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INTEGRATED STRUCTURAL AND CHEMICAL ANALYSIS OF YARN FOR COMPRESSION KNITWEAR FOR THERAPEUTIC PURPOSES

Abstract. This paper presents a comprehensive assessment of the structural, chemical, and physical-mechanical characteristics of yarn intended for the production of therapeutic and prophylactic compression knitwear. Samples of natural, blended and elastomeric yarns of various fibre compositions (cashmere, wool, cotton, acrylic, polyurethane) were studied. Microscopic analysis allowed the morphological features of the fibres to be established and their nature to be confirmed. The FTIR-ATR method provided molecular identification of protein, cellulose and synthetic components. The assessment of the physical and mechanical properties revealed the differentiated behaviour of the yarn under tension and determined its ability to form a stable elastic system in the structure of compression knitwear. It was established that blended systems based on wool and acrylic provide an optimal combination of strength and elasticity, while elastane yarn plays a key role in forming a stable compression effect. The results obtained form a scientifically sound basis for the selection of yarn in the development of medical knitwear.

Keywords: yarn, compression knitwear, structural characteristics, physical and mechanical properties, microscopic analysis, FTIR-ATR, blended fibres, elastane.

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Introduction. Compression hosiery for therapeutic and prophylactic purposes belongs to the category of highly functional textile materials that combine the requirements of medical effectiveness, biocompatibility, durability and increased comfort during use.

The key factor determining the degree and stability of therapeutic pressure distribution is the structure of the yarn used, its fibre composition, micromorphology and ability to form a stable elastic system in the knitted fabric [1-3].

The creation of a gradient compression effect is only possible with the use of complex thread systems that include natural fibres (cotton, wool, linen, cashmere), synthetic components (acrylic, polyester) and elastomeric filaments (spandex, elastane). The most widespread are core-spun, covered and plated designs, which provide a combination of strength, hygroscopicity and high elasticity [1,4].

The stability of compression pressure over time is determined not only by the structure of the weave, but also by the elasticity modulus of the original yarn, its ability to recover its shape and its resistance to cyclic deformation [5-7]. It has been shown that the residual deformation of the material after repeated cycles of stretching is a critical parameter for medical devices [5,8].

Optimising the fibre composition allows the balance of mechanical and hygienic properties of knitwear to be controlled. The introduction of wool and angora fibre into the acrylic matrix increases elasticity and reduces the friction coefficient [9], but increasing the proportion of synthetic components can reduce the breathability and comfort of the products [10,11].

Blended systems based on wool and acrylic demonstrate a pronounced synergistic effect: wool improves shape recovery and thermoregulatory properties, while acrylic increases the strength and dimensional stability of the material [9,10]. The elastomeric component, which forms the strength framework of the compression structure, is of particular importance [4,12,13]. Changes in the linear density of spandex and loop formation parameters significantly affect the elasticity and recovery of knitted fabric [12].

Along with mechanical characteristics, the identification of the fibre composition plays an important role. Modern methods of microstructural and spectroscopic analysis, including SEM and FTIR-ATR, allow the nature of the fibres to be reliably determined and the presence of synthetic and protein components to be identified. The combined use of morphological and molecular methods significantly improves the accuracy of interpreting the composition of textile materials [7,14-16].

Despite the significant amount of research devoted to the design of compression garments and the characteristics of knitted fabrics, a comprehensive assessment of the structural, chemical, and physical-mechanical characteristics of the raw yarn as the basic element in the formation of a compression system remains insufficiently represented in the scientific literature [2-4,7].

In this regard, an urgent task is to conduct an integrated study of the micromorphology, chemical composition, and physical and mechanical properties of yarns of various fibre compositions in order to make a scientifically sound choice of material for the production of therapeutic and prophylactic compression knitwear.

Materials and Methods. *Research objects.* The research objects were six samples of yarn with different fibre compositions (Nos. 1–6) intended for use in the production of therapeutic and prophylactic compression knitwear. The samples included natural (cashmere, wool, cotton), blended (wool/acrylic in various proportions) and elastomeric (polyurethane thread – spandex) fibre systems.

The selection of samples was determined by the need for a comparative assessment of the influence of fibre composition and structural features of yarn on its morphological and physicochemical characteristics, which determine the suitability of the material for forming a stable compression effect in the knitted structure.

Sample preparation. Before testing, the yarn was pre-cleaned of surface contaminants using 70% ethanol for 2-3 minutes, followed by drying at room temperature. This treatment eliminated the influence of foreign impurities on the results of spectroscopic and elemental analysis.

For microscopic studies, individual fibres were separated from the yarn structure by hand in order to minimise mechanical damage. Samples for scanning electron microscopy were prepared by fixing the fibres on aluminium stabs using conductive carbon tape. If necessary, the surface of the samples was coated with a thin layer of gold or platinum 5-15 nm thick to ensure electrical conductivity and improve image quality.

Optical microscopy. Preliminary morphological analysis of the fibres was performed using optical microscopy at magnifications of ×100 and ×500. The study was conducted to assess the cross-sectional shape, the presence of characteristic structural elements (cuticle, lumen, longitudinal grooves), the degree of twist and the uniformity of fibre distribution in the yarn structure.

Optical microscopy allowed for the initial identification of fibres based on morphological characteristics and revealed differences between natural, blended and synthetic components.

Scanning electron microscopy (SEM). Detailed morphological analysis was performed using scanning electron microscopy in accordance with the requirements of GOST ISO 17751-2-2021. The SEM method made it possible to obtain high-resolution images and conduct a more accurate assessment of the micro-relief of the fibre surface, the structure of the wool cuticle, the condition of the longitudinal channels of the cellulose fibres, and the uniformity of the synthetic filaments.

The analysis was carried out to confirm the fibrous nature of the samples and assess their structural integrity, which is of fundamental importance when selecting materials for medical knitwear.

Elemental analysis (EDX). The elemental composition of the fibres was determined using energy dispersive X-ray spectroscopy (EDX) integrated with electron microscopy. This method allowed for the quantitative determination of the content of the main elements (C,O,N,S) characteristic of cellulose, protein and synthetic fibres.

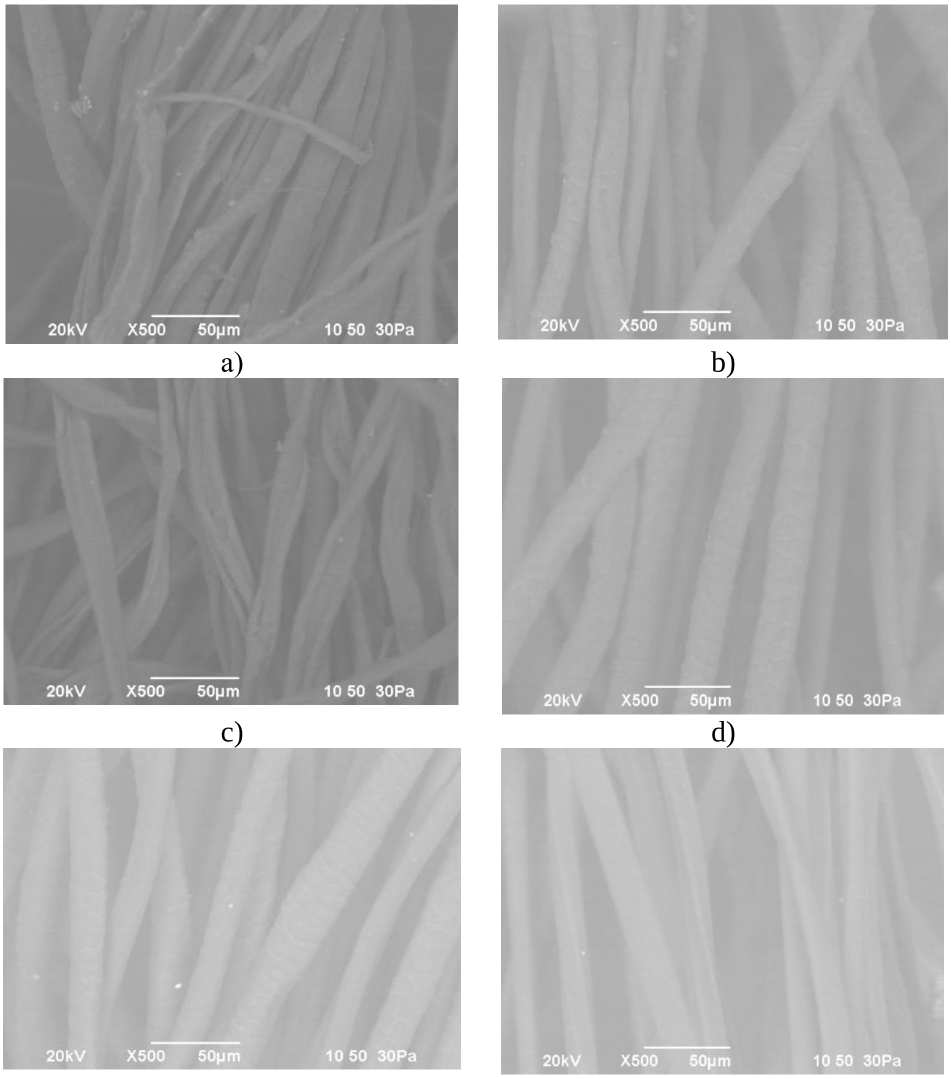
The data obtained was used to compare morphological features with the chemical nature of the material, which ensured comprehensive verification of the composition of the samples under study.

Spectroscopic analysis (FTIR-ATR). Molecular identification of fibres was performed using Fourier transform infrared spectroscopy in attenuated total reflection mode (ATR-FTIR) in the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans accumulated.

The spectra were interpreted based on the analysis of diagnostic bands of functional groups, including amide (Amide I, Amide II, Amide III), hydroxyl (O–H), carbonyl (C=O), nitrile (C≡N) and ether (C–O–C) vibrations. Comparison of the obtained spectra with library data confirmed the chemical nature of the fibres under study.

The comprehensive application of morphological, elemental and spectroscopic methods ensured reliable identification of the fibre composition and allowed us to form a scientifically sound basis for assessing the technological suitability of yarn in the production of therapeutic and prophylactic compression knitwear.

Results and Discussion. Morphological examination of yarn samples revealed marked differences in the structure of natural, blended and synthetic fibres, confirming the influence of fibre composition on the mechanical and performance characteristics of the material. Figure 1 shows micrographs of the samples studied.



Optical microscopy, magnification ×500: (a) – sample No. 1; (b) – sample No. 2; (c) – sample No. 3; (d) – sample No. 4; (e) – sample No. 5; (f) – sample No. 6.

Fig. 1. Microscopic image of yarn (samples 1–6)

Analysis of sample No. 1 revealed a combination of thin protein fibres with a characteristic cuticle structure and more pronounced longitudinal elements, indicating a mixed composition. The presence of morphological features of keratin fibres confirms the presence of cashmere, which ensures the softness and plasticity of the material.

Sample No. 2 demonstrated a typical scaly wool structure combined with smooth cylindrical acrylic fibres. The contrast between the surface texture of the natural and synthetic components is clearly visible, confirming the mixed nature of the yarn.

Sample No. 3 is characterised by ribbon-like fibres, spiral twists and a narrow lumen, which corresponds to the morphological characteristics of cotton. These features determine the increased hygroscopicity and stability under static load.

Samples No. 4 and No. 5 demonstrate the predominance of wool component with a uniform fine-scaled cuticle structure characteristic of fine wool (merino), combined with synthetic acrylic fibre. This morphology indicates the possibility of forming a system that is balanced in terms of elasticity and strength.

Sample No. 6 is represented by a homogeneous smooth fibre of cylindrical shape without signs of cuticle and lumen, which corresponds to a polyurethane elastane thread. The pronounced elasticity of the fibre determines its key role in the formation of the compression effect.

Thus, morphological analysis confirmed the correspondence of the structural features to the declared composition of the samples and revealed differences that determine their functional properties.

Spectroscopic analysis (FTIR-ATR). Fourier transform infrared spectroscopy was performed to confirm the chemical nature of the fibres. Figure 2 shows the spectra of the samples studied.

The spectra of samples containing protein fibres (No. 1, No. 2, No. 4, No. 5) are characterised by the presence of pronounced Amide I (≈1630–1650 cm^{-1}) and Amide II (≈1510–1550 cm^{-1}) bands, which is a diagnostic feature of keratin structure. The presence of Amide III bands in the 1230–1270 cm^{-1} region further confirms the protein nature of the fibres.

The spectrum of sample No. 3 lacks amide bands, but there is an intense broad O–H band (≈3300 cm^{-1}) and pronounced C–O–C vibrations in the range 1030–1060 cm^{-1}, which corresponds to the cellulose structure of cotton.

Samples containing acrylic demonstrate the presence of a characteristic nitrile group C≡N band in the ≈2240 cm^{-1} region, which confirms the presence of a polyacrylonitrile component.

The spectrum of sample No. 6 is characterised by a dominant carbonyl group band (≈1710–1730 cm^{-1}) and intense C–O–C vibrations typical of a polyurethane structure. The absence of amide and cellulose bands excludes the presence of natural impurities.

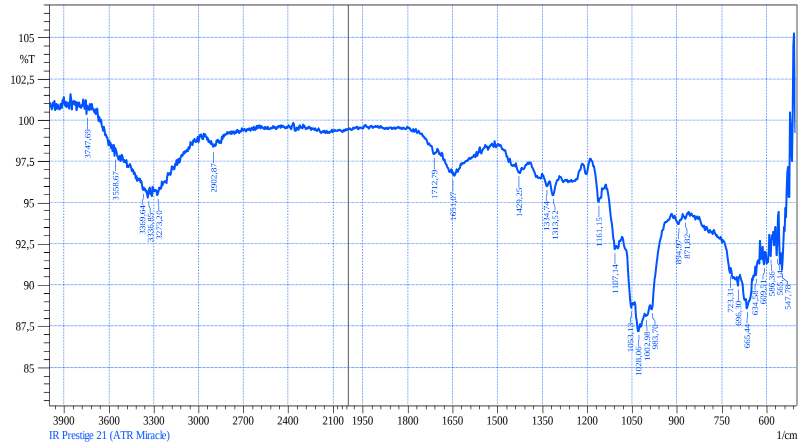
The spectral data obtained are fully consistent with morphological observations and elemental analysis results.

A comprehensive comparison of the results of microscopy, EDX and FTIR analysis confirmed the reliability of the identification of the fibre composition of all samples studied. Morphological features (cuticle, lumen, smooth surface) correlate with characteristic elemental and spectral characteristics.

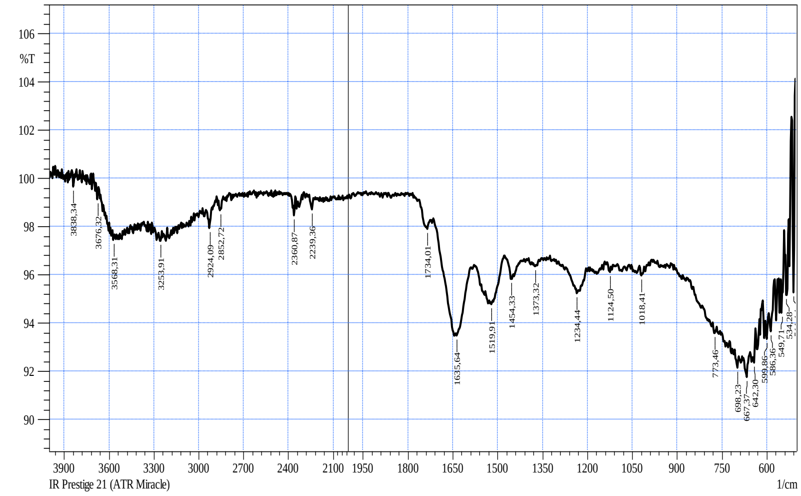
This comprehensive approach increases the accuracy of data interpretation and eliminates the possibility of misidentification of fibres.

The identified structural and chemical characteristics of the yarn are directly relevant to the formation of a stable compression system. Protein fibres provide elasticity and comfort, cellulose fibres provide hygroscopicity and breathability, synthetic components provide strength and resistance to cyclic loads, and elastane thread forms the strength framework of the product.

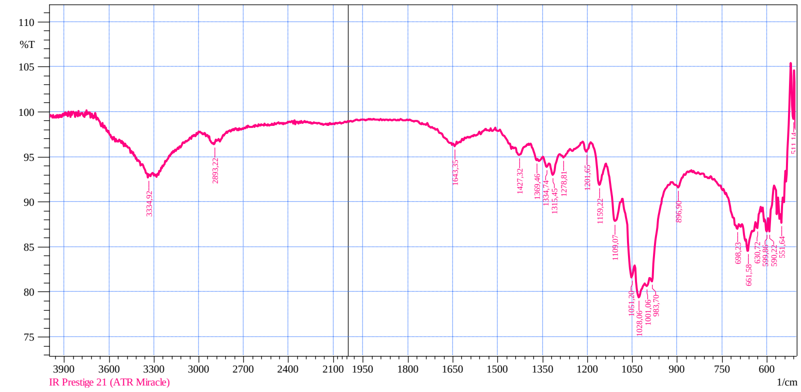
Blended systems based on wool and acrylic have demonstrated the most balanced combination of strength, plasticity and structural stability, making them promising for use in therapeutic and prophylactic compression knitwear.



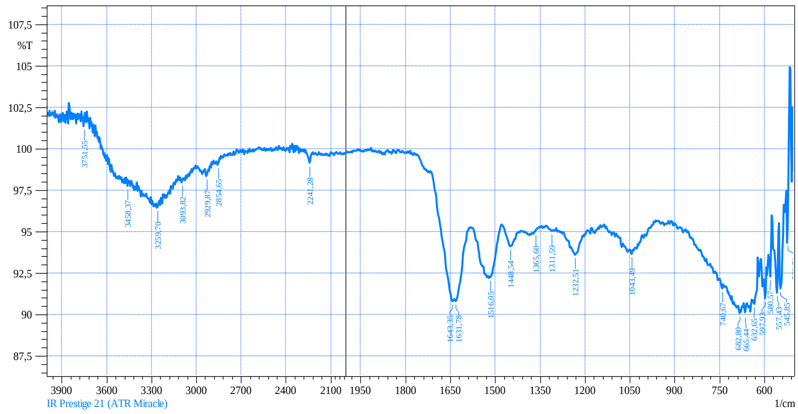
(Sample 1)



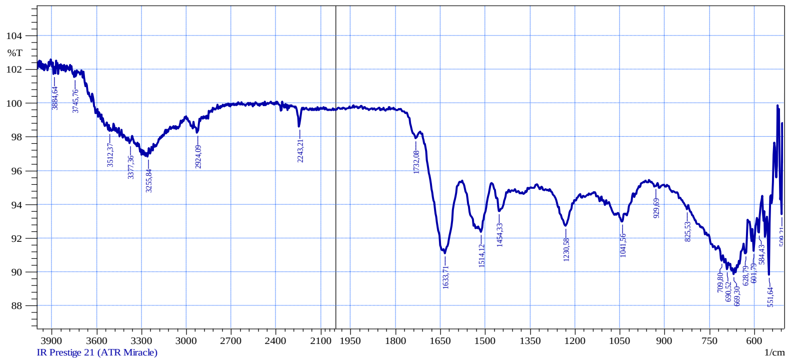
(Sample 2)



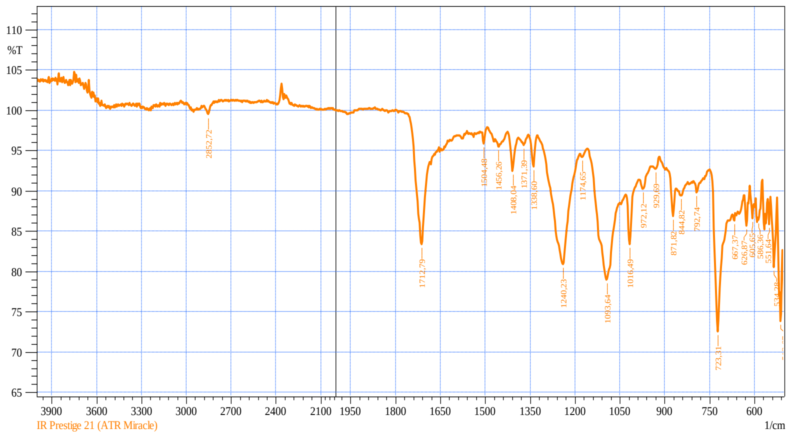
(Sample 3)



(Sample 4)



(Sample 5)



(Sample 6)

Fig. 2. FTIR spectra of yarn samples No. 1–6

Conclusion. As a result of a comprehensive study, it was established that the structural, morphological and chemical characteristics of the yarn samples under investigation directly determine their technological suitability for the production of therapeutic and prophylactic compression knitwear.

Microscopic analysis revealed distinct morphological differences between natural, blended and synthetic fibres, including the presence of a scaly cuticle in protein fibres, a ribbon-like structure and lumen in cellulose components, and a uniform cylindrical shape in synthetic and elastomeric yarns. Scanning electron microscopy made it possible to clarify the micro-relief of the surface and confirm the structural integrity of the fibres.

Spectroscopic analysis using the FTIR-ATR method provided reliable molecular identification of the composition of the samples based on the characteristic diagnostic bands of amide, hydroxyl, carbonyl and nitrile groups. The spectroscopy results are fully consistent with the morphological and elemental analysis data, confirming the correct identification of the fibrous nature of the studied systems.

It has been established that blended systems based on wool and acrylic are characterised by an optimal combination of strength and elasticity properties, providing a balance between comfort and operational stability. Elastane polyurethane thread forms the strength component of the structure, ensuring the stability of the compression effect under cyclic loads.

Thus, a comprehensive assessment of the structural and physicochemical characteristics of the yarn made it possible to scientifically justify the choice of fibre systems for the development of therapeutic and prophylactic compression knitwear. The results obtained can serve as a basis for the further design of knitwear with specified parameters of compression and operational stability.

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ЕМДІК ПРОФИЛАКТИКАЛЫҚ КОМПРЕССИОНДЫ ТРИКОТАЖҒА АРНАЛҒАН ИІРІМЖІПТІҢ КЕШЕНДІ ҚҰРЫЛЫМДЫҚ ЖӘНЕ ХИМИЯЛЫҚ ТАЛДАУЫ

Аңдатпа. Бұл мақалада терапиялық және профилактикалық компрессиялық шұлық өндірісіне арналған жіптің құрылымдық, химиялық және физика-механикалық сипаттамаларының кешенді зерттеу келтірілген. Әртүрлі талшық құрамының (кашемир, жүн, мақта, акрил және полиуретан) табиғи, аралас және эластомерлі жіптерінің үлгілері талданды. Микроскопиялық талдау бізге талшықтардың морфологиялық қасиеттерін анықтауға және олардың табиғатын растауға мүмкіндік берді. FTIR-ATR әдісі ақуыздың, целлюлозаның және синтетикалық компоненттердің молекулалық идентификациясын қамтамасыз етеді. Физика-механикалық қасиеттерді бағалау жіптің керілу кезіндегі дифференциалданған сипатын анықтады және оның компрессиялық шұлық құрылымында тұрақты серпімді жүйені қалыптастыру қабілетін анықтады. Жүн мен акрилге негізделген аралас жүйелер беріктік пен серпімділіктің оңтайлы үйлесімін қамтамасыз ететіні, ал эластан жіп тұрақты компрессиялық әсерге қол жеткізуде маңызды рөл атқаратыны анықталды. Алынған нәтижелер медициналық шұлық өндірісін дамытуда жіптерді таңдау үшін ғылыми негіз болып табылады.

Тірек сөздер: иірімжіп, компрессионды трикотаж, құрылымдық сипаттамалары, физикалық және механикалық қасиеттері, микроскопиялық талдау, FTIR-ATR, аралас талшықтар, эластан.

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КОМПЛЕКСНЫЙ СТРУКТУРНЫЙ И ХИМИЧЕСКИЙ АНАЛИЗ ПРЯЖИ ДЛЯ КОМПРЕССИОННОГО ТРИКОТАЖА ЛЕЧЕБНО-ПРОФИЛАКТИЧЕСКОГО НАЗНАЧЕНИЯ

Аннотация. В данной статье представлена комплексная оценка структурных, химических и физико-механических характеристик пряжи, предназначенной для производства лечебно-профилактического компрессионного трикотажа. Были исследованы образцы натуральной, смесовой и эластомерной пряжи различного волокнистого состава (кашемир, шерсть, хлопок, акрил, полиуретан). Микроскопический анализ позволил установить морфологические особенности волокон и подтвердить их природу. Метод FTIR-ATR обеспечил молекулярную идентификацию белковых, целлюлозных и синтетических компонентов. Оценка физико-механических свойств выявила дифференцированное поведение пряжи при растяжении и определила ее способность формировать стабильную упругую систему в структуре компрессионного трикотажа. Установлено, что смешанные системы на основе шерсти и акрила обеспечивают оптимальное сочетание прочности и эластичности, тогда как эластановая нить играет ключевую роль в формировании стабильного компрессионного эффекта. Полученные результаты составляют научно обоснованную основу для выбора нитей при разработке медицинского трикотажа.

Ключевые слова: пряжа, компрессионный трикотаж, структурные характеристики, физико-механические свойства, микроскопический анализ, FTIR-ATR, смешанные волокна, эластан.