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ANALYZING THE RELATIONSHIP BETWEEN AIR PERMEABILITY AND THE PERFORMANCE OF TECHNICAL TEXTILES

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Abstract: *Workers need to wear protective clothing in hazardous environments to stay safe. If protective equipment is not used correctly or causes discomfort, it can reduce its effectiveness and put workers at risk. It's essential to ensure that work can be done safely and comfortably. In the textile industry, fabric features were often described by air permeability. This research examines how different fabric patterns affect comfort by analyzing air permeability. The study explores the air permeability of six fabric samples in dry and wet conditions, showing that treating them with a saline solution during conditioning can impact their comfort.*

Key words: *air permeability, comfort level, occupational safety, personal protective equipment.*

1. INTRODUCTION

The rise of new technology, the introduction of novel work procedures, and changes in organizational structures has resulted in an increase in various risks in the work environment [1]. As a result, occupational injuries and illnesses remain persistent issues [2]. With the new socioeconomic framework, the adoption of personal protective equipment acts as a protective barrier, ensuring the safety and well-being of workers from potential hazards. In addition, the changing landscape has created a need for workers to have better protective and comfortable clothing while in the workplace [3]. The worker should be able to comfortably wear protective clothing for long periods and have sufficient mobility to prevent potential injuries. In recent years, the focus has been on improving the comfort of the wearer's protective clothing through advancements in technical textiles [4]. Comfort can be described as a feeling of contentment and a sense of well-being, experienced by the person wearing PPE [5]. For a long time, it was commonly believed that hazardous work environments could not provide both comfort and protection. The comfort provided enables a seamless workflow, ensuring that the equipment operates efficiently during work [6]. The level of comfort can be influenced by various PPE features, including the type of fabric, and external factors such as extreme temperatures [7]. One method to assess the comfort level of PPE is by conducting an air permeability test on technical textiles. Technical textiles are developed to meet this specific performance standards, especially in challenging environments. Air permeability plays an important role in determining their effectiveness, impacting important aspects, such as comfort, durability, and protection. Understanding how air permeability affects the overall performance of technical textiles is vital for enhancing their design and guaranteeing they fulfill end-users' protection and comfort requirements. The air permeability of a textile depends on its material composition and structure [8]. Nonwoven fabrics, in particular, can have different air permeability values based on how they are made and the characteristics of the fibers [9]. These differences in air permeability can greatly affect the functional properties of technical textiles [10].

Air permeability is a parameter of clothing comfort that is affected by fundamental properties of a fabric, such as thickness, fabric

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weight, etc. Air permeability is an important fabric property because it has a decisive influence on the use of the fabric for protective clothing [11]. The measurement of air flow through a fabric's surface area is known as air permeability [12]. The PPE comfort properties are greatly impacted by this parameter. The connection between a fabric's air permeability and porosity is widely recognized. A fabric with higher porosity will have greater permeability. A fabric with greater porosity is more permeable [13, 14]. Burleigh et al. [15] pointed out that the porosity created between yarns and interfibers is a key factor in determining effective porosity. According to them, the porosity between fibers and inter-yarns varies based on factors such as fiber fineness, fiber shape, fabric type, yarn density, and yarn twist.

When evaluating comfort, air permeability is an effective measure because of the significance of material breathability. When PPE is breathable, it effectively disperses heat and prevents the accumulation of water vapor caused by sweat, providing a comfortable experience for the wearer.

While most PPEs are comfortable in their dry state, the transfer properties of fabrics can be affected by changes in moisture content when used under conditions of humidity and extreme temperature. Several studies have been conducted on the comfort properties of PPE under initial and dry conditions. However, only few studies have considered the impact of sweating and the aging process resulting from repeated washing [16, 17].

The comfort level of a worker can be compromised when working in extreme working conditions, such as extreme temperatures (cold and hot) and wet environments. When exposed to cold environments, the body temperature decreases, which decrease heat loss from the body. This can result in workers feeling cold and uncomfortable, and a decrease in performance, increasing their risk of hypothermia. Conversely, in situations involving cold temperatures and intense physical activity or hot environments, the human body temperature increases, resulting in greater heat dissipation and prompting sweat release. The permeability of protective clothing plays an essential role in determining how effectively sweat can evaporate. Extreme discomfort will be felt by the wearer if the PPE prevents the evaporation of sweat [18]. To prevent this occurrence, it is important to verify that the protective equipment provides adequate insulation, weatherproofing, and proper airflow (breathability).

The air permeability test is a key method for understanding how materials interact with airflow, providing essential information for quality control, material selection, performance evaluation, development, and meeting standards in different industries. Analysis of samples from production batches allows PPE manufacturers to recognize any changes in material permeability.

There is no doubt that measuring the air permeability in the woven material is essential. Various efforts have been made to simulate fabric air permeability, with Robertson [19] defining the primary framework for analysis. Hoerner [20] expanded on this concept by likening airflow through fabric to that in a tube, but with a greater aspect ratio. Lawrence [21] introduced a two-term equation to predict fabric air permeability in filament fabrics with a plain weave, incorporating pressure drop, air viscosity, fabric density, void geometry, and air velocity as significant model parameters. R. Milašius [22] studied the influence of fabric firmness, including fabric density and thread count, on air permeability, while also considering structural parameters.

The progress in testing methods and equipment for high-performance technical textiles has not always kept up with material innovations, as highlighted in a study by Somogyi and Pezelj (2012) [8]. Analyzing how air permeability impacts the overall performance of these fabrics can pose difficulties due to varying application requirements and conditions, as discussed by Mukhopadhyay and Midha (2008) [10]. Nevertheless, grasping the correlation between air permeability and factors, such as abrasion resistance, water resistance, and thermal comfort is crucial for designing and enhancing technical textiles to meet the requirements of their specific environments.

The importance of air permeability testing becomes important when protective clothing is used in extreme work environments.

The safety and comfort of workers are significantly affected by heat and moisture transfer from the skin through the fabric. Intense physical activities and harsh environmental conditions can lead to perspiration, resulting in a moderate to heavy flow of liquid sweat [24]. Therefore, the main focus is on developing fabrics that maintain an equilibrium between thermal protection from fires and the thermal stress caused by high temperatures and increased metabolic rates in the environment.

Several researchers have explored the protective and comfort aspects of protective clothing in thermal environments, however there is a clear research void concerning the impact of air permeability on comfort.

This study allows for comparing different fabrics air permeability to selecting the most appropriate one for a specific purpose, such as providing thermal protection to workers in environments with extreme temperatures. Analysis of the connection between material structure and permeability can lead to enhancements in current PPEs or the creation of novel materials for diverse applications and environmental scenarios. Assessing the air permeability of fabrics under dry and wet conditions enables manufacturers to determine the protective and performance characteristics of textile materials for personal protective equipment designed for thermal protection.

2. MATERIALS AND METHODS

The study adopted a cross-sectional approach. Employing a mixed-methods approach that combines experimental tests and data analyses to provide a comprehensive understanding of the comfort properties of five commonly used fabrics in the production of protective clothing. The fabric used in the study was purchased from local marketplace. Fabrics were selected from the usual materials commonly used for thermal protection. Table 1 displays the fabric characteristics of the textile materials used.

Table 1

Fabric composition

Fabric code	Composition	Mass per unit area (g/m^2)
A	80% Cotton, 19% polyester and 1% anti-static fibres	185
B	75% Cotton, 24% polyester and 1% anti-static fibres	275
C	98% Aramid (93% Nomex/ 5% Kevlar) and 2% anti-static fibres	265
D	54% Viscose, 20% wool, 20% polyamide, 5% aramid and 1% anti-static fibres	375
E	26% Cotton, 41% polyester, 32% modacrilice and 1% anti-static fibres	330
F	99% Cotton and 1% anti-static fibres	220

The laboratory experiments were conducted according to the various specified test conditions.

To prepare for testing, all the samples were exposed to a conditioning period of 24h at a temperature of 20±2^o C and a relative humidity of 65±5%.

Before further testing, the samples were analyzed in their initial condition (dry state).

The effectiveness of a fabric's protection and comfort is compared with its counterpart after washing. Different factors like the number of wash cycles are considered in the study. The textile underwent a cleaning process involving 5 and 50 washing cycles, followed by testing in both dry and wet conditions (conditioning at 85% humidity). Washing cycles of both 5 and 50 meet the minimum and maximum requirements set by the manufacturers. All samples were washed using the same method, with a professional-grade washing machine: a full cycle with at least two rinses, using a powder standardized detergent.

A preliminary prewash procedure was performed on all samples before analysis. All samples were subjected to a preliminary step before analysis, which included washing at 60^o C and drying in a dryer at 70^o C.

Furthermore, the fabric samples were assessed in dry and wet states following a 7h treatment in a salt water solution with a concentration of 25 g of salt per liter. Artificial sweating replicate the sweat-inducing conditions experienced by workers during a 7h work period.

The samples were subjected to a 7h conditioning period at 50º C and -10º C before being tested to evaluate their properties. As 20º C or 23º C and -5º C standard laboratory conditions are rare worldwide, these temperatures were selected to mimic some of the environmental settings where the materials will be used. For wearers to work safely and efficiently, protective clothing must have a range of characteristics, such as the ability to ensure users comfort in extremely cold or hot conditions. This includes features like insulation for cold environments and breathability for hot conditions. Protective clothing must also be designed to allow for ease of movement and flexibility to accommodate various tasks that wearers may need to perform [23].

The air permeability test was performed in accordance with SR EN ISO 9237:1999 Textiles. Determination of the permeability of fabrics to air [24]. The air permeability of the fabric was tested under an air pressure of 200 Pa using a 20 cm^2 sample surface. The air permeability of the selected samples was measured using a textile materials apparatus specified by the standard.

By analyzing multiple outcomes, it can be established whether there is a connection between air permeability and the functionality of technical textiles. This examination can offer valuable perspectives on how the performance of these textiles is influenced by varying levels of air permeability under different conditions. Additionally, a clear understanding of this association can lead to the production of technical textiles that are more appropriate and efficient for particular uses.

3. RESULTS

The current situation lacks clear findings on air permeability measurements. Instead of using a comprehensive approach, only scattered and varied results from randomly selected papers have been used to address the issue [25]. This fragmented approach has resulted in inconsistencies and gaps in understanding the true extent of air permeability in different materials. An in-depth investigation is required to shed more light on this important property.

The fabric samples were subjected to three humidity levels for testing: initial (unused), dry, and wet. Tables 2-7 display the data acquired from the tests conducted on selected material samples.

Table 2

Air permeability under dry condition

Fabric code	Air permeability l/m^2.s		
	Initial state	Washing cycles	
		5	50
A	269,54	247,49	224,78
B	112,22	105,54	115,23
C	141,62	147,29	162,66
D	28,69	38,51	38,64
E	58,58	64,96	70,14
F	119,24	173,35	141,95

Table 3

Air permeability under wet condition, after conditioning at 23° C and 85% humidity

Fabric code	Air permeability l/m^2.s		
	Initial state	Washing cycles	
		5	50
A	269,54	155,98	203,41
B	112,22	57,75	53,17
C	141,62	144,29	152,30
D	28,69	4,73	2,08
E	58,58	23,98	47,03
F	119,24	77,35	111,89

Table 4

Air permeability under dry condition, after prewash treatment and 7h of conditioning in saline solution

Fabric code	Air permeability l/m^2.s		
	Initial state	Washing cycles	
		5	50
A	269,54	205,74	189,71
B	112,22	117,90	63,13
C	141,62	144,96	74,25
D	28,69	32,83	18,50
E	58,58	67,13	71,48
F	119,24	155,98	123,58

Table 5

Air permeability under wet condition (conditioning at 23° C and 85% humidity), after prewash treatment and 7h of conditioning in saline solution

Fabric code	Air permeability l/m^2.s	
	Initial state	Washing cycles

		5	50
A	269,54	55,14	184,03
B	112,22	60,96	18,54
C	141,62	38,74	6,35
D	28,69	0,74	4,18
E	58,58	9,25	48,06
F	119,24	4,28	44,09

Table 6

Air permeability after prewash treatment, 7h of conditioning in saline solution and 3h of conditioning at 50°C

Fabric code	Air permeability l/m^2.s		
	Initial state	Washing cycles	
		5	50
A	269,54	241,59	209,31
B	112,22	88,77	83,31
C	141,62	115,39	116,94
D	28,69	24,51	25,33
E	58,58	51,33	50,78
F	119,24	120,73	120,73

Table 7

Air permeability after prewash treatment, 7h of conditioning in saline solution and 3h conditioning at -10°C

Fabric code	Air permeability l/m^2.s		
	Initial state	Washing cycles	
		5	50
A	269,54	201,31	184,33
B	112,22	101,71	61,88
C	141,62	133,87	131,88
D	28,69	28,31	27,39
E	58,58	61,31	68,47
F	119,24	125,33	129,19

The air permeability of the tested fabrics is graphically represented in Figures 1-6, which show the distribution of the experimental values influenced by temperature and humidity.

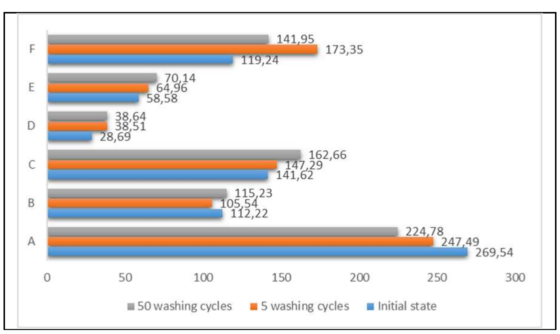

Fig. 1 Distribution of air permeability values under dry condition

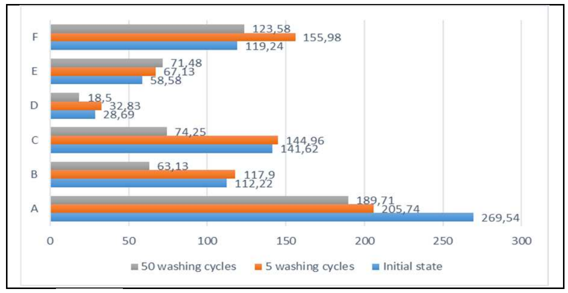

Fig. 2 Distribution of air permeability values under wet condition, after conditioning at 23° C and 85% humidity

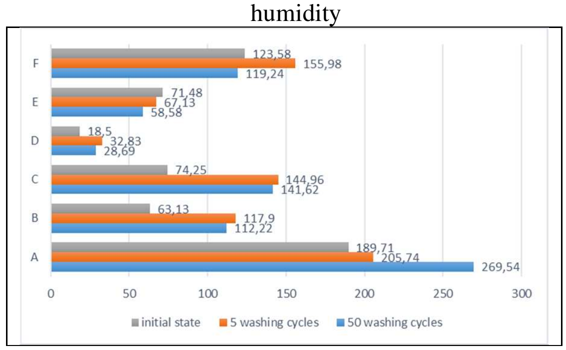

Fig. 3 Distribution of air permeability values under dry condition, after prewash treatment and 7h of conditioning in saline solution

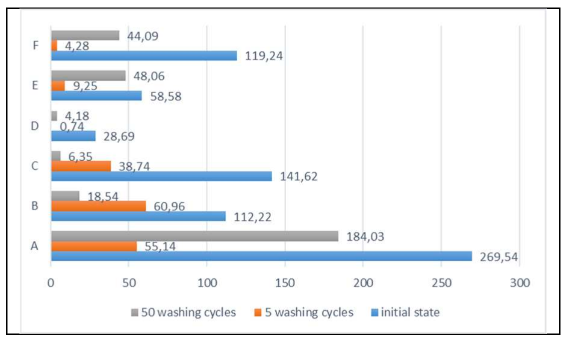

Fig. 4 Distribution of air permeability values under wet condition (conditioning at 23° C and 85% humidity), after prewash treatment and 7h of conditioning in saline solution

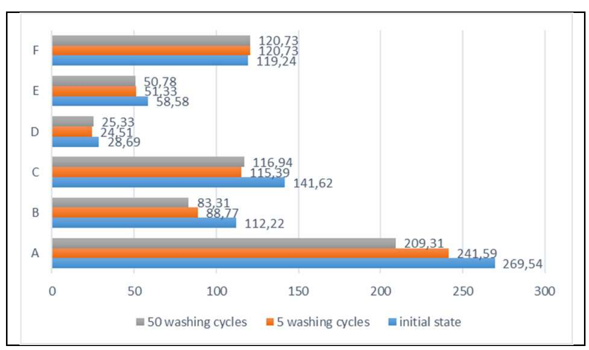

Fig. 5 Distribution of air permeability values prewash treatment, 7h of conditioning in saline solution and 3h of conditioning at 50°C

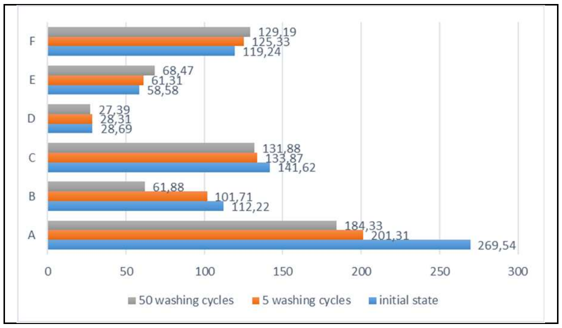

Fig. 6 Distribution of air permeability values prewash treatment, 7h of conditioning in saline solution and 3h of conditioning at -10°C

4. DISCUSSION

The importance of air permeability in fabrics lies in its ability to control airflow through a specific area of the fabric [26]. When air is unable to flow through the fabric's pores or faces resistance, it will cause discomfort. Therefore, the air permeability of the fabric plays an important role in improving the overall comfort of protective clothing. The study of air permeability was conducted to gain a comprehensive understanding of the comfort properties of the fabrics being analyzed.

For this study, a variety of textile material samples were selected, including some with a dominant cotton composition (over 75%) and others made predominantly of synthetic fibers.

A visual representation of the distribution of air permeability values can be seen in Figure 1-6. Typical examples of the humidity-dependent air permeability of the selected fabric are shown in Figures 2 and 4. For comparison, fabrics in dry condition are also shown in Figures 1, 3, 5, and 6.

By comparing the experimental data on air permeability measurements for different fabrics under various conditions, the following aspects are highlighted. The initial comparison indicates that fabric A has the highest air permeability at the beginning, whereas fabric D has the lowest air permeability initially. As a result of washing cycles, most fabrics experience a decrease in air permeability with more washes (5 vs 50) under dry conditions. Fabric C and E are exceptions, showing slight increases in air permeability with more washes under dry conditions. Wet versus dry conditions demonstrate that air permeability is generally lower when the material is wet compared to when it is dry. This difference is particularly noticeable for Fabric A and F. Prewash treatment typically reduces the air permeability of most fabrics. However, Fabric E demonstrates an increase in air permeability after prewash treatment under dry conditions. When is compared the effects of temperature on air permeability, most fabrics exhibit slightly lower air permeability at -10 °C compared to 50 °C. However, Fabric C and E are exceptions as they show higher permeability at -10 °C. In terms of consistency across conditions, Fabric D consistently exhibits the lowest air permeability in most situations. On the other hand, Fabric A typically maintains the highest air permeability, except in specific wet conditions. The largest variations are shown by Fabric A, indicating the most dramatic changes across different conditions. Fabric D, on the other hand, exhibits the least variation across conditions. Unusual observations indicate that Fabric C exhibits very low air permeability (6.35 l/m2.s) when wet after undergoing prewash treatment and 50 washing cycles.

This study gives an overview of how different fabrics react to various treatments and conditions regarding air permeability. The initial state of samples A, B, and F indicate a high level of air permeability. However, after being subjected to pre-wash treatment and conditioning in saline solution, air permeability decreased. The air permeability values for those samples are initially high in the dry state due to their cotton content being greater than 75%. These values decrease after pretreatment because of the thickening effect that occurs after washing and drying. The wet state of these samples experiences an even more significant decrease after exposure to simulated sweat. No difference in air permeability was observed in sample C after the pre-wash treatment. Nevertheless, there was a substantial decrease in air permeability when the sample was conditioned in saline solution. No significant changes in air permeability were observed in samples D and E after prewashing and conditioning in saline solution.

The data presented in Figures 1-6 clearly demonstrate that, in their dry state, fabrics composed mostly of cotton have a high level of air permeability. However, this value decreased after prewashing and conditioning in saline solution. The presence of aramid fibers did not alter the air permeability of the samples during the prewash treatment, but significantly decreased the air permeability after the samples were conditioned in saline solution. The use of a saline solution for pretreatment before washing and conditioning does not have a notable effect on the air permeability of materials with a high proportion of modacrylic or viscose fibers.

The air permeability data collected in this study is analyzed statistically, as shown in Figure 7. The box plot provides a detailed summary of the statistical results regarding air permeability.

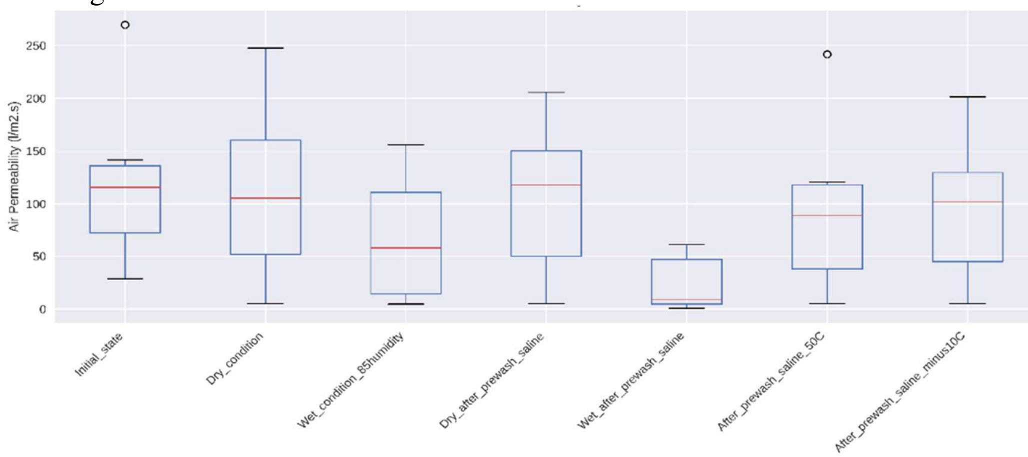

Fig. 7 Box plot distribution of air permeability measurements for each state condition

The box plot illustrates how various conditions impact air permeability. It emphasizes the significant influence of moisture and the consistent measurements under dry conditions. The initial state and dry condition have the highest median air permeability values, followed closely by the measurements after prewash and saline treatment at both 50°C and -10°C. Most conditions exhibit significant variability in air permeability, as shown by the height of the boxes and the length of the whiskers. Wet conditions, such as 85% humidity and after prewash and saline treatment, demonstrate notably lower air permeability values compared to dry conditions. This indicates that moisture significantly reduces air permeability in these fabrics. The dry condition after prewash and saline treatment shows slightly lower air permeability compared to the initial dry condition, but the difference is not significant. The measurements after prewash and saline treatment at 50°C and -10°C are quite similar, suggesting that temperature changes within this range do not greatly affect air permeability.

It is showed that moisture has the most significant effect on reducing air permeability in all tested conditions. The fabrics tend to maintain consistent air permeability properties in dry conditions, even after undergoing treatments. Notably, there is a notable difference in air permeability among the fabric samples, as indicated by the range of each box and whisker plot. The existence of outliers indicates that certain fabric samples exhibit unusually high air permeability compared to the rest in the dataset.

The data showed that the weight of the materials used in protective clothing significantly affects the comfort provided by PPE in hot and humid environments, as these conditions are strongly influenced by the total weight of the materials used. Additionally, the breathability of the materials is considered, in conjunction with this factor, to swiftly carry warm air away from the body's surface and assist in maintaining a cool body temperature.

The experimental findings demonstrated a strong correlation between air permeability and the fibrous composition, specific gravity, and structure of the material. With the exception of sample A, which is cloth-bonded and known for its porous structure, all textiles are diagonally bonded.

The air permeability of sample C was not affected by the washing pretreatment, but it significantly decreased when soaked in the perspiration-simulating solution. This decrease indicates that the aramid fiber is damaged by contact with the basic solution.

Sample D, which combines viscose (based cellulosic fiber) and aramid fibers, and sample E, made of modacrylic fibers and cotton, show an almost linear distribution of air permeability with no visible changes after pretreatment and exposure to simulated sweat contact. Furthermore, sample D indicates a notable decrease in wet permeability as a result of conditioning at 23º C and 85% humidity, as well as being conditioned in saline solution.

Sample F, consisting of 99% cotton, demonstrates a high level of permeability that decreases only after being conditioned in a saline solution while in a wet state.

The wet state's impact on air permeability can be explained by the capillary absorption of moisture, which causes fibers to expand and significantly reduces the fabric's porosity. In this context, materials with a medium or low cotton content or similar fibers are considered more comfortable for hot weather because they allow air to exchange more quickly between the skin surface and the surrounding environment.

The findings show that air permeability is affected by the fabric porosity. Moreover, it has been observed that the comfort properties of woven fabrics are influenced by the raw material composition, weave type, and fabric condition.

Based on this experimental study, the following deductions can be inferred:

- The results show that there is a relationship between air permeability and comfort for most of the selected fabrics.
- Among the parameters that have that affect fabric properties, composition influences the relation between the air permeability of the fabric and its comfort. According to the study, the comfort features of the fabric can be influenced by its composition. It was evident from the analysis that all comfort properties varied significantly across the selected fabrics, with few deviations. The results also showed that sample A (fabric with large cotton composition) had the highest air permeability whereas sample B (fabric with 75% cotton in the composition) had the lowest.

A study conducted by Milenkovi et al. [27] yielded comparable findings, showing that the air permeability of a fabric plays a role in determining its comfort. Previous research supports these findings, showing that comfort depends on a variety of factors, including fiber properties, yarn properties, fabric properties, finishing treatments, and clothing conditions [28, 29]. Lee and Obendorf (2007) [30], McGregor and Naebe (2013) [31], and Prasad et al. (2002) [32] all reported similar findings.

In this study, it is crucial to acknowledge certain limitations. Initially, the fabrics were obtained from the local market, lacking fabric label information such as thickness and weight. This absence made it challenging to control these unidentified variables that could impact the test results. Additionally, the limited sample size might not fully reflect the entire spectrum of textiles found in the European market.

In future research, increasing the number of textile samples and considering a wide range of factors that affect air permeability will enhance the probability of obtaining valuable data for the advancement of technical textiles.

5. CONCLUSION

Experimentally and theoretically, the effect of air permeability on protective fabrics has been studied. Through the analysis of various results, it can be determined whether there is a correlation between air permeability and the performance of technical textiles.

Exploring how alterations in fabric composition impact air permeability can result in a textile material that meets the comfort criteria needed for work environments experiencing temperature variations.

Future research can be conducted with more specimens with more variety in composition. Additional comfort features of fabric such as porosity and breathability can be included as characteristics and examined. A possible area for further investigation is exploring the relationship between air permeability in technical textiles and different manufacturing processes. This suggested approach for evaluating comfort under various conditions serves as a valuable tool for finding a balance between comfort and protection.

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EVALUAREA INFLUENȚEI PERMEABILITĂȚII LA AER ASUPRA FUNCȚIONALITĂȚII TEXTILELOR TEHNICE

Rezumat: Lucrătorii trebuie să utilizeze îmbrăcăminte de protecție în medii periculoase pentru a fi în siguranță. Dacă echipamentul de protecție nu este utilizat corect sau provoacă disconfort, acesta își poate diminua proprietatea de protecție și poate expune lucrătorii la riscuri. Este esențial să se asigure că munca poate fi efectuată în condiții de siguranță și confort. În industria textilă, caracteristicile țesăturii sunt adesea descrise de permeabilitatea la aer. Această cercetare examinează modul în care diferite modele de țesături afectează confortul prin analizarea permeabilității la aer. Studiul explorează permeabilitatea la aer a șase mostre de țesături în stare uscată și umedă, arătând că tratarea acestora cu o soluție salină în timpul condiționării le poate afecta confortul.

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