OPTIMIZATION OF SHAPE STABILITY OF HEMP FOOTWEAR TEXTILES THROUGH CONSTRUCTIVE AND TECHNOLOGICAL SOLUTIONS

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Abstract. The relevance of this study is driven by the growing demand in the footwear industry for high-quality, eco-friendly, and shape-stable materials based on natural fibers. Hemp textiles demonstrate significant potential due to their strength and biological resistance; however, their efficient application in footwear manufacturing requires optimization of structural and technological parameters. The research experimentally proves that factors such as the structure of modified hemp fibers, the type and repeat of the weave, as well as the integration of cotton yarn, determine surface uniformity, resistance to deformation, and the ability of the material to retain its shape. The use of a 2/2 broken twill weave provides reduced elongation at break and enhanced dimensional stability, which is critical for upper footwear components. An additional functional role is played by decorative elements, particularly machine-made national embroidery, which, with a dense stitch length of 1-2 mm, not only provides aesthetic value but also reinforces structural zones, increasing their stability and wear resistance. The production of a pilot batch of textile and its laboratory testing confirmed that hemp fabric optimized in fiber structure, weave parameters, and decorative-constructive features demonstrates high abrasion resistance, low deformability, and stable geometry. These findings underscore the relevance and practical significance of the proposed solutions for developing competitive, environmentally sustainable footwear materials.

Keywords: hemp fabric, shape stability of footwear textile, technological parameters, fabric composition, properties, decorative cross-stitch embroidery.

Introduction

The growing demand for environmentally safe, high-quality, and dimensionally stable footwear materials stimulates an active search for innovative technological solutions in the field of textile engineering, which serves as the basis for this study. Natural fibers, particularly hemp, are of considerable interest to manufacturers due to their high strength, biodegradability, hygroscopicity, and low environmental footprint [1-4]. Moreover, hemp fiber represents a promising raw material owing to its renewability and energy-efficient cultivation, aligning with global trends in sustainable production [5; 6].

Despite this potential, the intrinsic variability of hemp fiber structure, its increased stiffness, and its tendency toward plastic deformation limit direct application in footwear manufacturing without preliminary technological modification [7; 8]. To develop durable, shape-stable, and long-lasting footwear materials, it is necessary not only to enhance the mechanical and technological properties of the fibers but also to ensure the structural stability of yarns and fabrics under operational loads.

In this context, a comprehensive technological approach becomes essential. Such an approach encompasses fiber modification, optimization of fiber-blend compositions, selection of rational weave structures, and the application of structural-decorative reinforcement techniques to improve local dimensional stability. Therefore, this study focuses on identifying the technological factors that influence the quality, shape retention, and durability of hemp-based textile materials. This integrated strategy expands the prospects for the widespread adoption of hemp textiles in modern footwear manufacturing.

The aim of the study is to develop an integrated technological strategy for enhancing the dimensional stability and performance characteristics of textile materials for footwear uppers based on modified hemp fiber. To achieve this objective, three interrelated and consecutive stages were implemented: fiber modification, optimization of the blended yarn composition, and selection of a rational fabric structure followed by structural reinforcement.

Materials and methods

For the study, modified hemp fibers were used, and their properties were assessed according to standard methods for evaluating mechanical, physical, geometric, and chemical parameters. Fiber length was determined by the single-fiber measurement method; linear density was evaluated based on fiber fineness (degree of splitting); fiber diameter was assessed using the microscopic method developed by V.A. Arkhangelsky. Breaking load, elongation at break, modulus of elasticity, and hygroscopicity were determined in accordance with the current standard specifications (DSTU ISO 5079:2004; DSTU 5015:2008; DSTU ISO 6741-1:2004). The cellulose content in the fibers was determined using the Willstätter–Schudel method; lignin content was assessed by the hydrolytic gravimetric method; and pectin content was determined using the method proposed by M.A. Sobolev and A.A. Krasivska. Fiber modification was carried out through steaming under rationally optimized conditions, which enabled alterations in the crystalline structure of cellulose and improved the dimensional stability of the material (Fig. 1). After treatment, a comparative analysis of the fiber properties before and after steaming was performed.

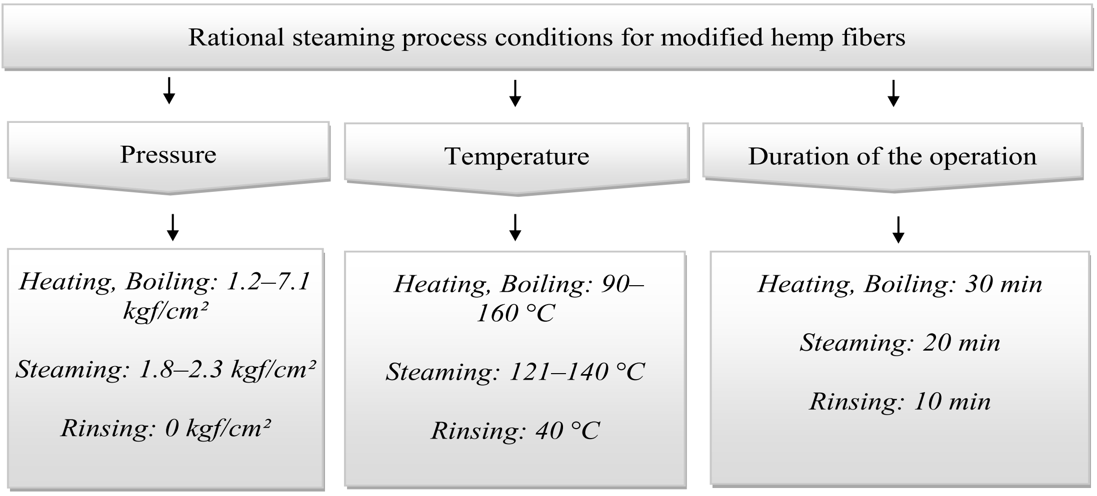


Fig. 1. **Scheme of rational steaming regimes for modified hemp fibers**

To produce hemp-polyester blends, a laboratory fiber blender was used [9]. Six blend variants with different polyester contents were examined for their physicomechanical properties, and the results were statistically processed using MathCAD and CurveExpert software to determine the optimal composition. The breaking load and elongation of the fiber blend composed of modified hemp and polyester fibers were determined according to DSTU 5015:2008. The breaking load and elongation of the blended hemp yarn were assessed in accordance with DSTU ISO 2062:2004. Linear density of the fiber blends and yarns was measured based on weight per unit length. Hygroscopicity of the fiber blends and yarns was evaluated using a climatic chamber, while thermal conductivity and electrostatic properties of the yarns were determined according to the relevant standard specifications (DSTU ISO 11092:2005; DSTU EN 1149-5:2019). Blend yarn samples with an 80/20 hemp-polyester ratio were produced under industrial conditions, followed by evaluation of their textile and performance characteristics.

The structure and properties of the experimental fabric were assessed through a comprehensive evaluation of technological, geometric, and physicomechanical parameters [10-12]. Organoleptic characteristics were analyzed using profile diagrams created in Microsoft Excel.

At the final stage, experimental samples of textile footwear incorporating the developed hemp material were designed and manufactured. The design was carried out in the graphic editor Paint Tool SAI 2, and the quality of the finished footwear was evaluated using wear testing, including analysis of consumer-related and deformation characteristics.

For the design of embroidery patterns, Autodesk AutoCAD 2022 was employed, while the pattern design on footwear components was created using raster graphics software. Embroidery was applied to the hemp-based textile using a Janome Memory Craft 550 E embroidery machine.

Results and discussion

A comprehensive study of modified hemp fibers allowed the identification of key changes in their structural, physicomechanical, and chemical characteristics, forming the basis for their technological suitability for spinning and subsequent use in footwear materials [13-14]. The analysis focused on establishing the relationships between fiber modification conditions and fiber properties, which influence yarn uniformity, fabric dimensional stability, and service durability. Particular attention was given to strength, elongation, hygroscopicity, and structural stability, as these parameters determine the behavior of the textile material under mechanical loads.

A detailed investigation of the properties of modified hemp fibers and their chemical composition (Table 1) enabled the determination of the main parameters that govern the spinning performance of the raw material.

The modified fiber is characterized by a linear density of 5.8 tex and an optimal crimp of 0.05%, providing the prerequisites for producing uniform and structurally stable yarn. The fiber's hygroscopicity and breaking load exceed the generally accepted minimum values for spinning, confirming its technological suitability. At the same time, the elevated relative breaking elongation of 17.2% indicates the fiber's tendency to plastic deformation, as it does not return to its original state after mechanical stretching due to the disruption of some hydrogen bonds between cellulose macromolecular chains. This property highlights the need for technological treatment to reduce plasticity and enhance dimensional stability.

Table 1

Properties of modified hemp fiber

No.	Property, unit	Value
	Mechanical properties	
1	Breaking load of fibers, cN	21.5
2	Absolute breaking elongation, mm	6.7
3	Relative breaking elongation, %	17.2
4	Elastic modulus, GPa	8.5
	Geometric properties	
5	Linear density, tex	5.8
6	Fiber thickness, μm	18.0
	Physical properties	
7	Hygroscopicity, %	12.0
8	Electrostaticity	none
9	Thermal conductivity, $W \cdot (m \cdot K)^{-1}$	0.05
10	Colour	light beige with a grayish tint
	Technological properties	
11	Crimp, %	0.05
	Chemical composition	
12	Cellulose, %	71.9-90.0
13	Hemicellulose, %	10.0-18.0
14	Lignin, %	3.7-8.0
15	Pectins, %	5.1-10.4
16	Ash, %	1.6-3.0
17	Resins, waxes, and fats, %	3.0-4.0

A key technological solution was the application of steaming as a fiber modification method, which preserves its environmental compatibility under optimized regimes. Steaming caused significant changes in the fiber structure, with the results presented in Table 2.

The reduction of absolute breaking elongation by 45% and relative breaking elongation by 49% indicates a significant increase in the fiber's resistance to deformation, thereby enhancing its contribution to the dimensional stability of future woven materials. Simultaneous decreases in linear density by 35% and fiber thickness by 39.5% confirm the reorganization of the cellulose crystalline structure: the reduction of the amorphous fraction, responsible for elasticity, limits excessive displacement of macromolecular chains and renders the fiber technologically more stable.

The next technologically significant stage involved the formation of blended compositions with polyester fiber content ranging from 5% to 30%, followed by evaluation of their physical and mechanical properties (Table 3).

Table 2

Properties of modified hemp fiber after steaming

No.	Property, unit	Value
	Mechanical properties	
1	Fiber breaking load, cN	12.4
2	Absolute breaking elongation, mm	3.7
3	Relative breaking elongation, %	9.3
4	Elastic modulus, GPa	10.7
	Geometric properties	
5	Linear density, tex	3.8
6	Fiber thickness, µm	7.1
	Physical properties	
7	Hygroscopicity, %	8.0
8	Electrostaticity	none
9	Thermal conductivity, $W\cdot(m\cdot K)^{-1}$	0.05
10	Colour	light beige
	Technological properties	
11	Crimp, %	0.02
	Chemical composition	
12	Cellulose, %	70.3-81.4
13	Hemicellulose, %	3.0-7.8
14	Lignin, %	2.6-5.2
15	Pectins, %	1.1-3.5
16	Ash, %	1.0-1.8
17	Resins, waxes, and fats, %	1.0-2.0

Table 3

Average physical and mechanical properties of fiber blends with different component ratios

Property, unit	Polyester 5%/Hemp 95%	Polyester 10%/Hemp 90%	Polyester 15%/Hemp 85%	Polyester 20%/Hemp 80%	Polyester 25%/Hemp 75%	Polyester 30%/Hemp 70%
Breaking load, daN	21.6	21.9	23.4	24.2	24.5	25.0
Relative breaking elongation, %	18.5	17.2	16.5	15.8	15.4	15.0
Linear density, tex	178.4	169.9	155.3	140.0	128.2	117.0
Thermal conductivity, $W\cdot(m\cdot K)^{-1}$	0.120	0.122	0.124	0.125	0.126	0.128
Hygroscopicity, %	11.43	10.84	10.28	9.70	9.13	8.55

Polyester, as a structural stabilizer, is introduced to reduce deformation during use and to ensure uniformity of the yarn. Mathematical analysis of the relationships between the fiber blend ratios and yarn properties allowed determination of the optimal composition – 20% polyester. This specific blend demonstrates the best balance between strength, elongation, thermal conductivity, and hygroscopicity, ensuring enhanced technological stability of the material during subsequent fabric production. The relationships between the blend composition and the studied properties are illustrated in Fig. 2.

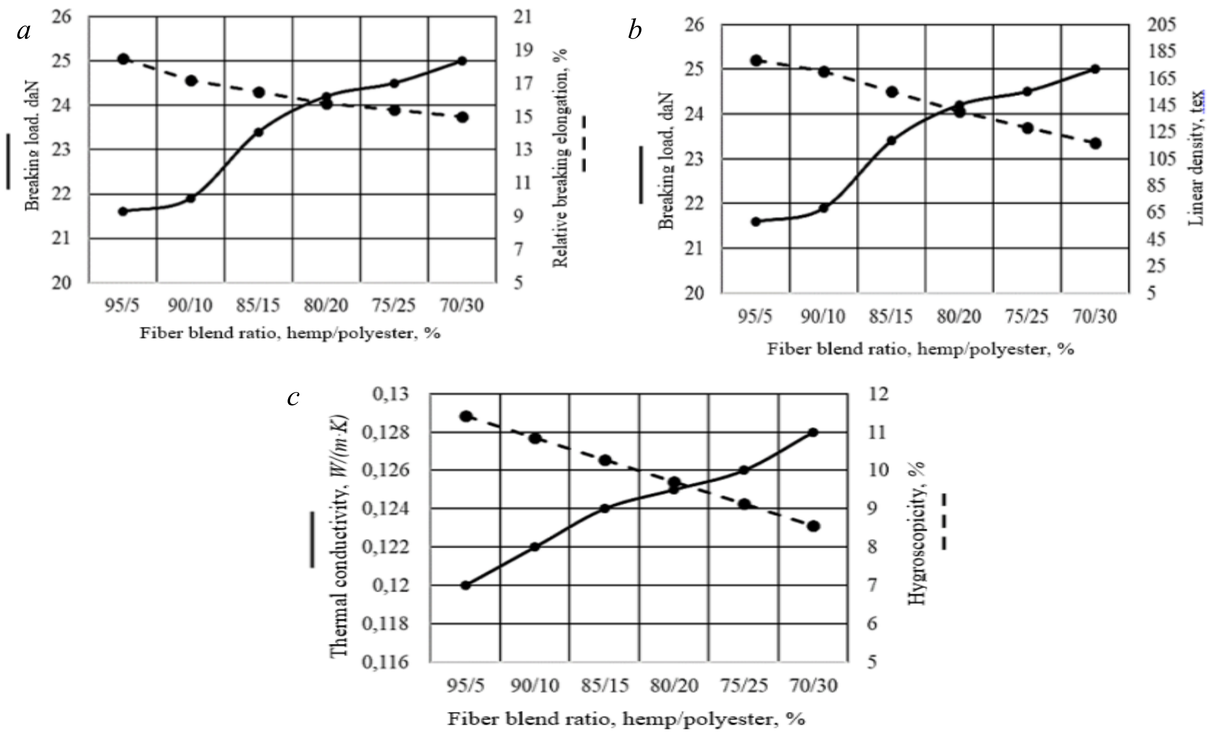


Fig. 2. **Dependencies:** a – breaking load and elongation at break of the blends as a function of their percentage content; b – breaking load and linear density of the blends as a function of their percentage content; c – thermal conductivity and hygroscopicity of the blends as a function of their percentage content

Based on the obtained properties of the blended yarns, technological requirements for the structure of shoe-upper fabrics were established. The use of cotton yarn in the warp and hemp-polyester yarn in the weft enables optimization of the stress distribution within the material, while the selection of twill or plain weave contributes to improved dimensional stability of the product. Under production conditions, five variants of woven fabrics with different weave structures were manufactured. The comparative analysis presented in Table 4 showed that materials with an areal density of 350-450 $g \cdot m^1$ and twill weaves are the most suitable for intensive use. The best performance was demonstrated by Sample 4 with a broken twill 2/2 pattern, which exhibited a uniform structure, moderate pliability, low elongation (14.5% in the warp, 15.8% in the weft), and the highest water resistance at 1035 mm H_2O. This weave structure ensures stable fabric geometry, enhanced resistance to mechanical stress, and improved shape retention. According to all evaluated indicators, the developed textile materials are suitable for use in footwear manufacturing as upper materials.

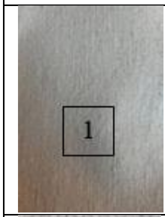
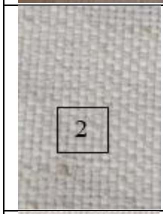
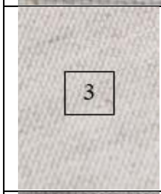
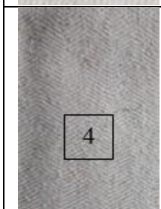
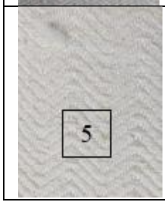
After selecting the optimal structure, a pilot batch of fabric measuring 10×1.50 m was produced under industrial conditions. It demonstrated increased strength, density, and controlled extensibility compared to typical textile materials used for footwear. This confirms the technological effectiveness of the implemented modifications at the fiber, yarn, and weave levels.

The final stage involved producing footwear from the pilot batch of fabric and implementing a technological solution for enhancing shape stability through national machine embroidery. The application of Ukrainian cross-stitch ornaments combined with an optimal stitch length of 1-2 mm significantly improved the stability of the zones subjected to the highest loads. The dense packing of the embroidery thread not only enhances the decorative effect but also serves as a local reinforcement element. Testing of the finished products showed minimal residual deformations of the heel counter and toe cap (0.1-0.2 mm) and high color fastness to washing, confirming the technological feasibility of such a structural–decorative reinforcement method.

Thus, the application of a complex set of technological solutions, from fiber modification and optimization of blended yarn to the selection of a rational weave structure and the use of machine embroidery, resulted in a substantial improvement in shape retention, mechanical strength, and overall quality of hemp-based textile materials for footwear uppers. This integrated technological strategy demonstrates a high potential for hemp textiles in modern footwear manufacturing.

Table 4

Physical and mechanical properties of the developed textile materials with different weave structures

Sample	Weave type and repeat (warp/weft)	Breaking load, N	Elongation at break, %	Areal density, $g \cdot m^{-2}$	Water resistance, mm $H_2O \cdot s^{-1}$	Hygro-scopicity, %
	Plain weave 1/1 (cotton/hemp) – warp/weft	750/790	16.7/19.4	326	940	14.8
	Plain weave "basket" 2/2 (cotton/hemp) – warp/weft	788/825	16.0/17.9	344	1035	15.8
	Twill 2/1 (cotton/hemp) – warp/weft	821/854	14.2/16.8	388	1010	15.6
	Broken twill 2/2 (cotton/hemp) – warp/weft	832/862	14.5/15.8	406	885	15.0
	Broken twill 3/2 (cotton/hemp) – warp/weft	859/878	15.9/16.2	428	915	15.6

Conclusions

The comprehensive research confirmed the effectiveness and technological feasibility of the engineering and technological solutions applied at all stages of forming textile materials for footwear uppers based on modified hemp fibers. It was established that the primary fiber modification and optimized steaming significantly improve the structural and physical-mechanical characteristics required for high-quality spinning. Reductions in linear density and fiber thickness, increased elasticity, and a considerable decrease in elongation at break confirmed the stabilization of the structural–morphological organization of the cellulose matrix, which is critically important for obtaining materials with controlled deformation behavior.

The results of studying blended compositions showed that the introduction of polyester fibers ensures technological stability of the yarn, while mathematical modeling allowed determining the optimal content of the synthetic component – 20%, which ensures a balanced combination of strength, elongation, thermal conductivity, and hygroscopicity. Further variable fabric formation with different weave types confirmed that for footwear applications the most effective option is the broken twill 2/2 weave, which demonstrates enhanced water resistance, optimal areal density, uniform structure, and low deformability. The produced pilot batch confirmed the reproducibility and effectiveness of the selected technological parameters under real manufacturing conditions.

The use of machine embroidery as a decorative-structural element proved to be an effective method for locally reinforcing zones exposed to maximum operational loads. Reducing residual deformations to 0.1-0.2 mm in critical parts of the footwear confirmed the practical significance of this solution. Testing of the finished products demonstrated improved shape retention, structural stability, and reliable material performance during use.

Thus, all conducted experiments, from fiber modification to yarn formation, fabric structure optimization, and the application of machine embroidery, consistently confirmed the technological suitability of the developed process for obtaining high-quality, shape-stable, and durable hemp-based textile materials for footwear manufacturing. The integrated combination of the investigated stages, from structural fiber modification to rationalization of fabric interlacing and structural reinforcement, ensures the achievement of the required dimensional stability and durability. An isolated analysis of each stage without technological integration would not have allowed for a balanced performance outcome.

Author contributions

Conceptualization, S.Y.; methodology, B.H.; software, H.T.; validation, M.N.; formal analysis, B.H.; investigation, B.H.; data curation, B.H. and S.Y.; original draft preparation, S.Y.; writing – review and editing, H.T. and M.N.; visualization, H.T. and S.Y.; project administration, B.H. All authors have read and agreed to the published version of the manuscript.

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