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COMPREHENSIVE APPROACH TO EVALUATING THE MACRO- AND MICROPORE STRUCTURES OF TEXTILE MATERIALS

Introduction. *The assessment of the macro- and microporous structure of textile fabrics is increasingly relevant for predicting their permeability, dyeability, and decorative potential. This evaluation plays a crucial role in determining the hygienic properties of clothing materials, optimizing dyeing and finishing processes, and assessing the filtration capabilities of technical fabrics in various dispersed media.*

Problem Statement. *Challenges persist in accurately predicting the permeability of textile fabrics, as well as in determining the optimal parameters for dyeing and finishing processes.*

Purpose. *The purpose of this research is developing a rapid, cost-effective, and accurate method to evaluate the macro- and microporous structure of textile materials is essential for assessing their permeability and suitability for dyeing and finishing processes.*

Materials and Methods. *To study the porous structure of textile fabrics, we select the fabrics that varied in the thread structure — yarn produced by traditional and shortened methods — and in the fibrous composition. The first fabric is made from complex polyamide threads in a plain weave, the second from twill-woven polyester fiber yarn, and the third differs from the second in the structure of the weft thread. The macro- and microporous structures of these textile fabrics have been assessed by means of drying methods and sorption thermograms.*

Results. *The micro- and macroporous structures of textile fabrics made from polyamide threads and polyester fibers have been compared. It has been found that the fabric made from polyamide threads exhibits a significantly higher sorption capacity than the fabric made from polyester fibers. This finding suggests that the fabrics made from polyamide threads possess a more developed microporous structure. This fact enhances their dyeing and decorating capabilities as compared with the fabrics made from polyester fibers. A comprehensive approach, utilizing both drying methods and sorption thermograms, has been employed to evaluate the macro- and microporous structures of the textile fabrics.*

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Conclusions. *The proposed comprehensive approach enables comparative studies of various textile materials, allowing for the refinement of technological processes for dyeing and decorating, as well as the identification of potential applications for these materials.*

Keywords: textile materials, textile fabrics, fabrics, micropore structure, complex approach, macropore structure, drying thermogram method, sorption method.

Various methods and devices are used to assess the pore structure of textile materials and their permeability. For example, research [1] has proposed the development of warp threads for the design and manufacture of fabric with a given pore size. At the same time, they found that two-component network materials of the "island in the sea" type can be precisely designed to achieve the target pore diameters and porosity. The defined mathematical models can be used to develop fabric specifications under standard manufacturing conditions of basis weight and fiber diameter. The measured mean pore diameters for the test fabrics showed a high correlation with the target mean pore diameters for both models. Experimental agreement with the Breiner model is the better of the two mathematical models, but requires refinement of fabric thickness in addition to bulk mass and fiber diameter to achieve an actual mean pore diameter that approximates the target value.

The virtual permeability benchmark [2] is used to predict the permeability of fibrous reinforcements based on real images. At the first stage, the focus is on the microscale computation of fiber bundle permeability. Subsequently, various numerical methods, boundary conditions and identification techniques are used to calculate the permeability. Dominant effects on the permeability have been found to be the boundary conditions in tangential direction, number of sub-domains used in the renormalization approach, and the permeability identification technique.

In [3], the model for predicting the pore size distribution of non-woven structures has been developed by combining the stochastic and stereological or geometrical probability approaches. These techniques have incorporated the effects of fibre orientation characteristics in non-woven structures. The analytical model formulated is compared with the existing theories to predict the pore size distribution of non-woven structures. A comparison is also made between the experimental and theoretical pore size distributions of spun-bonded and needle-punched non-wovens. The effect of various fibre and fabric parameters including fibre volume fraction, fibre orientation distribution characteristics and number of layers on pore size distribution of non-woven structures has been investigated.

The paper [4] considers the capillary flow of Newtonian fluids along a single fibre yarn and through a plain-woven fabric. In the first case, one-dimensional Darcy's flow is considered through the micro-pores of the fibre yarns. In the second case, two-dimensional in-plane network infiltration is considered through the micro-pores of the network of fibre yarns in the fabric. In both cases predictions include the infiltration length as a function of time, the apparent permeability and the capillary pressure. The latter case also includes the number of unsaturated transverse yarns and the degree of saturation.

Non-destructive measurement of air permeability of materials is proposed in the work [5]. This method is based on the flow of air, which is created between flat circular templates containing flow rate and pressure sensors. The presented studies show that, based on data on flow rate and pressure distribution, the method clearly distinguishes changes in volume fraction and pore arrangement, while it can be applied to a number of woven and non-woven textile materials.

The paper [6] presents a method for determining the equivalent average pore size in woven materials. The equivalent average pore diameter is defined as the diameter of a certain number of cylindrical pores that provide the same air permeability as real woven sample with the same number of pores (macropores). It gives the realistic correlation with air permeability taking into account all characteristics of pores involved in energy loss, i.e. the length of pores, their structure and their bottle necks. The method, combined with the geometrical porosity parameters determined by planar structure of woven materials can give connection between them and better understandings of porous structure in relation to its transmission properties.

An immersion method for measuring porosity parameters for woven and knitted fabrics and even thin non-wovens is presented in [7]. The experimental results correlate to the theory to a great extent. The method is based on the selective squeezing out fluid from the pores of wet fabrics under air pressure. Porosity parameters such as hydraulic pore diameter, pore distribution, open area for fluid flow and the number of hydraulic pores are estimated. The parameters have been estimated based on the measurement of the air volume velocity through dry and wet samples as a function of the air pressure. All measured data are input into a computer programme developed for this purpose. The method is quite rapid and the results obtained by this method are in good agreement with those received optically.

In the paper [8], the effect of fabric structure on its macroporosity properties is reported. The cross-sectional area of the macropore, equivalent, maximum, and minimum pore diameters, pore density, and open porosity are considered taking into account the parameters of the fabric structure — yarn linear density, fabric tightness, weave type, and denting. Using genetic programming, we have obtained predictive models describing the effect of fabric structure. The results have shown good agreement between experimental and predicted values. This work provides guidelines for engineering staple-yarn cotton fabrics in a grey state in terms of macroporosity properties.

The determination of a small number of parameters that have the greatest impact on the air permeability of cotton fabrics and enable its prediction is presented in the paper [9]. To specify the influence of fabric structure parameters, a combined parameter, the hydraulic pore diameter, known from fluid theory, is included. It considers rectangular pores as round. In addition to the hydraulic pore diameter, two other parameters are used to predict air permeability: the number of macropores and the total porosity of woven fabrics. The resulting multivariate statistical method confirms the suitability of the three selected parameters for predicting air permeability, which has been done by multiple linear regression.

Research [10] describes the flow mechanism that is realized in 3-D depending on the porosity structure of the fabric and determines the fabric's permeability characteristics. In this method, the cross-sectional image of the cotton yarn in the fabric is first obtained, and then the porosity in yarns is predicted by image processing and analysis. In addition, the intra-yarn porosity is calculated theoretically depending on fibre and yarn parameters. The results obtained through the image analysis method and theoretical approaches are compared with experimental data obtained with the Stereo Investigator. As a result, it has been found that the image analysis method gives fast, objective, successful, and expected results while predicting the intra-yarn porosity.

A theoretical model is proposed to predict the porosity and air permeability of single-layer knitted fabrics [11] depending on parameters such as weave type, vertical and horizontal density, loop step, fabric thickness, yarn diameter, and linear fibre density. For this purpose, a theoretical model of porous systems based on Darcy's law has been used, the validity of which has been confirmed by experimental results using 100% cotton plain knitted fabrics produced from ring and compact yarns of different yarn linear density and tightness.

An artificial intelligence method based on texture features is developed to predict the porosity and air permeability of non-wovens [12]. For this purpose, two image processing algorithms have been developed to measure the porosity of the fabric and extract texture statistical characteristics. An Artificial Neural Network (ANN) model is built to predict the properties of the studied fabrics. The tested samples consist of polyester and viscose fibres with different specific gravities. High regression values have been obtained between the predicted and actual values for both porosity and air permeability. According to ANN results, it has been found that the air permeability and porosity properties of non-wovens can be predicted with high accuracy from their texture images.

The paper [13] deals with the possibility of a fast and accurate assessment of the number, size, and distribution of pores in transparent woven materials based on light penetration. The procedure of analysing the pore structure in the fabrics based on digital images is described in detail. Fibre pores are treated as image particles and analysed with the Java-based image processing software ImageJ. The obtained data relate to the structural parameters of the fabric that allow for further analysis, provide the possibity to compare structurally similar or different samples as well as double check the results generated by optical or other means. This paper describes work on plain and similar to plain weaves. The analysis revealed several expected and some unexpected results. The former include the range of pore sizes in the woven materials under study, the distribution of pores by their degree of similarity, and the effect of dents. Examples of the latter are the magnitude of the cumulative percentage of pores in regard to the weave and the degree to which they participate in the inter-yarn and inter-fibre pores.

Prediction of the pore diameter of cotton fabrics by considering yarn count, twist, and packing density is presented in the paper [14]. After finding the warp and weft densities of the fabric, the pore area and their equivalent diameter in the fabric are predicted. The predicted values had very good agreement with the experimental results in yarn diameter and other structural parameters of fabric. The air permeability of fabrics is measured and several well-known analytical models for predicting air permeability are compared. The results showed that the Hagen-Poiseuille equation had much better prediction than other models and also had good agreement with experimental results, especially when applied to dense fabrics at the low-pressure drop ($\leqslant 60$ Pa). The Hagen-Poiseuille equation could be improved by considering the Reynolds number, interfiber interstices, and the deformation of pores under higher pressure drop.

In [15], the fabric porosity has been determined by the light transmission coefficient and this characteristic has been compared with the air permeability and idealised geometric structure of the selected weaves. The standard equipment is used to determine air permeability. Light transmission through the fabrics is measured by the LUCIA image analysis system. The porosity of fabrics is measured with the use of the relevant design parameters and idealised models of the fabric geometry. The relationships between the above characteristics are formalised by regression analysis.

The theoretical 3D modelling of stitch overlapping, maximum set, and open structures by using AutoCAD software is presented in [16]. Fabric thickness is divided into several sections, and the theoretical porosity at each section is analysed and calculated. Furthermore, single jersey knitted fabrics SJKF with and without spandex are produced to obtain overlapping and open structures. The total porosity has been measured and calculated theoretically, with the values compared. The study has shown the effect of stitch overlapping on fabric porosity. In addition, the results show that the proposed model captured to some extent the change in fabric porosity as its structure changes.

The SCP method, as well as SEM and TEM [17], are used to diagnose the pore structure of the skin dermis. Thus, pores formed by spirals, microfibrils, fibrils, fibril bundles, and fibres are identified. The model that describes the hierarchical structure and includes porosimetry data has been developed. Therefore, the contribution of elements of each structural level to the overall dermis porosity has been determined. The parameters that characterise the porosity due to the elements and allow estimating the loosening-compaction and shrinkage-swelling of the hierarchical structure have been proposed.

The concept of mesoscopic intrafilament porosity of any woven and non-woven textile materials is formulated in this paper [18]. Based on this concept, an alternative basic model for estimating the effective porosity of hydrophilic and hydrophobic materials is developed. Following the developed method, the formulas of the basic model are proposed. They make it possible to estimate the density of the material (wet and dry), the observed effective porosity (at any moisture level), and the maximum hygroscopicity of the textile material.

The paper [19] describes analytical studies of the process of liquid absorption by a fibrous material based on non-woven fabrics produced in different ways and consisting of different types of fibres (monofilaments). An analytical description of the process of liquid lifting by porous media — fibrous materials — is carried out. The proportionality coefficients of a certain function $Y(x)$ that ideally describes the process of absorption of a viscous liquid by a fibrous material have been determined.

The calculation of the total, surface, and volumetric fabric porosity in the paper [20] is carried out by taking into account the yarn diameters and the structural characteristics of the woven fabrics themselves.

Research [21] proposes the use of a thermogravocalorimetric (TGC) method for calculating the material porosity. By this method, the porous structure of a textile material has been quantified, making it possible to conclude about its permeability.

The above methods of studying the pore structure of textile materials can be conditionally divided into the following: based on capillary phenomena; based on filtration phenomena; electron microscopy; analytical and mathematical-statistical.

Methods based on capillary phenomena have the complexity of methodological support for research and calculations. Methods based on filtration phenomena have approximate calculations, as well as determination of pore sizes only in the range of about 5—50 microns.

Electron microscopy methods require rather complicated sample preparation and characterise mainly the micropore structure of materials, which does not allow them to determine the macropore structure and predict the air and water permeability of materials.

Analytical methods are used to calculate the total porosity of materials, the volume of through pores, pores in fibres and the volume of dents on the surface of materials. These methods are also used to calculate the structural characteristics of materials. The disadvantage of analytical methods is the inability to calculate the pore size distribution function.

Mathematical and statistical methods allow for calculating macropores in textile fabrics. At the same time, they provide virtually no information about the micropore structure of fibres and yarns. This makes it impossible to use them to predict the dyeing and finishing ability of textile materials.

Thus, the search for sufficiently accurate and fast methods for studying the macro- and micropore structure of textile fabrics is relevant [22—26].

The purpose of this scientific work is to propose and apply a comprehensive approach to determining the macro- and microporous structure of textile materials to assess their permeability and ability to dye and finish. Along with this, an example of the application of the proposed complex approach that involves of thermographic and sorption methods, is given to evaluate the pore structure of fabrics of different fiber composition and structure.

The main quantitative characteristics of the pore structure of textile materials that belong to capillary-porous bodies are: total porosity, pore diameter (radius), integral and differential functions of pore size distribution, and their specific surface area. The total porosity or simply porosity is calculated as the total number of all pores in a textile material and is determined by various methods [22—26]. In a capillary-porous material, the pores are modelled by a system of interconnected cylindrical capillaries. In this case, the con-

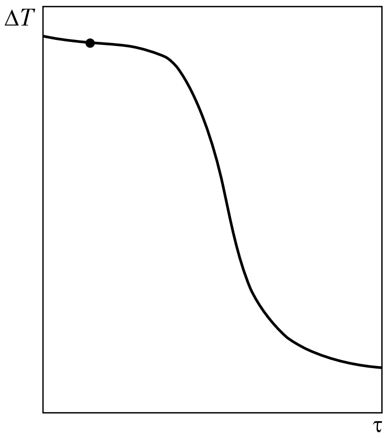

Fig. 1. Fabric drying thermogram (general view)

cept of pore radius (diameter) is conditional and it is used to estimate its size.

In the presented research, it has been proposed to apply a comprehensive approach to assessing the porous structure of textile materials, which uses a combination of drying thermogram methods, as well as sorption methods. By combining these methods, it is possible to calculate with sufficient accuracy (up to 2%) the micro- and macroporous structure of textile materials, predict their permeability and ability to be dyed and processed. Below are the components of a comprehensive approach to assessing the porous structure of textile materials.

The method of drying thermograms or thermographic method allows considering the pore structure of capillary-porous bodies in the material-water system, which is typical for textile materials. This method is the least labour-intensive, fastest (up to 2 hours) and makes it possible, based on the results of one study of moisture evaporation from a material sample, to obtain data on the differential moisture exchange properties of the material in relation to moisture of various forms and types of bonding with it. Also, the drying thermogram method allows to calculating the specific pore surface and determining the volume of micro- and macropores of the material.

The thermographic analysis of the form of moisture bonding with the material is based on the regularities of the drying kinetics of a wetted sample at a constant ambient temperature. On the curves of the drying thermograms, critical areas that correspond to the boundaries of the periods of successive moisture removal during the drying process from the textile material are identified. Such moisture differs from each other in terms of its bonding forms and position in the pores of the material.

The thermograms of textile materials (Fig. 1) are *S*-shaped, which is typical for capillary-porous bodies [22].

Critical point 1 (Fig. 1) on the thermogram corresponds to the total moisture capacity of the sample, point 1′ — to the beginning of evaporation of hygroscopic moisture from macropores with a radius of more than 10^{-7} m. The moisture content at this point can characterise the volume of open macropores of the sample. Point 2 corresponds to the beginning of the evaporation of adsorbed moisture from the polylayer and point 3 is the beginning of the evaporation of adsorbed moisture from the fibre polymer monolayer, which corresponds to the evaporation of moisture from the sample of micropores with a radius of less than 10^{-7} m. For textile materials (capillary-porous bodies), the area between points 2 and 3 on the thermogram is straightforward. By calculating the difference in the moisture capacity of samples at adjacent critical points of the drying thermograms, it is possible to determine the pore volumes that characterise the micro- and macropore structure of the fabrics.

The thermographic method of analysing the forms of moisture bonding with textile material is fast enough to determine the ability of a test sample to retain moisture in relation to all possible forms and types of moisture bonding in the material based on the results of one experiment during the drying process.

To increase the accuracy of predicting (up to 2%) the ability of textile materials to be dyed and finished, it is advisable to use the sorption method along with the drying thermogram method.

The sorption method uses the isotherms of moisture sorption-desorption from materials and allows determining the amount and forms of bonding of moisture absorbed by the material, determining the specific pore surface and volume of absorbing pores, and calculating pore distribution curves. The sorption process of absorption of various substances by textile materials is considered as a combination of adsorption and capillary condensation. The adsorption isotherm is the dependence of the moisture content of a fabric sample (*W*) on the relative pressure of the vapour of the substance above it at a constant temperature. To determine the adsorption isotherms, the samples of textile material are placed in an environment with appropriate humidity and kept until an equilibrium state is obtained. To accelerate the achievement of the equilibrium state of the textile material, the experiment is carried out in a vacuum (static method) or blown with air of constant humidity (dynamic method). For textile materials, sorption tests are carried out on vacuum sorption equipment based on the McBain tensometric method.

The analysis of sorption isotherms makes it possible to clarify the nature of the form of moisture bonding with the material and determine the structure of micropores in the textile material. A differential micropore size distribution curve is obtained in the textile material from the sorption-desorption isotherm curve. Thus, the section of the isotherm in the interval φ from 0 to 80% corresponds to the moisture of macrocapillaries with a radius of more than 10^{-7} m, and the section of the isotherm in the interval φ from 80 to 100% corresponds to the moisture of microcapillaries with a radius of less than 10^{-7} m.

The water vapour sorption isotherm is not only an independent characteristic of the sample under study but also helps to determine its integral and differential pore size distribution curves. These curves are calculated by the well-known Kelvin equation, formula (1):

$$\varphi = e^{-\frac{2V\cdot\sigma}{r\cdot R\cdot T}} \text{ whence } r = \frac{2V\cdot\sigma}{R\cdot T\cdot \ln 1/\varphi}, \tag{1}$$

where *V* is the molar volume of water; σ is the surface tension coefficient; *R* is the gas constant; *T* is the temperature; *r* is the effective radius of the liquid meniscus curvature; φ is the relative humidity.

From formula 1, the effective radius of curvature of the liquid meniscus in the pore is determined, which means that each value of the relative pressure of water vapor above the tissue sample corresponds to a certain effective pore radius that is determined from well-known tables that contain the dependence between the relative pressure of water vapor above the water meniscus at full wetting, the radius of the capillary, and the free energy of binding of the liquid at a temperature of 293 K. Knowing the dependence of $W(\varphi)$ for the fabric according to formula 1 or the tables, it is possible to proceed to the dependence of $W(r)$ and thus find the integral curve of the pore size distribution.

Thus, the results of measuring adsorption isotherms can provide information about the moisture exchange properties and pore structure of textile materials. A specific example of the pore size distribution using the sorption method is given in the *Results and discussion* section.

The proposed complex approach, consisting of sorption methods and a drying thermogram, is quite accurate and simple and allows studying the peculiarities of the porous structure of textile materials in a wide range of pore sizes. It makes it possible to determine the structure of micro- and macropores based on recorded drying thermograms, and with the help of sorption-desorption isotherms to detail and clarify the micropore structure of the material.

The above-mentioned comprehensive approach makes it possible to predict the air and water permeability of textile fabrics, as well as the ability of textile materials to be dyed and processed. The larger the macropore structure of a textile material, the better its ability to penetrate various substances. As the microporous structure of the material increases, the absorption of various substances increases, increasing its ability to be dyed and processed.

In order to study the porous structure of textile fabrics, fabrics with different structure and composition of fibers are selected by the mentioned complex approach.

The fabrics selected for the study in terms of physical and mechanical properties met the requirements of the manufacturer's specifications. Comparative characteristics of the properties and structural parameters of the investigated fabrics are presented in Table 1.

The fibre composition of fabric samples 1 and 2 is the same. Fabrics 1 and 2 are produced with the use of a 2/2 twill weave with the same yarn density per 10 cm on the warp and weft. The difference lies in the structure of the weft yarns for sample 1, which have a different spinning technology. In sample 1, the SP weft yarn is produced with the use of a shortened technology and is as good is that of the standard twisted yarn in terms of its mechanical properties and can be used as an alternative in the production of fabrics for various purposes.

For comparison, fabric 3 that has a fibre composition, structure and weave different from samples 1 and 2, has been also studied. Fabric 3 is made of complex polyamide (PA) yarns with a plain weave.

The tasks of the research are the application of the proposed complex approach to determine the macro- and microporous structure of textile fabrics.

For using the drying thermogram method, the prepared fabric samples of 40 × 40 mm are placed in a pump room and moistened as much as possible. Subsequently, the samples are dried at the temperature of 373 K. Constant atmospheric pressure is maintained, the drying temperature (thermogram) is constantly measured, and the weight loss of the samples on the potentiometer strip is recorded.

After obtaining the drying thermograms, critical points that correspond to certain types of moisture bonding with the material have been identified on them (Fig. 1). By projecting the critical points onto the weight curve, the moisture content of the samples is determined by the following formula:

$$W = 100\,(M_w - M_d)\,/\,M_d, \tag{2}$$

where W is the moisture content of the material at a certain point in time, %; M_d is the mass of the dry sample, kg; M_w is the mass of the wet sample, kg.

Based on the analysis of drying thermograms, the values of the pore volume of the studied fabrics, presented in Table 2, have been obtained. The last column of the Table shows the values of the fabric specific surfaces, calculated from the amount of adsorbed moisture in the monolayer.

It is noted that the characteristics of the micropore structure of the studied fabrics, such as hygroscopicity, the amount of adsorbed moisture, and moisture in micropores do not depend on the density and structure of fabrics, but are determined mainly by their fibre composition.

Table 1. **Characteristics and Properties of Fabric Structure**

No.	Super-ficialdensity, g/m^2	Fibre composition, %	Thickness, mm	Water permeability, $\frac{\text{l}}{\text{m}^2 \cdot \text{c}}$	Air permeability, $\frac{\text{dm}^3}{\text{m}^2 \cdot \text{c}}$	Density, number of yarns per 10 cm		Type and linear density of the yarn, tex	
						Warp	Weft	Warp	Weft
1	457	PEL 100	1.3	2.23	170	157	113	72 × 2	SP 72 × 2
2	455	PEL 100	1.3	2.15	153	157	113	72 × 2	72 × 2
3	508	PA 100	1.7	2.17	160	119	81	250	250

Note: PEL — polyester fibres; PA — polyamide fibres; SP — yarn of a shortened production method.

At the same time, it has been determined that such characteristics of the pore structure of fabrics as the total moisture capacity and the amount of moisture in the macropores of fabrics are determined by the structure of yarns and fabrics.

The value V_1 determines the total volume of pores, the difference ΔV_{11} — the volume of macropores between filaments and fibre bundles ($r > 10^{-7}$ m), the difference ΔV_{1-2} — the volume of micropores ($r > 10^{-7}$ m), the difference ΔV_{2-3} — the volume of micropores of polymolecular adsorption, the value V_3 — the volume of ultramicropores of monomolecular adsorption of the material sample.

Table 2 shows that samples of fabrics 1, 2 and 3, which differ in structure and raw material composition, have differences in the micro- and macropore structure. In samples of fabrics 1 and 2, which have the same fibre composition, there are differences only in the macropore structure. Also, fabric samples 1 and 2 have a significant difference in the values V_1 and ΔV_{11}, which indicates a smaller macropore structure of fabric sample 1 due to the peculiarities of the structure of the weft yarn and the fabric as a whole. Sample 3 has lower than samples 1 and 2 values V_1 and ΔV_{11} but significantly higher values ΔV_{1-2} and ΔV_{2-3}.

The smaller macropore structure of sample 3 is explained by the peculiarities of the yarns (structure, fibre composition) and the structure of the fabric as a whole. Thus, the warp and weft yarn density of sample 3 is much lower than that of samples 1 and 2, but their linear density is almost twice as high as that of samples 1 and 2 (Table 1). The higher values V_3 indicate that sample 3 has a more developed ultramicropore structure, which is explained by the difference from samples 1 and 2 in its fibre composition (Table 1). This is also explained by the difference in the structure of the polyamide polymer from polyester. To verify this, the microstructure of the samples of the fabrics has been studied in detail.

To clarify and further detail the micropore structure of the fabrics, in addition to the thermogram method, they have been also studied based on sorption-desorption isotherms (the sorption method). The study is carried out with the use of laboratory equipment based on the McBain tensometric method at an ambient temperature of 293 K. For each sample, a curve of the moisture content of the sample (W) versus air humidity is made (φ). The curve is built both in the process of water vapour sorption by the fabric samples and in the process of desorption (Fig. 2).

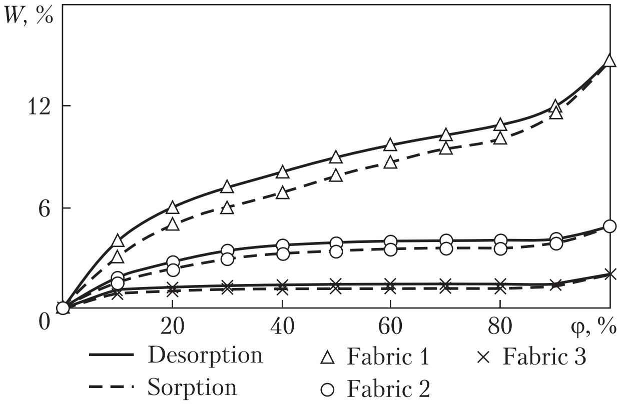

Fig. 2. Fabric sorption-desorption isotherms

Figure 2 shows that in terms of hygroscopicity and micropore volume, fabric 3 is the most hygroscopic, followed by fabrics 2 and 1, respectively.

The studies identified some quantitative differences obtained by the drying thermogram method and the sorption method, but they generally confirm the results obtained. According to this, the fabric made of polyamide yarns has a significantly higher sorption capacity than the fabric made of polyester fibres. This indicates a much more developed micropore structure of fabrics made of polyamide yarns and their better ability to be

Table 2. **Characteristics of the Pore Structure of the Studied Fabrics**

No.	Pore size, m^3/g ($\times 10^{-7}$)					Specific surface area, m^2/g
	V_1	ΔV_{11}	ΔV_{1-2}	ΔV_{2-3}	V_3	
1	87.7	78.9	6.3	1.7	0.8	32.3
2	104.8	95.3	6.4	1.8	1.3	44.9
3	84.5	67.4	10.1	5.6	1.4	59.8

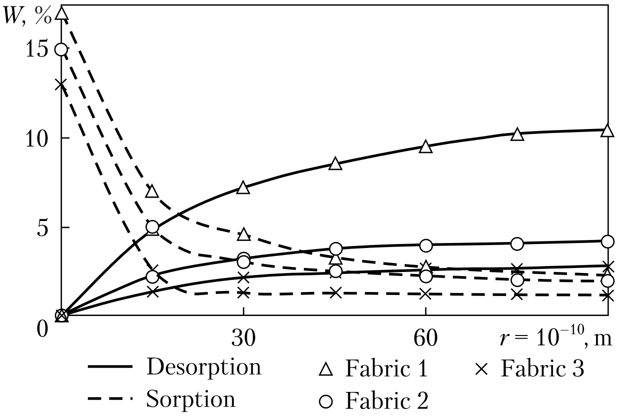

Fig. 3. Integral and differential curves of fabric pore size distribution

dyed and finished compared to fabrics made of polyester fibres.

The isotherms of fabric samples 1 and 2 (Fig. 3), which differ only in the structure of the weft yarns, have been also compared. It has been found that the hygroscopicity (Fig. 3) and micropore volumes of fabric 2 are higher than those of fabric 1 (Table 2). The above means that the technology of manufacturing yarns also affects the pore structure of fabrics.

Various methods of evaluating the macro- and microporous structure of various materials have been analyzed. It has been noted that some of them are quite complex and expensive, and others do not have sufficient accuracy, which does not allow a comprehensive approach to predicting the permeability of textile fabrics and the ability to dye and finish.

A comprehensive method for assessing the macro- and micropore structure of textile fabrics, consisting of drying thermogram and sorption methods, has been proposed. It enables to determine the macro- and micropore structure of textile fabrics quite accurately and quickly and, accordingly, to predict their permeability and ability to be dyed and finished. The larger the macropore structure of a textile material, the better its ability to permeate various substances. With an increase in the micropore structure of the material, the absorption of various substances grows, increasing its ability to by dyed and finished.

The studies have shown that the fibre composition and structure of yarns and fabrics significantly affect the micro- and macropore structure of the studied fabrics. The characteristics of the micropore structure of the studied fabrics, such as hygroscopicity, the amount of adsorbed moisture, and moisture in the micropores do not depend on the fabric density and structure, but are determined mainly by their fibre composition. Such characteristics of the pore structure of fabrics as total moisture capacity, the amount of moisture in the macropores of fabrics are determined by the structure of yarns and fabrics.

This comprehensive method makes it possible to conduct comparative studies of various textile materials, specify the technological modes of their dyeing and finishing and more accurately determine the scope of their application according to their intended use.

REFERENCES

1. Simmonds, G., Bomberger, J., Bryner, M. (2007). Designing Nonwovens to Meet Pore Size Specifications. *Journal of Engineered Fibers and Fabrics*, 2(1), 1—15. https://doi.org/10.1177/155892500700200101
2. Syerko, E., Schmidt, T., May, D., Binetruy, C., ... Vorobyev, R. (2023). Benchmark exercise on image-based permeability determination of engineering textiles: Microscale predictions. *Composites. Part A: Applied Science and Manufacturing*, 167, 107397. https://doi.org/10.1016/j.compositesa.2022.107397
3. Rawal, A. (2010). Structural analysis of pore size distribution of nonwovens. *The Journal of The Textile Institute*, 101(4), 350—359. https://doi.org/10.1080/00405000802442351
4. Amico, S., Lekakou, C. (2000). Mathematical modelling of capillary micro-flow through woven fabrics. *Composites Part A: Applied Science and Manufacturing*, 31(12), 1331—1344. https://doi.org/10.1016/S1359-835X(00)00033-6
5. Abdoli, H., Hermann, T., Bickerton, S. (2022). A novel, fast and clean 3D permeability measurement method for multilayer textiles and fabrics. *Composites Part A: Applied Science and Manufacturing*, 162, 107—167. https://doi.org/10.1016/j.compositesa.2022.107167

6. Dimitrovski, K., Zupin, Z., Kostajnšek, K., Branca, E. (2017). Use of air permeability for determination of equivalent average pore diameter in woven fabrics. *IOP Conference Series: Materials Science and Engineering*, 254(4), 042009. https://doi.org/10.1088/1757-899X/254/4/042009
7. Jakšić, D., Jakšić, N. (2007). Assessment of porosity of flat textile fabrics. *Textile Research Journal*, 77(2), 105–110. https://doi.org/10.1177/0040517506065892
8. Dubrovski, P., Brezocnik, M. (2002). Using genetic programming to predict the macroporosity of woven cotton fabrics. *Textile Research Journal*, 72(3), 187–194. https://doi.org/10.1177/004051750207200301
9. Zupin, Z., Hladnik, A., Dimitrovski, K. (2012). Prediction of one-layer woven fabrics air permeability using porosity parameters. *Textile Research Journal*, 82(2), 117–128. https://doi.org/10.1177/0040517511424529
10. Büyükbayraktar, R., Okur, A., Deveci, R., Acikel, M. (2012). Predicting the intra-yarn porosity by image analysis method. *Textile Research Journal*, 82(16), 1720–1728. https://doi.org/10.1177/0040517511427971
11. Ogulata, T., Serin, M. (2010). Investigation of porosity and air permeability values of plain knitted fabrics. *Fibres and Textiles in Eastern Europe*, 18(5), 7–10.
12. Gültekin, E., Çelik, H., Nohut, S., Elma, S. (2020). Predicting air permeability and porosity of nonwovens with image processing and artificial intelligence methods. *Journal of the Textile Institute*, 111(11), 1641–1651. https://doi.org/10.1080/00405000.2020.1727267
13. Kostajnšek, K., Zupin, Ž., Hladnik, A., Dimitrovski, K. (2021). Optical assessment of porosity parameters in transparent woven fabrics. *Polymers*, 13(3), 408. https://doi.org/10.3390/polym13030408
14. Zhu, G., Fang, Y., Zhao, L., Wang, J., Chen, W. (2017). Prediction of structural parameters and air permeability of cotton woven fabric. *Textile Research Journal*, 88(14), 1650–1659. https://doi.org/10.1177/0040517517705632
15. Militky, J., Travnickova, M., Bajzik, V. (1999). Air permeability and light transmission of weaves. *International Journal of Clothing Science and Technology*, 11(2/3), 116–125. https://doi.org/10.1108/09556229910276331
16. Khalil, A., Eldeeb, M., Tesinova, P., Fouda, A. (2023). Theoretical porosity of elastic single jersey knitted fabric based on 3D geometrical model of stitch overlapping. *Journal of Natural Fibers*, 20(1). https://doi.org/10.1080/15440478.2023.2181274
17. Mokrousova, E., Dzyazko, Y., Volfkovich, Yu., Nikolskaya, N. (2016). Hierarchical structure of derma affected by chemical treatment and filling with bentonite diagnostics with a method of standard contact porosimetry. *Springer Proceedings in Physics*, 183, 277–290. https://doi.org/10.1007/978-3-319-30737-4_23
18. Kotyukov, Yu. D., Levchenko, V. I., Rogankov, O. V., Shvets, M. V., Rogankov, V. B. (2015). Concept and model of mesotropic porosity of thin permeable media. *Refrigeration Engineering and Technology*, 51(5), 1–16. https://doiorg/10.15673/0453-8307.5/2015.44797
19. Baché, E., Dupleix-Couderc, C., Arquis, E., Berdoyes, I. (2018). Impregnation of Composite Materials: a Numerical Study. *Applied Composite Materials*, 25, 1287–1305. https://doi.org/10.1007/s10443-017-9666-9
20. Suprun, N. P. (2008). *Material science of sewing products: fibers and threads: textbook*. Kyiv [in Ukrainian].
21. Slizkov, A. M. (2010). *Development of scientific bases for forecasting physical and mechanical properties of textile materials for household purposes*. (PhD) (Tech.). Kyiv [in Ukrainian].
22. Lutsyk, R. V., Malkin, E. S., Abarzhy, I. I. (1993). *Heat and mass exchange during processing of textile materials*. Kyiv [in Ukrainian].
23. Lipatov, Yu. S. (1984). *Colloidal chemistry of polymers*. Kyiv [in Ukrainian].
24. Sabadash, V. V. (2019). *Theoretical foundations of sorption processes on natural and synthetic sorbents*. Doctoral dissertation. (Tech.). Lviv [in Ukrainian].
25. Ivanenko, I. M., Dontsova, T. A., Fedenko, Yu. M. (2018). Adsorption, adsorbents and catalysts based on them. URL: https://ela.kpi.ua/server/api/core/bitstreams/20ca11ec-a871-47d7-acbc-e91eb57a9c2e/content (Last accessed: 26.06.2024).
26. Antal, I. P., Basel, Y. R., Kormosh, Z. O. (2015). *Methods of separation and concentration of substances in the analysis*. Lutsk [in Ukrainian].
27. Glubish, P. A., Irklay, V. M., Kleiner, Y. Ya. Rezanova, N. M., Tsebrenko, M. V. (2007). *High-tech, competitive and ecologically oriented fibrous materials and products from them*. Kyiv [in Ukrainian].

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КОМПЛЕКСНИЙ ПІДХІД ДО ОЦІНКИ МАКРО- ТА МІКРОПОРОВОЇ СТРУКТУРИ ТЕКСТИЛЬНИХ МАТЕРІАЛІВ

Вступ. Актуальним на сьогодні є пошук підходу до оцінювання макро- та мікропорової структури текстильних полотен з метою прогнозування їхньої проникності, а також здатності до фарбування та оздоблення. Це є важливим для визначення гігієнічних властивостей матеріалів для одягу, процесів фарбування та оздоблення текстильних матеріалів, а для технічних полотен — можливості фільтрації різноманітних дисперсних середовищ.

Проблематика. На сьогодні ще є складності у прогнозуванні проникності текстильних полотен, а також визначенні параметрів режимів фарбування та оздоблення текстильних матеріалів.

Мета. Розробка швидкого, доступного та точного підходу до оцінки макро- та мікропорової структури текстильних полотен для оцінки їхньої проникності та здатності до фарбування й оздоблення.

Матеріали й методи. Для дослідження порової структури текстильних полотен були взяті тканини, які відрізнялися між собою структурою ниток — пряжа класична та скороченого способу виробництва, а також за волокнистим складом. Першу виготовлено з комплексних поліамідних ниток полотняним переплетенням, другу — саржевим переплетенням з пряжі поліестерних волокон, а третя мала відмінність від другої тканини структурою пряжі утоку. Для оцінки макро- та мікропорової структури текстильних полотен застосовано методи термограм сушки та сорбційний.

Результати. Порівняння мікро- та макропорової структури досліджуваних текстильних полотен показало, що тканина з поліамідних ниток має значно більшу сорбційну ємність порівняно з тканиною із поліестерних волокон. Це вказує на вищу розвиненість мікропорової структури тканин з поліамідних ниток і кращу їхню здатність до фарбування та оздоблення. Застосовано комплексний підхід до оцінки макро- та мікропорової структури текстильних полотен методами термограм сушки та сорбційного.

Висновки. Запропоновий підхід дає можливість проводити порівняльні дослідження різних текстильних матеріалів, уточнювати технологічні режими їхнього фарбування та оздоблення і визначати галузь подальшого застосування.

Ключові слова: текстильні матеріали, текстильні полотна, тканини, мікропорова структура, комплексний підхід, макропорова структура, метод термограм сушки, сорбційний метод.