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Improving helmet comfort

- Liquid moisture management of polyurethane foam and fabrics used for helmet paddings.

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Abstract

When performing hobbies like biking, motorcycling, skiing, climbing or horse riding it is, if not mandatory, highly recommended to wear a helmet. However, many people still do not wear helmets when practising these hobbies for different reasons, one of which is that wearing a helmet can be uncomfortable when the wearer gets warm and sweats.

The main purpose of helmet paddings is to absorb impact and induce comfort by creating a soft layer between the wearer's head and the hard materials in the helmet shell. A better thermophysiological comfort of paddings would not only improve the wearers' experience, but also increase the usage of helmets. The focus of this study is to examine if polyurethane foam can work as a moisture transfer layer in a helmet padding, and to compare four different fabrics regarding their liquid moisture management. All materials were obtained by Mips AB, a Swedish company producing helmet components. The materials used in this study were polyurethane foam in two different thicknesses, two perforated, knitted fabric, one knitted interlock fabric, and one woven fabric with a brushed surface. There were also combinations of the fabrics with the foam. To further explain the different properties of the fabrics their thickness, area weight and porosity were assembled, including air permeability and water absorption capacity. Liquid spreading was tested in a WickView, where the aim was to observe the samples' behaviour regarding wetting and wicking. As transverse wicking is an important property for the product, the intent of this test was to determine if the foam could obtain this, and if so in combination with which fabric it performed the best. However, the foam showed to be very disinclined to wetting, and not able to transport liquid. Results from the fabrics tested as single layers showed that the perforated, knitted fabrics obtained the largest spreading area, the interlock sample was neither best nor worst, and the woven, brushed fabric was quite resistant to both wetting and wicking. The difference in spreading area in the fabric samples when tested as single layers and in combination with the foam was very small or completely insignificant. Drop absorption tests were performed on the fabric samples with the polyurethane foam and a cotton fabric as backing, to see if the samples performed differently in combination with an absorbent layer instead of the hydrophobic foam. Once again, the perforated, knitted fabrics performed the best by easily transporting the droplet through to the backing fabric to spread, leaving the sample fabric dryer.

The conclusion was that possible substitutes for polyurethane foam in helmet paddings should be examined for improved moisture management and thermal comfort. Based on the results and literature review of the study, the inner fabric of a helmet padding construction should consist of hydrophobic filament fibres and have a porous, perforated fabric structure.

Popular abstract

When performing hobbies like biking, motorcycling, skiing, climbing or horse riding it is, if not mandatory, highly recommended to wear a helmet. However, many people still do not wear helmets when practising these hobbies for different reasons, one of which is that wearing a helmet can be uncomfortable when the wearer gets warm and sweats.

The main purpose of helmet paddings is to absorb impact and induce comfort by creating a soft layer between the wearer's head and the hard materials in the helmet shell. A better thermophysiological comfort of paddings would not only improve the wearers' experience, but also increase the usage of helmets.

In this study helmet padding components including foam and four different fabrics were examined. The focus was their ability to transport moisture, representing the scenario when the helmet wearer sweats. All materials were obtained by Mips AB, a Swedish company producing helmet components. Tests of these abilities were performed, showing that the foam did not allow for any transportation of liquid. Among the fabrics, the samples with a perforated structure performed the best, and being combined with the foam did barely or not significantly affect the fabrics' moisture management. The conclusions reached were that possible substitutes to foam in helmet paddings should be examined, and that the inner fabric should consist of hydrophobic filament yarns and have an open, perforated structure for optimal liquid moisture transportation capacity.

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1. Introduction

This chapter contains a background of the work, along with an explanation of the problem and definition of the aim. The research questions will also be presented, as well as a scope stating the limitations of the work.

1.2 Background

Even though outdoor activities like biking, skiing and climbing have always been popular as interests, it has along with the last few years' trends in wellness and fitness become even more popular. The growing awareness of environmental issues has also increased the interest for a lifestyle closer to nature. Simultaneously with these trends, people are keener to have proper gear for their outdoor activities, and the market for outdoor equipment is predicted to continue growing (Medium, 2023). One piece of equipment included in this category is helmets.

Today, wearing a helmet is in many countries mandatory by law when riding a motorcycle or a bike, and not wearing a helmet when for example climbing or skiing is an unusual sight. Thus, the overall usage of helmets has increased considerably during the last 20 years. During the winter of 2021/2022, around 90% of skiers in the U.S. wore helmets, compared to 25% during 2002/2003 according to a study by the National Ski Areas Association (NSAA) (2022). A similar report made in Switzerland obtained the result that the use of a helmet when skiing had increased from 14% in 2002/2003 to 95% in 2021/2022 (Niemann, Brügi & Brügger 2022).

A report from Trafikverket (2017) shows that the usage of bicycle helmets in Sweden had increased from less than 5% in 1988 to 35,6% in 2016. Nationella Trafiksäkerhetsförbundet (NTF) made a report in 2016 where they interviewed over 3500 people about bicycle helmets. The results showed that 53% of the participants always or most often wore a helmet when biking, while 47% never or rarely did so. When the latter group was asked about the reasons for not wearing a helmet 5% answered that it was because it gets too warm. In an Austrian study regarding attitudes towards ski helmet use around 30% of the participants declared that they did not use ski helmets. Out of those, 30,9% rather or totally agreed with the statement that ski helmets are uncomfortable, and 62% rather or totally agreed with the statement that ski helmets make the wearer sweat if the weather is warm. Over half of this group, 51,4%, did also rather or totally agree with the statement that all winter sports participants should use a ski helmet (Ruedl, Kopp, Rumpold, Holzner, Ledochowski & Burtscher 2012). It seems so that most people today are aware that helmets do increase safety and decrease the risk of head injury. However, many still have different reasons for not wearing one, one of which is discomfort due to sweat and heat.

1.1 Problem statement

As stated, wearing a helmet can cause discomfort due to heat and sweat, and is one of the reasons used for not wearing one. Much research has been done on the safety of helmets, yet very little on the subject of improved comfort of helmet paddings. The testing of helmet safety is of great importance, as is standards and certifications as false marketing of a safety product would be highly unethical. Increased thermal comfort of helmets might however lead to an increase in helmet usage, and fewer injuries. The main responsibility of helmet paddings, as for all helmet components, are to dampen the impact in case of an accident. This property is surely superior to the comfort of the paddings, yet an increase in comfort may not only improve the wearer's experience but also, as stated, increase the overall helmet usage.

Helmet padding constructions generally consist of an inner fabric, a dampening layer such as foam, and in many cases a backing fabric. The inner fabric is the one worn next to the skin, and the backing fabric faces the interior of the helmet shell. In the research field of thermal comfort and moisture transport in textile assemblies, fabric-foam plies have not been as widely investigated as other constructions, leaving room for improvement in the comfort of helmet paddings.

Polyurethane foam is a material widely used in many applications, from helmet paddings to car interiors, due to its low density and flexibility making it an easy material to work with. Yet, apart from being a petroleum-based material, does most often at its end-of-life stage end up in landfills as the recycling methods for the material have not shown to be neither profitable nor give a useful product (Kemona & Piotrowska 2020). Helmets are to be replaced when one has crashed, and every three to five years even when the helmet has not been exposed to any heavier impact (Mips, n.d.). Thus, from an environmental point of view polyurethane foam is not an optimal choice for a product with a life span of three to five years due to the difficulties with its recyclability.

1.3 Aim

This work aims to study the liquid moisture transfer properties of polyurethane foam and of four different fabrics of different structures used as inner fabrics for helmet paddings. The materials will be tested separately and as fabric-foam assemblies. Moreover, a literature review of what textile properties, including fibres, yarns, fabrics and fabric-foam assemblies, make an optimal helmet padding construction will be made.

1.3.1 Research questions

1. Does polyurethane foam work as a moisture transfer layer in helmet paddings?
2. Which fabric structure among the common fabrics used in helmet paddings performs the best regarding liquid spreading and transverse wicking?
3. How should helmet paddings be composed to provide the best possible moisture transfer?

1.4 Scope

The study is within the field of helmets but is restricted only to the subject of helmet paddings. Other components of a helmet have not been considered.

All materials used were obtained by Mips AB and are presented in section 3.1, any other materials have not been investigated.

The testing process is limited to liquid moisture management, and does not include vapour transmissions.

The polyurethane foam has not been examined further regarding its chemical and physical properties. The specification about the foam is limited to it being a flexible polyurethane foam.

2. Theory

In this chapter follows a literature review on subjects relevant to this work's aim and materials.

2.1 Thermophysiological comfort

The human body wants to be kept in thermal balance, and retain a constant core temperature of around 37°C. It generates heat internally from the metabolic system, by burning calories, and obtains further required heat from external sources. In a resting state and without clothing for thermal insulation, an air temperature of 28-29°C would be required for comfort. During physical activity the metabolism increases and results in an excess of heat energy. The thermoregulation system of the body makes the skin sweat, resulting in liquid at the skin. It takes a great amount of energy to turn liquid into vapour, and when the sweat evaporates the energy required is removed from the skin, and cools it. When the physical activity stops and the generated metabolic heat decreases the evaporation of sweat might still occur, causing one to feel cold (Saville 1999).

Thermophysiological comfort includes comfort related to heat and moisture. Fabrics in a wearable product should possess a suitable level of thermal resistance to give proper isolation, air permeability to provide sufficient air movement, and be wind and waterproof if fitting the application. The fabric should also provide moisture management properties for the wearer to be dry and comfortable, which in this report is the main focus.

2.2 Moisture transfer in textile materials

For physiological comfort in a garment or other wearable textiles, moisture transfer capacity is one of the most crucial properties. In sportswear it is important to have a material that can absorb the sweat of the wearer's skin, and transport it through the fabric to evaporate, to keep the wearer from being wet and keep the textile from clinging to the skin.

How moisture is transported in textiles depends on whether it is in the form of vapour or liquid. Different transfer mechanisms of moisture, in vapour and liquid form, are shortly described below.

2.2.1 Water vapour transfer

Water vapour can be transferred through a textile in four different ways: diffusion, adsorption and migration, absorption, and forced convection (Das & Alagirusamy 2010).

In the case of diffusion, the moisture vapour diffuses through the air gaps of textile layer with the vapour pressure gradient as the driving force, meaning that the atmosphere on one side of the textile has a different vapour concentration than the other, and this differential vapour pressure strives towards equalisation. This transfer of mass occurs on a molecular level and at a low speed, depending on the diffusion coefficient of the vapour and medium. The moisture diffuses either through the air spaces of the textile structure, or along the fibres (Das & Alagirusamy 2010).

Adsorption occurs due to the surface energy created at the textile surface because of Van der Waals' forces between the moisture vapour molecules and the solid fibre or fabric surface. Thus, the moisture molecules only adhere to the fibre surface and do not penetrate the fibre (Britannica 2024). The moisture then migrates along the fibre surface due to the pressure difference of the atmospheres of the different sides of the textile, and can then evaporate away from the textile and its wearer. Absorption, on the other hand, involves moisture (the absorbate) being taken in by another material (the absorbent, in this case, the fibre or textile component) (ASTM). The absorbency of a fibre depends on

its chemical composition and morphology (Begum, Tanni, & Shahid 2021). The terms absorption and adsorption are often merged and referred to as sorption, and the reversed process (releasing of sorbed moisture) is referred to as desorption. For a good absorbency of water vapour, the material needs to be hygroscopic, meaning that it can absorb moisture from the surrounding atmosphere, unlike hydrophilic materials which absorb liquid water well. Many materials are however both hygroscopic and hydrophilic.

The process of forced convection occurs when air flows over a moisture layer, e.g. in windy conditions. The amount of moisture transmitted depends on the difference in moisture concentration between the source of moisture vapour and the surrounding atmosphere (Das & Alagirusamy 2010).

2.2.2 Liquid water transfer

The process of transferring liquid water in a textile consists of two sequential steps: wetting and wicking.

At the wetting stage, the air in connection with the solid (e.g. fibre or fabric) is replaced by a liquid. The liquid spreads on the fibre or fabric surface at a rate depending on the cohesive forces within the liquid itself and the adhesive forces between the liquid and the fibres or fabric (Miao & Xin 2018, p. 248-249). A water droplet on a fabric with low wettability will remain fairly intact as a drop on the surface, while on a fabric with high wettability, it will spread over the fabric. The wettability depends on the hydrophilicity of the solid material, the surface tension between the solid surface and the liquid, and the liquid's density, viscosity, and temperature (Das & Alagirusamy 2010).

Wicking is described as the spontaneous transport of a liquid driven into a porous system by capillary forces (Kissa 1996). Spontaneous wetting results in wicking due to capillary forces in the fabric pores, and wicking cannot occur in the absence of wetting. The capillary action is determined by the liquid's cohesive forces (intermolecular bonding), the system's adhesive forces, i.e. the attraction between the liquid and the solid, and the liquid's surface tension. The most common example when explaining capillary action is the rise of water in a tube. In the case of textiles, the porous structure of a textile contains many tube-like sections, e.g. lengthwise between the yarns and between the fibres. The capillary action in these sections causes movement of the liquid, known as wicking.

Wicking is often divided into three different processes: vertical wicking, horizontal wicking, and transverse wicking. Vertical wicking happens when a liquid is transported upwards through a fabric in a vertical position, and a fabric's ability of vertical wicking rate is measured in mm/s. Horizontal wicking occurs when a liquid migrates in a horizontally positioned fabric. When examining horizontal wicking a controlled amount of liquid is dropped onto the fabric surface, and the horizontal wicking rate can after a specific time be determined in mm²/s. When a liquid is transported through the thickness of a fabric or multilayered composition, transverse wicking occurs. This is a desirable property in many products that require moisture transport for the sake of the wearer's comfort, such as in sportswear or helmet paddings.

2.3 Impact of helmet padding components on moisture transfer

2.3.1 Fibre

Fibres are often classified as hydrophilic, hydrophobic, or hygroscopic. Hydrophilic fibres attract water, and the water molecules can penetrate the fibre due to a less crystalline molecular structure. This also applies to hygroscopic fibres, although they are more prone to absorb moisture vapour from the air than

liquid moisture. Most natural fibres are hydrophilic or hygroscopic. Hydrophobic fibres do not attract or are penetrated by water, as they tend to have a more crystalline structure, but do in general have better wicking ability. Many fibres can however undergo finishes to change their moisture-attracting properties.

A study investigating the effect of fibre cross-section on its wicking ability (Das, Das, Kothari, Fanguiero, & de Araújo 2008) included polyester fibres with circular, circular microdenier, trilobal, and triangular cross-sections (Figure 1). It showed that the fabric made from microdenier polyester with circular cross-section had the highest wicking height and rate in the vertical wicking test, which corresponds with other studies (Kumari, Mishra, Renasamy & Chattopadhyay 2023). The study by Das et al. (2008) did however conclude that the best performing fabric in the in-plane wicking test was the one made of trilobal fibres, closely followed by the triangular and microdenier circular. Similar results were also obtained by Wang, Zha, and Wang (2008) when comparisons in wicking behaviour were made between polyester filament yarns with circular or five-leaf cross-section (Figure 2). The five-leaf variant reached a significantly higher wicking height, as the cross-section creates channels along the fibre that facilitate moisture transport. This is also the approach of the Coolmax[®]-fibre, which has a cross-section with incorporated channels (figure 3).

Polyester is one of the most commonly used fibres when wicking ability is required (Kadolph, 2014). Polypropylene has also, in combination with a hydrophilic component, shown to be a suitable option for transporting sweat away from the skin to the outer layer of the fabric (Jhanji, Gupta & Kothari 2015). As previously mentioned, non-circular cross-section or a finer diameter of the filament fibre is beneficial for a good wicking ability (Das et al. 2008; Wang, Zha, & Wang 2008).

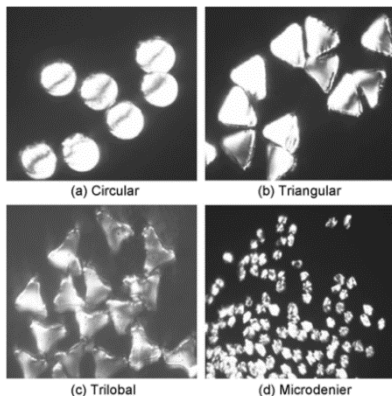


Figure 1. Fibre cross sections (Das et al. 2008)

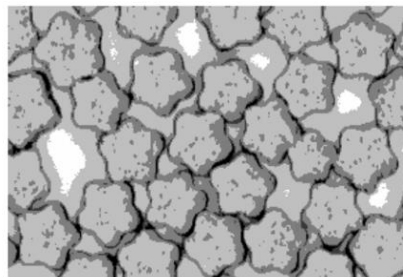


Figure 2. Five-leaf fibre cross section (Wang, Zha & Wang 2008).

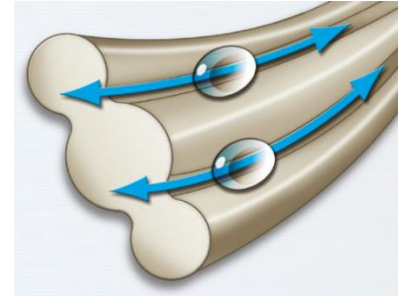


Figure 3. Coolmax[®] fibre (Textil Santanderina n.d.)

2.3.2 Yarn

Whether to use staple yarn or filament yarn depends on the end use of the product. For comfort properties, a staple yarn provides a softer feel and is most common in garments. For technical applications filament yarns are common due to their strength and smoothness, and often provide better wicking ability due to the continuous capillary pores created within the yarn structure.

Ito and Muraoka (1993) investigated the ability to transport water for a different number of fibres of different kinds by using an electrical capacitance technique and concluded that the critical number of fibres, that is the lowest number of fibres needed, for water transportation to occur in both PET and nylon yarns was ten. In the case of only five filaments in the yarn, hardly any transportation occurred, while 20 filaments per yarn gave an even higher transportation rate than 10 filaments. This implies that a too low number of filament fibres per yarn decreases the wicking ability in the yarn significantly, which is likely as too few filaments do not produce any capillaries. No maximum number of filaments

was investigated, but too many would for most applications result in a too thick yarn. It should also be noted that the yarns used in the study were not twisted.

Multifilament yarns are twisted to hold the filaments together and create a more compact yarn. The twist is most often measured in twist per inch (tpi) or twist per meter (tpm). Wang et al. (2008) investigated the effect of yarn twist on its wicking ability. The results show that there is a range of twist factor that provides better wicking ability. All different yarns used in the study had a peak around 200-300 tpm, regardless of their other properties. Similar results were obtained by Hollies, Laessinger and Bogaty (1956) where most of the sample yarns provided the highest wicking rate at a twist around 4 tpi, which translates to around 150-200 tpm. When twisted too hard, the yarn is very compact and has fewer capillary tubes among the fibres for liquid transportation.

2.3.3 Fabric

Similar to the yarns, the ability of wicking in a fabric is dependent on the capillary air spaces. An increase of pores in the fabric structure, i.e. a sufficiently open and porous fabric structure, improves the capillary effect (Yang, Chen, Naveed, Zhang & Farooq 2019; Palani Rajan, Prakash & Ramakrishnan 2019). Double-sided fabrics are common within sports apparel, with one hydrophobic side and one hydrophilic side. The hydrophobic side makes up the inner layer, next to the skin, and the hydrophilic makes up the outer layer of the fabric. When sweating occurs, the inner layer wicks the moisture to the outer layer where it is absorbed and with time evaporated, keeping the skin dry (Jhanji, Gupta & Kothari 2015; Patnaik, Rengasamy, Kothari & Ghosh 2006; Ullah, Lejeune, Cayla, Monceaux, Campagne & Devaux 2022). Spacer fabrics, especially in combination with special use-fibres like Coolmax, has also shown to be successful when it comes to one-way moisture transfer (Ertekin & Özgüney 2017; Bagherzadeh, Gorji, Latifi, Payvandy & Kong 2012; Svensson & Halldorf 2023).

Finishing processes of the textile also present a range of possibilities for improved moisture management. Alterations of a material's wetting tendency, improved wicking rate and height, and moisture retention can be obtained by chemical treatments or other methods, e.g. plasma treatment. The finishing can be applied before spinning, i.e. in the spinning dope, at the fibre stage, the yarn stage, or to the complete fabric (Patnaik et al. 2006).

Many hydrophobic finishes are however in combination with unsuitable fabric structures not beneficial for the wicking properties. Fabrics made to be water repellent, such as rain gear, are often coated and of a dense fabric structure. As imaginable, liquid will not wick from one side of these fabrics to the other, as that is in opposition to their objective. Flocked or piled fabrics are in general repellent as well due to their topography, similar to lotus leaves or wool fibre surfaces (Melki, Biguenet & Dupuis 2019; Darmanin & Guittard 2015). Thus, to improve the transverse wicking ability by using hydrophobic materials the fabric needs to be of a structure that allows mass transfer, yet consisting of hydrophobic fibres or yarns.

2.3.4 Multilayered moisture transporting textile assemblies

To keep the wearer dry, moisture needs to be transported from the inside of the textile to the outside. The inner layer, next to the skin, should stay dry to prevent the clingy, uncomfortable feeling that a wet fabric next to the skin causes. As stated by Jhanji, Gupta and Kothari (2015), a double-sided fabric or fabric assembly with a hydrophobic, wicking top layer (worn next to the skin) in combination with a hydrophilic bottom layer constitutes a well-performing fabric regarding one-way moisture transfer. As the helmet shell construction is of hard, solid materials a flexible, compressible layer between the head and the helmet shell is needed, i.e. paddings. This additional layer often consists of foam. To keep the

function of the moisture-transporting textile assembly the foam either needs to be absorbent, or work as a moisture gradient that can continue the transportation of liquid to the outer, absorbent layer. The use of a one-way moisture transfer layer in multi-layer assemblies has been shown to be beneficial (Miao, Huang, Wang, Yu & Ding 2018). A series of studies have been made of fabric-foam-fabric plied materials regarding their moisture management properties, including water transport capability, absorption rate, liquid spreading speed, and is overall moisture management capability (OMMC) (Kan, Vuthiganond, Rungruangkitkrai, Ko & Mongkholrattanasit 2018). The OMMC includes the composition's absorption rate of the bottom surface, accumulative one-way transport capability, and spreading speed of the bottom fabric. The bottom fabric refers in this case to the outer layer, not in contact with the skin. In the studies by Kan et al. (2018) samples consisting of a more hydrophilic bottom fabric and a hydrophobic top fabric generally achieved the best results, similar to the double-sided fabrics studied by Jhanji et al. (2015). Three different foams were included, and when tested separately, the densest foam achieved the highest OMMC value, while in combination with the fabrics the most porous, less dense foam performed the best. This indicates that not only the performance of the separate components is of importance, but also the combination of components. Thus, to ensure the best performance all samples and combinations need to be tested.

3. Method and materials

The following sections describes the materials used in this study, along with the tests performed.

3.1 Materials

Material samples of helmet paddings and specifications were obtained from Mips AB, a Swedish company producing helmet components. The samples are not produced by Mips, but are used in their products.

Sample K1, K2, K3 and W1 are inner fabrics, i.e. worn closest to the head in a helmet. K1 and K3 are perforated, knitted fabrics. K2 is a uniform, smooth interlock knit fabric. W1 is woven with a soft, velvet-like front side. The PU foam comes in thicknesses of five and ten millimetres. Further specifications about the samples are found in Table 1 and images in Figure 4.

Table 1. Material specifications.

Sample Code	Material Composition	Material Structure	Purpose	Wales per inch (WPI)	Courses per inch (CPI)	Mass per unit area
K1	90% Polyester, 10% Elastane	Warp knit fabric	Inner fabric	48,3 WPI	76,2 CPI	139 g/m ²
K2	86% Polyester, 14% Elastane	Knitted, interlock	Inner fabric	51 WPI	43,2 CPI	175 g/m ²
K3	90% Polyester, 10% Elastane	Weft knit fabric	Inner fabric	51 WPI	76,2 CPI	158 g/m ²
W1	90% Polyester, 10% Elastane	Woven, brushed	Inner fabric	-	-	182 g/m ²
PUF5	100% Polyurethane	Foam, 5 mm thickness	Foam	-	-	87 g/m ²
PUF10	100% Polyurethane	Foam, 10 mm thickness	Foam	-	-	173 g/m ²

The stitch density of K1, K2 and K3 is approximated by manual counting. The weave density is unknown, and due to its brushed surface difficult to identify. The porosity and permeability do however indicate a tight structure.

Table 2. Assembled samples specification

Sample code	Components
K1-PUF5	Knitted fabric K1 in combination with 5 mm thick PUF
K2-PUF5	Knitted fabric K2 in combination with 5 mm thick PUF
K3-PUF10*	Knitted fabric K3 in combination with 10 mm thick PUF
W1-PUF5	Woven, brushed fabric W1 in combination with 5 mm thick PUF

All samples apart from K3 came in combination with PUF5. This has however not affected any of the test or results.

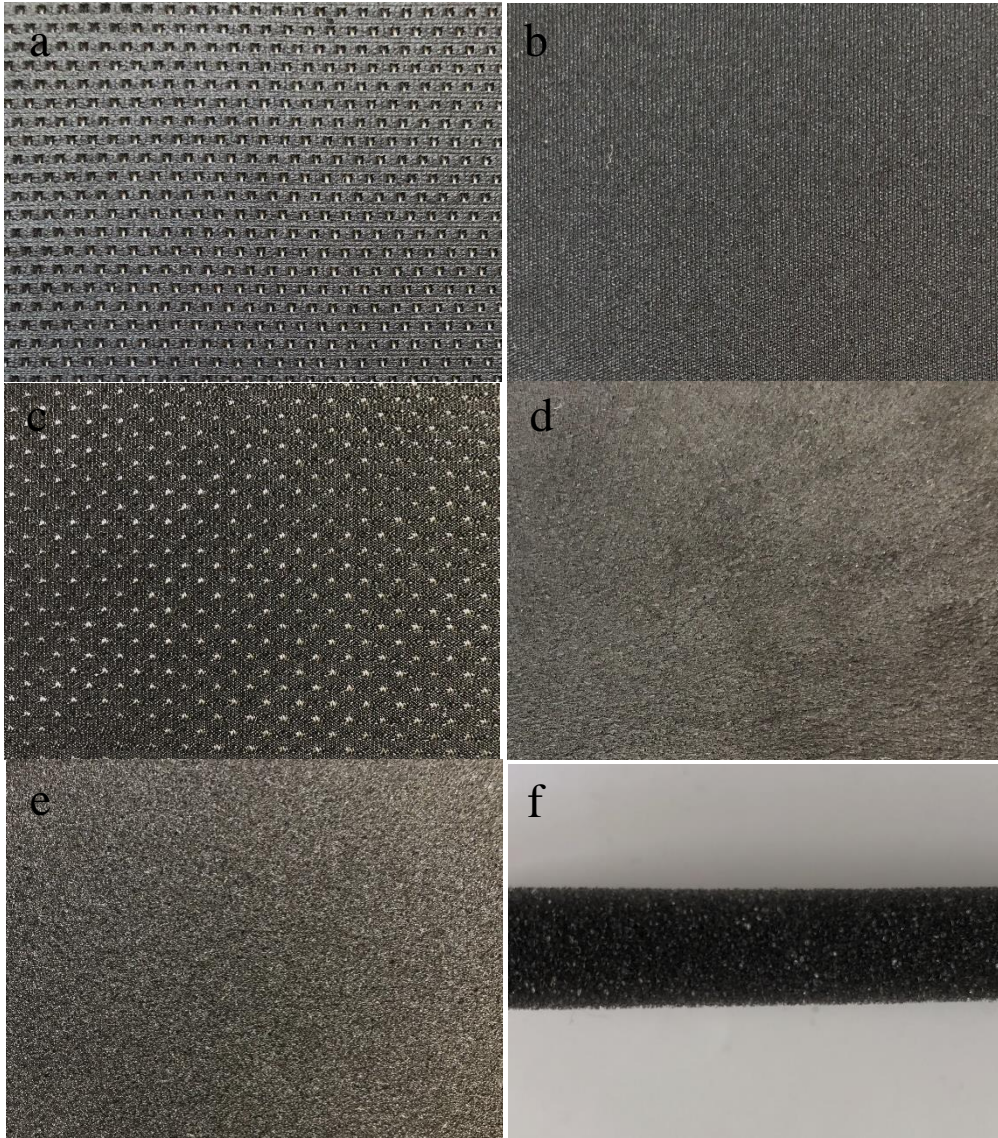


Figure 4. Material samples, a) K1, knitted fabric, b) K2, knitted fabric, c) K3, knitted fabric, d) W1, woven fabric, e) PUF, polyurethane foam, f) PUF, polyurethane foam cross-section.

3.2 Test methods

The test methods performed are here shortly described, along with a standard if such was used, and eventual deviations from standard test procedures.

3.2.1 Fabric thickness

The thicknesses of the fabrics were determined according to ISO 5084:1996. The test was performed using a thickness tester on five specimens per sample. Summarized results are presented in section 4.1, and all results in appendix A.

3.2.2 Porosity of fabrics

The fabric porosity is the volume percentage of the fabric that is not made up by textile material, but by void. This was calculated according to equation 1:

$$P = \left(1 - \frac{\rho_f}{\rho_m}\right) \times 100 \quad (1)$$

where P = Porosity of fabric [%]
 ρ_f = density of fabric [g/cm^3]
 ρ_m = density of material [g/cm^3].

The densities of the fabrics were calculated using equation 2:

$$\rho_f = \frac{M}{D \times 1000} \quad (2)$$

where ρ_f = density of fabric [g/cm^3]
 M = fabric mass per unit area [g/m^2]
 D = thickness of fabric [mm].

The density per cubic centimetre used for polyester was $1,38 \text{ g}/\text{cm}^3$ and for elastane $1,2 \text{ g}/\text{cm}^3$, and the material density of the samples of mixed materials was calculated upon those values. Results are presented in 4.2.

3.2.3 Air permeability test

All material samples underwent tests of their air permeability following ISO 9237:1995, using a TexTest FX 3300 with a pressure drop of 200 Pa. Ten specimens of each material sample were tested. Summarized results are presented in section 4.3 and all results in appendix A.

3.2.4 Absorption capacity

The absorption capacity of samples K1, K2, K3, W1 and BF were tested following ISO 20158:2018. Only the water absorption capacity (WAC) was measured, not the water absorption time, which is a deviation from the standard. This is because some of the samples were immersed very quickly, and in combination with their dark colours the timing was too unsure to provide any reliable results. Twelve specimens of each sample tested were weighed in dry condition, i.e. after being conditioned in a standardized atmosphere for 24 hours. They were then immersed in deionized water and then held

vertically to drain off for 60 seconds, before being weighed again. The WAC percentage was then calculated with equation 3:

$$WAC = \frac{m_2 - m_1}{m_1} \times 100 \quad [\%] \tag{3}$$

Where WAC = water absorption capacity [%]
 m₂ = weight in wet condition [g]
 m₁ = weight in dry condition [g].

The absorption capacity of the foam was however performed according to ISO 9073-6:2000, Test methods for nonwovens: Absorption, as it was more suitable for the material. A deviation from the standard was that only the liquid absorption capacity was measured. The result is calculated by the same formula as, equation 3. Summarized results are found in section 4.4, and all results in appendix A.

3.2.5 Liquid spreading and transverse wicking

The testing of spreading and transverse wicking was carried out on a James Heal WickView. The samples were placed horizontally into the machine, which is equipped with IR cameras on both sides of the fabric sample. The specimens were mounted in the machine so that the top side, where the liquid was applied, was the face side of the fabrics, i.e. the side facing the skin when worn. A pipette distributed 0,2 ml of liquid onto the top side of the fabric during the initial 10 seconds of the testing procedure. The tests went on for 300 seconds for the foam/fabric assemblies and for 120 seconds for the fabrics. Three specimens of each sample were tested. The cameras took two photos per second, which were also combined into video footage. The chosen points for the machine to measure were the spreading length in x and y direction, and the area into which the liquid spread along the test procedure on both sides of the specimen. The results were automatically converted into computer files. See example of imaging from the machine in Figure 5.

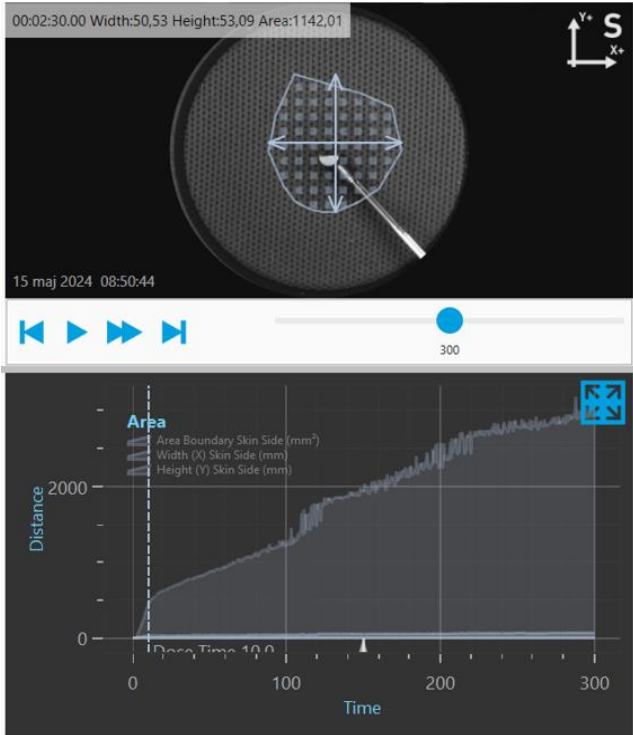


Figure 5. Image from WickView testing. Spreading area is marked on the photo and rate and spreading distance are illustrated in the graph.

An indication of the transverse wicking properties was to be obtained by noting how much spreading occurred on the back side of the specimen, i.e. the side that was not exposed to the feeding of the liquid droplets. As it is not visible or measurable how much volume of the liquid is still in the centre of the specimen and how big volume of liquid the spreading can be translated into, this method would not give any numerical results regarding the volume that had been wicked through the specimen, nor the transverse wicking rate. However, testing several samples would give a comparable result among the test samples. Summarized results are presented in 4.5, and all results in appendix B. Tests were not performed on combination samples including PUF10, apart from K3-PUF10 as that was the only sample with K3 and foam. As no liquid could pass through PUF5 it was considered unnecessary.

3.2.6 Drop absorption test

A drop absorption test according to AATCC TM-79-2010 (procedure option B) was performed on K1, K2, K3 and W1. Each sample was tested with the foam as backing, and with a cotton fabric as backing. The cotton fabric was a plain weave of 100% cotton with an area weight of 102,3 g/m² and a thickness of 0,06 mm. The purpose of the different backings was to determine if there would be a difference in spreading and wetting time depending on whether the backing was hydrophobic, as the foam, or hydrophilic, as the cotton fabric. Five droplets were released on each specimen, and the time until the drops were absorbed was timed. If the time exceeded 60 seconds, the test was to be terminated. Results are found in section 4.6.

4. Results

The results from the tests performed are presented as mean values or summaries below. Raw data are found in appendix.

4.1 Fabric thickness

The mean value was calculated based on measurements from five different areas of each sample, and are presented in table 3.

Table 3. Mean thicknesses of samples.

Sample code	Mean thickness [mm]
K1	0,198
K2	0,199
K3	0,210
W1	0,181

4.2 Porosity of fabrics

The fabric porosity calculations were based on the mean values of fabric thickness and fabric weight per unit area, and are presented in table 4.

Table 4. Porosity of samples.

Sample code	Porosity [%]
K1	48,5
K2	35,1
K3	44,8
W1	26,2

4.3 Air permeability

The air permeabilities of the samples are presented in Figure 6. As all inner fabrics (K1, K2, K3 and W1) had a lower permeability than the foam, the permeability of assemblies would not exceed that of the inner fabrics alone.

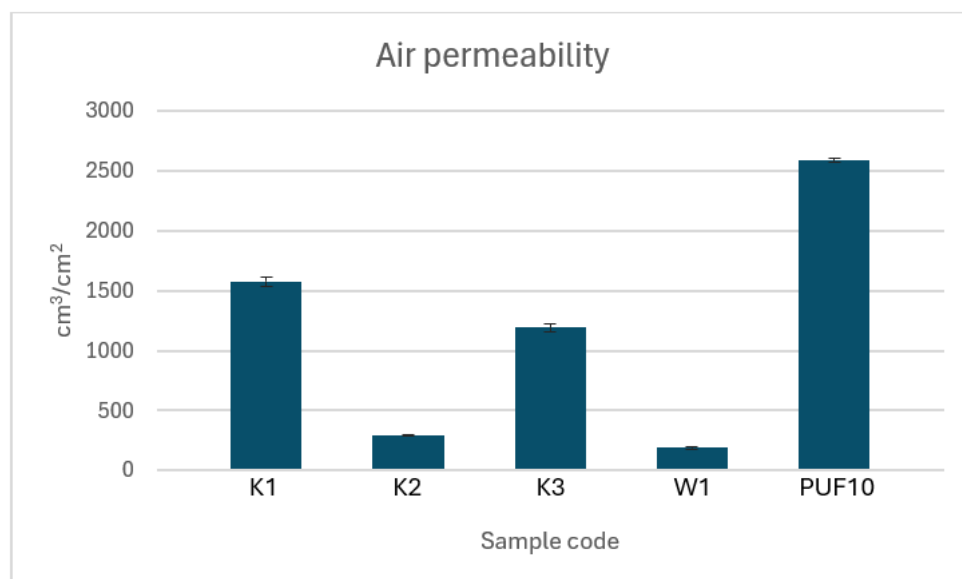


Figure 6. Air permeability of samples.

4.4 Absorption capacity

The water absorption capacity, WAC, represents the weight of water that a material can absorb relative to its dry weight, calculated by formula 1. The results are presented in Figure 7.

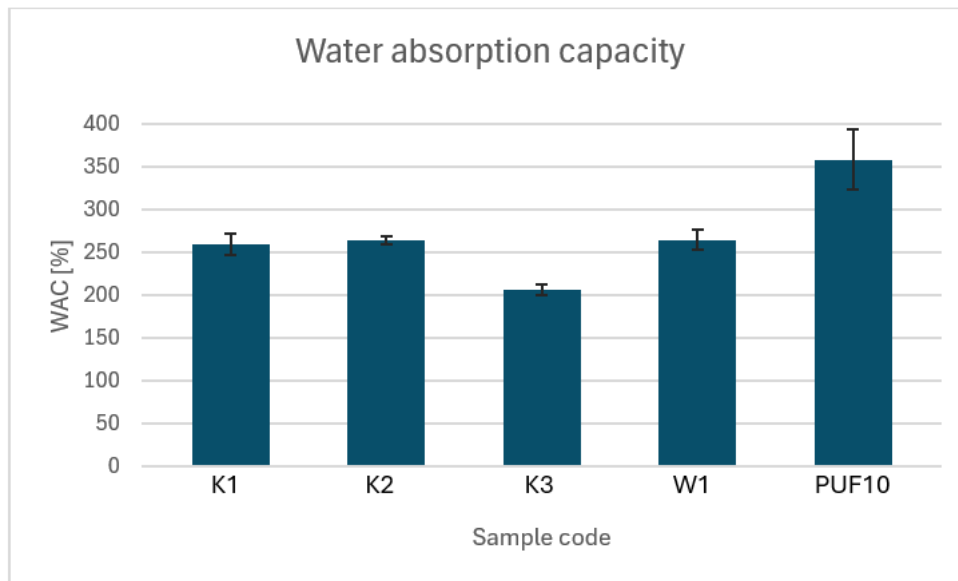


Figure 7. Water absorption capacity, WAC.

The testing of the foam, F1, was carried out following 9073-6:2000 which is meant for nonwovens instead of fabrics like ISO 20158:2018 that was used for the other samples. This is due to the foam floating and needing some force to be kept under the liquid surface, which is the procedure of ISO 9073-6:2000. The results are however calculated by the same formula and are expressed in the same unit.

4.5 Liquid spreading and transverse wicking

Below are the results from the WickView tests. They are presented in spreading area per unit time, mm^2/s . A summary of all samples is presented in Figure 8.

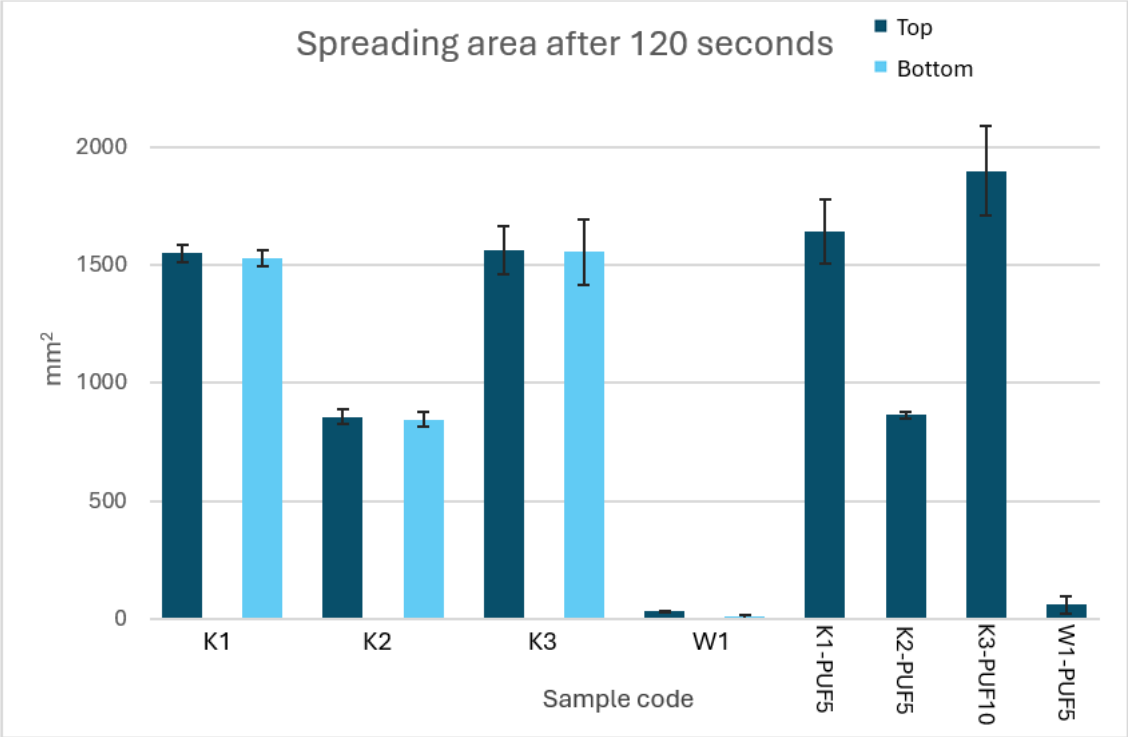


Figure 8. Spreading area after 120 seconds WickView testing of all samples.

The results from the foam, F1, do not seem to be reliable as the numerical result implies a wetting of 25 cm^2 , while it on images both from the machine and from outside of the machine after the test is visible that the droplet has not spread (Figure 19).

Only two specimens of sample K1F5 were tested with 0,2 ml of liquid. As no liquid went through the foam one test sequence using 2 ml was made. This gave no result, and all other tests were executed using 0,2 ml.

4.5.1 K1, K1-PUF5

There was very little difference in the spreading on the top and bottom sides of the K1 samples, as seen in Figure 9. The foam appeared to slightly decrease the spreading rate, which is shown in the comparison between K1 and K1-PUF5 in Figure 10.

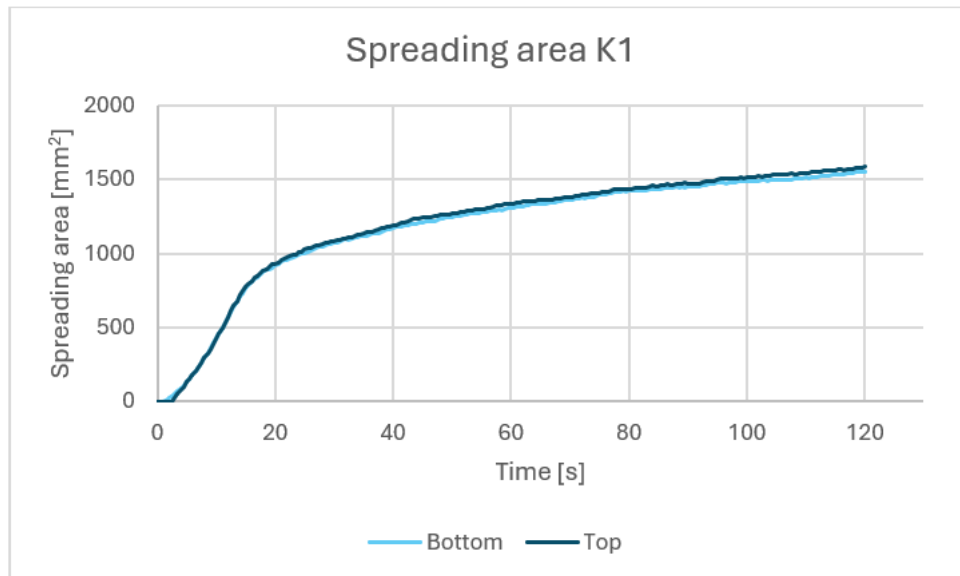


Figure 9. Spreading area of top and bottom side of K1.

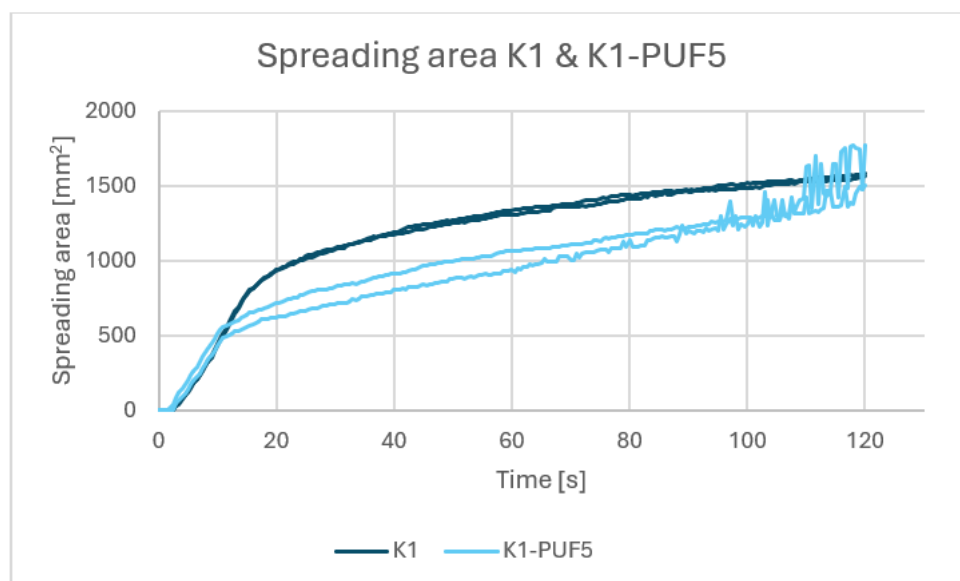


Figure 10. Spreading area on top side of K1 and K1-PUF5.

4.5.2 K2, K2-PUF5

The spreading on the top and bottom sides of K2 was very similar, as seen in Figure 11. The spreading on the top side when paired with the foam did not show any significant difference from when tested as a single layer (Figure 12).

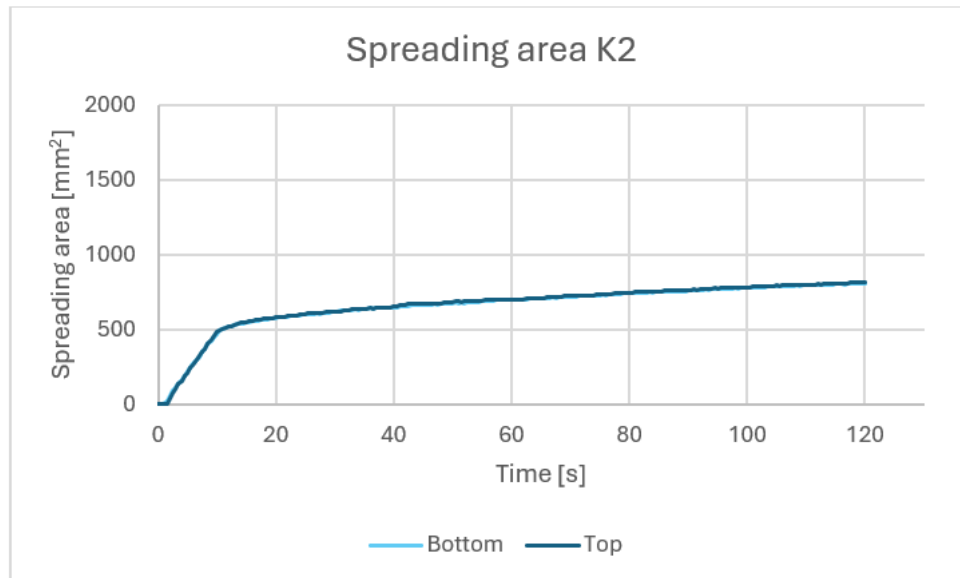


Figure 11. Spreading area of top and bottom side of K2.

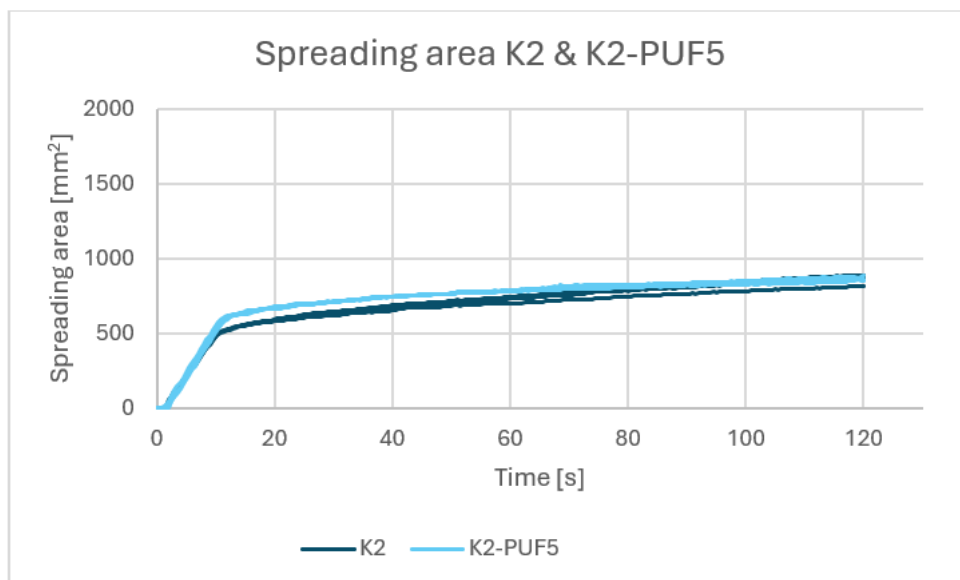


Figure 12. Spreading area of top side of K2 and K2-PUF5.

4.5.3 K3, K3-PUF10

The spreading on the top and bottom sides of K2 was very similar, as seen in Figure 13. No significant difference between the spreading of K3 and K3-PUF10 was detected.

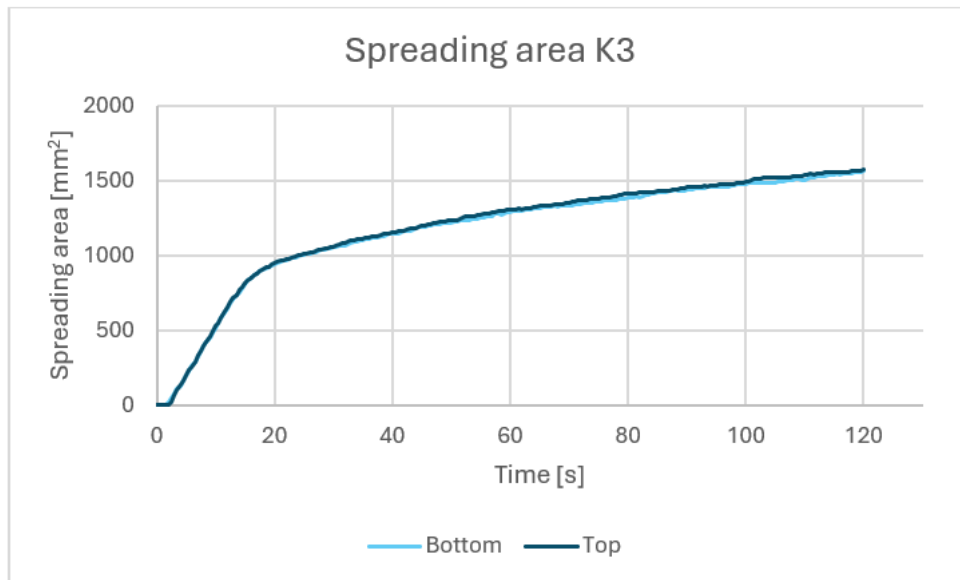


Figure 13. Spreading area of top and bottom side of K3.

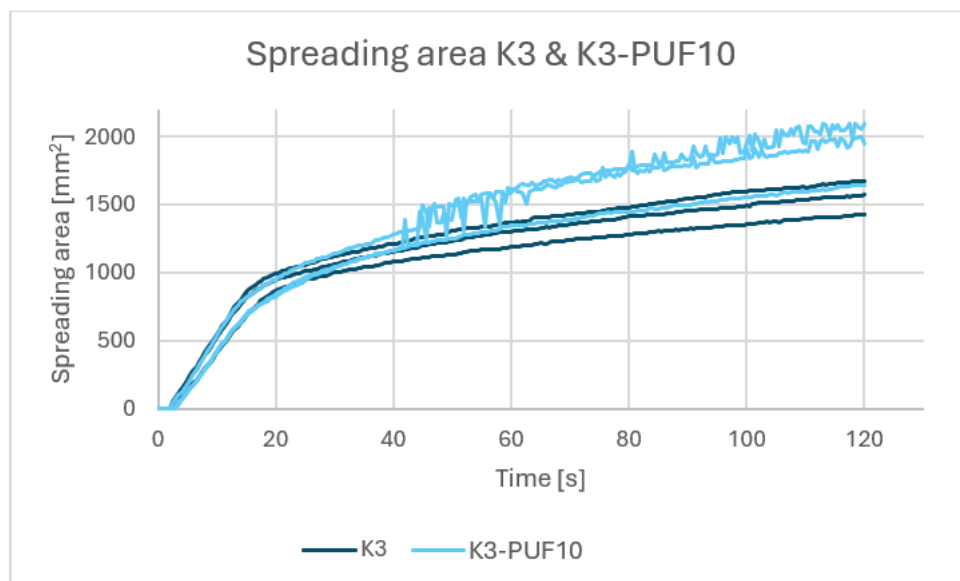


Figure 14. Spreading area of top side of K3 and K3-PUF10.

4.5.4 W1, W1-PUF5

The spreading on W1 was compared to the other fabrics very low, and hardly present on the bottom side (Figure 15), and the droplet was fairly intact after the test procedure (Figure 16). There was no significant difference in the spreading on W1 when paired with the foam and when tested separately (Figure 17).

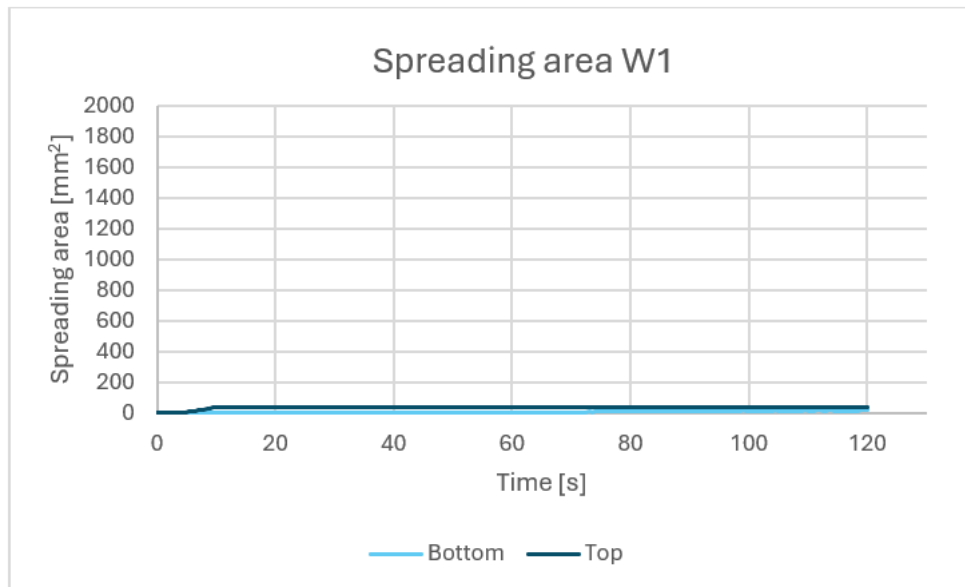


Figure 15. Spreading area of top and bottom side of W1.

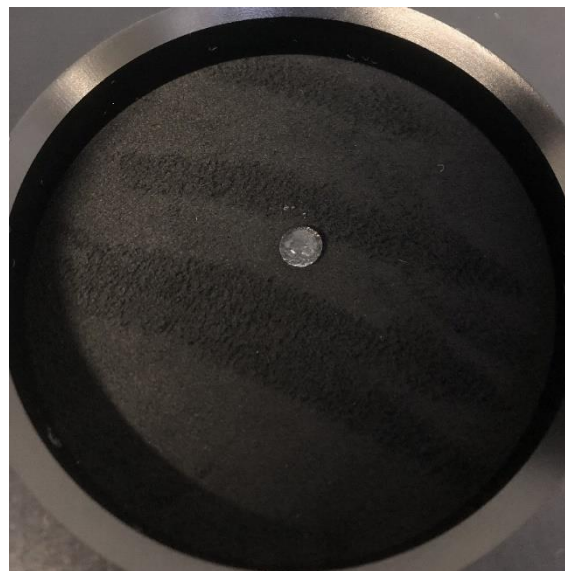


Figure 16. W1-PUF5 after WickView testing, the liquid has not spread or been absorbed.

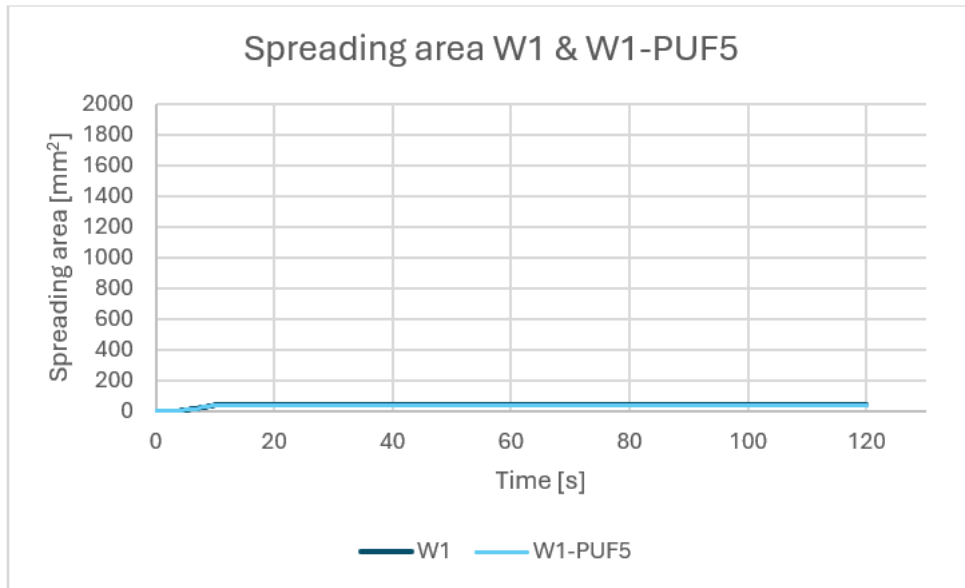


Figure 17. Spreading area of top side of W1 and W1-PUF5.

4.5.5 PUF

The WickView test of the foam, PUF, did not give any reliable results. The cameras appear to have interpreted the slight reflectance of the material as liquid, and the spreading graph thereby looks as in Figure 18. When the specimen was removed from the machine the droplet was intact (Figure 19), and no extensive spreading seemed to have occurred.

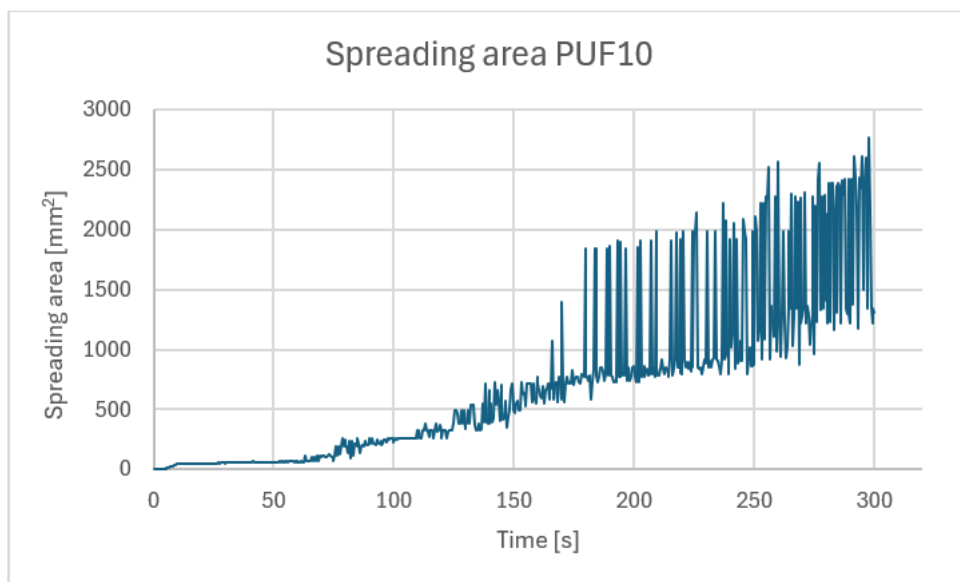


Figure 18. WickView results from sample PUF10. This is not considered as a reliable result.

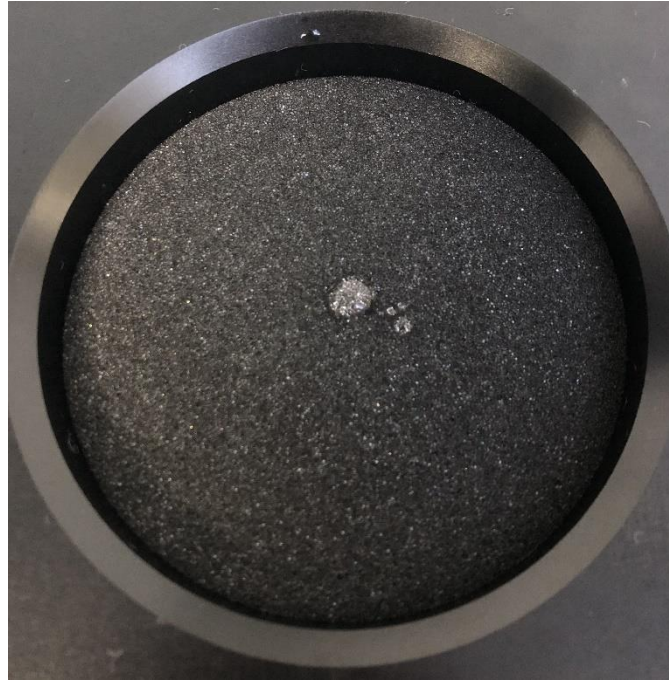


Figure 19. PUF10 after WickView testing, the liquid has not spread or been absorbed.

4.6 Drop test

The mean absorbency times for the five droplets per specimen are presented in Figure 20 below. For sample W1 the test was terminated as over 60 seconds passed without the droplet being absorbed, and it is therefore not included in the bar chart. For all other samples, the absorbency time was lower when paired with the hydrophilic cotton fabric. Photos of all specimens were taken (Figure 21), except for sample K3 where the spreading was not visible. The decrease in absorption time and spreading area when paired with the cotton fabric was most significant for sample K1.

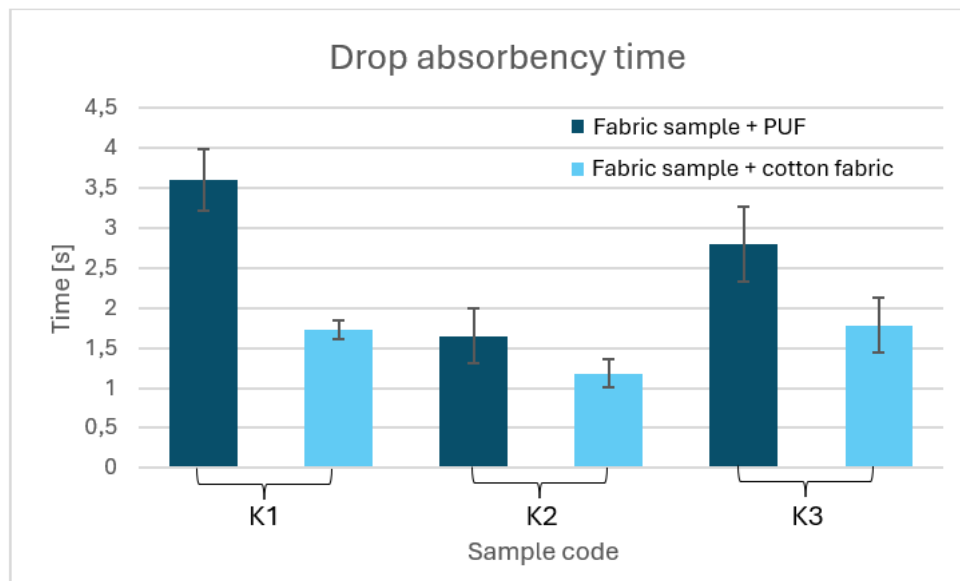


Figure 20. Drop absorbency time of samples K1, K2 and K3 in combination with PUF10 and cotton fabric.

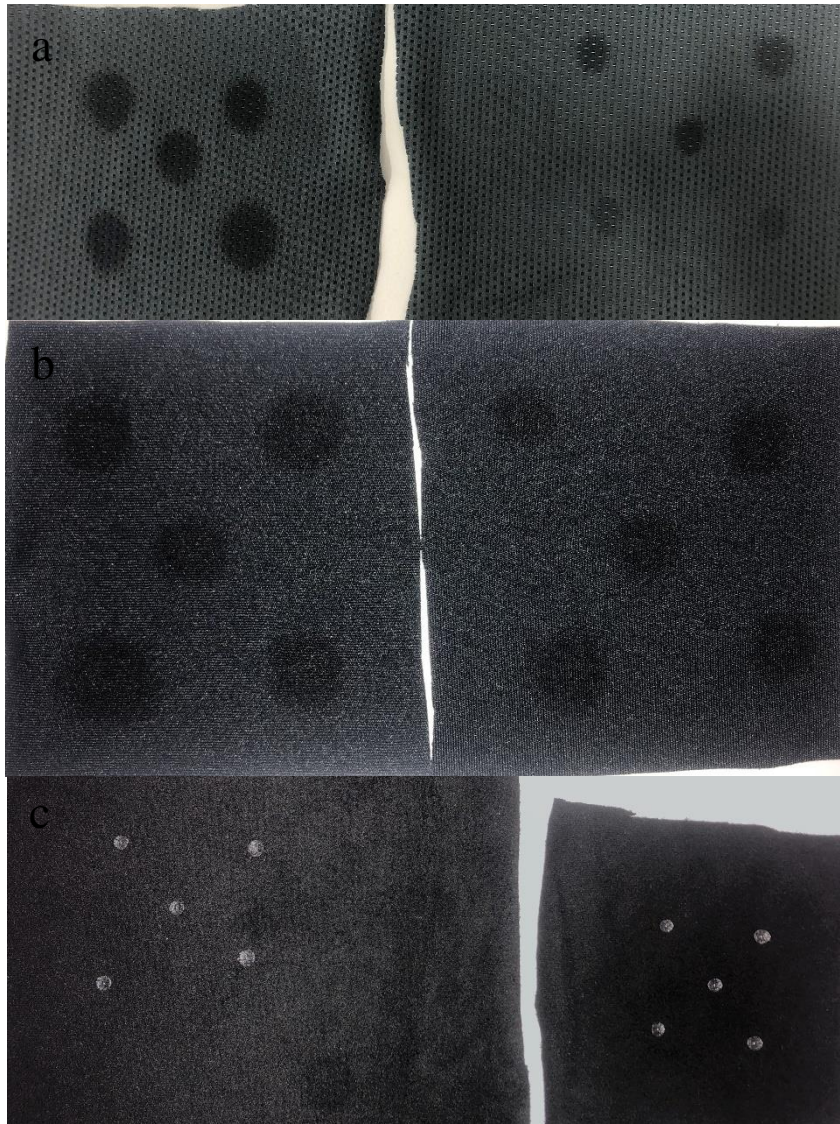


Figure 21. Drop absorbency test of samples, left side is paired with PUF10 and right side with cotton fabric. a) K1, b) K2, c) W1.

5. Discussion

The results obtained and their causes are discussed in this chapter, along with eventual error sources.

5.1 Porosity, air permeability and water absorption capacity

The porosity and air permeability of the samples were as anticipated from their structures, and do show a correlation (Figure 22). A permeable, in popular speech referred to as breathable, structure is in this case considered advantageous for improving thermal comfort by letting out excess heat. As all fabrics were quite dense in the transverse direction the difference in porosity are predominantly dependent on the tightness of the structure, and the size and quantity of gaps through the surface.

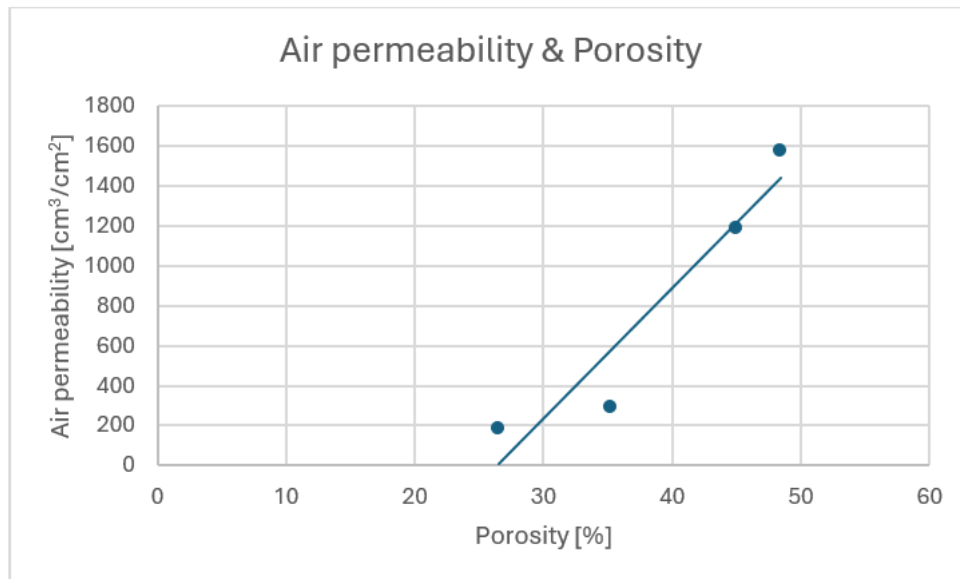


Figure 22. Correlation between air permeability and porosity of fabric samples.

The fabrics had similar water absorption capacities (WAC) even though their potential for wetting differed. The prominent number was however the absorption capacity of the foam. Foams are in general light and more porous than fabrics, and although the exact porosity of the PUF sample was unknown due to limited access to specifications it appears to be sufficiently porous in relation to its mass to absorb a higher amount than the fabrics. In this study the liquid moisture transport and management while under pressure from other elements were not examined, even though it might be of relevance considering the scenario of when a helmet is worn. The paddings are then subject to many external, influencing factors, yet that has not been included in this work's scope. The WAC-values did not show any correlations to the spreading area or spreading rate.

5.2 WickView

As seen in Figure 8 K1 and K3 achieved the biggest spreading area, while W1 and PUF10 barely had any. On samples K1, K2 and K3 the liquid quickly passed through to the bottom side of the fabric and the wetting areas of the top and bottom side were approximately equivalent.

The liquid was applied to the fabrics during the first ten seconds, where all samples showed a higher spreading rate. After the initial ten to fifteen seconds the rate decreases. The initial spreading rate thus gives an indication of the sample's tendency to wet, while the later spreading rate can be interpreted as the wicking rate. Sample K1, K2 and K3 had a similar spreading rate during the initial ten seconds of

testing, while K1 and K2 had significantly higher spreading rates after the first ten seconds (Table 5). Thus, samples K1 and K2 do appear to have a higher wicking ability. Studies have previously confirmed that more porous fabric structures have better wicking abilities (Yang et al. 2019; Palani et al. 2019), and a correlation is implied between the porosity and spreading area of the materials of this study as well (Figure 23). W1 shows no tendency for neither wetting nor wicking.

Table 5. Spreading rate of fabric samples.

Sample code	Approximate spreading rate [mm ² /s]	
	0 ≤ t ≤ 10	10 < t ≤ 120
K1	42,1	10,3
K2	47,7	3,6
K3	49,2	9,7
W1	3,7	0,5

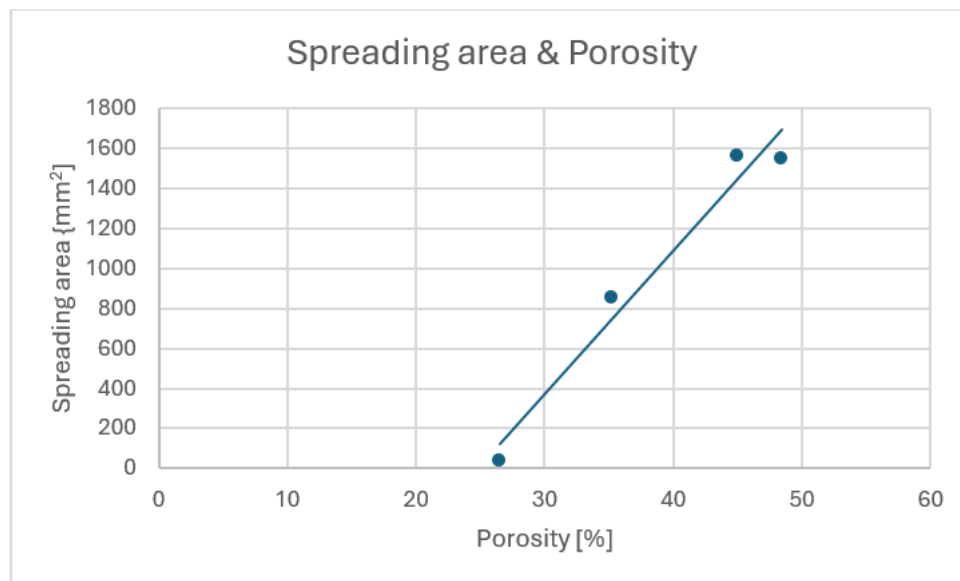


Figure 23. Correlation between spreading area and porosity of fabric samples.

The spreading rate of PUF has not been included as the results given from the test machine were considered not to be reliable (Figure 18). The reason for the foam's resistance to wetting is not established, but can be affected by several factors. Polyurethane is a hydrophobic material, so the material itself will not absorb moisture. A hydrophobic material can as mentioned however provide good wicking ability. As described, the wicking ability of yarn in section 2.3.2, for capillary action to occur the pores in the material need to be of a certain width and shape (Ito & Muraoka 1993; Wang et al. 2008; Hollies et al 1956). One reason for the foam's inability to neither absorb nor transport liquid is, except its hydrophobicity, that the pores are too large and discontinuous to allow for sufficient capillary force.

The combination with foam did show to have a slight influence on the spreading rate of K1 (Figure 10), and little to none for K2 and K3 (Figure 12 & 14). The reason for this might be that the hydrophobic foam surface interrupted the liquid from spreading through the whole thickness of the fabric sample, or that a small amount of the liquid passed into the pores of the foam. To statistically confirm that the foam decreases the spreading rate of the fabric at some points, a larger number of specimens would have to be tested.

To determine the eventual spreading in the foam other test methods or equipment would be necessary. Numerical results were indeed obtained from the machine, yet as the liquid was still in a droplet form on the surface when the specimens were removed from the machine, the given results were simply not

possible regarding the amount of liquid that spreading would have required. If a small amount of liquid in reality did spread is thus unknown. The study by Kan et al. (2018) shows that PU foam can not only not influence but even improve the transverse liquid moisture transfer. However, the foam used in this study was of a much higher thickness. Thus, it is possible that PU foam can perform in this application, but only up to a certain, unknown thickness. A thinner foam might however compromise too much on its pressure dampening properties, which in a helmet concerns the wearers' safety and is superior. One option is to examine potential substitutes to the foam, e.g. spacer fabric which has shown good moisture management qualities as well as compression recovery (Ertekin & Özgüney 2017; Bagherzadeh et al. 2012; Svensson & Halldorf 2023).

5.3 Drop test

As the differences in the spreading behaviours between the fabrics on their own or in combination with foam were very small or insignificant, a test including an absorbing component was made. The results showed a difference in absorption rate for all samples, and for K1 in particular. K1 also showed the biggest difference in spreading area (Figure 21). It was noticeable that when the droplets were released onto the K1-cotton combination they were pulled through the K1 fabric into the cotton fabric, as described in studies about double-sided fabrics allowing for a one-way moisture transport (Jhanji et al. 2015; Patnaik et al. 2006; Ullah et al. 2022). Fabric K2 did have the fastest absorption time both in combination with the foam and the cotton fabric, yet the absorbent backing did not change the spreading area remarkably. This is believably due to the smooth, uniform fabric structure of K2, without gaps through the fabric to create transverse capillary tubes like the K1 structure. The effect showed by K1 in combination with the absorbent backing would in practical use mean that sweat would be more easily transported to a layer not in direct contact with the wearer's skin, while the inner fabric remains dryer and therefore more comfortable to wear.

6. Conclusion

Does polyurethane foam work as a moisture transfer layer in helmet paddings?

Given the results of this study polyurethane foam with a thickness of five millimetres or more does not work as a moisture transfer layer. It does not show any proneness of wetting or wicking, which can be explained by the hydrophobic nature of polyurethane and the foam pores being too large and unidirectional to induce sufficient capillary action. Thinner polyurethane foams have in previous studies demonstrated an ability of transverse wicking, yet the main purpose of a foam in a helmet padding is to decrease eventual head impact which might not be as effective, or possible, with a thinner foam. Due to the poor test results of polyurethane in this study, and regarding its difficulties with recycling, there are many reasons for examining the possibility to replace the foam. One example which is investigated as an example to foam in other applications is spacer fabric. If it should show to be suitable to use in helmets it could improve both comfort and environmental related properties.

Which fabric structure among the common fabrics used in helmet paddings performs the best regarding liquid spreading and transverse wicking?

The overall best performing fabrics were K1 and K3. They showed to be permeable to air, porous, and obtained large spreading areas. K1 did show better tendencies regarding transverse wicking abilities, however only in combination with an absorbent backing material. The main resemblance between K1 and K3 was their perforated structure, which confirms to be beneficial for the purpose.

How should helmet paddings be composed to provide the best possible moisture transfer?

These conclusions are based on this work's results and literature review, and do not include aspects regarding helmet safety. The inner fabric should consist of hydrophobic filament fibres with a non-circular cross-section. The yarns should have a sufficient number of filaments and a correct twist level, which are dependent on each other and the properties of the filament. The fabric should be porous and of a perforated structure, creating passageways for the liquid to be transported in the transverse direction. As foam did not show to benefit the assembly, alternatives should be considered. Suggestions of possible substitutes are found in section 6.1.

6.1 Suggestions for further research

Whether a helmet is used for biking, skiing, working, or for other purposes, it is often not worn non-stop for a whole day. When the wearer takes the helmet off for e.g. having a break, the paddings should be able to dry quickly as putting on a wet or damp helmet is not comfortable, and possibly the helmet will then not be used for the rest of the day. Investigations on how to make a helmet padding that meets all safety and other comfort requirements yet also dries as quick as possible would benefit both safety and comfort.

3D spacer fabric is becoming a common element within the field of technical textiles and is a possible substitute for foam in helmet paddings. It is in that case of most importance to determine whether the spacer fabric can sufficiently absorb impact in case of accidents.

If 3D spacer fabric meets the safety requirements needed, studies on how to optimise the moisture transport through the fabric can be done. As spacer fabric normally has an inner and an outer layer, an additional inner fabric in a helmet padding construction might not be needed. This could benefit not only comfort, but also have economic advantages and save material.

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Appendix

Appendix A: Thickness, density, porosity, air permeability & water absorption capacity

Fabric thickness [mm]				
Specimen	K1	K2	K3	W1
1	0,188	0,194	0,215	0,159
2	0,158	0,212	0,196	0,174
3	0,243	0,192	0,218	0,21
4	0,201	0,196	0,205	0,184
5	0,201	0,202	0,218	0,18
mean	0,1982	0,1992	0,2104	0,1814
STD	0,0273598	0,0072222	0,0086394	0,0166325

Calculations of material densities [g/cm ³]	
90% Polyester, 10% Elastane	$\rho_m = (0,9 \times 1,38) + (0,1 \times 1,2) = 1,362$
86% Polyester, 14% Elastane	$\rho_m = (0,86 \times 1,38) + (0,14 \times 1,2) = 1,3548$

Fabric porosity calculations		
Sample	Fabric density [g/cm ³], $\rho_f = \frac{M}{D \times 1000}$	Fabric porosity [%], $P = \left(1 - \frac{\rho_f}{\rho_m}\right) \times 100$
K1	$\frac{139}{0,198 \times 1000} = 0,702$	$\left(1 - \frac{0,702}{1,362}\right) \times 100 = 48,5$
K2	$\frac{175}{0,199 \times 1000} = 0,879$	$\left(1 - \frac{0,879}{1,3548}\right) \times 100 = 35,1$
K3	$\frac{158}{0,210 \times 1000} = 0,752$	$\left(1 - \frac{0,752}{1,362}\right) \times 100 = 44,8$
W1	$\frac{182}{0,181 \times 1000} = 1,006$	$\left(1 - \frac{1,006}{1,362}\right) \times 100 = 26,2$

Air permeability of samples [cm ³ /cm ²]					
Specimen	K1	K2	K3	W1	PUF10
1	1540	301	1170	189	2600
2	1610	300	1210	187	2580
3	1520	302	1230	200	2570
4	1550	301	1170	179	2570
5	1610	296	1240	184	2620
6	1560	282	1180	191	
7	1560	284	1230	189	
8	1620	288	1150	180	
9	1650	288	1190	189	
10	1550	295	1150	197	
Mean	1577	293,7	1192	188,5	2588
STD	40,012498	7,1979164	31,874755	6,2968246	19,390719

Water absorption capacity															
Specimen number	K1			K2			K3			W1			PUF10		
	dry [g]	wet [g]	WAC [%]	dry [g]	wet [g]	WAC [%]	dry [g]	wet [g]	WAC [%]	dry [g]	wet [g]	WAC [%]	dry [g]	wet [g]	LAC [%]
1	1,327	4,916	270,4596835	1,815	6,578	262,4242424	1,57	4,76	203,1847134	1,852	6,695	261,5010799	1,787	9,306	420,761052
2	1,392	4,855	248,7787356	1,697	6,257	288,7094873	1,526	4,516	195,9370904	1,854	6,444	247,5728155	1,848	7,673	315,2056277
3	1,338	5,058	278,0269058	1,661	5,932	257,1342565	1,581	4,819	204,8070841	1,79	6,212	247,0391061	1,857	8,314	347,7113624
4	1,451	5,009	245,2101999	1,75	6,508	271,8857143	1,543	4,627	199,8703824	1,8	6,21	245	1,866	8,227	340,8896034
5	1,421	4,919	246,1646728	1,733	6,195	257,4725909	1,523	4,762	212,6723572	1,782	6,106	242,6487093	1,831	8,568	367,9410158
6	1,372	4,836	252,4781341	1,736	6,324	264,2857143	1,605	4,935	207,4766355	1,75	5,728	227,3142857			
7	1,409	4,911	248,5450674	1,713	6,18	260,7705779	1,6	4,862	203,875	1,765	6,387	261,8696884			
8	1,36	4,811	253,75	1,771	6,417	262,3376623	1,566	4,742	202,8097063	1,819	6,495	257,0643211			
9	1,411	5,348	279,0219702	1,779	6,447	262,3946037	1,593	5,111	220,8411802	1,823	6,127	236,09435			
10	1,411	5,152	265,1311127	1,771	6,471	265,3867871	1,66	5,066	205,1807229	1,805	6,6	265,6509695			
11	1,414	5,017	254,8090523	1,757	6,464	267,8998293	1,594	4,841	203,7013802	1,888	6,318	234,6398305			
12	1,403	5,234	273,0577334	1,801	6,703	272,182121	1,569	4,879	210,9623964	1,864	6,661	257,3497854			
mean	1,392416667	5,0055	259,4829134	1,748666667	6,373	264,4491041	1,5775	4,826666667	205,9693608	1,816	6,331916667	248,6738253			358,5017323
std			12,183247			4,783088608			6,193947575			11,68212805			35,40196268

Appendix B: WickView spreading area

Sample	Specimen	spreading area [mm ²], top	spreading area [mm ²], bottom	
K1	1	1586,6705	1555,9927	
	2	1564,3286	1553,0654	
	3	1495,2269	1479,8819	
	mean	1548,742	1529,6467	
	std	38,924637	35,209277	
	K2	1	812,71143	806,81938
2		889,02979	878,53917	
3		871,1365	853,09384	
mean		857,62591	846,1508	
std		32,588597	29,688226	
K3		1	1427,9046	1381,1406
	2	1679,597	1721,6125	
	3	1576,0927	1563,4237	
	mean	1561,1981	1555,3922	
	std	103,29135	139,11305	
	W1	1	37,862605	0
2		37,269458	14,86187	
3		37,664889	21,279495	
mean		37,598984	12,047122	
std		0,2465951	8,9124009	
PUF10			t=300s	t=120s (top)
	1	3470,7059	0	1935,0461
	2	2831,8856	0	1128,0684
	3	1310,3625	0	265,03824
	mean	2537,6513	1109,3842	
	std	906,16454	681,90583	
K1-PUF5		t=300s	t=120s (top)	
	1	2991,2447	0	1775,687
	2	7990,4926	0	
	3	2242,1978	0	1503,7287
	mean	2616,7212	1639,7078	
	std	374,52345	135,97915	
K2-PUF5		t=300s	t=120s (top)	
	1	967,42417	0	852,45234
	2	989,66721	0	861,05298
	3	993,81925	0	882,99946
	mean	983,63688	865,50159	

	std	11,588753	12,861419
K3-PUF10		t=300s	t=120s (top)
	1	2564,8702	0 1946,7113
	2	2161,2331	0 1647,7648
	3	3269,2333	0 2098,9526
	mean	2665,1122	1897,8095
	std	457,85912	187,41424
W1-PUF5		t=300s	t=120s (top)
	1	170,03572	0 39,246617
	2	365,18137	0 34,402576
	3	286,2927	0 114,77411
	mean	273,8366	62,807768
	std	80,153278	36,79893