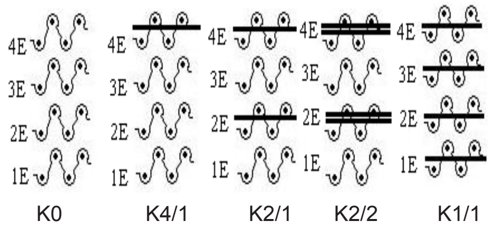

Figure 1. *Pattern of investigated knitted fabrics.*

The linear density of elastic covered yarns was estimated according to Standard D 2591–01. Five segments of yarn of approximately 1300 mm length were cut from each package, taking them at irregular intervals of at least 2 m. The specimens, without tension, were preconditioned on a specimen board in the standard atmosphere for testing textiles (LST EN ISO 139:2005) for a minimum of 4 h. One end of the conditioned specimen was fastened in the top clamp and the tension weight (~1.0 cN/tex) was attached to the opposite end. After approximately 5 s, the bottom clamp was closed. The specimen was cut centrally in the bottom slot and then in the top slot. The actual length of the specimen after cutting was 1 m ± 1 mm. Last of all, the specimen was weighted and its linear density was calculated according to the formula:

$$T = \frac{1000 \cdot M}{L}; \qquad (1)$$

where T is a linear density in tex; M is a mass of the specimen in g; L is a length of the specimen in m.

Average linear density with 1 tex accuracy was calculated from five elementary tests.

The samples were made on a flat double needle-bed knitting machine CMS 340TC-L (f. STOLL, Germany) with an laid-in structure knitted on a rib 1×1 pattern base, differing in the inlay-yarn linear density and that of the insertion into the knitted structure. Two types of yarn for basic structure knitting were used: PA 6.6 yarns with a linear density of 7.8 tex and PU yarns with a linear density of 31 tex double covered by PA yarns with a linear density of 2.2 tex. There were five variants of knitted structures made for this research work: variant K0 knitted in a basic rib 1×1 pattern without elastic inlay-yarn, variant K4/1 knitted in a laid–in pattern with one inlay-yarn inserted in every fourth course, variant K2/1 – with one inlay-yarn inserted in every second course, variant K2/2 – with two inlay-yarns inserted in every second course, and variant K1/1 – with one inlay-yarn inserted in each course. The structure of the knitted fabrics is presented in ***Figure 1***. For each knitting variant (K4/1 ÷ K1/1) four groups of samples, respectively, with inlay-yarns: PM2, P3, PM1, and P2 were knitted. Characteristics of the knitted fabrics tested are presented in ***Table 2***.

The tensile behaviour of the knitted fabrics tested was evaluated using a universal testing machine - ZWICK/Z005 according to Standard LST EN ISO 13934–1:2000. The distance between clamps was 100 mm, tensile speed – 100 mm/min, and pretension – 2N. Knitted samples were strained till 10% fixed extension. Five tests were performed in each case.

Compression of the knitted fabrics tested is calculated by the Laplace formula [12, 13]:

Table 2. *Characteristics of tested knits.*

Sample code	Structure of knit	Linear density and raw material of ground yarns, tex	Inlay-yarn type	Course density Pc, cm^{-1}	Wale density Pw, cm^{-1}
K0	Knitted samples without inlay-yarn	PA 6.6 (7.8 tex) + PU (31 tex) double covered with PA 6.6 (2.2 tex)	–	14.5 ± 0.27	8.5 ± 0.27
K4/1	Knitted sample with inserted one inlay-yarn in every fourth course		P2	14.8 ± 0.28	8.1 ± 0.21
			PM1	14.0 ± 0.01	8.0 ± 0
			P3	14.0 ± 0.79	7.5 ± 0.39
			PM2	14.5 ± 0.92	7.3 ± 0.46
K2/1	Knitted sample with inserted one inlay-yarn in every second course		P2	14.2 ± 0.43	8.0 ± 0
			PM1	12.2 ± 0.27	7.5 ± 0
			P3	13.3 ± 0.46	7.0 ± 0
			PM2	12.5 ± 0	6.8 ± 0.46
K2/2	Knitted sample with inserted two inlay-yarns in every second course		P2	14.8 ± 0.27	7.8 ± 0.27
			PM1	12.5 ± 0.57	7.5 ± 0
			P3	12.6 ± 0.39	7.0 ± 0
			PM2	12.6 ± 0.39	6.5 ± 0
K1/1	Knitted sample with inserted one inlay-yarn in each course		P2	12.5 ± 0.57	7.2 ± 0.27
			PM1	12.0 ± 0	7.0 ± 0
			P3	10.0 ± 0.39	6.5 ± 0.65
			PM2	10.0 ± 0.40	6.5 ± 0.65

Table 3. *Tensile force F values considering to inlay-yarn linear density and insertion into the knit density.*

Inlay-yarn code	Structure of knit			
	K1/1	K2/2	K2/1	K4/1
	Tensile force F, N			
PM2	26.04 ± 0.41	16.88 ± 0.56	14.80 ± 0.47	11.49 ± 0.54
P3	23.87 ± 0.52	15.56 ± 0.21	13.73 ± 0.35	11.23 ± 0.43
PM1	13.69 ± 0.23	10.87 ± 0.41	10.12 ± 0.13	10.02 ± 0.23
P2	15.23 ± 0.31	11.43 ± 0.19	10.68 ± 0.12	10.37 ± 0.13

$$P = \frac{2 \cdot \pi \cdot F}{S}, \qquad (2)$$

where P is the pressure in Pa, F the force in the knitted sample in N, S the area of the knitted sample in m^2.

All experiments were carried out in a standard atmosphere for testing according to Standard ISO 139:2002. Structure parameters of the knitted samples were analysed according to British Standard BS 5441:1998.

Results and discussions

In order to analyse the influence of the inlay-yarn's linear density and insertion density on the elasticity of weft knitted orthopaedic supports, research of tensile properties was carried out with four groups of elastic double covered inlay-yarns laid in the knit in four different variants (as presented in ***Table 2***). Values of the tensile force measured are presented in ***Table 3***. The coefficient of variation of the tensile force measurements ranged from 0.99 % to 3.42 %. The experiment is informative because the Fisher criterion found much more than the tabular: 155.04÷302.42, $F_{tabular}$ = 0.6287.

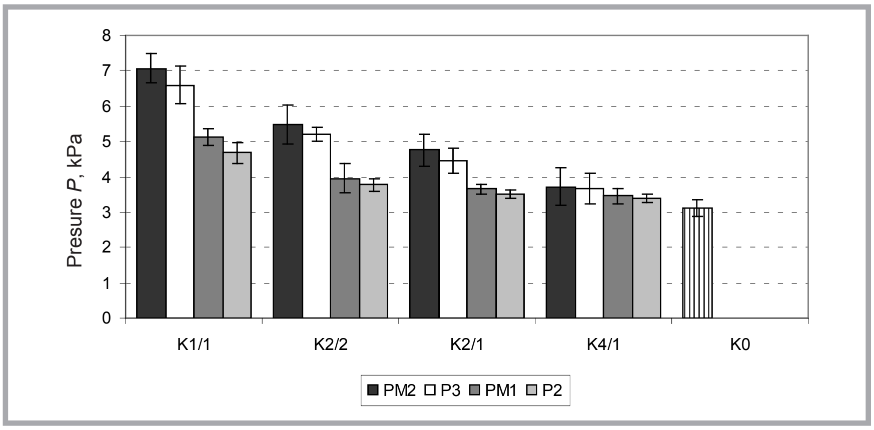

Figure 2. *Pressure P generated by knits considering to elastic inlay-yarn linear density and insertion density.*

Pressure generated by the knitted sample (strained till 10% fixed extension) is calculated by formula (2) and the influence of the elastic inlay-yarn's insertion density on pressure values of the knits is presented in ***Figure 2.*** The results presented show an evident tendency that by increasing the elastic inlay-yarn's insertion density the pressure of the knitted samples increases also. As might have been expected the highest pressure values are reached for knitted samples K1/1, with the highest insertion density (inlay-yarn is inserted in each course), compared with those without inlay-yarn - K0. Depending on the inlay-yarn type selected, pressure values significantly increased from approximately 50% till 127% (~50% for inlay-yarn P2, ~ 65% for inlay-yarn PM1, ~ 112% for inlay-yarn P3, and ~ 127% for inlay-yarn PM2). The results obtained show that for samples with the lowest inlay-yarn insertion density - K4/1, the pressure, depending on the elastic inlay-yarn's linear density, increased from 8.6% till 19.5%, for K2/1 – from 12.2% till 52.6%, and for K2/2 samples – from 21% till 76.45% (comparing with knits without inlay-yarn - K0). Comparing the pressure values of sample K2/1 with those of sample K2/2, which differ in the additional inlay-yarn in each second course, it can be noticed that pressure values increase only from 7.8% till 16.8% (depending on the inlay-yarn's linear density). Additional inlay-yarn insertion into the knitted structure does not have a significant influence on the increasing of pressure; however, the knitted structure of these samples is much rougher and stiffer. It can be concluded that compared with samples which have got inlay-yarn in each course, the pressure decreases approximately 1.5 times when inlay-yarn is inserted in every second course and approximately 1.9 times when inlay-yarn is inserted in every fourth course. However, it is interesting that in all cases for samples with the same insertion density of inlay-yarn (K1/1, K2/2 or K2/1), values of pressure differ significantly only when the linear density of the inlay-yarn differs twice or more. In the case of sample K4/1 the pressure values differ in ranges of error, notwithstanding the linear density of the inlay-yarns, of even approx. 6 times. Moreover a similar pressure can be obtained with a twice lower insertion density using inlay-yarns with higher core yarn linear density, thus saving elastic yarns. For medical applications elastic covered yarns are relatively very expensive. The price of elastic yarns depends on many factors: the raw material and linear density of covering yarns, those of the PU core yarn, the linear density of the total elastic yarn, etc. But in any case the same amount of yarns with the same raw material and twice higher core linear density will be less expensive than a twice higher amount of yarns with a twice lower linear density.

As mentioned above, particular parts of a knitted orthopaedic support can have different pressure values. It may also depend on the knitted support purpose. If the support is designed for prophylactic purposes with low compression values, the inlay-yarn can be saved. Consequently in such supports a lower amount of inlay-yarn can be laid and expenses for raw material can be saved. However, for therapeutic or postoperative knitted supports the compression must be higher and the number of inlay-yarns must be selected taking into account what level of compression must be achieved. The elasticity of such supports can be controlled through the insertion density of elastic inlay-yarns.

By analysing the influence of the inlay-yarn's insertion density on the pressure properties of the knitted samples, the influence of the elastic inlay-yarn's linear density on pressure values of the samples was observed. Therefore in the next stage of investigations, we researched how much of the inlay-yarn's linear density influenced the compression of the samples tested.

The inlay-yarns used comprised of elastomeric (PU) core yarn and two covering yarns (PA, viscose or cotton). All samples were divided into four groups according to the inlay-yarn's insertion density. Investigation of the influence of the inlay-yarn's linear density on pressure changes was carried out and the results obtained are presented in ***Figure 3***. The results presented in ***Figure 3*** demonstrate that in the area of low extension (in our case – 10% fixed extension), the linear pressure (with high coefficients of determination) depends on the inlay-yarn's linear density, but the influence of the inlay-yarn's linear density on the compression of the samples investigated is not high. For samples K4/1, with a relatively low inlay-yarn insertion density, that of these

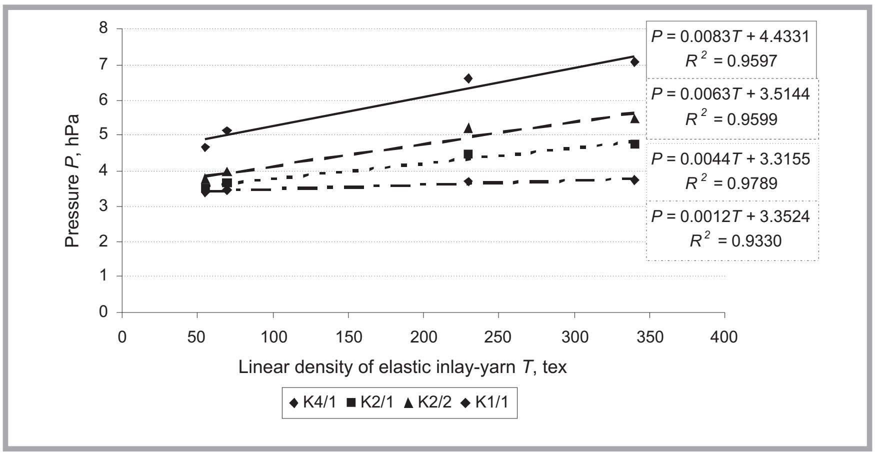

Figure 3. *Dependence of pressure P of knits on linear density of inlay-yarn T.*

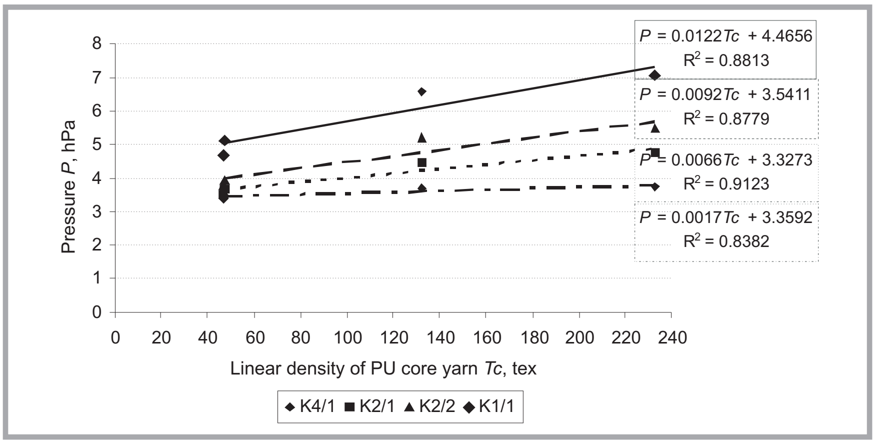

Figure 4. *Dependence of pressure P of knits on linear density of PU core yarn T_c.*

yarns is overall not significant. In this particular case, more than a six times higher yarn linear density changes the pressure of samples only in the ranges of error. For samples K1/1 and K2/1, with a high inlay-yarn insertion density, the linear density of inlay-yarn has a significant influence on pressure only when linear density values differ twice or more. Moreover the influence of the raw material and linear density of covering yarns on the pressure of the knit is wholly insignificant. The raw material of yarns covering the inlay-yarn may be important only for the hygienic and comfort properties of knitted orthopaedic supports, but not for the compression properties.

In the area of low elongations, practically only the elastomeric core of the inlay-yarn is affected by the tensile strength, which is proved by values of coefficients in formulas which describe linear dependences of the pressure upon the total inlay-yarn linear density (***Figure 3***) or linear density of the inlay-yarn's PU core (***Figure 4***). As demonstrated by results presented in ***Figure 4***, by increasing the linear density of the inlay-yarn's PU core, pressure values also increase - from 5.7% till 48.7% for 47.5 tex linear density yarn, from 21.1% till 79.4% for 132 tex linear density yarn, and from 27.7% till 90.1% for 233 tex linear density yarn (depending on the inlay-yarn's insertion density). Certainly the highest influence of changes in the elastic core's linear density was obtained for knitted samples K1/1 (with the highest density of inlay-yarn insertion). Thus it may be concluded that in the case of low insertion density of the inlay-yarn (in our case – K4/1), inlay-yarns with a linear density as low as possible can be used. The knitted orthopaedic support with lower linear density inlay-yarn is more flexible and softer to the touch, hence more comfortable to wear.

The influence of elastic inlay-yarn's insertion density on pressure in relation to to the inlay-yarn's linear density is evident in ***Figure 5***, being of an exponential character. It demonstrates that with increasing the linear density of the inlay-yarn, its insertion density in the knit has a

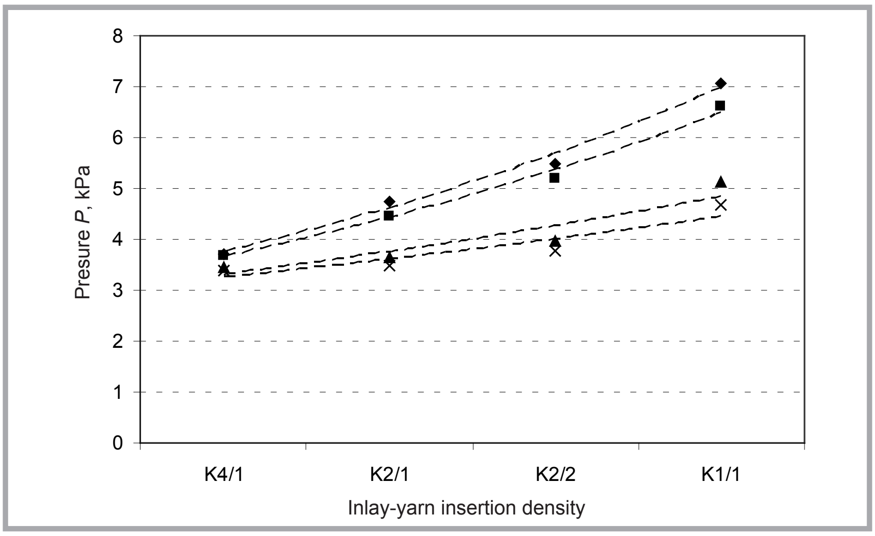

Figure 5. *Influence of elastic inlay-yarn insertion density on pressure P, according to inlay-yarn linear density: ♦ P2, ■ PM1, ▲ P3, × PM2.*

higher impact on compression. And vice versa - an increase in the inlay-yarn's insertion density in the knit increases the influence of the inlay-yarn's linear density on compression. Consequently when designing an orthopaedic support with a certain compression, it is necessary to choose the most appropriate combination of the inlay-yarn's linear density and insertion density, leading to an improvement in wear comfort properties and achieving economic benefits, because not always does a higher linear density of the inlay-yarn give a significant higher pressure value. On the other hand, inlay-yarns with a higher linear density make a knit rougher and more rigid, unacceptable for wear comfort. This is extremely important in order to make a support not only a design element, but also to have medical benefits.

Conclusion

In the area of low extensions, pressure generated by the knit's linear density depends on the linear density of the inlay-yarn's PU core, while the influence of elastic inlay-yarn's insertion density on pressure has an exponential character. Comparing with the samples which have got inlay-yarn in each course, the pressure decreases approximately 1.5 times when inlay-yarn is inserted in every second course and approximately 1.9 times in every fourth course. A similar pressure can be obtained with a twice lower insertion density using inlay-yarns with a higher core yarn linear density, thus saving elastic yarns.

In all cases, for samples with the same insertion density of inlay-yarn (in each course or in every second course), values of pressure vary significantly only when the linear density of the inlay-yarn's PU core differs twice or more. In other cases the variation is in the limits of error. Moreover the influence of the raw material and linear density of covering yarns on the pressure of the knit is wholly insignificant because in the area of low elongations only the elastomeric core of the inlay-yarn is affected by the tensile strength. Hence compression properties depend only on the linear density of elastomeric core yarn.

Means of fulfilling compressive, wear comfort requirements and having an economical effect are commonly different and even contradictory. Therefore when designing a compressive knitted support it is necessary to find an optimal ratio between the elastic inlay-yarn's linear density and insertion density, thereby achieving the best compressive, wear comfort and economical result.

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