COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Innovative textile sealing systems for natural ventilation of buildings

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ABSTRACT

In the construction sector, elastic plastic seals are used for windows and doors. They seal against cold, draughts and moisture. The aim of this research is to develop innovative textile sealing concepts which guarantee conventional sealing properties as well as offering filtered gap ventilation. Knitted spacer fabrics offer air permeability due to their porous structure and have an adjustable structural elasticity. The innovation aims to offer another ventilation concept and reduce the needed artificial room ventilation, thereby reducing investment and operating costs. Their suitability for seals is evaluated in the research presented. Initially, a requirements profile for sealing systems is developed and appropriate testing methods are selected. To determine a suitable structure, a variety of different textiles are tested. Therefore, knitted spacer fabrics with different spacer yarns are developed. Two monofilaments with different diameters and a high-volume yarn are used as spacers. The fabrics are investigated based on the requirement profile for their grammage, thickness, compressibility, shape recovery, air permeability, thermal resistance, and thermal conductivity. The results show that the spacer fabric with the finer monofilament exhibits the greatest thickness, as well as the highest compressibility and air permeability. The fabric with the coarser monofilament achieves the highest values for thermal resistance, as well as the lowest thermal conductivity. The suitability of the developed seals and their influence on the indoor climate will furthermore be investigated using a self-developed test bench. The test bench determines the tightness of the sealing profiles with regard to moisture, air and particle (pollen) permeability.

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1 Introduction

In the building sector, buildings are constructed to be as airtight as possible to save energy and heating costs. The prevention of moisture damage also plays a role, as good airtightness reduces the penetration of moisture into the building fabric [1]. At the same time, the reduced joint ventilation via leaks prevents the moisture as well as the accumulated CO_2 concentration associated with the occupancy from being removed without intensive and constant window ventilation. Higher levels of CO_2 can lead to a lack of concentration and discomfort for users [2] and high moisture encourages mould growth [3] Therefore new ventilation concepts must always be planned for refurbishments and new buildings that ensure the minimal air exchange for moisture protection regardless of the occupancy. In Germany the planning of ventilation concepts is mandatory by the Energy Conservation Act and Ordinance (EnEG and EnEV) since 2002. The EnEG serves as an overarching legal basis, while the EnEV formulates specific regulations and standards to implement the objectives of the EnEG. Both together promote sustainable construction methods and are intended to help reduce energy consumption in the building sector. In 2020 the Building Energy Act (GEG) replaced and combined the regulations of the EnEG and EnEV as well as the Renewable Energies Heat Act (EEWärmeG) into one legal Act to standardize the energy requirements for buildings. It sets standards for the energy requirements of new and existing buildings and promotes the use of renewable energies to reduce CO_2 emissions. The standard DIN 1946-6 describes the requirements of ventilation concepts since 2009. At that time the standard only considered mechanical ventilation concepts and after some criticism, the revised version (December 2019) also considers free and mechanical ventilation concepts both individually and in combination [4].

The aim of the TexDicht project is to investigate the use of textile seals in residential buildings with a focus on replacing traditional window seals. On the one hand, the textile seal should meet the requirements of conventional seals in terms of airtightness, weather resistance and water impermeability, but also enable a ventilation concept in the form of gap ventilation. Gap ventilation supports the required ventilation concepts and offers the possibility of promoting a healthy indoor climate by reducing high levels of CO_2 and preventing moisture to penetrate into the building fabric. In addition to the energy-related aspects, textile seals could offer the advantage of directly filtering pollen, particulate matter, and protecting against insects, significantly benefiting indoor air quality and health. The reduction of pollen and other allergens helps alleviate symptoms in individuals with allergic reactions or respiratory conditions such as asthma, leading to an improved quality of life. Studies indicate that approximately 20 % of children and 30 % of adults are affected by allergies at some point in their lives [5], making the minimization of allergen exposure indoors particularly crucial. Such filtration also enhances overall indoor air quality by reducing the accumulation of particulate matter, which could enter the respiratory system and exacerbate health issues such as respiratory diseases and cardiovascular problems [6]. Additionally, filtration protects against insects, which can be potential carriers of diseases or allergies and contribute to unhygienic conditions. These factors allow for windows to remain open for ventilation while maintaining a clean, healthy, and comfortable indoor environment.

To date, no textile-based solutions have been considered for the gap ventilation concept. However, textiles offer natural air permeability and excellent moisture transportation, which can be influenced by the choice of yarn/material, textile technology, construction and finishing [7]. The same parameters also influence other relevant properties such as waterproofness, UV resistance, compressibility and resilience. Innovative textile sealing concepts could therefore offer another option for ventilation concepts for reducing moisture and air exchange without complex systems. The aim is to achieve an even and targeted supply of air for a gap ventilated window. Textile seals are already being used successfully in highly thermal applications in heating and air conditioning technology (oven and chimney doors, flue gas ducts). They consist of silicate, aramid and glass fibres (e. g. patents DE10353757A1, DE102017200681 [8, 9]) and are woven, knitted or braided depending on the application. Woven tubes are usually compact and dimensionally stable and must be assembled for the finished product, which means an additional production step and is therefore more expensive and time-consuming [10]. Knitted hoses, on the other hand, are flexible in all directions, can be permeable to air in any direction and require little manufacturing effort. Knitted fabrics have properties that are advantageous for innovative textile seals, such as elasticity, pore structure (air permeability and filter function), compressibility and retention capacity as well as good insulating properties. Due to the mesh structure, knitted fabrics have a porous surface. The type and arrangement of the meshes determine the ratio of the cavity volume to the total volume and thus the permeability [11]. The structure can be adjusted depending on the technology, which makes the properties of the knitted

fabric definable. The weather-related requirements for windows, doors or façades, such as UV resistance and waterproofness, can be met by choosing the right yarn and/or textile coating. In addition, multi-layer structures, such as spacer knits, have good compressibility and resilience. Spacer knitted fabrics consist of two parallel textile cover surfaces and at least one spacer yarn system. The spacer yarn connects the outer surfaces and keeps them apart at the same time [12, 13].

Research results show the influence of the pore size, the fibre polymer and the fibre finish on the thermal energy transfer of knitted fabrics [14]. Furthermore, fibre material, yarn type, density and thickness of the surface layers have an influence on thermal conductivity, compressibility and water vapor permeability [15]. In addition, studies record the compressibility of spacer fabrics and the resulting curvature of the spacer yarns [16]. Thin and lightweight spacer fabrics are also used in the sports sector. Similar to room ventilation, air exchange, keeping cool or warm and transporting (body) moisture to the outside are also important here [17]. A control of the pore size as required was described and realized for shading textiles, in particular shading warp knits, by the company Penn Textile Solutions GmbH in patent DE102022059 A1 [18]. The present research proves that knitted fabrics, in particular knitted spacer fabrics, fulfil the requirements placed on sealing materials for windows and doors. By partially binding the layers of multi-layer knitted fabrics, lanes or chambers can also be formed in flat knitting. These can be specifically filled and thus provide wind and cold insulation, specific thermal insulation and noise absorption [19-21]. The aforementioned properties can also be achieved using binding or weft threads. These are also used as reinforcement to increase the tensile strength. The main advantage of the flat knitting technique is the form and multidimensional knitting with firm edges. Three-dimensional shapes can be created, such as kinked tubes or angular three-dimensional shapes. It is also possible to knit to a precise fit. In addition, a mono material production is possible and aims for good recyclability and easy cleaning in the washing machine.

In the research presented, the suitability of warp knitting, circular knitting and flat knitting technologies for the production of textile seals is examined and evaluated. Based on this, spacer knitted fabrics are developed on a flat knitting machine with different yarns. Two monofilaments with different diameters (0.22 mm and 0.35 mm) and a high-volume yarn (334 dtex) are used as spacers. The knitted fabrics are tested for their grammage, thickness, compressibility, shape recovery, air permeability, thermal resistance, and thermal conductivity on the basis of the requirement profile. The flat spacer fabrics are further developed into a sealing form and fitted into a test bench developed in-house. The test bench determines the tightness of the sealing profiles with regard to moisture, air and particle permeability (pollen) and is described in terms of its design and functionality.

2 Method

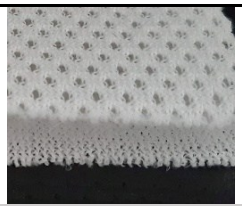
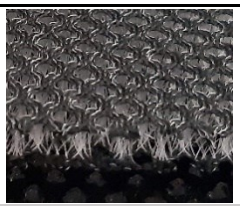
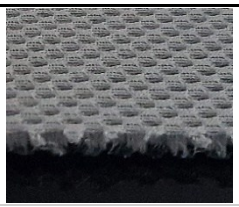
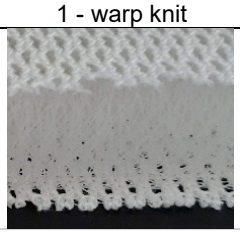
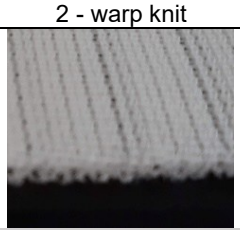
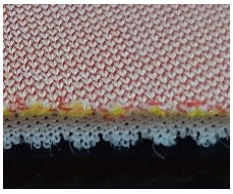
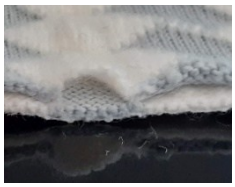
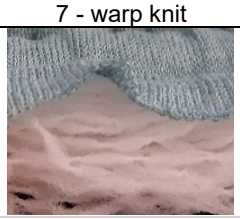
2.1 Classification of knitting technologies

In order to investigate the suitability of the different knitting technologies for the use of natural air supply in windows and doors, various 3D samples (Table 1) were analysed on the basis of the following tests:

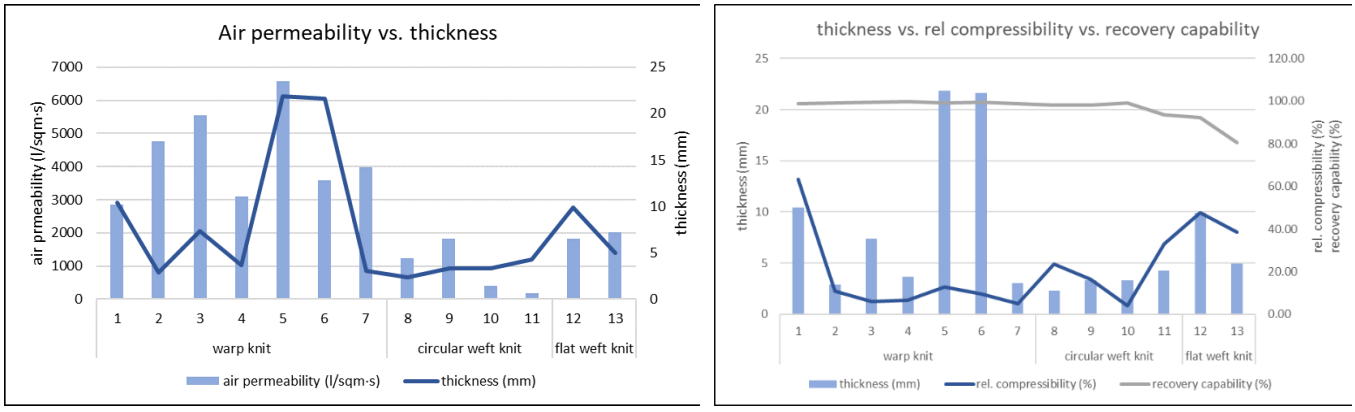
- Air permeability according to DIN ISO 9237 [22] (test device FX 3300 LabAir, Textest),
- Thickness according to DIN 5084 [23] (test device Frank-PTI), and
- Compressibility according to DIN 53885 [24] (test device Frank-PTI).

It should be noted that the air permeability tests become less accurate with greater sample thickness, as air can escape from the sides of the samples during the testing process.

Table 1. Overview of 3D samples (warp and weft knitted samples).

				
1 - warp knit	2 - warp knit	3 - warp knit	4 - warp knit	5 - warp knit
				
6 - warp knit	7 - warp knit	8 - circular weft knit	9 - circular weft knit	10 - circular weft knit
				
11 - circular weft knit	12 - flat weft knit	13 - flat weft knit		

The samples are made of 100 % synthetic material. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the results of the tests and demonstrates that there is no correlation between thickness and air permeability of samples. Furthermore, the pore size of the top and bottom layer is equally important for air permeability. The spacer textiles with spacer yarn show a very good recovery of the fabric after 1 min applying pressure of 10 kPa (98 % on average) compared to the 2-ply knitted fabrics. The compressibility correlates with the fineness of the monofilament in the spacer (cf. sample 3,5,6).



a) *b)*

Figure 1. Air permeability vs. thickness and thickness vs. compressibility vs. recovery, x-axis: samples by knitting technology.

For the selection of the textile sealing concepts, it is decisive how the textile properties tested affect the air exchange and the permanent recovery. These parameters can be specifically adjusted.

In terms of air permeability, warp knitted fabrics appear to achieve the best results. However, as flat knitting machines offer the most flexible patterning options and allow to imitate warp knitted structures, tests are being carried out on flat knitting machines as part of the research presented. In addition, flat knitting machines offer great flexibility in the choice of materials, so that experiments can be carried out with a variety of different materials. Furthermore, flat knitting machines enable the production of shaped knits, which is particularly advantageous in the development of sealings.

2.2 Developed spacer knits

Four different spacer knits (samples A - D) were produced on a CMS E6.2 flat knitting machine from Karl Mayer Stoll and developed in such a way that they resemble warp knitted spacer textiles in their shape and properties (Table 2).
To make the trials comparable, samples A – C are knitted with the same repeat (Table 2). Only the pile yarn is varied. For the three samples, the single jersey structure that is knitted on the front side of the fabric is using 3 x Enka Diolen, a texturized polyester yarn with a yarn count of 176 dtex and 30 filaments. The single jersey structure on the back side of the fabric is knitted with Colorific Q371, a shrinking polyester monofilament with a diameter of 0.2 mm. In sample A, a polyester monofilament with a diameter of 0.35 mm is used as a pile yarn, while in sample B a finer polyester monofilament of 0.22 mm is inserted. In sample C, a texturized high-volume polyester yarn with a yarn count of 334 dtex and with 72 filaments is used.
To better understand the influence of the material selection, in sample D, also the rear needle bed knits with 3 x Enka Diolen. Additionally, two more courses of the high-volume polyester yarn are inserted.
The top of each sample is knitted with a melting yarn in combination with Enka Diolen. When the yarn is heated it fixes the knitted structure to avoid unravelling.
These materials (Table 3) were chosen because they differ significantly from each other. This variation allows for a clear assessment of how different materials affect various parameters. The knitted fabrics will be processed into seals in the course of the project. Depending on the processing, either the front or back side of the fabric could serve as the outer layer. The different fabric sides facilitate the evaluation of which material is best suited for use in textile sealing applications. Additionally, the yarns are all made of 100 % polyester. This mono-material composition allows for recyclability, which plays an important role in the sustainability of the products.

Table 2. Figures of the developed weft knitted spacer fabrics.

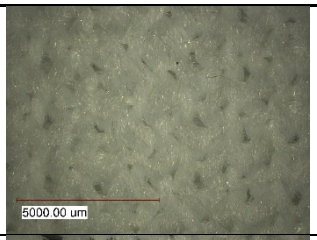
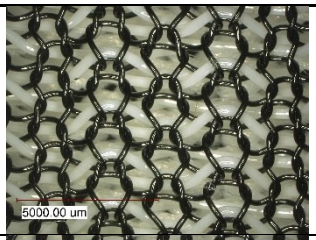
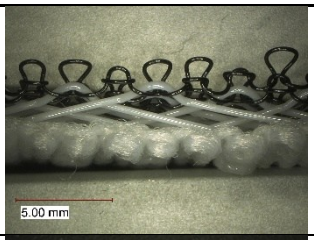
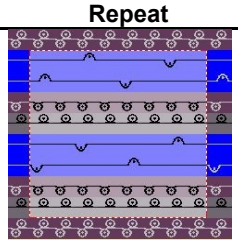
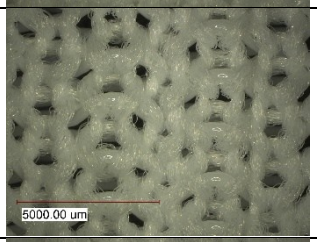
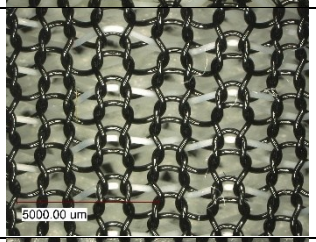
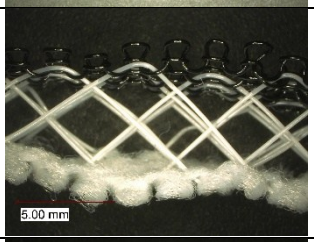
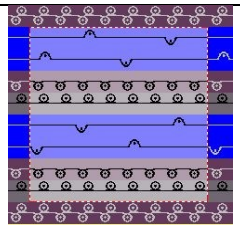
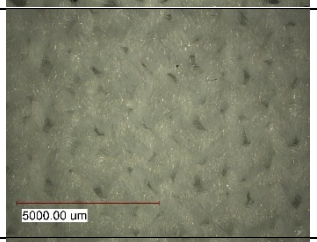
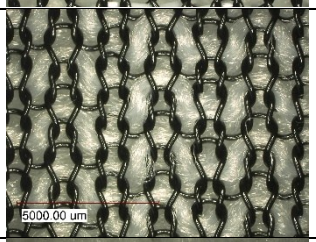
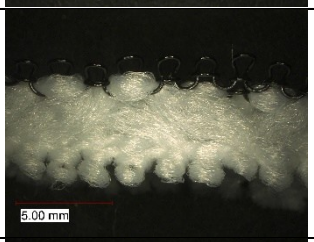
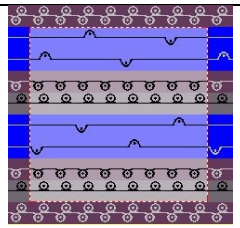
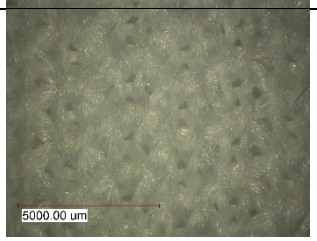
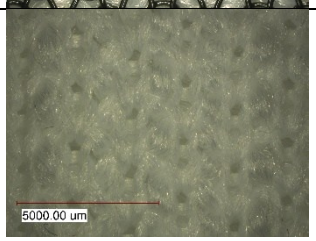
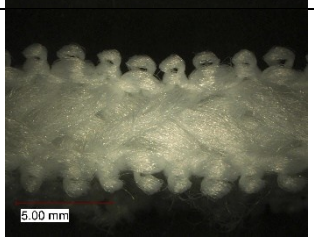
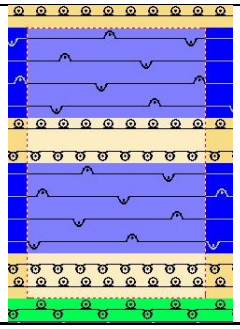
	Technical Front x30	Technical Back x30	Cross section x20	Repeat
Sample A				
Sample B				
Sample C				
Sample D				

Table 3. Yarn material used for the developed patterns.

	Structure	Material
Sample A	Single jersey front needle bed	3 x Enka polyester texturized Diolen 176dtex / 30f
	Single jersey rear needle bed	Colorific polyester monofilament Q371 elastic yarn 0.2 mm
	Spacer yarn	Nextrusion monofilament 940C 0.35 mm
	Safety courses /Melting yarn	1 x melting yarn EMS Grilon KE-60 167 dtex / 34f 2 x Enka polyester texturized Diolen 176dtex / 30f
Sample B	Single jersey front needle bed	3 x Enka polyester texturized Diolen 176dtex / 30f
	Single jersey rear needle bed	Colorific polyester monofilament Q371 elastic yarn 0.2 mm
	Spacer yarn	Monofilament 0.22 mm
	Safety courses /Melting yarn	1 x melting yarn EMS Grilon KE-60 167 dtex / 34f 2 x Enka polyester texturized Diolen 176dtex / 30f
Sample C	Single jersey front needle bed	3 x Enka polyester texturized Diolen 176dtex / 30f
	Single jersey rear needle bed	Colorific polyester monofilament Q371 elastic yarn 0.2 mm
	Spacer yarn	polyester texturized Diolen high-volume 334 dtex / 72f
	Safety courses /Melting yarn	1 x melting yarn EMS Grilon KE-60 167 dtex / 34f 2 x Enka polyester texturized Diolen 176dtex / 30f
Sample D	Single jersey front needle bed	3 x Enka polyester texturized Diolen 176dtex / 30f
	Single jersey rear needle bed	3 x Enka polyester texturized Diolen 176dtex / 30f
	Spacer yarn	polyester texturized Diolen high-volume 334 dtex / 72f
	Safety courses /Melting yarn	1 x melting yarn EMS Grilon KE-60 167 dtex / 34f 2 x Enka polyester texturized Diolen 176dtex / 30f

3 Results and discussion

The performance of the four samples are evaluated based on their grammage, thickness, compressibility, shape recovery, air permeability, thermal resistance, and thermal conductivity. These parameters were measured according to the respective DIN EN ISO standards as listed in Table 4.

Table 4. Testing results of Sample A – D for their grammage, thickness, compressibility, shape recovery, air permeability, thermal resistance, and thermal conductivity.

		Grammage (g/m^2)	Thickness (mm)	Compressibility (%)	Shape recovery (%)*	Air permeability ($l/m^2 \cdot s$)	Thermal resistance ($mK \cdot m^2 \cdot W^{-1}$)	Thermal conductivity ($W/(m \cdot K)$)
Standard DIN EN ISO		**12127 [25]**	**5084 [23]**	**5084 [23]**	**5084 [23]**	**9237 [22]**	**11092 [26]**	**11092 [26]**
Sample A	**Av**	725	3.95	13.6	99.4	3204	199	0.024
	SD	9	0.15	2.1	-	61	69	0.009
Sample B	**Av**	506	6.58	27	97.8	3233	168	0.04
	SD	14	0.13	7.9	-	141	18	0.003
Sample C	**Av**	756	4.13	13.3	98.6	892	90	0.05
	SD	15	0.05	1.2	-	21	17	0.004
Sample D	**Av**	1111	4.79	14.6	98.5	655	116	0.044
	SD	4	0.09	0.8	-	23	29	0.008

*n=1

3.1 Grammage

Sample B shows the lowest grammage of 506 g/m². The diameter of the spacer yarn of Sample B is finer (0.22 mm) than the diameter of the spacer yarn of Sample A (0.35 mm). Therefore, the same length of yarn is expected to be lighter. Sample D has the highest grammage of 1,111 g/m². Compared to Sample C it contains twice as much spacer yarn which increases its mass. Samples A and C have a moderate grammage of 725 g/m² and 756 g/m².

3.2 Thickness, Compressibility and Shape Recovery

The samples show varying thicknesses, with Sample B having the highest thickness at 6.58 mm, despite its lower grammage, suggesting that it contains much air. Sample A has a thickness of 3.95 mm, while Sample C and Sample D exhibit thicknesses of 4.13 mm and 4.79 mm, respectively.

Compressibility values reveal that Sample B has the highest compressibility at 27 %, with a standard deviation of 7.9 %, indicating significant variability in its deformation under compression and that the compressibility varies significantly and is therefore not reliably predictable. The compressibility of the other three samples is similar and ranges between 13 % to 15 %, implying better structural stability under mechanical stress than Sample B.

Shape recovery refers to the change in thickness after being compressed 10 times for 10 seconds each with a pressure of 10 kPa. The higher the percentage, the better the shape recovery. Good recovery is desirable, as the seal in the window is compressed over extended periods and should subsequently return to its original state to ensure long-term effective sealing. Sample A demonstrates the highest shape recovery at 99.4 %, indicating excellent resilience after deformation. Sample C and Sample D follow closely with 98.6 %, with 98.5 %. Sample B shows slightly lower shape recovery at 97.8 %, which may affect its performance in applications requiring frequent deformation and recovery, such as window sealings.

3.3 Air Permeability

Sample A demonstrates high air permeability at 3,204 l/m²·s, significantly outperforming Sample C (892 l/m²·s) and Sample D (655 l/m²·s). Sample B shows slightly higher air permeability than Sample A, at 3,233 l/m²·s, suggesting that Sample B's structure allows for substantial airflow. The monofilaments in Sample A and Sample B only contain one filament and are therefore less voluminous than the texturized high-volume material that is used as spacer yarn in Sample C and Sample D. The voluminous yarns restrict the airflow through the knitted structure causing a lower air permeability.

3.4 Thermal Properties

Thermal conductivity is a key factor in evaluating the insulation capabilities of textiles.

It describes a material's ability to conduct heat and can be calculated from the thermal resistance. It indicates the amount of heat transferred through a material per unit of time and temperature difference. A high value indicates that the knitted structure has lower insulation performance.

Sample A exhibits the highest thermal resistance at 199 m^2mKW^{-1} and the lowest thermal conductivity at 0.024 W/(m·K), indicating superior thermal insulation properties. However, this sample also exhibits the highest standard deviation, suggesting that the results vary significantly and thus cannot be reliably predicted. Although Sample B shows lower values, the difference between Sample A and Sample B is not statistically significant.

Conversely, Sample C and Sample D exhibit the highest thermal conductivity values of 0.05 W/(m·K) and 0.044 W/(m·K), respectively, which are associated with their lower thermal resistance values (90 m^2mKW^{-}

^{1} for Sample C and 116 m²mKW^{-1} for Sample D). That suggests that the high-volume yarn is a good conductor of heat and therefore not suitable as a thermal insulator. Sample B exhibits a thermal resistance of 168 m²mKW^{-1} and a conductivity of 0.04 W/(m·K), placing it in the intermediate range for insulation effectiveness.

Although the differences in the test results are not statistically significant, they indicate that samples knitted with monofilament are better suited as thermal insulators compared to those knitted with high-volume yarn.

4 Conclusion and outlook

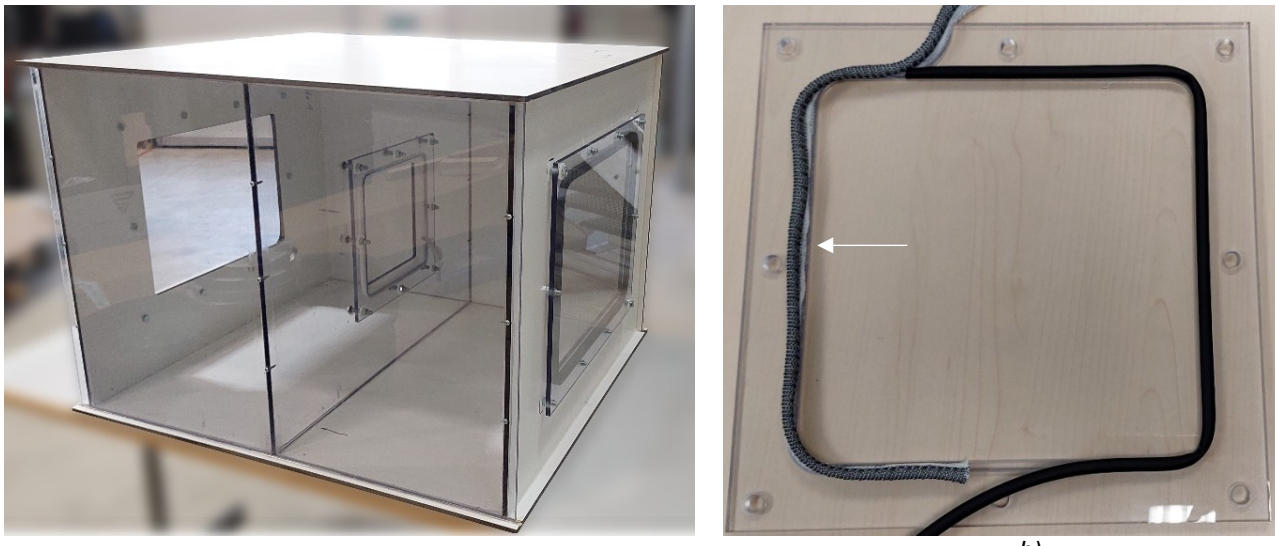
Some of the desired properties exhibit opposing effects. For example, while air and moisture permeability are desirable features for textile seals, they must also ensure high thermal resistance, low thermal conductivity, and water impermeability. This interaction complicates the data analysis, requiring that each parameter must be evaluated with different priorities to balance these conflicting requirements.

The samples with monofilaments demonstrate a low fabric weight. Additionally, when monofilaments are used, the air permeability is higher. When texturized materials are employed, thermal resistance decreases and thermal conductivity increases. These results indicate a trend suggesting that fabrics containing monofilaments are well-suited for use as textile sealing systems.

When measuring the air permeability of spacer fabrics, it is essential to distinguish between permeability in different axes. Our current measurements are limited to assessing vertical permeability through the fabric. Depending on the intended use of the sealing in windows, horizontal permeability through the fabric, as described in DIN 60022-2 [27], may also become relevant in the progress of the project. Such measurements require a special adapter that allows air flow through the spacer yarns. The pressure differential is measured under a constant airflow, and from this, the air resistance is calculated.

In further trials, the textile samples will be developed into the shape of window sealing molds to test their suitability for sealing applications. To carry out the performance tests, a small double-chamber test bench is being designed and built at the Institute for Energy Efficiency and Sustainable Building. The chambers have a mountable technical plate and a recess is provided in the partition wall of the double chamber. This recess of 200 x 200 mm is closed with a polycarbonate plate and pressed on evenly with the help of spacers and eight screws. A typical groove for window seals is milled into the polycarbonate sheet and a conventional or textile seal can be fitted for testing purposes. A reference measurement with a conventional seal will be used as the basis for measuring textile prototypes and their properties. Various test setups can be inserted into the respective chamber via the technical plates. The technical panels are individually assembled and optimized to investigate a certain property of the seal (e.g. air tightness, particle/pollen permeability with gap ventilation, moisture transport). The basic construction of the test bench with an installed textile prototype, but still with empty technical panels, is shown in Figure 2.

Relevant DIN standards are used as a basis for the design, construction, and verification of the technical panels. For example, DIN EN 1026 is used for the airtightness test method and DIN EN 12207 serves as the informative source for the classification of airtightness. In this test bench, prototypes of textile seals are to be examined and primarily the further development, optimization of suitable knitting methods, as well as material selection and manageability are to be evaluated. The test bench will not be able to carry out any standard-certified tests, which would need to be carried out externally in certified laboratories for a final selection of the most promising prototypes.



a) b)

Figure 2 a) Basic construction of the two-chamber test bench. The two plates on the front sides with the cut-outs are placeholders for the technical plates with measurement equipment and e.g. fans to introduce air pressure; b) For illustrative purposes the recess in the partition wall was sealed with a textile prototype (white arrow) inside a standard window groove.

Author Contributions

J. Klausmann: writing, original draft preparation, methodology, analysis, investigation, conceptualization, visualization; P. Holderied: writing, original draft preparation, conceptualization, investigation, analysis, review and editing; D. Kastner: writing, conceptualization, review and editing; M. Küperkoch: writing - review and editing; K. Ratovo: investigation, analysis; funding acquisition; T. Mutschler: conceptualization, funding acquisition; M. O. Weber: supervision, review and editing, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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