CHARACTERISATION OF BARRIER PROPERTIES OF WOVEN FABRICS FOR SURGICAL PROTECTIVE TEXTILES

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Abstract:

The pore morphology of textile filter structures is important for numerous technical applications. It determines the functional properties of surgical textiles, such as the effective barrier function and wearing comfort. Surgical and protective textiles must fulfil both of these contradictory functions. To date, basic research has not been successful, either theoretically or experimentally, in describing the complex correlation between the 3D pore structure of woven textiles and their barrier properties while simultaneously remaining permeable. In an attempt to clarify this issue, high density multi-filament woven textiles were categorised according to their geometry, pore morphology, permeability and retention properties by virtual modelling of their 3D pore morphology. Differentiation was made between mesostructures (pores between the yarns) and microstructures (pores within the yarn itself). In this process it was possible to identify the influence of weaving parameters on the pore morphology and determine their resulting functional properties. Various new testing methods were developed and successfully implemented to characterise and evaluate the barrier properties. The experiments show that by selecting specific yarns and weave constructions, the permeability and woven structure can be positively influenced and adapted to fulfil a wide range of requirements. A major finding is that the permeability and retention properties of the weave can be independently controlled by choosing suitable machine parameters. Specifically, by varying the shed closing time a clear shift in the pore size distribution to smaller pore diameters can be achieved without altering the air permeability. A correlation between the construction and processing parameters and the 3D pore morphology of the woven textile was ascertained. The relation between the properties of a weave and the machine and construction parameters is extremely complex due to their interaction.

Key words:

Filtration, micromodelling, high density weave, surgical textiles.

Introduction

Numerous technical applications require textile structures that combine clearly defined permeability and retention properties. Surgical protective textiles, such as operating room scrubs and patient draping materials, must provide a barrier to particle-laden fluids [1]. This is especially true for bodily fluids such as blood or salt solutions, which contain biological agents (viruses, bacteria, fungi including yeast, algae, protozoa and pathogens of transmittable spongiform of Encephalopathy (TSE, prions) [2]) that can cause infection in humans. Thereby, germs from the body's own flora (endogenous infections) are transmitted by contaminated fluids, while germs from foreign sources and individuals (exogenous infections) can also be transmitted through the air (airborne) [3]. Ensuring that the barrier properties of operating room textiles are not compromised is a perioperative procedure, to protect patients from nosocomial infections (hospital-acquired infections) and to avoid personal injury to healthcare personnel. At the same time, it is important to create surgical scrubs that have a high wearing comfort. Numerous studies have proven the importance of good physiological properties in operating room textiles in regards to guaranteeing complication-free operations [4, 5]. Therefore, in the development of filtration textiles, it is extremely important to guarantee a balance between good barrier properties and high comfort, while fulfilling the requirements and maintaining the required standards.

The pore structure of a multi-filament weave is comprised of the pores between the yarns in the warp and weft directions (meso pores or meso level) where a bimodal pore distribution is present [6-8]. This combination of micro and meso pores structures is used by Bénesse et.al [9] to characterise coarse fabric filters.

Experimental investigation

In order to explain the correlation between the 3D pore structure of the fabric, its permeability and barrier properties, various model weaves were developed and characterised. The development of a model weave was based on a trial matrix, which served to record the influence of the processing and construction parameters (Table 1).

With respect to processing parameters, the machine speed and shed closing time were varied. The machine speed was set between 200 rpm and 380 rpm. This parameter is of importance to processing productivity and influences the dynamic behaviour of the machine. It also affects also the properties of the fabric.

Also, various changes to the shed closing time can directly alter a weave's properties. The shed closing is the moment at which all shed positions of the changing heald shafts are at the same height or level. The shed closing time determines the period of time between the rotation angle of the loom's main shaft and the shed closing. The 0° position of the loom is defined by the foremost turning point of the batten. The closing of the shed always takes place before beating of the weft. Thereby, the incorporated weft yarn is immediately bound tight. The shed closing time should be adjusted earlier for a

Table 1. Trial Plan 1 - Analysis of the influence of weaving process parameters: machine speed, shed closing time and warp thread tension and their effects on the pore morphology and permeability of the fabric

Model Weave No.	Warp Yarn	Weft Yarn	Number Weft Yarns [cm^{-1}]	Binding	Index, I	Machine Speed r [rpm]	Shed Closing t [°]
14	Yarn 1	Yarn 1	36	L1/1	0.90	380	5
2	Yarn 1	Yarn 1	36	L1/1	0.90	380	0
17	Yarn 1	Yarn 1	36	L1/1	0.90	380	-5
13	Yarn 1	Yarn 1	36	L1/1	0.90	300	5
1	Yarn 1	Yarn 1	36	L1/1	0.90	300	0
15	Yarn 1	Yarn 1	36	L1/1	0.90	300	-5
16	Yarn 1	Yarn 1	36	L1/1	0.90	200	5
3	Yarn 1	Yarn 1	36	L1/1	0.90	200	0
18	Yarn 1	Yarn 1	36	L1/1	0.90	200	-5
11	Yarn 1	Yarn 1	48	K2/2Z	0.67	380	5
5	Yarn 1	Yarn 1	48	K2/2Z	0.67	380	0
8	Yarn 1	Yarn 1	48	K2/2Z	0.67	380	-5
10	Yarn 1	Yarn 1	48	K2/2Z	0.67	300	5
4	Yarn 1	Yarn 1	48	K2/2Z	0.67	300	0
7	Yarn 1	Yarn 1	48	K2/2Z	0.67	300	-5
12	Yarn 1	Yarn 1	48	K2/2Z	0.67	200	5
6	Yarn 1	Yarn 1	48	K2/2Z	0.67	200	0
9	Yarn 1	Yarn 1	48	K2/2Z	0.67	200	-5

smoother yarn material. The shed closing time is set in degree-machine angle and is relative to the reed beat-up. The conventional notation of, for example, 350° is also given as -10°. For this study, the shed closing time varied between -5° and +5°. Table 1 enumerates the trial parameters for varying machine speeds and shed closing times conducted with only one yarn type, but for plain weave and twill weave. Innately, these two weave types possess different fabric densities, characterised by the fabric index I by WALZ-LUIBRAND, and are calculated as follows:

$$I = b \cdot (d_{KF} + d_{SF})^2 \cdot \frac{(n_{KF} \cdot n_{SF})}{100}$$

$$d = \sqrt{\frac{Tt_F \cdot 4}{100000 \cdot \pi \cdot \rho_F}}$$

where:

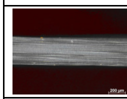
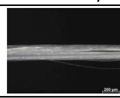
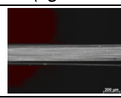
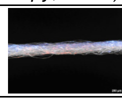
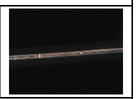
- b - weave binding coefficient (1.00 for plain weaves 1/1; 0.56 for twill weaves 2/2),
- d_{KF} - diameter warp thread,
- d_{SF} - diameter weft thread,
- n_{KF} - number of warp threads/cm,
- n_{SF} - number of weft threads/cm,
- Tt_F - yarn count tex,
- ρ_F - thread material density.

Depending on the type of yarn implemented and the type of weave, only a certain number of threads can be arranged in each individual fabric piece. High density weaves demonstrate a fabric index between 0.8 and 1.1 and can only be manufactured with increased effort and resources. Normal woven fabrics are easily manufactured and have a fabric index ranging between 0.4 and 0.8.

Fabrics with an index under 0.4 can only be produced as leno weaves due to excessive yarn slippage. It is not possible to create fabrics as monofil with a fabric index greater than one. The weave density also influences the properties of the fabric to be manufactured. With an increased weave density, air permeability and drapeability decrease, together with yarn slippage. These factors directly impact on the mechanical properties of the fabric. With an increased weave density, the elasticity modulus increases as does the stiffness.

The variable "yarn construction" reflects three sub variables, i.e. number and fineness of the individual filaments and yarn count (see Table 2).

Table 2. Yarn selection

Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5
Manufacturer and Specification				
TREVIRA Multifilament 100 dtex f40 glatt (Type 611)	TREVIRA Multifilament 100 dtex f128 glatt (Type 611)	TREVIRA Multifilament 150 dtex f48 glatt (Type 611)	TREVIRA Multifilament 100 dtex f128 texturiert (Type 511M)	Siderarc Monofil 108 dtex
Yarn count [dtex]				
100	100	150	100	108
Filament Fineness [dtex]				
2,5	0,8	3,1	0,8	-
Filament Diameter d_f [µm]				
15,2	8,6	16,9	8,6	100
Yarn – Top View (light microscopy, 100 x)				
				
Application in Model Weave				
warp beam 1 weft thread 1	warp beam 1 weft thread 2	weft thread 3	weft thread 3	weft thread 5

To evaluate the influence of "weave construction," the two variables, binding type and weave density, were varied as listed in Table 3. The target variables for these variations were the pore morphology and permeability properties.

With warp thread system 1, comprised of multi-filament yarn with a normal yarn count, a total of 41 model weaves were created using a Dornier rapier weaving machine (Table 1 and Table 2). Further tests were conducted with microfilament yarn (Yarn 2) used as the warp thread system to create a model which could provide a correlation between the production parameters and the weave's properties. In these tests, the warp thread's tensile forces were measured at five different points over the working width of the loom to evaluate the impact of non-uniform warp tension on the breadth of the fabric.
The measurements were taken at various phases during the weaving process and over several cycles (at least six cycles) at a closure of 5° (Figure 1) with the warp tension measuring system "WAWEON" (Manufacturer VÚTS/ CZ). The values were analysed with the aid of the WAWEON v.1.3 software.

The experimental analysis included the characterisation of the morphology and the permeability of the model weaves. To generate the virtual weave morphology, 2D microtome pictures were taken over the length of the pattern repeat. To illustrate the weave's morphology, over 100 2D microtome pictures were necessary for each model weave (Figure 2). The 3D weave morphology, with special consideration given to the pore morphology, was recorded using a Mikrotoms RM2255,

Table 3. Partial Trial Plan 2 - Analysis of the influence of the weave construction parameters on the pore morphology and the permeability of the fabric

Model Weave No.	Warp Yarn	Weft Yarn	Number Weft Yarns [cm^{-1}]	Binding	Index I	Machine Speed r [rpm]	Shed Closing t [°]
33	Yarn 1	Yarn 1	39	K2/2Z	0.55	380	0
19	Yarn 1	Yarn 1	22	L1/1	0.55	380	0
5	Yarn 1	Yarn 1	48	K2/2Z	0.67	380	0
20	Yarn 1	Yarn 1	27	L1/1	0.68	380	0
2	Yarn 1	Yarn 1	36	L1/1	0.90	380	0
34	Yarn 1	Yarn 2	39	K2/2Z	0.55	380	0
21	Yarn 1	Yarn 2	22	L1/1	0.55	380	0
35	Yarn 1	Yarn 2	48	K2/2Z	0.67	380	0
22	Yarn 1	Yarn 2	27	L1/1	0.68	380	0
23	Yarn 1	Yarn 2	36	L1/1	0.90	380	0
37	Yarn 1	Yarn 3	39	K2/2Z	0.55	380	0
26	Yarn 1	Yarn 3	22	L1/1	0.55	380	0
36	Yarn 1	Yarn 3	48	K2/2Z	0.67	380	0
25	Yarn 1	Yarn 3	27	L1/1	0.68	380	0
24	Yarn 1	Yarn 3	36	L1/1	0.90	380	0
38	Yarn 1	Yarn 4	39	K2/2Z	0.55	380	0
27	Yarn 1	Yarn 4	22	L1/1	0.55	380	0
39	Yarn 1	Yarn 4	48	K2/2Z	0.67	380	0
28	Yarn 1	Yarn 4	27	L1/1	0.68	380	0
29	Yarn 1	Yarn 4	36	L1/1	0.90	380	0
41	Yarn 1	Yarn 5	39	K2/2Z	0.55	380	0
32	Yarn 1	Yarn 5	22	L1/1	0.55	380	0
40	Yarn 1	Yarn 5	48	K2/2Z	0.67	380	0
31	Yarn 1	Yarn 5	27	L1/1	0.68	380	0
30	Yarn 1	Yarn 5	36	L1/1	0.90	380	0

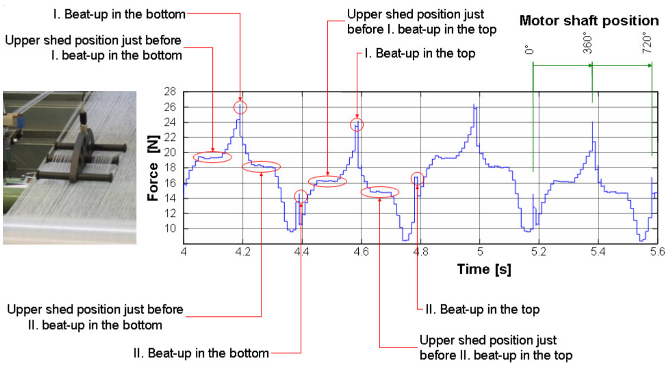


Figure 1. Measurement of the warp thread tension relative to weaving process parameters

manufactured by Leica, Germany. With the aid of the optical multistep method developed [11, 12], virtual images of the fabric, which realistically reflected the actual weave's geometry, could be generated from the 2D images taken in the various layer depths.

Results

Characterising the Model Weaves

The permeability was determined using values of "air permeability" and "water vapour transmission resistance" tested according to the physical textile testing methods based on ISO 9237 (test device: FX 3300, Textest AG (CH)) for "air permeability" and ISO 11092 (test device: Permetest, Sensora (CZ)) for "water vapour transmission resistance". In evaluating the test results, correlations between the processing parameters, the weave construction as well as the pore morphology and the permeability were elicited using the experimental flow behaviour results gathered.

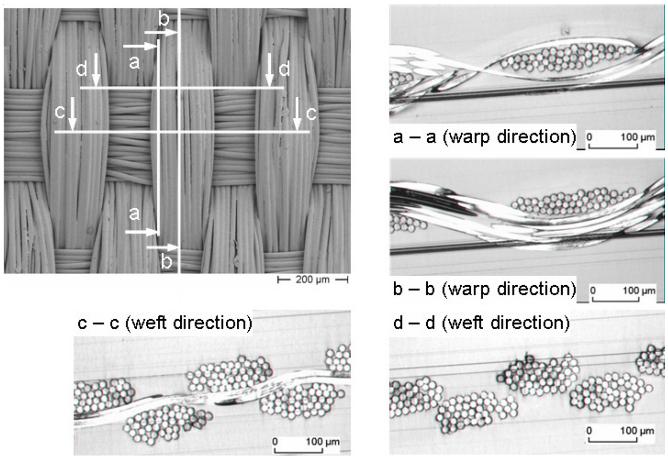


Figure 2. Pore morphology of the fabric's yarns (micro pore structure) in various sectional planes

Figure 3 illustrates the permeability of nine model weaves as plain weaves subjected to the machine speed and shed closing time. The experiment shows a clear correlation between the warp thread tension and air permeability traits, whereby values for greater air permeability tendentially corresponded to greater warp thread tensions. Accordingly, the plain weaves show significantly greater air permeability in the reference specimen (t = 0°, r = 300 rpm).

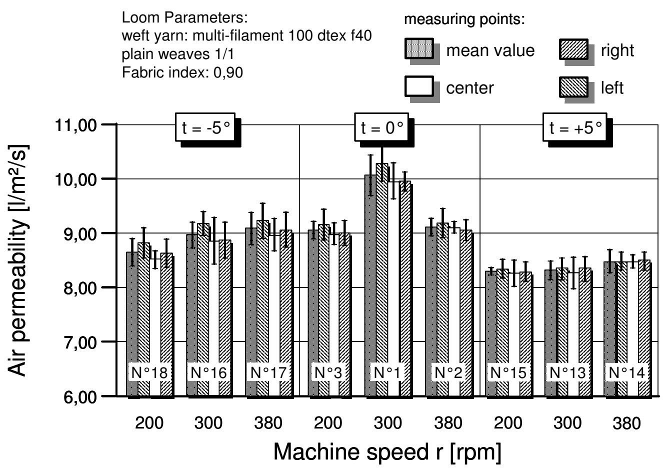


Figure 3. Air permeability of grey fabrics as plain weaves over the width of the fabric and with varying loom parameters

Air permeability in the twill weaves only increased slightly with a delayed shed closing time (t= +5°) and higher machine speed (380 rpm). However, as seen in Figure 4, there is a significant difference for some specimens in the air permeability of the twill weave fabric in the middle of the fabric versus the edges. These measured differences correlate with the recorded tension forces of the warp yarns.

By removing the sizing (desizing process), which caused partial sticking and clumping of the warp thread filaments, the permeability could be increased by approximately 30% to 40% while maintaining the desired weave preferences controlled and determined by the set machine parameters (machine speed and shed closing time). The increase in the permeability can be attributed to micro pores that were created between the individual filaments after removal of the sizing.

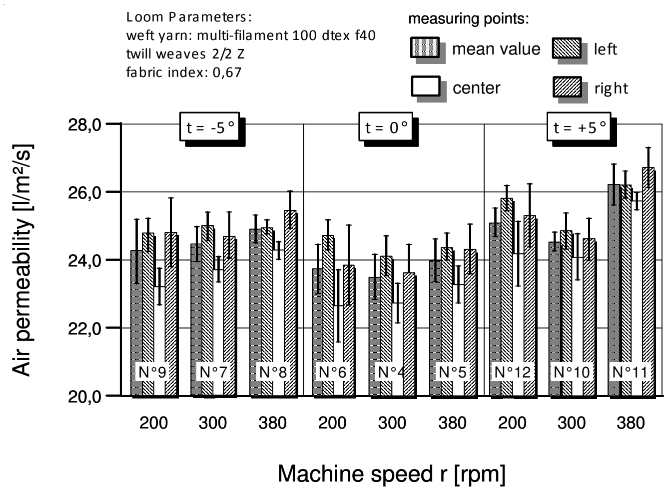


Figure 4. Air permeability of grey fabrics as twill weaves over the width of the fabric and with varying loom parameters

Figure 5 illustrates the air permeability of the woven textiles before and after the desizing process, for the individual binding types and fabric indices. In general, greater air permeability can be reached with twill weaves than compared to plain weaves for similar degrees of coverage (fabric index). In contrast, the air permeability of weave constructed with a monofil weft yarn remained the same after desizing. It can be assumed that the micro pores between the individual filaments of the multi-filament yarn play a critical role in the permeability of the woven fabric.

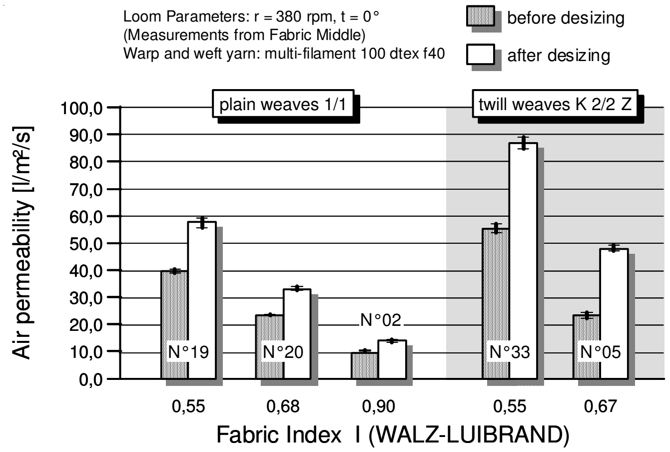


Figure 5. Air permeability of the woven fabrics before and after desizing according to binding type and fabric index

In addition to weave construction, the air permeability of the grey fabric is also influenced by the yarn construction. Multifilament yarns greatly reduce air permeability. The yarn fineness and its impact on the air permeability can be deduced by comparing Yarn 1 (100 dtex) with Yarn 3 (150 dtex). By comparing Yarns 2 and 4, the influence of the number of filaments can also be observed. In weaves with a greater number of filaments and similar weave densities, the micro pores are smaller which in turn slightly reduces the air permeability properties.

The yarn construction itself greatly influences the air permeability of the manufactured fabric. Using texturised yarns (Yarn 4), fabrics can be manufactured with reduced permeability, compared to textiles processed with smooth yarns (Yarn 2) and monofil yarns (Yarn 5).

In summary, the following can be concluded: By implementing multi-filament yarns, a higher fabric index can be achieved, and in turn the increased density of the fabric reduces the size of the meso pores. Air permeability levels can be carefully regulated in fine increments down to a minimum of 4 l/m²/s (Figure 6) by increasing the number of filaments per yarn cross-section and by using texturised yarn structures.

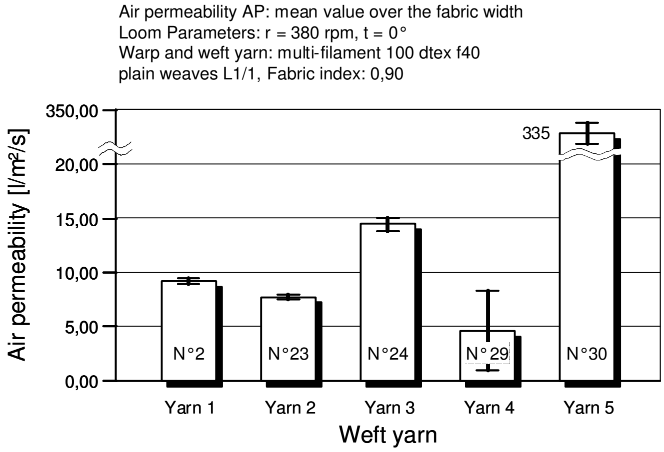


Figure 6. Air permeability of grey fabrics (plain weaves) relative to weft yarn construction (mean average over the complete working width of fabric); Influence of yarn construction: yarn 1, 2 (multi-filament) vs. yarn 5 (monofil); Influence of yarn count: yarn 1 (100 dtex) vs. yarn 3 (150 dtex); Number of filaments: yarn 1 (40) vs. yarn 2 (128); Influence of texturised yarn: yarn 2 (smooth) vs. yarn 4 (texturised)

Figure 7 shows the measurement of the water vapour transmission resistance in the plain weave grey fabrics with varying loom parameters. Measured values range between 6.1 and 7.2 m² Pa/W. Lower values indicate that water vapour can pass easily through the fabric. According to [13], fabrics with water vapour transmission resistance values between 8 and 17 m² Pa/W can be labelled as having “good to adequate wearing comfort.” Textiles with a water vapour transmission resistance value lower than 8 m² Pa/W are characterised by [13] as barrier textiles with very good wearing comfort.

The measured data for the water vapour transmission resistance of the model weaves are practically the same. Therefore the results do not offer any evidence regarding the effects of the machine parameters or fabric construction on the manufactured textile’s water vapour transmission resistance.

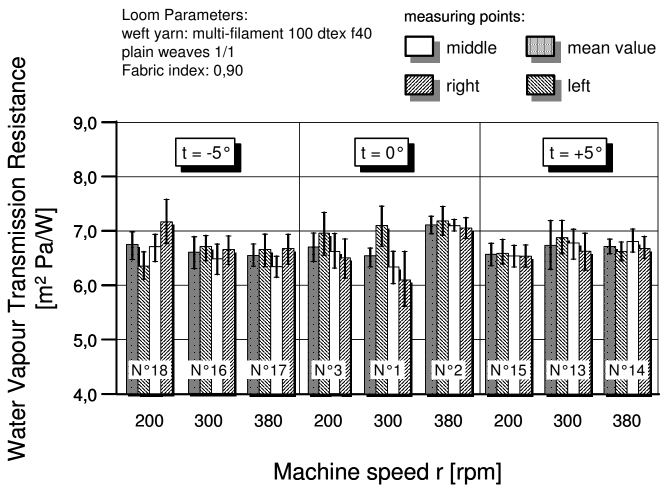


Figure 7. Water vapour transmission resistance of grey fabrics as plain weaves with varying loom parameters

Porometry Values

To more clearly characterise the weaves and to better understand the effects of the loom's settings (parameters) on the permeability of the fabric, the pore sizes in the model weaves were measured by flow porometry [14] using the TOPAS PSM-165 Porometer, manufactured by Topas GmbH Dresden, Germany. Figure 8 illustrates the collected results of the porometry measurements for model weaves No. 1 to No. 3. The values are shown as flow volume to distribution density. Depicted together with the machine parameters, the porometry results exhibit clear distinctions in the pore size distribution despite unchanged permeability properties. In particular, the shed closing time seems to have a significant impact on the pore size, causing a distinctive shift in pore size levels to smaller pore diameters without altering the air permeability (Figure 8). Model weaves 2 and 3 exhibit the same permeability although they were manufactured at different machine speeds. It is especially interesting to note that model weave No. 3 exhibits the highest number of pores, with values ranging from 4 to 5.5 µm. Model weave No. 2, manufactured at a higher machine speed (more repetitions), exhibits a greater distribution in pore size with diameters up to approximately 10 µm. This effect was observed in a series of multiple measurements and is reproducible. By varying the construction parameters and selecting the respective machine parameters, it is possible to control the permeability and retention properties of the manufactured textiles.

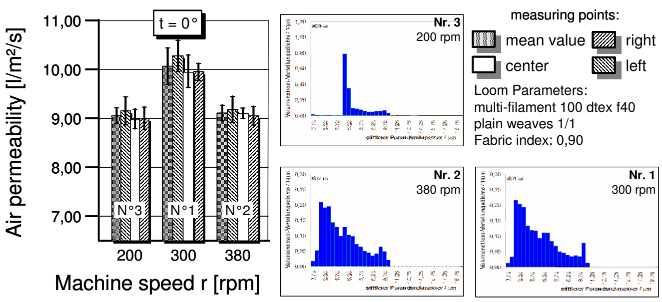


Figure 8. Influence of machine parameters on permeability

Implementing Artificial Neuronal Networks to predict fabric properties

Just as air permeability is a distinctive measure of a fabric's permeability properties, the warp thread tension is also decisive in the running performance of the loom and the stability of the weave process. A direct analysis of the correlation between the two machine settings (machine speed and shed closing time), the various construction parameters (i.e. filament fineness, binding, yarn type and Fabric Index), the resulting warp thread tension and the woven fabric's properties (i.e. air permeability) is not feasible due to the complex interaction of the above-mentioned variables. With the aid of neuronal networks, these complicated interactions could be linked to one another.

A neuronal network is a constructed network comprised of numerous simple processing elements which exchange information that are processed in parallel. Generally, the more a neuronal network is trained with experimental data, the more reliable and satisfactory are the prediction results. In the above-mentioned case, between 200 and 250 trials will be required to successfully train the network. A suitable artificial neuronal network for this investigation will be developed at the ITM, to evaluate the interaction between the various parameters and the textile properties.

Conclusions

The air permeability of the grey fabric appears to be more intensely influenced by weaving construction parameters than does the water vapour transmission resistance. In general, with a comparable degree of coverage (Index I), lower levels of air permeability can be reached with plain weaves than with twill weaves. Together with the weave construction, the yarn construction can selectively influence the grey fabric's air permeability. For example, multifil yarn construction can greatly reduce air permeability. By increasing the number of filaments in the yarn cross-section and implementing texturised yarn structures, air permeability can be reduced in fine increments down to a minimum of 4 l/m²/s. The permeability and the morphology of a specific filter fabric can be directly controlled by varying the machine settings. In general, differences were seen in the air permeability in the middle of the model weave fabric versus the edges. For some measurement points the differences are significant. These measured differences correlate with the recorded tension forces of the warp yarns. To date, experimental results of the machine setting trials conducted show that the effects of individual machine parameters on the permeability properties of the textile cannot be isolated. Fundamental influencing factors on the woven fabric's properties are the shed closing time and the machine speed. The experimental results show that the air flow permeability and the 3D pore morphology of grey fabrics can be independently regulated within a certain range. Therefore, fabrics with the same air permeability and the same spectrum width of pore size distribution can possess significantly different physical filtration properties. Specifically, by varying the shed closing time a clear shift in the pore size levels to smaller pore diameters can be achieved without altering the air permeability properties. The permeability and retention properties of the manufactured woven fabric can be directly controlled by varying the construction parameters and by selecting the machine settings respectively. This is of great importance for the particle deposition in filtration. By implementing fabricated neuronal networks, the weaving process flow can be prognosticated, providing a reliable prediction of the machine and construction parameters' impact on the permeability properties of the woven fabric manufactured.

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