EXPERIMENTAL STUDY ABOUT INFLUENCE OF REPEATED WASHING ON THE AIR-PERMEABILITY OF COTTON WOVEN FABRICS IN THE DRY AND WET STATE

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Abstract: *This work deals with the influence of washing and moisture on the change of air-permeability of cotton fabrics and the impact of different types of seams on air-permeability. It turns out that the effect of the kind of seams does not significantly affect the air-permeability. Repeatable washing has a much more significant impact when the fabric is in a dry or wet state.*

Keywords: *air-permeability, cotton woven fabrics, repeated washing.*

1 INTRODUCTION

Air permeability is one of the basic textile properties that affect the comfort of textile users [1]. Currently, thanks to the COVID - 19 pandemic, knowledge of these phenomena is gaining importance. It turns out that home-made face masks did not achieve additional effectiveness of protection against the penetration of viruses as disposable masks or as respirators. Medical [2] and physical studies [3] show that maintain an additional distance of 2 meters are not sufficient to prevent the transfer of aerosol droplets containing viruses. Regulating the wearing of masks by the public may increase the demand for respirators and disposable masks, which are especially important for healthcare professionals. Extending knowledge of the physical phenomena to them during the use of woven fabrics cotton masks could help their widespread use, which is not least more economical [4] and more environmentally friendly than the use of disposable masks.

This study aims to compare the effect of moisture on the change in the air-permeability of cotton woven fabrics, as the formation of condensation due to respiration occurs during the wearing of the mask. It is generally known that the wet strength of cotton fibers increases. It is also known that the moisture content of fabric can significantly change its properties. Currently, there is no standard defining this issue, so the experiment was designed to compare the air-permeability of selected woven fabrics in extreme humidity cases. There were two experimental woven fabrics evaluated in this work. Both fabrics were made of 100% cotton fibers, 120-130 g/m^2 mass. The chosen weave was plain weave, as this weave shows the densest weave of warp and weft threads in comparison with the twill or satin weave [5]. Therefore, in the experimental part of this work, only samples of fabrics with plain weave were used to suppress the effect of fabric weave on its air-permeability. The work also evaluates the influence of three types of fabric seams on the air-permeability of the fabric. The types of seams were selected concerning the currently most frequently used seams in the production of masks.

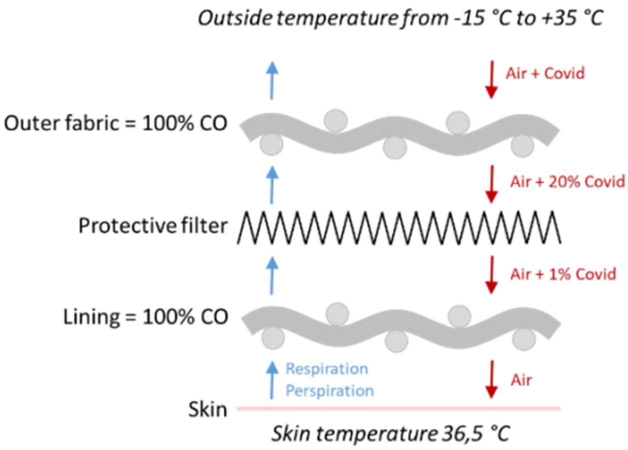

Figure 1 Scheme of an ideal face mask (section cut)

One of the factors influencing the suitability of fabrics for masks may be resistance to water vapour penetration. Permeability depends mainly on the fabric structure, which can be described by linear yarn density, type of yarn, warp/weft density and weave. When comparing the air-permeability of polymeric fiber fabrics, the air-permeability decreases rapidly with the density of the fabric, proving that pores are the primary route of penetration through these materials.

In the case of cotton, the permeability of high-density fabrics is about twice as low as that of conventional fabrics used in the clothing industry (mass 140-210 g/m^2) suggesting that a considerable amount of water vapour passes through the fibrous material itself, as confirmed in 1947 by Lyman [6].

Figure 1 shows a possible scheme of a suitable cover, and it is understood that the face mask. The masks play an important role in reducing the penetration of pathogens into the respiratory system through the nose or mouth and thus minimize the transmission of diseases. According to WHO guidelines, wearing masks in public, together with sufficient social distance, is the most accessible and easiest means of preventing the transmission of COVID-19 [7].

1.1 Material

Woven fabrics in a plain weave of 100% cotton were chosen for the experiment. Cotton is one of the natural fibers. The average composition of cotton fibers is: cellulose 94.0%, protein 1.3%, pectins 1.2%, mineral salts 1%, org. acids 0.75%, waxes 0.6%, sugars 0.3% and a further 1.4% [5]. The wet ductility of cotton fibers increases. Dry elasticity is usually 3-10% and wet elasticity is 11%. The moisture content at 65% RH is 8.5% [8]. The fiber length is on average 10-60 mm, fiber diameter ≈26 μm [8]. It is important to be aware, in particular, of the dimensions of the individual cotton fibers, since these fibers form the cotton yarn from which the cotton fabric is woven and their tendency to moisture substantially affects the wet permeability of cotton fabrics.

1.2 Air-permeability of fabrics

Air-permeability is one of the physiological and hygienic properties. Passages can generally be realized in both directions but the direction from the organism to the surrounding environment prevails. Air -permeability in fabrics occurs when there is a different pressure *p* [Pa] on both sides of the fabric and when the fabric has non-zero porosity. The air-permeability of textile materials can be characterized as the ability to permeate air under specified conditions. It is defined as the velocity of the airflow passing perpendicular to the test specimen under the specified requirements for the test area, pressure drop and time. In the fabrics, the air-permeability is determined primarily upon the fabric’s weight and construction (thickness and porosity). The size of the voids, their shape, the arrangement of individual pore types and voids frequency are decisive characteristics of fabrics in terms of their air-permeability. Air-permeability also depends on the humidity. In the case of fabrics made of cotton fibers, the air-permeability usually decreases with increasing humidity. As the voids are filled with water, the fibers swell and thus prevent the passage of air. Moisture sorption also depends on temperature. At higher temperatures, the moisture content of the fiber decreases as the fibers dry out. Conversely, at higher relative humidity, the fiber moisture may be slightly higher. Moisture significantly affects the mechanical properties of the fibers.

The essence of the test for measuring the air-permeability of fabrics is the suction of air through the surface of the tested fabric at a specified pressure drop. Air-permeability is then expressed as the speed of airflow through a given area of fabric.

1.3 Porosity

In terms of air-permeability, porosity is considered one of the most critical parameters of the fabric structure. Porosity can be determined by several theoretical methods as well as by various experimental techniques. Due to the complexity of the textile structure, each of the methods contains some simplifying assumptions. It is therefore difficult to find the best variant for expressing the porosity of a textile material. Porosity also affects the use of fabrics for masks, where low porosity can cause small comfort for wearers of masks.

The volume porosity *P* [%] is essentially the opposite of the cover factor of textile structures. Interpretation of porosity based on density of fibers ρ_{fibre} [g/m^3] and fabric density and is given by [9-10]:

$$P = \left(1 - \frac{\rho_{fabric}}{\rho_{fibre}}\right).100 \tag{1}$$

$$\rho_{fabric} = \frac{\rho_{mass}}{t} \tag{2}$$

where the density of the fabric ρ_{fabric} [g/m^3] is given by the ratio of the mass ρ_{mass} [g/m²] and the thickness of the fabric *t* [m].

The mass of a fabric expresses the weight per unit area of the fabric. The bulk density of a fabric expresses the weight of a volume unit of the fabric. The thickness of the fabric is defined as the vertical distance between the two fabric surfaces, measured under the prescribed pressure, which is usually 1 kPa [11]. The thickness of the fabric depends not only on the warp and weft threads' diameter but also on the used weave and used production technology.

There are three types of pores = voids in the fabric: 1) pores inside the fibers, 2) voids inside the yarn formed between the fibers and 3) voids formed between the warp and weft yarns. The pores inside the fibers can be neglected entirely in terms of the fabrics' air-permeability because they do not pass through the fabric and are negligible in size. The literature [12] states that the air-permeability of yarns is 200 to 2000 times less than the air-permeability of woven fabrics. It follows that the voids between the fibers in the woven fabric may also be omitted for this article.

2 EXPERIMENT

2.1 Characteristics of used materials

Two 100% cotton (CO) woven weaves were selected for experiments. The used weave was plain. The warp and weft yarns were of the same linear density for both fabrics: warp for sample A 13 tex and for sample B 19 tex. A number of turns were for sample A 1042 turns/m and for sample B 896 turns/m. Physical density of the cotton fibres was constant 1.52 g/cm^3. All samples were woven using classical ring technology and yarns have a right turn. Results of the actual warp/weft density measurements and physical characteristics of samples (mass per square meter and thickness) are shown in Table 1. Porosity and bulk density of fabric were calculated using equations (1) and (2).

Table 1 Basic properties of used fabrics

Properties of fabrics	Fabric A	Fabric B
Mass per square meter [g/m^2]	130	120
Bulk density of fabrics [g/m^3]	0.59±0.03	0.43±0.01
Warp density [cm^{-1}]	45.8±0.8	35.4±1.1
Weft density [cm^{-1}]	40.8±1.1	24.0±0.4
Thickness of fabrics [cm]	0.0220±0.0010	0.0270±0.0001
Porosity [%]	60.62±1.65	71.45±0.71

Three types of seams were compared: back seam, overlapped seam and double-sided back seam, and there was always one sample without a seam from each fabric (Figure 2). A total of 8 types of samples were measured. All samples were measured in dry and wet conditions.

2.2 Testing methodology

The study investigated the following properties of woven samples: physical properties (mass per unit area ČSN 12127:1999, the thickness of textiles ČSN ISO 5084:1998). Furthermore, the porosity of the fabrics was determined using equations (1) and (2). In the next part of the experiment, the air-permeability of the fabrics was evaluated.

2.2.1 Air-permeability measurement

The measurement was performed on an FX 3300 Air Permeability Tester III instrument (TexTest company) according to the standard ČSN ISO 9237:1996 [13] and according to the standard DIN 53 887 [14] at a pressure drop of 100 Pa (recommended for clothing textiles), 150 and 200 Pa (recommended for technical textiles). The measurement was performed on samples with an area of 20 cm². The seam was guided through the center of the test area.

2.2.2 Conditioning of samples

The experiment included two sets of samples. One set of fabrics A, B was washed and dried once. The second set of fabrics A, B was washed, dried and ironed 5 times. The minimum number of washes was chosen to be 1x, as this assumption was based on the fact that the drape will be washed by the user before the first use. The maximum number of washes was set at a total of 5 washes according to the knowledge obtained from the shrinkage of the yarns [15], the dimensions of the fabric stabilize after the fifth wash and the fabric usually does not coagulate.

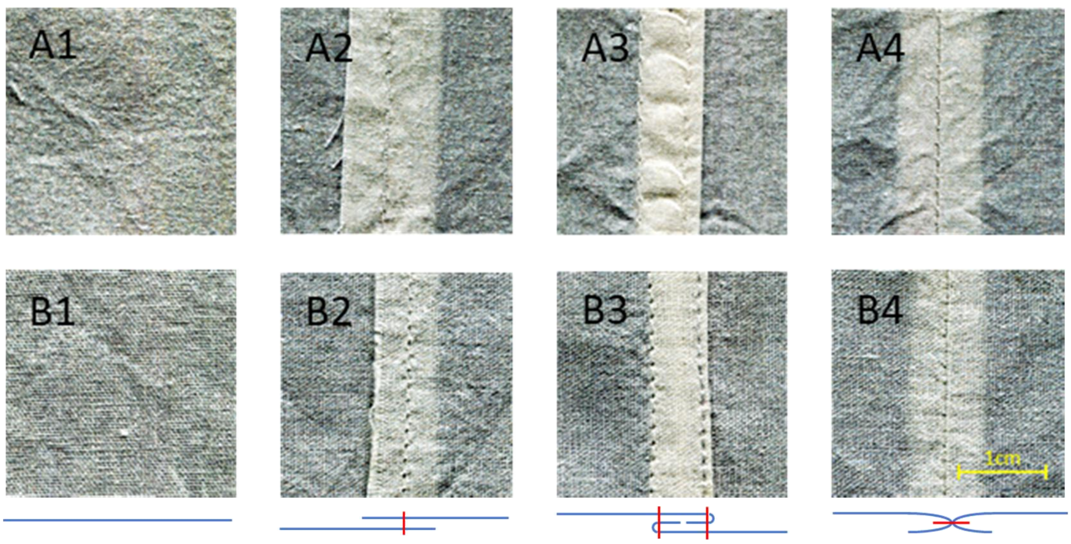

Figure 2 Overview of used fabrics - types of used seams: A1, B1 - without seam, A2, B2 - overlapped seam, A3, B3 - back seam bent on both sides, A4, B4 - back seam; at the bottom of the figure, cross-sectional drawings of the seams are shown schematically

The standard: EN ISO 6330: 2000 "Domestic washing and drying procedures for textile testing" was used for the domestic washing and drying procedure of tested textiles. An automatic washing machine was used for washing; a washing cycle of 2 hours at 90°C. After the complete wash cycle, the material was removed from the washing machine without being stretched or deformed. Subsequent drying took place in a horizontal position in the spread state. The ironing was carried out as follows: the temperature was set at 150±15°C without steaming applied. The iron was laid gradually over the entire surface of the sample for 5 s each without sliding motion. After washing, drying and ironing, the samples were always conditioned according to EN ISO 139:2005 "Standard atmospheres for conditioning and testing before measurement". The selected temperature and washing time were intentionally chosen as the limit for 2 hours at 90°C. Although in the literature [16] the thermal deactivation of the virus is already mentioned at 56°C after 30 min exposure time and in the literature [17] is reported as the deactivation temperature of 70°C with a shorter exposure time.

A Kern DLB 160-3A halogen analyser with a halogen emitter using the thermogravimetric method was used to analyse fabric moisture. In accordance with this method, the sample was weighed before and after heating and the moisture content of the material was determined by calculating the difference in weight. The applied radiation penetrated the sample, where it was transformed into thermal energy, so the heating took place from the inside outwards. Testing procedure: dry, air-conditioned samples with an RH of 65±2% were sprayed with water and dried the material to the humidity of RH 88±2% (Table 2).

Table 2 Climatic conditions during measurement

	RH [%]	T [°C]
standard environment	65±2	20±2
humid environment	88±2	20±2

3 RESULTS AND DISCUSSION

In the case of fabrics made of cotton fibers, the air-permeability decreases with increasing humidity; as the pores are filled with water, the fibers swell and prevent the passage of air.

Based on the experimental measurements, the mechanism of dimensional changes due to moisture is the swelling of cellulose-based fibers. These differences are particularly evident by fabrics' sample A. By cotton fabrics, the axes of the warp and weft yarns are deflected due to the swelling of the fibers [18] and the fabric shrinks. In Figure 3 we can see how the porosity decreases with increasing bulk density.

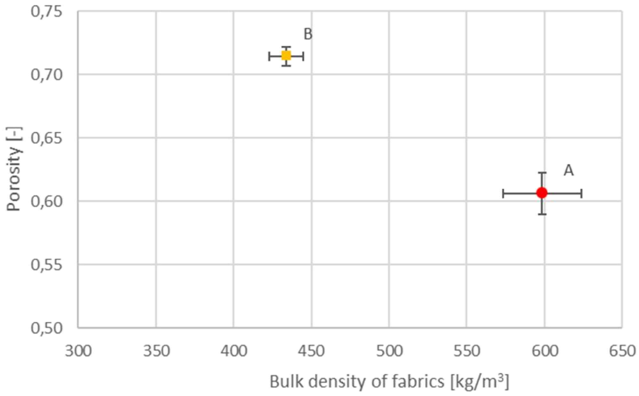

Figure 3 Dependence of bulk density on porosity of both types of fabrics

A comparison of the air-permeability of both types of 1x and 5x washed fabrics in the dry and wet state is shown in Figure 4. It is evident that the air-permeability increases linearly with increasing pressure for all types of fabrics and seams. As seen from Figure 4, the air-permeability of samples washed 5x almost always decreases compared to samples washed 1x. Comparing Figures 4 and 5, it is evident that the air-permeability of cotton woven fabrics generally decreases due to washing. During repeated washing, the fabrics shrinkage and thus the overall pores between the warp and weft threads are reduced.

In general, shrinkage prevention can be only achieved by preventing the swelling of the cotton fibers, which seems unrealistic for textile technology. By performing repeated precipitation of the fabric at such a stage of technology where this phenomenon is not complication, a large reduction in the manifestations of dimensional changes of the cotton fabric can be achieved. However, it is necessary consider the fact that cotton fabric usually reacts with moisture throughout its life. If the masks made of 100% cotton were used in the future, it would be appropriate to precipitate before using the fabric, for example, through a sanforization process, as repeated washing will shrink the fabric. Sanforization [18] is one of the most important precipitation processes. It is controlled pressure precipitation where the whole process is based on mechanical action without chemicals. The essence of the sanforization process is the precipitation of the fabric before its further use what guarantees the stability of the finished textile product during washing. Another solution to shrinkage may be treating the cotton fibers with various chemicals [19, 20] what increases the cross-section of the cotton fibers and thereby reducing the porosity of the yarn, in a manner very similar to mercerization.

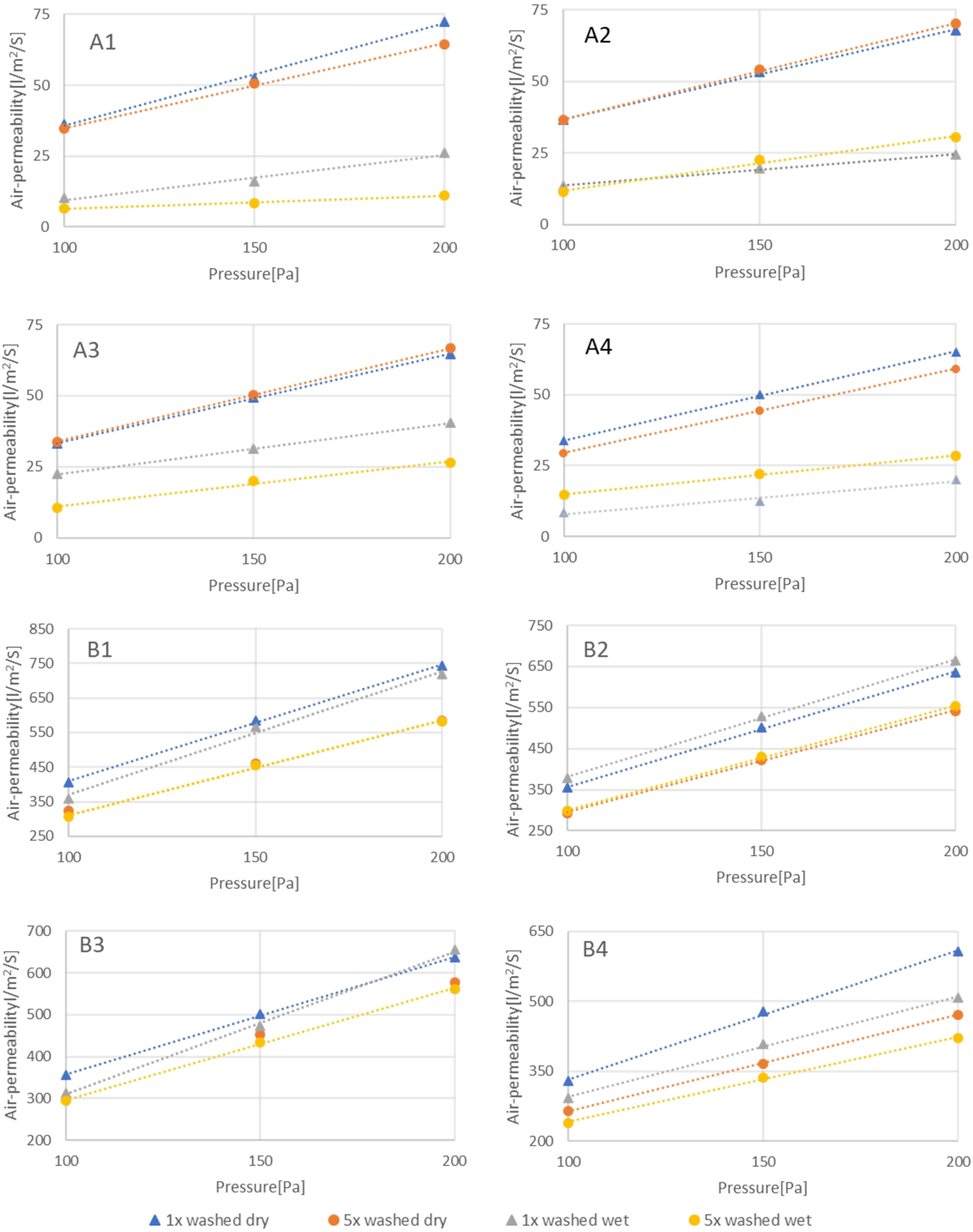

Figure 4 Effect of pressure on air-permeability of 1x and 5x washed fabrics in the dry and wet state: A1, B1 - without seam; A2, B2 - overlapped seam; A3, B3 - double-sided curved back seam; A4, B4 - back seam

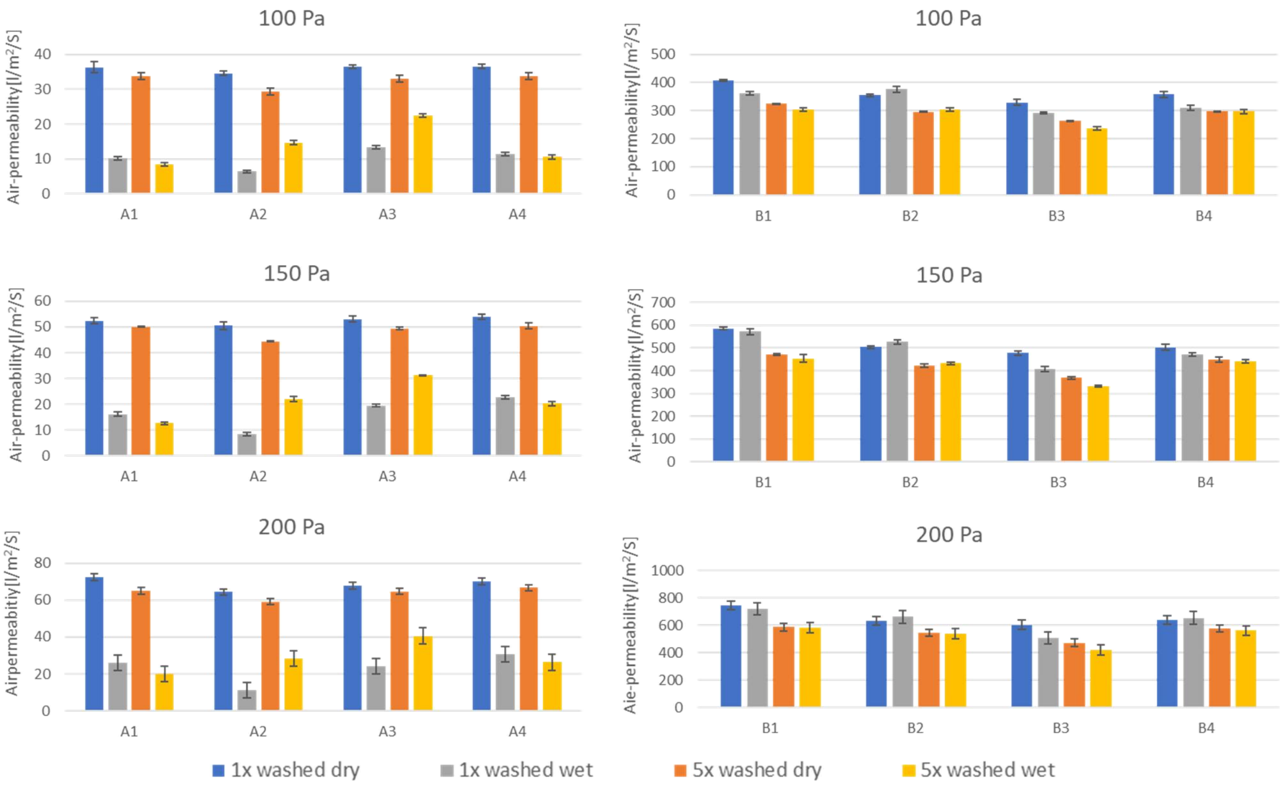

Figure 5 Comparison of air-permeability at three different pressures of both types of 1x and 5x washed fabrics in the dry and wet state: A1, B1 - without seam; A2, B2 - overlapped seam; A3, B3 - bent back seam; A4, B4 - back seam

4 CONCLUSION

Based on the performed experiment, the type of seams has a minimal effect on the air-permeability and can be neglected. However, what cannot be neglected is the influence of the used woven fabric with low porosity, the impact of repeated washing, humidity and pressure. With increasing humidity, the air-permeability of cotton fabric with lower porosity (61%), represented by the type A samples, deteriorates rapidly. The difference between the samples with higher porosity (72%), represented by the type B samples, is less clear. On the contrary, with increasing pressure, the air-permeability improves for all types of samples. Therefore, this type of mask could be suitable for sports exercise because with accelerated breathing, the pressure on the fabric increases due to breathing. Due to washing, both types of samples reduce the air-permeability caused by the shrinkage of cotton fibers.

Since the main topic of this work was to analyze the effect of fabric wetting on its air-permeability, two types of woven fabrics with different porosity were chosen for the experiment. In densely packed cotton samples A, where moisture is held not only in the inter-fiber voids but the fiber is likely to absorb it into its structure. As a result of its diameter increases, there is more significant difference in air-permeability between dry and wet samples, as shown in Figures 4 and 5. Thus, the air-permeability decreases with increasing warp/weft density because the fabric contains fewer pores. In terms of air-permeability, fabrics with lower porosity have lower air-permeability and this dependence increases even more when wet.

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5 REFERENCES

1. Mukhopadhyay A.J., Midha V.K.: A Review on Designing the Waterproof Breathable Fabrics Part I: Fundamental Principles and Designing Aspects of Breathable Fabrics, Journal of Industrial Textiles 37(3), 2008, pp. 225-262, https://doi.org/10.1177/1528083707082164
2. Feng Y., Marchal T., Sperry T., Yi H.: Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study, Journal of Aerosol Science 147, 2020, No. 105585, https://doi.org/10.1016/j.jaerosci.2020.105585

3. Iannone P., Castellini G., Coclite D., Napoletano A., Fauci A.J., Iacorossi L., D'Angelo D., et al.: The need of health policy perspective to protect Healthcare Workers during COVID-19 pandemic. A GRADE rapid review on the N95 respirators effectiveness, PLoS One 15(6), 2020, pp. 1-13, https://doi.org/10.1371/journal.pone.0234025
4. Abaluck J., Chevalier J.A., Christakis N.A., et al.: The case for universal cloth mask adoption and policies to increase supply of medical masks for health workers, 2020, Available at SSRN: http://dx.doi.org/10.2139/ssrn.3567438
5. Ondryášová M.: The influence wetting of the fabric at its air permeability, Diploma thesis, Technical University of Liberec, 2015 (in Czech), https://dspace.tul.cz/bitstream/handle/15240/17953/Ondry%C3%A1%C5%A1ov%C3%A1.pdf?sequence=1
6. Fourt L., Harrist M.: Diffusion of water vapor through textiles, Textile Research Journal 17(5), 1947, pp. 256-263, https://doi.org/10.1177/004051754701700502
7. O'Dowd K., Nair K.M., Forouzandeh P., et al.: Face masks and respirators in the fight against the COVID-19 pandemic: A review of current materials, advances and future perspectives, Materials 13(15), 2020, pp.1-27, https://doi.org/10.3390/ma13153363
8. Militký J.: Textile fibers (Textilní vlákna), TU Liberec, 2002, 238 p., ISBN 807083644X (in Czech)
9. Křemenáková D., Militký J., Šesták J.: Fiber structures for special applications (Vlákenné struktury pro speciální aplikace), Liberec 2013, pp. 229-233, ISBN 978-80.87269-32-9 (in Czech)
10. Dubrovski D.P., Ziberna-Sujica M.: The connection between woven fabric construction parameters and air permeability, Fibres &Textiles in Eastern Europe 11(4), 1995, pp. 37-41
11. ČSN EN ISO 5084 Determining the thickness of textiles and textile products (Zjišťování tloušťky textilií a textilních výrobků), 1998 (in Czech)
12. Gooijer H., Warmoeskerken M.M.C.G., Groot Wassink J.: Flow resistance of textile materials: Part II: Multifilament fabrics, Textile Research Journal 73(6), 2003, pp. 480-484, https://doi.org/10.1177/004051750307300603
13. ČSN EN ISO 9237 Determination of breathability of fabrics (Zjišťování prodyšnosti plošných textilií),1996 (in Czech)
14. DIN 53887:1986-08 Prüfung von Textilien; Bestimmung der Luftdurchlässigkeit von textilen Flächengebilden, 1986 (in German)
15. Nohejlová M.: Contractility of cotton fabric in washing process (Sráživost bavlněných tkanin), Diploma thesis, Technical University of Liberec, 2006 (in Czech), https://dspace.tul.cz/bitstream/handle/15240/3385/mgr_12324.pdf?sequence=1&isAllowed=y
16. Rabenau H.F., Cinatl J., Morgenstern B., Bauer G., Preiser W., Doerr H.W.: Stability and inactivation of SARS coronavirus, Medical Microbiology and Immunology 194(1-2), 2005, pp. 1-6, doi: 10.1007/s00430-004-0219-0
17. Leclercq I., Batéjat C., Burguière A.M., Manuguerra J.C.: Heat inactivation of the Middle East respiratory syndrome coronavirus, Influenza and Other Respiratory Viruses 8(5), 2014, pp. 585-586, doi: 10.1111/irv.12261
18. Matějková K.: The changes of proportions of cotton textile fabric after having been washed (Rozměrové změny bavlněných tkanin v důsledku praní), Diploma thesis, Technical University of Liberec, 2006 (in Czech), https://dspace.tul.cz/bitstream/handle/15240/8251/mgr_11740.pdf?sequence=1&isAllowed=y
19. Moore A.T., Scott L.W., deGruy I.V., Rollins M.L.: The swelling of cotton in water: A microscopical study, Textile Research Journal 20(9), 1950, pp. 620-630, https://doi.org/10.1177/004051755002000904
20. Remadevi R., Gordon S., Wang X., Rajkhowa R.: Investigation of the swelling of cotton fibers using aqueous glycine solutions, Textile Research Journal 87(18), 2017, pp. 2204-2213, https://doi.org/10.1177/0040517516665267