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3D Knit Fabrics

- Optimizing Spacer Knit fabrics for Comfort and Breathability in Infant Products

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SAMMANFATTNING

I den här studien tittade vi på en befintlig barnvagnssits i textil och undersökte om det kan vara någon fördel med att ändra materialet till ett distanstyg ur perspektiv som funktionalitet, komfort och hållbarhet. Ämnet 3D-stickning och avancerad stickning undersöks mer och mer på grund av dess mångsidighet när det kommer till att producera och ändra parametrar för stickade högkvalitativa produkter. Det finns däremot en brist på studier gjorda om komfort i barnprodukter i korrelation till distanstyger och det har inte gjorts många studier om distanstyger som används i barnprodukter eller cykelvagnar. En anledning till vidare forskning inom området 3D-stickning är att det kan ge produkterna ett bättre utseende, funktionalitet eller potential för mer hållbar produktion, vilket skulle kunna leda till bättre möjligheter att producera mer attraktiva avancerade textilprodukter. Detta kan i sin tur göra företaget mer attraktivt bland kunder samt sticka ut mer bland konkurrenter på marknaden.

Senaste forskningen kring distanstyger har fokuserat på användning av varpstickade distanstyger för ökad dämpning och skydd mot stötar. Termoreglering, kompression, luftgenomsläpplighet och bra energiabsorption är några egenskaper hos distanstyger, vilka gör dem intressanta att undersöka i barnprodukter (Gokarneshan 2015). En annan anledning till ytterligare undersökning av distanstyger, och deras goda dämpningsegenskaper, i barnprodukter är att det i en tidigare studie visat sig att barn som transporteras i cykelvagnar utsätts för mer vibrationer jämfört med barn som transporteras i bilstolar (Rothhamel 2023). Ett skäl till att undersöka möjligheterna vad gäller ersättandet av PU-skum med distanstyg är att PU-skum generellt sett har lägre luftgenomsläpplighet i kombination med högre värmebeständighet, vilket kan leda till problem gällande komfort. (Gokarneshan 2015).

I studien utfördes testning av olika distanstygprover baserat på luftgenomsläpplighet, bristningsstyrka och fukthantering. Dessa tester utvärderades sedan för att fastställa de optimala parametrarna för ett distanstyg ämnat för ökad komfort och funktionalitet i en barnsits. Andra tester som utfördes var specifikt utformade tester för barnprodukter såsom bit-test, finger-test och drag-test för att undersöka säkerheten hos varje tygprov. Vi drog slutsatsen att det optimala distanstyget borde vara konstruerat av polyester för att ha så bra fukttransporterande egenskaper som möjligt. Tyget bör ha en sida av distanstyget som inte består av nät för att kraven från fingertestet ska uppfyllas. Den andra sidan av distanstyget bör vara konstruerad av en nätstruktur för att säkerställa goda egenskaper av luftgenomsläpplighet. Hålen bör dock inte vara för stora, eftersom det kan göra tyget obekvämt mot huden. Nätstrukturen som rekommenderas är ett sexkantigt nät som ger god genomsläpplighet av både vatten och luft. Tyget bör även konstrueras med ett multifilament som mellanlager på grund av säkerhetsskäl.

Nyckelord: Distanstyg, trikå, varptrikå, rundstick, textiltestning, Procad Warpknit, spädbarnsprodukt, barnprodukt, komfort, mekaniska egenskaper.

ABSTRACT

In this study we looked into an existing textile baby stroller seat and investigated whether there can be any advantage in changing the material to a spacer fabric from perspectives such as functionality, comfort, and sustainability. The subject of 3D knitting, and advanced knitting is being researched more and more because of its versatility in producing and changing parameters of knitted high quality products, but there is a lack of studies done on comfort for children when it comes to knitted spacer fabrics and not many studies have been done on spacer fabrics used for baby seats in strollers or other types of seats for children. A reason for further development and research in the area of 3D knitting is that it could be giving products a better appearance, functionality or potential for more sustainable production which could lead to better possibilities of producing more attractive advanced textile products. This could in turn make the producer more attractive among customers as well as stand out more amongst competitors on the market.

Recently there has been attention on the use of warp knitted spacer fabrics in the application of cushioning to protect against impact. Thermoregulation, compression, air permeability and good energy absorption are some characteristics of spacer fabrics which are being further investigated in this study (Gokarneshan 2015). Another reason for further investigation of spacer fabrics, and their good cushioning properties, in child products is that it was shown in a previous study that children who are transported in carriers for bicycles are exposed to more vibration compared to children who are transported in automotive rides (Rothhamel 2023). A reason for examining the possibilities of replacing polyurethane foam with spacer fabric is that PU foams generally have lower air permeability in combination with higher heat resistance which can lead to problems regarding comfort. (Gokarneshan 2015). Testing of different spacer fabric samples was carried out based on air permeability, burst strength, and moisture management. These tests were then evaluated to determine the optimal parameters of a spacer fabric for increased comfort and functionality in an outdoor child product. Other tests that were carried out were specific tests for child products such bite test, finger probe test, and pulling test to examine the safety of each sample.

We concluded that the optimal spacer fabric should be constructed of polyester rather than cotton to have as good wicking properties as possible. The fabric should have one side of the spacer fabric that does not consist of mesh so that the requirements from the finger probe test will be fulfilled. The other side of the spacer fabric should be constructed of a mesh structure to ensure good properties of air permeability. The holes should, however, not be too big since this might be less comfortable against the skin. The mesh structure recommended for this purpose is a hexagonal mesh which results in both good permeability of both water and air flow. The fabric should also be constructed with a multifilament for the spacer yarn for safety reasons.

Keywords: Spacer fabric, knitting, warp knit, circular knit, textile testing, ProCad Warpknit, infant product, comfort, mechanical properties.

SAMMANFATTNING - POPULÄRVERSION

Studien undersöker möjligheterna att ändra materialet i en befintlig barnprodukt till ett distanstyg, samt hur egenskaperna hos produkten skulle påverkas av detta.

En anledning till att forskning kring 3D-stickning har ökat senaste tiden är intresset hos företag att ändra parametrar i stickade produkter för en ökad kvalitet och funktionalitet. Det finns däremot en brist på forskning kring distanstyg i barnprodukter med syfte att öka komfort, och därför har vi valt att undersöka detta. En annan anledning till att vidare undersöka 3D-stickning är att det kan bidra till en bättre produkt ur perspektiv som utseende, funktionalitet och hållbarhet, vilket i sin tur kan bidra till ett bättre rykte på marknaden.

Ny forskning kring 3D-stickning fokuserar på distanstyg i varptrikå och dess goda dämpningsegenskaper. Andra egenskaper hos distanstyg som kan vara attraktiva ur ett barnproduktsperspektiv är termoreglering, kompression, luftgenomsläpplighet och bra energiabsorption. (Gokarneshan 2015). En annan tidigare studie att ta hänsyn till visar att barn som transporteras i cykelvagn utsätts för mer vibrationer jämfört med barn som transporteras i bilstol, vilket gör det relevant för oss att undersöka om det går att öka vibrationsisolering i produkten genom att byta till distanstyg (Rothhamel 2023). Något som undersöks i vår studie är tjocklek av distanstyg, eftersom en tidigare studie visar att tjockleken har stor betydelse för hur bra distanstyget isolerar mot vibrationer. (Liu & Hu) 2015). Något annat som undersöks är huruvida man kan eliminera polyuretanskummet i produkten genom att byta det mot ett distanstyg. En studie so gjorts på polyuretanskum visar att skummet har lägre luftgenomsläpplighet i kombination med högre värmebeständighet, vilket bidrar till bristande komfortegenskaper. (Gokarneshan 2015).

Vi utförde tester av luftgenomsläpplighet, bristningsstyrka och fukthantering på tio distanstygsprover för att jämföra funktions- och komfortegenskaper med den befintliga produkten. Andra tester som utfördes var specifikt utformade tester för barnprodukter såsom bit-test, finger-test och drag-test för att undersöka säkerheten hos varje tygprov. Från testerna och litteraturstudier konstaterade vi att det optimala distanstyget för produkten borde vara konstruerat av polyester för bra fukthanteringsförmåga, ena sidan bör bestå av en sexkantig nätstruktur för bra luft- och vattengenomsläpplighet medan andra sidan bör bara utan hål för att uppnå säkerhetskrav. Det konstaterades även att mellanlagret bör bestå av multifilament på grund av säkerhetsskäl.

Foreword

This bachelor thesis in textile technology examines the possibilities of changing the current fabric of an infant product into a spacer fabric, and how the properties of this product would be affected by this. The subject was presented and examined in collaboration with Thule, and we chose this subject based on interest in spacer fabrics and a curiosity of learning more about warp knitted and circular knitted technical textiles. The work has been distributed equally between the authors.

We would like to thank our examinator Behnaz Baghaei and our supervisor Joel Peterson for guidance during the work and for providing us with material samples. We also want to thank Müller textiles and Mayer & Cie together with the lab technician Stefan Gustafsson in the knitting lab for also providing us with material for the study. Thanks to Sofia Morsten in the test lab for taking the time to help us with the test equipment. And thanks to Carin Backe for helping us understand Procad Warpknit.

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1. INTRODUCTION

1.1 BACKGROUND

The subject of 3D knitting, and advanced knitting is being researched more and more because of its versatility in producing and changing parameters of knitted high quality products. A reason for further development and research in the area of 3D knitting is that it could be giving products a better appearance, functionality or potential for more sustainable production which could lead to better possibilities of producing more attractive advanced textile products. This could in turn make the producer more attractive among customers as well as stand out more amongst competitors on the market.

1.1 PROBLEM DEFINITION

Recently there has been attention on the use of warp knitted spacer fabrics in the applications of cushioning to protect against impact and some areas spacer fabrics can be used in are seat covers and sofas etc. The reasons for their applicability in products where polyurethane (PU) foams would traditionally be used is because of the 3D structure resulting in characteristics such as thermoregulation, compression, and air permeability. Spacer fabrics are also able to absorb energy and force impacts which could protect the body from obtaining injuries (Gokarneshan 2015).

A study over vibration and comfort for children in transportation of bicycle carriers showed that children who are transported in carriers for bicycles are exposed to more vibration compared to children who are transported in automotive rides (Rothhamel 2023). This might be another reason as to why spacer fabrics should be investigated to be used in such applications of child products and could potentially give sufficient cushioning when it comes to comfort for children in different ways of transportation.

Another study showed that knitted spacer fabrics made from materials such as polymeric fibers can be used as vibration isolators with a good performance. It was also shown that a spacer fabric which is thicker has better performance in vibration isolation, when producing such an isolator for humans a knitted spacer fabric can therefore be used to maintain comfort (Liu & Hu 2015).

There can also be some comfort problems concerning PU foams as they generally have a lower air permeability in combination with a higher heat resistance compared to a spacer fabric which results in the PU foam feeling uncomfortable and too warm when it is used in warmer conditions. This happen because the PU foam can contain higher levels of heat compared to a warp knitted spacer fabric of the same thickness (Gokarneshan 2015).

There is a lack of studies done on comfort for children when it comes to knitted spacer fabrics and not many studies have been done on spacer fabrics used for baby seats in strollers or other types of seats for children.

Due to guideline CEN/TR 13387-1:2018 monofilament is not recommended to be used in baby products because of safety reasons.

1.2 AIM

Look into an existing textile baby stroller seat and investigate whether there can be any advantage in changing the material to a spacer fabric from perspectives such as functionality, comfort, and sustainability. Investigate the different possibilities for constructing an advanced knitted product with the use of spacer fabrics. To optimize the functionality of the product, properties such as air permeability, burst strength and moisture management will be further investigated and evaluated since this could bring more comfort for the user. Testing of different fabric samples will be carried out based on these properties and thereafter suggestions will be made about how the fabric should be constructed.

1.3 THESIS QUESTIONS

- What properties does an outdoor baby stroller seat need to fulfill for the product to be more comfortable for the child?
- What is gained in functionality and sustainability by producing the chosen product with spacer fabric?
- How should a spacer fabric be constructed for the product to fulfill the factors of air permeability, moisture management, and safety parameters?

1.4 SCOPE

The study is based on the material of a baby seat product from Thule which is a construction of a 100% polyester fabric heat laminated together with a polyurethan (PU) foam. The study is limited to warp knitted and circular knitted spacer fabrics and the test methods used for the study are air permeability, moisture management, burst strength together with specific test methods for baby products; bite test, finger probe test and pulling test. The tests conducted are limited to the fabric of the product and do not consider seams or other parts and components that are attached to the baby seat. The study is focused on fabrics for use in baby product/seat and does not consider the fabrics suitability for other purposes or products.

1.5 LITERATURE REVIEW

1.5.1 COMFORT PROPERTIES

One of the most important functions after protection is comfort. This is a property that is complex because of the interaction between the skin and body and the textiles of a product or garment. When heat and moisture is to be transported away from the body with the help of a textile material can be explained by thermophysiological comfort. This includes properties such as sweating, feeling of warmth and coolness (Dolez, Vermeersch & Izquierdo 2018).

There is always an attempt and effort put into improving the comfort properties of textiles since this is one of the most important aspects and requirements. The needs a person has may differ depending on if the product is aimed for a baby or an elderly person but the need of comfort will always be existent and needs to be fulfilled. There are three categories in which physiological discomfort can be divided into, and these are the fit of garment, thermophysiological discomfort and sensorial discomfort. Thermophysiological comfort is dependent on the temperature of both skin and body, lung function and tactile sensations among others. When moisture is present on the textile surface it can lead to intensified abrasion of the skin. This can result in uncomfortable feeling against the skin in warmer climates because of the increased friction when the fabric is in contact with the skin. Fabric for babies should have some ventilation and the fabric should also be permeable to moisture because babies tend to have skin which is more sensitive (Fan & Hunter 2009).

Thermophysiologial comfort can also be considered as the properties which makes the maintenance of heat balance possible, such as transport of both moisture and heat. It takes a lot of energy for a liquid to change into vapor which is why it cools the skin when water on the skin evaporates. In a hot climate which is dry sweat being converted into vapor to cool the skin works well but if the climate is humid this can become a problem. There are two different means of perspiration which are possible to occur, one is when the moisture is moved away from the skin through the fabric in the form of vapor and the other possibility is when a lot of sweat is accumulated and thereby wetting the fabric. When a textile garment or product is used in a hot climate heat dissipation is needed to create a balance in the comfort. Fabrics should be able to keep the skin dry for the wearer to be comfortable. This can be done by either allowing the moisture in the form of vapor to easily pass or for the fabric to quickly dry the moisture content that is obtained in the fabric. The structure of the fabric can be seen as a main factor in how easily water vapor can pass through the fabric. This relates to air permeability and the fabrics air permeability measurements can be used as a guide, where a high air permeability results in water vapor being able to pass through with more ease. One factor that is dependent on the structure of the fabric is the fabrics ability to wick liquid away from the skin which is also done by capillary transportation (Saville 1999).

1.5.2 Spacer fabric construction

Warp knitted spacer fabrics have been shown to have performed better than PU foams when it comes to reducing pressure concentrations which means that the spacer fabrics are more fitted for applications requiring relief from the body pressure, such applications can be mattresses and other seats. 3D knitted spacer fabrics are usually constructed as a sandwich construction with three layers. Two surface layers, commonly made with the same structures, are connected by a middle layer, the spacer yarn, which creates space between the two outer layers and adds thickness to the fabric. The structure in warp knitted spacer fabrics often consists of in-laid yarn combined with pillar stitches to give the fabric structural stability without having to perform lower air permeability (Gokarneshan 2015).

It is observed that better recovery properties can be attained by using monofilament yarns in the spacer compared to multifilament yarns. However, the use of multifilament yarns for the spacer layer results in a fabric which is more stretchable compared to spacer fabrics made with monofilament yarns in the spacer of weft knitted spacer fabric (Yip & Ng 2008).

A study shows that when constructing functional garments and fabrics that are intended to be worn and used next to the skin and to be used in warmer climates one of the most important aspects to consider is the heat transfer. This study also compared the surface temperature of clothing, and it could be seen that cotton had higher temperatures compared to polyester (Bagherzadeh, Gorji, Latifi, Payvandy & Kong 2012).

The compression resistance of a spacer fabric is dependent on the type of spacer yarn that is used, with a monofilament yarn a bigger compression resistance is usually obtained. (Yip & Ng 2008).

When a higher thickness of fabric and larger mesh of the outer fabric layers are used in combination with finer spacer yarn a fabric with efficient absorption of lower energies is obtained. Comparatively, for efficiency of higher energy absorption fabrics with thicker yarns in the spacer, smaller mesh sizes of the outer fabric layers and a smaller thickness of the fabric can be used (Gokarneshan 2015).

When different warp knitted spacer fabrics have been compared to PU foams in their functionality in tests such as heat resistance it was shown that the warp knitted spacer fabrics performed better than the foams for this property. The low air permeability attained from PU foams can cause a problem in comfort of the product because PU foam has a higher degree of heat resistance compared to spacer fabrics. When the fabric has high levels of heat resistance it means that the fabric can contain or keep the heat. This results in PU foams being more capable of containing the heat when compared to a spacer fabric that has the same thickness. For warm environments this can make PU foams uncomfortable and feel too warm because of the combined properties of low air permeability with high heat resistance. (Gokarneshan 2015).

Another study shows that a spacer fabric with a thickness of 3,1 mm in combination with a hexagonal mesh surface structure results in a fabric which has a relatively low thermal conductivity. (Rajan, Souza, Ramakrishnan & Zakriya 2016).

1.5.3 *Air permeability*

When engineering a warp knitted spacer fabric there are many parameters to take into consideration. One of them are the thickness of the fabric, which can have vital effect on properties like air permeability and moisture management. The thickness of warp knitted spacer fabrics are determined by the distance of the needle beds in the machine when producing the fabric. A commonly used structure in warp knitted spacer fabrics is a mesh structure on both fabric surfaces since this results in good air permeability properties. The structure often consists of laying in-laid yarn combined with pillar stitches since this also results in structural stability combined with good air permeability. A warp knitted spacer fabric can also result in easier recycling compared to PU foams (Gokarneshan 2015).

Another study shows that a spacer fabric with a thickness of 3,1 mm in combination with a hexagonal mesh surface structure results in a fabric which has a relatively low thermal conductivity as well as good permeability of both air and water vapor. Comparing this to a spacer fabric with a thickness of 4 mm which had a surface structure consisting of locknit gave lower results in permeability of water vapor and air permeability. The results of water vapor and air permeability of a spacer fabric depends on the pore size of the fabrics surface and the distance between the surface layers (Rajan et al. 2016).

When different warp knitted spacer fabrics were compared to PU foams in their functionality in tests such air permeability it was shown that the warp knitted spacer fabrics performed better than the foams for this property. The warp knitted spacer fabrics performed better because of their open mesh structures on the fabric surface. (Gokarneshan 2015).

Another study showed that the property that affects the air permeability properties of a spacer fabric the most is the density of the fabric. Fabrics with lower measurements of air permeability were found to have a higher density since this prevents the air from freely flowing from one side of the fabric to the other (Yip & Ng 2008).

1.5.4 MOISTURE MANAGEMENT

When constructing functional garments and fabrics that are intended to be worn and used next to the skin and to be used in warmer climates some of the most important aspects to consider are the heat and moisture transfer that comes from the body. To keep the body dry and therefore accomplishing a higher comfort level, the fabric layers should be able to absorb moisture in the form of perspiration and then move the moisture to the surface of the fabric which is not touching the skin. In textile fabrics and materials, the moisture absorbency and transfer are primarily affected by the capability of wicking in the fibers used. The factors contributing to a fibers wicking efficiency are the distribution of capillary pores, pathways, and the surface tension. However, the factors that correlates to a materials drying rate is the fibers geometrical parameters and its molecular structure. When the surface temperatures of clothing were compared it could be seen that cotton had higher temperatures compared to polyester. The cross-section of the fibers used in the production of the spacer fabrics are shown to have significant effect on improving the properties of moisture transfer in the fabrics (Bagherzadeh, Gorji, Latifi, Payvandy & Kong 2012).

When the moisture that comes in contact with a fabric is spread quickly throughout it, the surface which will be in contact with the skin can dry faster. Good wicking then results in the moisture being able to spread in the fabric with more ease which in turn makes the fabric more comfortable. When the wicking of polyester and cotton fabrics were compared it was found that the wicking rate of polyester was faster. This could be explained by the cotton fibers being hydrophilic and therefore can soak up water and liquids which influences the wicking, because of the swelling of the fibers. It was found that properties that affect wicking of the fabric surface the most was the materials of the fibers. When comparing the polyester and cotton fabrics the polyester performed best, which again could be explained by its hydrophobic nature (Kumar & Das 2014).

Another study showed that the parameter that affects the thermal properties of a spacer fabric the most is the density of the fabric. Compared to laminated fabrics or foam materials, spacer fabrics can attain a higher comfort level because of its breathability which leads to less moisture being contained. This also means that situations such as cases of skin maceration can be decreased (Yip & Ng 2008).

Transverse wicking measures the wicking of a fabric through its thickness, the reason this is an important parameter is because the sweat from the skin is moved through the thickness of the fabric away from the skin in this direction (Saville 1999).

1.5.5 SUSTAINABILITY AND RECYCLING

Approximately 3-10% of the global emissions of carbon dioxide comes from the textile industry. One reason for this is that the industry of textiles requires a lot of resources as well as the big amounts of waste that is generated from the textile industry (de la Motte & Ostlund 2022).

When it comes to the recycling of PU foams at the end of product life, several problems should be addressed such as an expensive delamination process, low efficiency as well as emissions of toxic gases. The PU foam needs to be separated from the fabric layers which is why a delamination process is required. This process is not very efficient since the separated materials does not have high levels of purity. The low purity is an effect from the PU foam not being able to be completely separated from the polyester fabric and therefore not 100% separation of the materials can be accomplished. This separation process can also be expensive. Depending on what lamination process that is used for the production of the PU foam and polyester fabric, toxic gasses and other emissions can be emitted which is not environmentally sustainable. Flame lamination is one example of a process that emits gasses that can be toxic (Njeugna et al. 2013).

Because of the fact that PU foam has a low density in combination with being a thermosetting material, PU foams are more difficult to recycle. It is often that materials which are thermoset gets sent to landfills once their product lifetime is over. The biggest use for PU foams in cars comes from seats which is a volume of almost 15 kg of PU foam material for each car (Quadrini, Bellisario & Santo 2013).

For PU foams that are used for beddings there is an estimation that carcinogens have above 75% impact in life cycle assessment for the products treatment at the end of life (Sabu Thomas 2018).

Since the recycling of PU foams require the fabric to be separated from the foam this is why disposing products including this type of material is difficult. When comparing this to warp knitted spacer fabrics the spacer fabrics do not have these save problem in recycling as they are also produced with fiber materials. This is one reason why spacer knitted fabrics can be easier to recycle when the product reaches the end of life (Xiaohua, Hong & Xunwei 2008).

2. MATERIAL AND METHODS

This is a quantitative study where the data has been collected through testing of fabric samples.

This chapter contains a presentation of the samples used in the study followed by test methods used to evaluate thickness, air permeability, moisture management, burst strength, and safety of all samples. A statistical analysis was performed to examine the air permeability and a simulated construction of warp knitted spacer fabric was performed in ProCad Warpknit.

2.1 FABRIC SAMPLES

WK – Warp knitted
CK – Circular knitted
RF – Reference fabric from the current infant sling prototype, heat laminated with a PU foam.

Warp knitted spacer fabric from supplier Müller Textiles: WK1, WK2, WK3, WK4

Unknown supplier: WK5, WK6

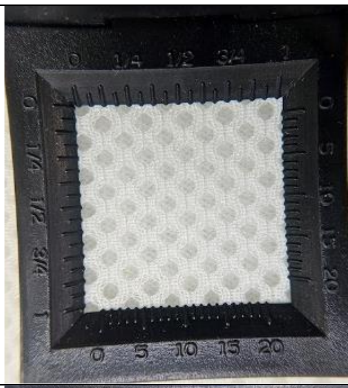
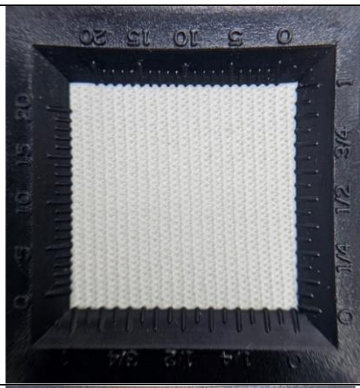
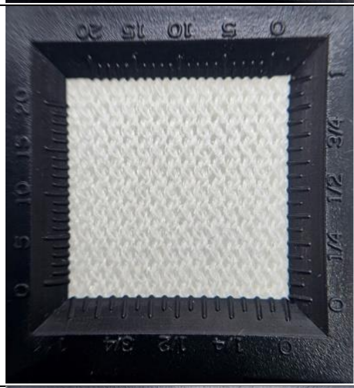
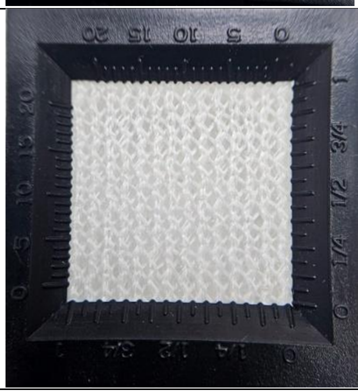
Circular knitted spacer fabric from supplier Mayer & Cie: CK1, CK2, CK3, CK4

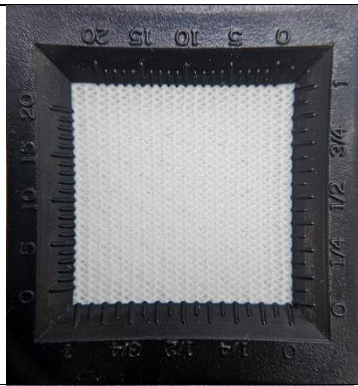
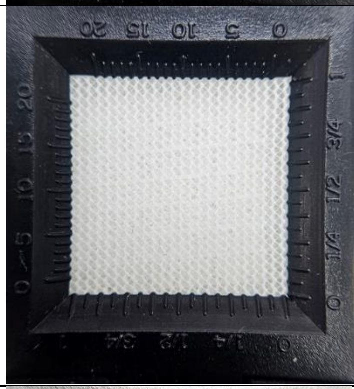
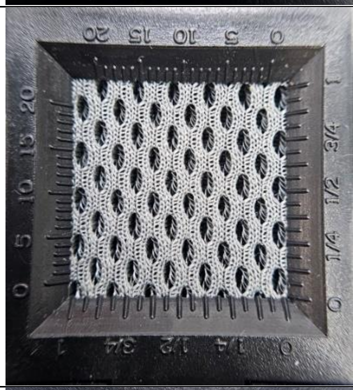
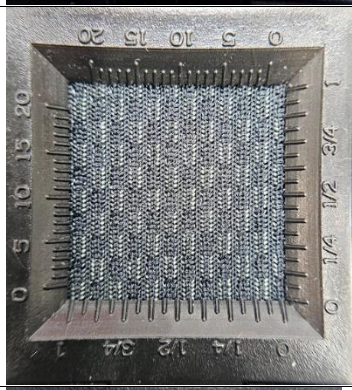
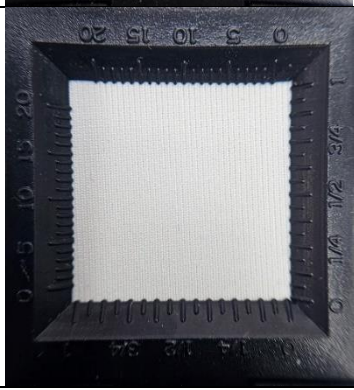
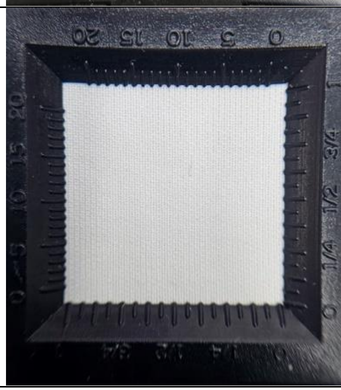
Each fabric sample is defined with a front and a back side. Where the fabric sample has a different construction on each side of the fabric, the side with a mesh structure is chosen for the front side and is facing up. A visualization of this can be seen in table 2. Fabric sample RF has the knitted fabric as front and the mesh as back. In table 1 the material and gauge of each fabric sample can be seen. The gauge is given as needles per inch (N.P.I), when the N.P.I of the fabric was not known from the supplier it was approximated by counting the number of loops or stitches per inch. Where a material percentage is not given for the fabric samples in table 1, the percentage is unknown.

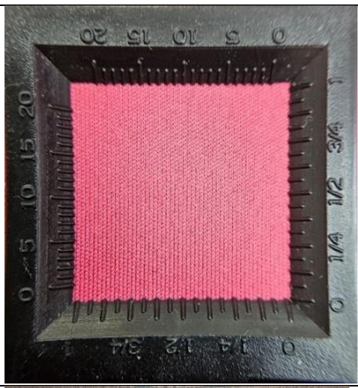
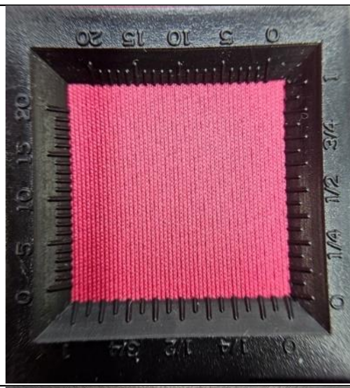
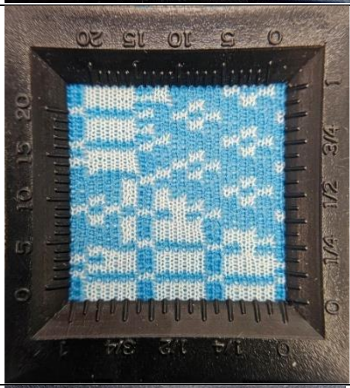
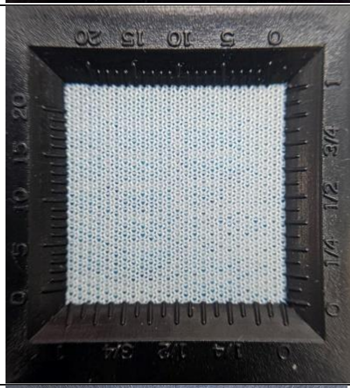
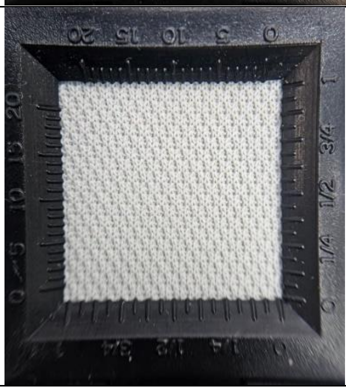
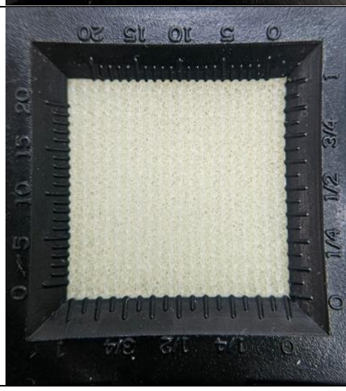
TABLE 1, INFORMATION SUCH AS THE MATERIAL AND GAUGE ABOUT EACH FABRIC SAMPLES.

Fabric	Material	Gauge N.P.I (approximated)	Gauge N.P.I (known)
WK1	100% polyester	20	
WK2	100% polyester	18	
WK3	100% polyester	16	
WK4	100% polyester	14	
WK5	100% Polyester	20	
WK6	100% Polyester	24	
CK1	100% polyester		20
CK2	Polyester and elastomer		28
CK3	Polyester and elastomer		32
CK4	100% Polyester	24	
RF	100% polyester and PU foam	28	

TABLE 2, VISUAL REPRESENTATION OF THE CONSTRUCTION FOR FRONT AND BACK SIDE OF EACH FABRIC SAMPLE.

Fabric	Front	Back
WK1		
WK2		
WK3		
WK4		

WK5		
WK6		
CK1		
CK2		

CK3		
CK4		
RF		

2.2 Test methods

The fabric samples were tested in a conditioned atmosphere according to iso 139:2005, the fabric samples were conditioned in the atmosphere for at least 24 hours before testing. For the testing of bite test, pulling test and finger probe test, the fabric samples were not conditioned and were not tested in an atmosphere adhering to this standard.

2.2.1 Thickness

The fabric thickness was measured for all fabrics except for the four first warp knitted fabrics: WK1, WK2, WK3 and WK4 according to EN ISO 5084:1996. The pressure plate that was used had an area of 2000 mm^2 and the thickness was measured on five different places of the fabric. The thickness of the fabric was recorded after 30 ± 5 seconds of the pressure of 1 kPa being applied. The first four warp knitted fabrics were not measured for thickness since the thickness was already known from the producer of the fabric.

2.2.2 Air permeability

The air permeability was tested according to ISO 9237:1995. Each specimen was tested ten times at different points of the fabric. Excel were used to calculate a mean value for each sample. The machine used was FX 3300 LabAir IV Air Permeability Tester and can be seen in figure 1. Air permeability is measured by calculating the pressure difference of the fabric area being tested divided by time.

Both front and back of the fabric was tested, meaning that the side which was exposed to “wind”. When the front side of the fabric was tested it was this side that was measured for air permeability and vice versa.

Figure 1, The air permeability tester machine

2.2.3 Moisture management

The wicking was tested with the wickview machine from James Heal. 0,2 ml of distilled water was released on the test specimen and each test had a duration time of 300 seconds. Each fabric sample consisted of a circular test specimen with a diameter of approximately 150 mm. The skin side of the fabric sample should be facing up when inserted into the machine. Each fabric sample was tested one time with the mesh/front side placed up. The machine calculates the area which is becomes wet by taking 2 picture every second on both front and back side of the fabric. This makes it possible to look at the transverse wicking where the liquid moves from one side of the fabric to the other, through the thickness of the fabric. The machine was put in a vertical position as opposed to a horizontal position, the vertical position ensured that the water was dropped on the surface and then travelled down vertically in the fabric thickness.

There is no standard yet for this test method, the instructions from the machine manufacturer were followed, and the results of wicking area for the fabric samples used in this study were compared against each other.

2.2.4 BURST STRENGTH

The burst strength was executed according to SS-EN ISO 13938-2:2019. The method used was the Pneumatic method to determine the bursting strength of the different fabrics used in this study and the machine that was used can be seen in figure 2. The smaller circular clamping ring was chosen and used for all fabrics tested in this study, this made the actual test area 50 cm^2 (79,8 mm in diameter). The fabric that should be tested is placed over an expansive diaphragm which expands the fabric until burst by air pressure being applied. The test specimens were circular fabric pieces of sizes approximately 15 cm in diameter. The test specimens were clamped with a pressure of 450 Pa and only one test specimen of each fabric was tested in this test.

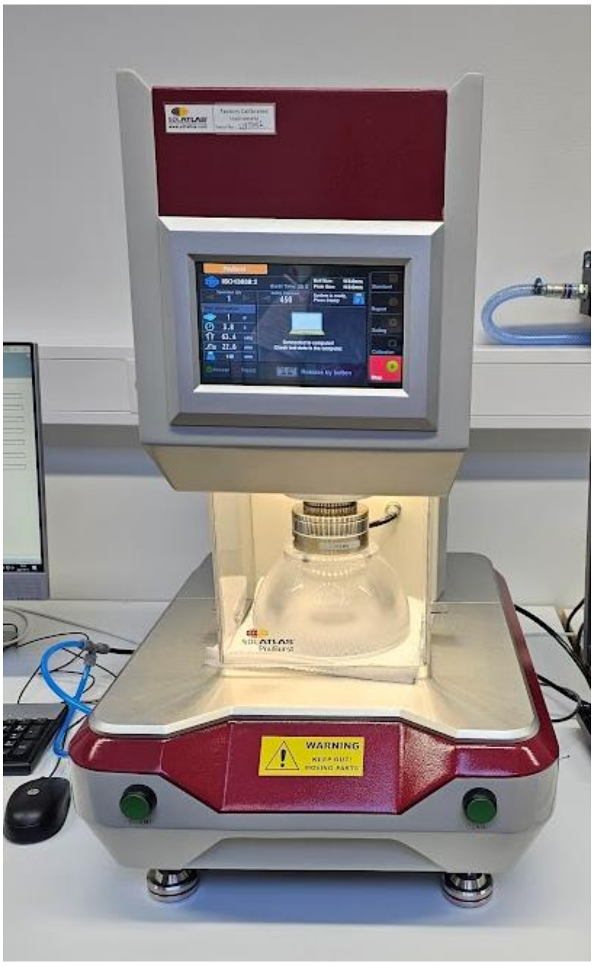


FIGURE 2, THE MACHINE USED FOR THE BURST STRENGTH TESTING WHILE IT IS BEING IN USE.

2.2.5 BITE TEST

The bite test was performed with equipment in accordance with SS-EN 1888-1:2019, which specifies the measurement of the instrument emulating a child's teeth, this can be seen in figure 3 and 4. The test instrument teeth are clamped on to the fabrics surface and then pulled. The fabric should be able to withstand being pulled by 50 N for a total of 10 seconds. If the surface of the fabric is broken by the test and the structure and material underneath the surface level is exposed the test should be performed again on the exposed material.

FIGURE 3, THE INSTRUMENT USED FOR THE BITE TEST WHICH CONSISTS OF A FORCE GAUGE METER AND THE DETACHABLE METAL TEETH.

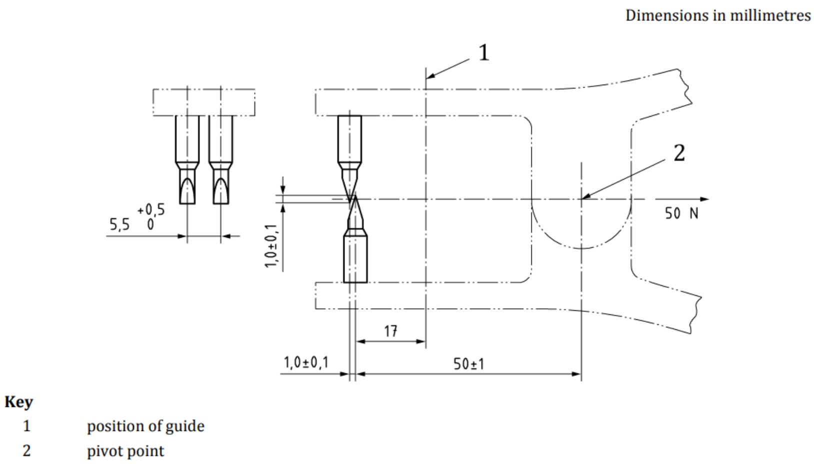


FIGURE 4, AN EXPLANATION OF THE BITE TESTER AND ITS MEASUREMENTS TAKEN FROM SS-EN 1888-1:2019.

2.2.6 PULLING TEST

A small parts cylinder in accordance with SS-EN 13209-1:2022 was used for checking the size of any parts, fabric pieces or threads that may be pulled out during the test.

The pulling test is performed by fastening a clamp on the fabrics surface which is visually represented in figure 5. This clamp is the attached to a force gauge meter that shows with which force the fabric is being pulled. The fabric should be able to withstand getting pulled with 90 N to pass the test. If any small parts such as small threads get pulled out it is considered a failure. If the “small part” that is pulled off is greater than what can fit in the small parts cylinder the fabric can be considered to pass the test. If the surface of the fabrics surface gets damaged by the test but no loose strings or threads are pulled out the fabric can in this case also be considered to pass the test.

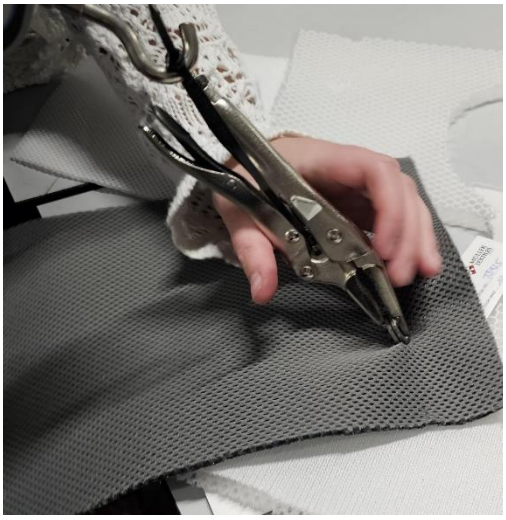


FIGURE 5, THE CLAMPING OF A FABRIC WHILE THE PULLING TEST WAS PERFORMED.

2.2.7 FINGER PROBE TEST

The equipment for the finger probe test was in accordance with standard SS-EN 13209-1:2022 specifically for mesh fabrics, the probe can be seen in figure 6. The tests were performed on the fabric only and not on a finished assembled product such as stated in the standard. The probe was attached to the force gauge meter and the probe was pushed against the mesh with a force of 35 N. If the fabric passes the second line on the probe the fabric is a failure in this test. If the fabric does not pass the second line on the probe, the fabric passes the test and can be considered safe for use.

FIGURE 6, THE PROBE USED FOR THE FINGER PROBE TEST.

2.2.8 STATISTICAL ANALYSIS

An ANOVA was performed on the results of each fabric sample from the air permeability tester to compare the front and back side of each sample. This was to see if there is any significant difference between which side of the sample is used as the skin side and the other side which is then exposed to wind or air permeation.

2.2.9 PROCAD WARPKNIT

ProCad was used to visually create a 3D simulated spacer fabric construction. The program is specifically made for warp knitted and therefore a warp knitted construction was created with the use of this software.

3. RESULTS

3.1 Thickness

The thickness of WK1, WK2, WK3 and WK4 was already known from the producer of the fabrics, and they were therefore not tested for thickness nor calculated a mean value of thickness.

The thicknesses already known are illustrated in table 3. The thicknesses that were measured for the rest of the fabric samples can be seen in table 4.

Table 3, thicknesses of the fabric samples which were already known from the producer

Fabric	Thickness (mm)
WK1	6,5
WK2	13
WK3	15
WK4	10

Table 4, 5 measurements of thickness for each fabric sample and the calculated arithmetic mean value of the 5 measurements for each fabric sample.

Fabric	measurement 1 (mm)	measurement 2 (mm)	measurement 3 (mm)	measurement 4 (mm)	measurement 5 (mm)	Mean value (mm)
WK5	3,083	3,112	3,089	3,088	3,089	3,0922
WK6	3,543	3,453	3,515	3,482	3,558	3,5102
CK1	3,617	3,6	3,627	3,601	3,618	3,6126
CK2	2,942	2,936	2,945	2,95	2,952	2,945
CK3	2,974	2,944	2,978	2,998	3,076	2,994
CK4	3,129	3,118	3,116	3,125	3,17	3,1316
RF	5,024	5,019	5,048	4,997	5,026	5,0228

3.2 Air permeability

From the air permeability testing it can be seen that all fabric samples except CK2 and CK3 have better air permeability compared to RF for both front and back values. In table 5 the three fabric samples which had the highest results in air permeability were WK3 and WK4, and WK5. The mean value for each fabric sample is calculated from ten measurements that was made for both front and back values. A higher value represents better air permeability and more air flow through the fabric. The front side of the fabric presented higher values for all fabric samples except for WK3, WK4 and CK1 which had higher air permeability values of measurements for the back of the fabric.

From the ANOVA that was calculated for each fabric to compare and see if there is any difference on the air permeability depending on which side of the fabric that is exposed to the wind. The ANOVA shows that there is statistically significant difference between the front and back side of the following fabric samples: WK3, WK4, WK6, CK1, CK4 and RF. The full calculations of ANOVA can be found in appendix. In figure 7 it can be seen that the interval distance for fabric sample WK3 when comparing front and back is very small. Fabric sample WK4 has the biggest interval distance between front and back which can be seen in figure 8. Fabric sample CK1 also has a very short interval distance between the front and back and can be seen in figure 9. The full calculations for all fabric samples can be found in the appendix.

TABLE 5, THE MEAN VALUES OF AIR PERMEABILITY TESTING FOR ALL FABRIC SAMPLES BOTH FRONT AND BACK.

Fabric	Mean value mm/s, front	Mean value mm/s, back	Significantly different (Front vs Back)
WK1	3822	3788	No
WK2	3993	3981	No
WK3	4862	5330	Yes
WK4	5396	6508	Yes
WK5	4699	4563	No
WK6	3688	3364	Yes
CK1	3255	3342	Yes
CK2	544,9	538,9	No
CK3	451,4	424,8	No
CK4	3268	3028	Yes
RF	1769	1693	Yes

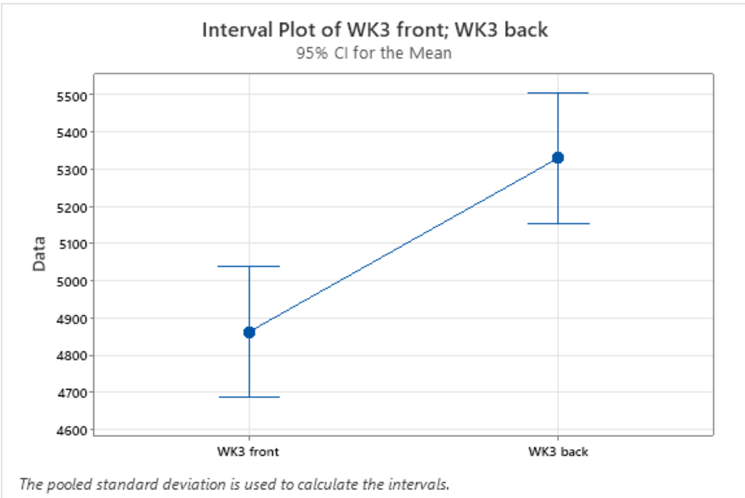


FIGURE 7, INTERVAL PLOT OF FABRIC SAMPLE WK3 FROM ANOVA. THE INTERVALS OF FRONT AND BACK DO NOT OVERLAP WHICH MEANS THAT THEY ARE SIGNIFICANTLY DIFFERENT.

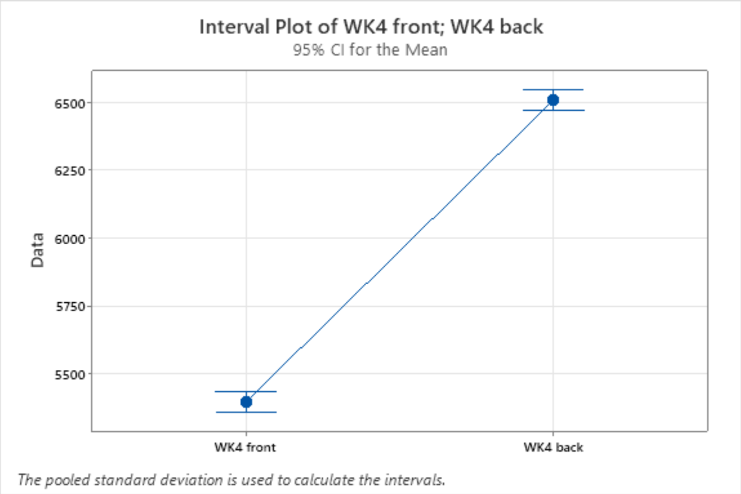


FIGURE 8, INTERVAL PLOT OF FABRIC SAMPLE WK4 FROM ANOVA. THE INTERVALS OF FRONT AND BACK DO NOT OVERLAP WHICH MEANS THAT THEY ARE SIGNIFICANTLY DIFFERENT.

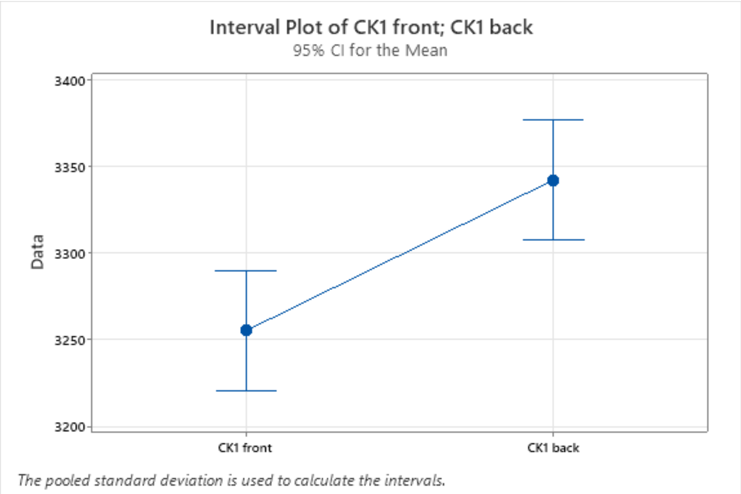


FIGURE 9, INTERVAL PLOT OF FABRIC SAMPLE CK1 FROM ANOVA. THE INTERVALS OF FRONT AND BACK DO NOT OVERLAP WHICH MEANS THAT THEY ARE SIGNIFICANTLY DIFFERENT.

3.3 BURST STRENGTH

The fabric samples that resulted in higher burst strength values compared to RF are WK2, WK6, CK2 and CK4. The fabric sample which had the highest burst strength is WK4 with a pressure of 868 kPa at burst compared to RF which had a value of 494 kPa at burst. The fabric sample which had the lowest value of all samples was WK5 which had a pressure value of 334,3 kPa at burst, these results are presented in table 6.

TABLE 6, THE PRESSURE, DISTENSION AND TIME AT BURST IS GIVEN FOR EACH FABRIC SAMPLE. THE FABRIC SAMPLES HIGHLIGHTED IN GREEN ARE THE FABRICS THAT HAVE A HIGHER BURSTING STRENGTH THAN RF

Fabric	Pressure (kPa)	Distension (mm)	Time (s)

WK1	364,1	37,5	13,2
WK2	513,2	31,7	26,0
WK3	411,6	30,7	23,4
WK4	373,5	34,9	21,7
WK5	334,3	35,2	12,3
WK6	569,1	27,8	26,8
CK1	405,3	30,5	23,1
CK2	518,5	57	26,2
CK3	480,1	51,7	25,6
CK4	868	33	31,1
RF	494	37,9	25,7

3.4 Bite test

RF is the fabric from the already existing product and was not tested in the bite test since the product has already passed these tests done by the company producing the product.

In table 7 the results from the bite test can be seen and all fabric samples were able to pass the test except for WK1. The bite test was first performed on WK1 which resulted in a broken surface where the spacer yarns were exposed, the test was then performed again on the broken fabric which exposed the spacer yarn. This resulted in yarns breaking of which could fit in the small parts tube and was therefore evaluated to fail this test.

Table 7, results of bite test done on 10 fabrics. All fabrics passed the test except for WK1 which failed the test.

Fabric	Bite test
WK1	Fail
WK2	Pass
WK3	Pass
WK4	Pass
WK5	Pass
WK6	Pass
CK1	Pass
CK2	Pass
CK3	Pass
CK4	Pass

3.5 Pulling test

RF is the fabric from the already existing product and was not tested in the pulling test since the product has already passed these tests done by the company producing the product.

The fabric samples that passed the pulling test are: WK1, WK2, WK4, WK6, CK3 and CK4. The fabric samples that failed this test are WK3, WK5, CK1 and CK2, these are constructions of both warp and weft knitted fabrics and these results are given in table 8.

Table 8, the results presented in the table show either a passing or failing grade for the tested fabric samples. The fabrics that failed the test have been highlighted with red.

Fabric	Pulling test
WK1	Pass
WK2	Pass
WK3	Fail
WK4	Pass
WK5	Fail
WK6	Pass
CK1	Fail
CK2	Fail
CK3	Pass
CK4	Pass

3.6 Finger probe test

According to table 9, all fabrics which consisted of a mesh construction passed this test. The fabric samples CK2, CK3, CK4 and RF does not consist of a mesh construction and did therefore not need to be tested for this specific property.

Table 9, results from the finger probe testing where the fabric sample could either pass or fail the test.

Fabric	Finger probe test, for mesh fabric
WK1	Pass
WK2	Pass
WK3	Pass
WK4	Pass
WK5	Pass
WK6	Pass
CK1	Pass
CK2	Not mesh
CK3	Not mesh
CK4	Not mesh
RF	Not mesh

3.7 Moisture management

The water is dropped on the side of the fabric that is inserted up, as the skin side, and the face side of the fabric is facing down in the machine for the wicking test. The fabric samples with the biggest area on the skin side are CK4, WK5 and WK3 which can be seen in table 10. The fabric samples which had the biggest area on the face side were WK5, WK2 and CK4. The fabric samples that hade the smallest areas of both skin and face side were RF and CK1, these had very similar results when looking at the size of the areas.

Table 10, Measurements over the area of wicking for each fabric sample.

Fabric	Time (s)	Area face side (mm^2)	Area skin side (mm^2)
WK1	300	3850,0	3733,04
WK2	300	4313,79	4079,97
WK3	300	3888,39	4656,49
WK4	300	4175,44	4571,98
WK5	300	5172,53	4819,11
WK6	300	4295,69	3547,60
CK1	300	0,00	50,37
CK2	300	3078,19	2628,11
CK3	300	471,29	428,62
CK4	300	4549,87	5933,10
RF	300	0,00	46,97

3.8 Procad warpknit

The construction of the 3D simulated fabric is shown in figures 20, 21 and 22. How the construction of the fabric is made is represented in figures 18 and 19.

The chain notations of the guide bars (GB) are as following:

GB1: 1-0-1-1/1-2-1-1/1-0-1-1/1-2-1-1/1-0-1-1/1-2-1-1/1-0-1-1/1-2-1-1

GB2: 2-3-2-2/2-1-2-2/2-3-2-2/2-1-2-2/2-3-2-2/2-1-2-2/2-3-2-2/2-1-2-2

GB3: (4-5-3-2/1-0-2-3) x4

GB4: (4-5-3-2/1-0-2-3) x4

GB5: 2-2-1-0/1-1-1-2/1-1-1-0/1-1-1-2/3-3-3-4/3-3-3-2/3-3-3-4/3-3-3-2

GB6: 4-4-4-5/4-4-4-3/4-4-4-5/4-4-4-3/4-4-2-1/2-2-2-3/2-2-2-1/2-2-2-3

GB1 and GB2 creates the back of the fabric, GB3 and GB4 is the spacer yarn and GB5 and GB6 is producing the mesh of the spacer fabric.

GB1 and GB2 is a 1 and 1 lapping movement (tricot), thereby creating a fabric layer without mesh and a visual representation of this can be seen in figure 21 and 22.

The spacer yarn, GB3 and GB4, create loops on both front and back side of the fabric and thus connecting the layers. The construction of GB5 and GB6 is creating a mesh structure which has a hexagonal type of shape where the holes are 4 stitches long. The guide bars which are creating the mesh structure should be threaded 3 in and 1 out instead of being fully threaded like the rest of the guide bars.

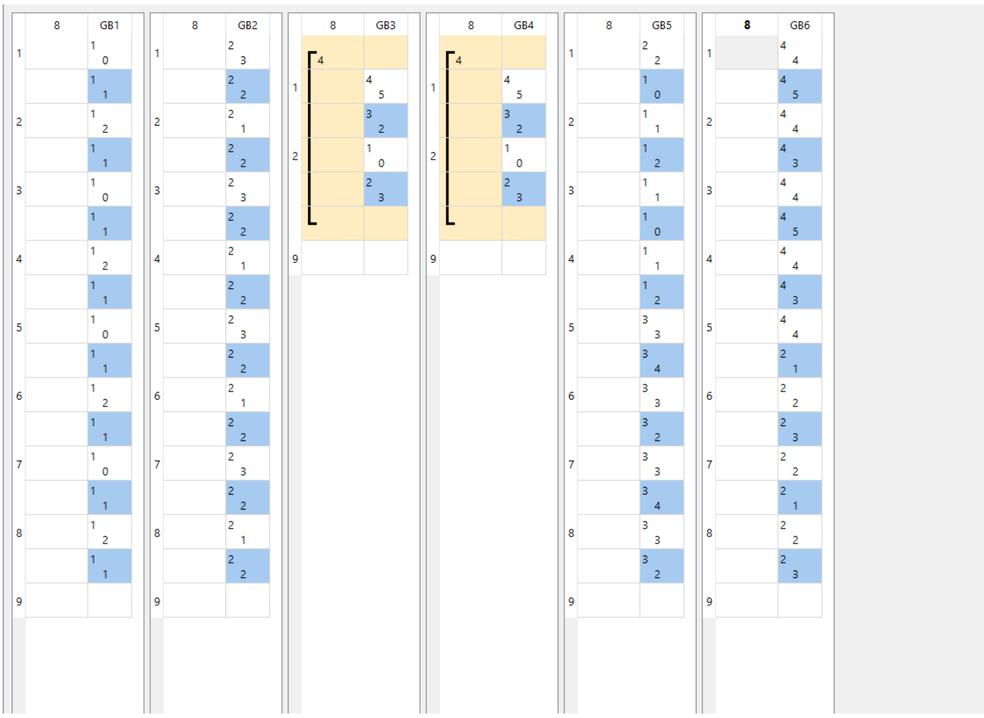


Figure 7, The chain notations for the 3D simulated spacer fabric made on 6 bars.

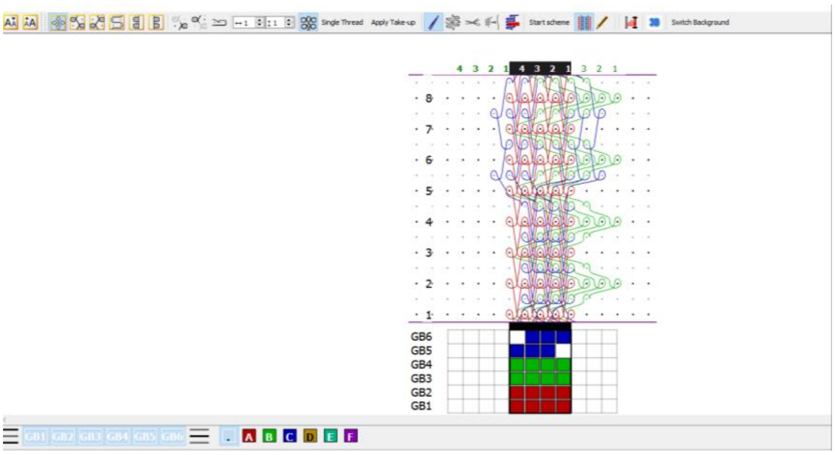


Figure 8, the lapping of six different bars where bar number 5 and 6 are threaded 3 in and 1 out. The rest of the bars are all fully threaded.

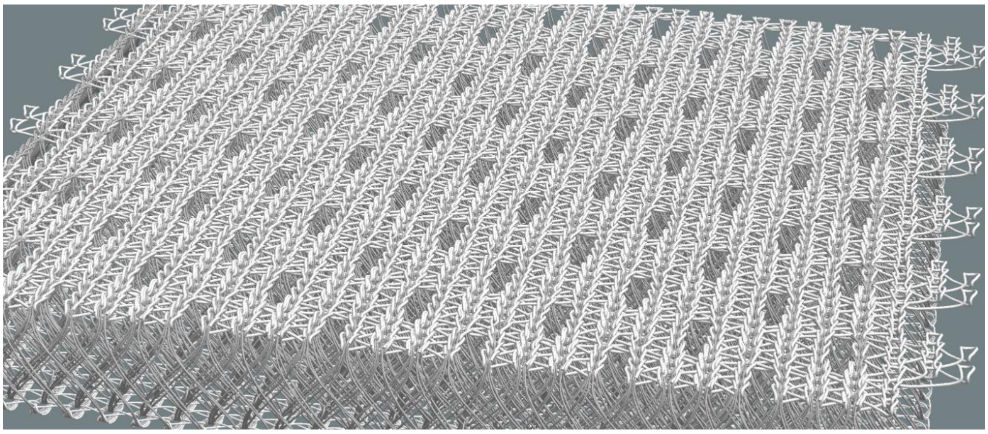


FIGURE 9, 3D SIMULATION OF A POTENTIAL FABRIC STRUCTURE WHERE THE FRONT OF THE FABRIC, THE MESH, IS FACING UP.

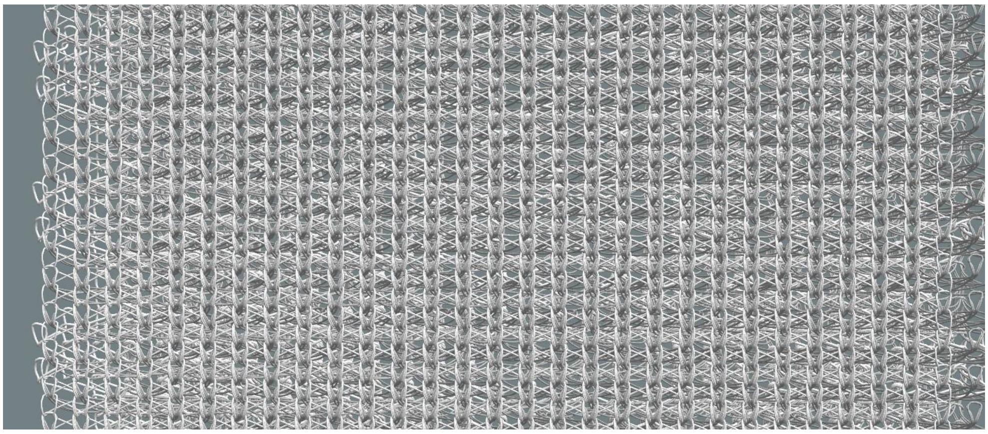


FIGURE 10, 3D SIMULATION OF A POTENTIAL FABRIC STRUCTURE SHOWING THE BACK SIDE OF THE STRUCTURE.

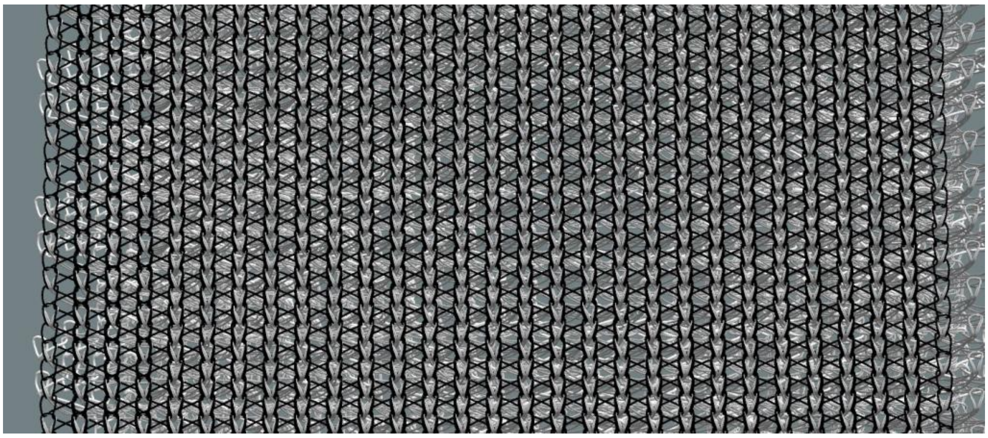


FIGURE 11, SHOWING THE SAME STRUCTURE OF THE BACK OF THE SIMULATED FABRIC AS IN FIGURE 21 BUT BLACK YARN WAS USED FOR A CLEARER VISUAL REPRESENTATION OF THE CONSTRUCTION.

4. Discussion

4.1 Air permeability

Out of the fabric samples that showed a statistically significant difference in whether the air permeability is applied on the front compared to the back of the fabric, were three fabric samples found to have higher air permeability on the fabrics back side. These fabrics were WK3, WK4 and CK1 which can be seen in table 5. The rest of the fabric samples performed better and resulted with higher air permeability on the front side of the fabric. The samples that had the highest air permeability overall were WK2, WK3, WK4 and WK5.

When comparing the air permeability of WK1 and WK5, which are very similar in their construction, mesh size as well as an approximated gauge of 20 for both fabric samples, the difference in air permeability could be explained by the thickness. As can be seen in table 5, WK1 has an air permeability value of 3822 while WK5 has a value of 4699. This means that fabric sample WK5 has higher air permeability, WK1 has a thickness of 6,5 mm while WK5 has a thickness of 3,09 mm. This shows that the thicknessis a relevant property that will affect the air permeability of the spacer fabric, this is also supported by previous studies such as Gokarneshan 2015).

When the air permeability testing was performed it is possible that edge leakage may have occurred and could therefore make the test results, comparing the front and back sides of the fabric samples, not as accurate. Edge leakage tried to be minimized and excluded altogether, this can however not be 100% certain due to human errors being possible when handling and conducting the testing.

4.2 Burst strength

Pneumatic bursting strength was chosen over hydraulic because of limited access to fabric as well as when the hydraulic burst method was tested on one of the fabrics, the fabric was pulled and broke off in the wrong direction (not along the vertical middle line of the fabric sample).

The bursting strength was also tested to compare the strength of the fabric samples to the RF to see what fabrics are stronger and may potentially be possible to be used in the product without having a back lining since a back lining would weaken the air permeability of the fabrics. If the fabric is strong enough to be able to be used without a back lining also depends on how the product is constructed and how straps and other parts are fastened and suspended. These are however not investigated in this study and the focus was therefore solely on comparing the burst strength of the different fabrics.

The fabric samples that performed better than RF in the burst strength were WK2, WK6, CK2 and CK4. These four fabric samples are then considered to have sufficient strength for the purpose of the product. These four fabrics have no mesh or a relatively small mesh structure where the shape of the holes is longer compared to the width of the holes, the holes of the mesh structure is also not as round as other fabrics. The fabric sample CK3 was also close in strength to RF but did not have a burst strength which was quite high enough. This might be explained by the gauge of the fabric, CK3 has a gauge of 32 N.P.I. The CK fabric samples that had a burst strength which was higher than RF had a gauge of 24 and 28 N.P.I.

The bursting strength test should have been done with 10 test subjects of each fabric type instead of 1 which was used in this study because of a lack of some materials. This could potentially lead to miscalculations and not correct values of the bursting strength since possible outliers for an example will not be shown when only one test subject has been tested. This means that the one value that is acquired from the test may be incorrect and could be an outlier which would then affect the results of the study. The probability of this being the case is however small and the assumption that the results are correct has been made.

4.3 Bite test

The only fabric sample that did not pass the bite test was WK1. One reason for this could be because this fabric had the next to lowest burst strength which can be seen in table 5. Fabric sample WK1 is the thinnest out of the warp knitted fabric samples but it is also thicker than all the other fabrics which are not warp knitted. One reason for this might be because the yarn or the spacer yarn in this fabric is thinner and therefore makes the fabric weaker. It could also be because of a human error of this method since the equipment is manually fastened to the surface of the fabric and pulled by hand. Depending on how the metal teeth are fastened to the fabric the result might differ and could potentially fluctuate.

4.4 Pulling test

From the pulling test it can be seen that both warp and weft knitted fabric constructions fail the test which is illustrated in table 6. From this it can be concluded that whether the fabric is warp or weft knitted is not the main contributing factor to how well a fabric will perform in this test. What can however be said about the weft knitted fabrics that failed the test is that the yarn pieces that were able to get pulled out were longer than those of the warp knitted fabrics. This is because of how the yarn runs in the construction. When yarn breaks in the weft knitted fabric, it is more susceptible to pull out one row of loops horizontally in a knitted construction, this is different from warp knitted fabrics since the loops are created simultaneously with many yarn feeders at the same time interconnecting with each other. This could mean that a warp knitted structure may be considered safer when it comes to usage in products for children because long pieces of yarn could be a cause of danger of strangulation if pulled out from the fabric.

These test methods are very dependent on how the equipment is clamped on to the fabric and can therefore have human errors in the results. Each person that is performing the test might attach the clamps on the fabric differently. The clamp may also not always be able to be clamped onto the fabric the same exact way because of the construction being different and differences in fabric thickness can make it difficult to only grab the very outer surface of the spacer fabric. When very little fabric on the surface only is attached to the clamps it will result in more force on less fabric and threads. This means that the fabric has to threads of the fabric has to be able to endure more pulling force to pass the test compared to when more fabric is clamped during the test which results in the pulling force being distributed more evenly through a higher number of threads that are interconnected in the fabric construction.

Another thing that should be considered about this test method is how well it represents reality and real-world situations and how likely it is for a baby to get a grip on the fabrics surface and pull with a force of 90 N. It may not be accurately representative of reality but at the same time it is always good to have heightened security for products that are intended to be used with children.

4.5 Finger probe test

All the fabric samples in this study passed the requirement of the finger probe test which can be seen table 8. Only the fabric samples consisting of a mesh construction was tested. The reason all of the mesh fabrics passed this test is because the mesh construction is only existent on the front of the fabric and the back of the fabric does not consist of any holes or mesh surfaces. This means that a mesh fabric construction can be used in products for babies and children if it has on side without the mesh. In this case the size of the mesh holes are not constricted to the size of the probe used in the test since the probe can’t go all the way through the fabric and will therefore not reach the second line on the probe which would result in a fail of the test. This could however be a problem if a very thick spacer fabric is considered, though this was not the case in this study.

4.6 Moisture management

The fabric sample RF and CK1 gave very similar results from the moisture management testing when looking at the area of wicking. Both of these fabrics had the smallest area of wicking after 300 seconds where no water was able to wick through and penetrate the fabric from one side to the other. The fabric samples that had the biggest area of wicking on the face side was WK2, WK5, WK6 and CK4. What these fabrics have in common are a mesh structure which is relatively small compared to a mesh fabric such as WK3, except CK4 which is not a mesh fabric. These four fabric samples have gauges ranging from 18-24 N.P.I which can be seen in table 1. When looking at the biggest area on the skin side it was fabric samples WK3, WK4, WK5 and CK4 that had the highest values.

It is good for a fabric to have wicking properties where the water or liquid can travel from the side that the water is dropped on to the other side. This means that fabrics that have a big area on the face side from the test have better wicking properties in the sense of liquid having moved further in the fabric. When the liquid is more spread out over a bigger area it can also dry faster. This relates to previous testing that has been done which showed that when the moisture can spread with more ease in the fabric it will result in the product having higher comfort levels (Kumar & Das 2014).

Something that could have affected the test results and may result in some errors are any remaining finishes or oils that could have been used in processing and production of the fabrics and can have altering effects on wicking properties and the tests.

4.7 Procad warpknit

To combine the results and the properties that have been tested in this study, the finger probe test will first be considered. In this test all of the fabric samples passed and can therefore be considered safe to be used in the specified product based on this property. Next the test results from the bite test will be evaluated and only fabric sample WK1 failed this test. Therefore, the conclusion can be made that fabric sample WK1 is not suitable to use in the baby product based on safety reasons. The results from the burst strength test will then be examined. Four different fabric samples performed better or on par with RF in this test and those were WK2, WK6, CK2 and CK4. These are the four fabrics that are now considered to have sufficient performance and safe to be used for the product. The pulling test also needs to be passed for the fabric to be accepted for use in the application. From this test the results show that CK2 failed the pulling test as well as WK3, WK5 and CK1. This leaves a remaining of three fabrics which have passed all of the previous tests: WK2, WK6 and CK4. These three will be compared to each other and RF to further evaluate moisture management and air permeability. These three fabrics were among the ones that had the biggest are in the moisture management test on the face side of the fabric. CK4 and WK2 hade results of bigger areas compared to fabric sample WK6. When comparing these three fabrics in their air permeability properties it can be seen that CK4 had the lowest air permeability of the three while WK2 had the highest air permeability of the three. WK2 was also the only one of the three which did not result in a significantly different result depending on which side that was tested for the air permeability and therefore giving a more homogenous flow of air from both sides.

The 3D simulated fabric was constructed while considering this and the properties of fabric sample WK2 which passed all of the tests for both safety measures as well as optimization of comfort.

The fabric constructed in procad is constructed with a back structure that does not contain any mesh since having a backing that does not have any holes will ensure that the probe test will be passed, and a finger will not be able to get stuck in the mesh fabric. This also means that the final spacer fabric should not be too thick since this could also make the fabric fail the probe test. Although there has not been much research done surrounding multifilament in warp knitted constructions for the spacer yarn other types of spacer fabrics have been knitted with multifilament's such as weft knitted spacer fabrics (Yip & Ng 2008). Because of hinders in relation to accessibility in production of spacer fabric, it was not possible to explore the use and the effect of multifilament spacer yarns on the spacer fabrics properties in this study. Because of this any recommendations regarding what type of yarn that should be used for the spacer layer can't be done based on the current information from this study when it comes to a multifilament yarn.

The thickness of the spacer fabric is recommended to be approximately 10 mm based on the air permeability results that shows that a lower thickness can give a higher air permeability measurement. Because fabric sample WK2 had a thickness of 13 mm a slightly smaller thickness can be chosen to increase the air permeability property. Whether this thickness would give a sufficient cushioning when a multifilament yarn is used for the spacer needs to be further investigated.

5. CONCLUSION

What properties does an outdoor baby stroller seat need to fulfill for the product to be more comfortable for the child?

The properties that should be fulfilled to increase the comfort of the product while still keeping the strength and other properties of the original fabric used in the product is an increase in air permeability compared to the material used in the current product. This means that a spacer fabric needs to have air permeability which exceeds 1769 mm/s. Another property which should also be implemented into the product that results in higher comfort levels for the child is better moisture management because when wicking occurs through the material and the liquid can spread to a larger area, the fabric will dry faster and therefore result in higher comfort.

What is gained in functionality and sustainability by producing the chosen product with spacer fabric?

The properties that are gained in function by producing the product with a spacer fabric instead of the conventional knitted fabric which is heat fused together with PU foam is that the product could potentially be easier to recycle at the end of product life. This is the result if the spacer fabric is constructed of 100% polyester in comparison to PU foam which is fused together with a fabric. The reason for this is because there would not be a need to separate the materials from each other which can be a difficult and expensive process. It is therefore more efficient in terms of recyclability to use fabrics that are 100% polyester since this would be both easier and faster to recycle when no extra separation processes are needed. If a mesh construction is used in the spacer, it would also lead to better air permeability which makes the product more compatible with warm climates. When this is combined with the moisture management property of fabric sample WK2 it will be more comfortable for the child since the sweat will be transferred away from the skin and body and will therefore dry faster in combination with good air permeability and achieve sufficient safety parameters of the fabric, unless a monofilament yarn is used.

How should a spacer fabric be constructed for the product to fulfill the factors of air permeability, moisture management, and safety parameters?

When the surface temperatures of clothing were compared it could be seen that cotton had higher temperatures compared to polyester.

A spacer fabric should therefore be constructed of polyester to have as good wicking properties as possible. The fabric should also have one side of the spacer fabric that does not consist of mesh so that the requirements from the finger probe test will be fulfilled, this can be done with a tricot, 1 and 1 lapping movement. The other side of the spacer fabric should be constructed of a mesh structure to ensure good properties of air permeability. The holes should, however, not be too big since this might be less comfortable against the skin, and also be a danger for the child with the risk of getting their fingers stuck in the holes if the back of the fabric is also constructed of mesh.

The mesh structure recommended for this purpose is a hexagonal mesh which can be assumed to result in good permeability of both water and air flow.

The fabric should also be constructed with a multifilament for the spacer yarn which has previously been accomplished in other studies as weft knitted spacer fabric. There are based on this, possibilities of producing spacer fabric with multifilament but it needs to be further investigated in terms of warp knitted fabrics.

The thickness of the spacer fabric is recommended to be approximately 10 mm if a monofilament yarn is to be used, this is because the thickness in combination with a mesh structure will result in improved air permeability of the product when compared to RF. However, as previously mentioned further investigation is needed to evaluate how a multifilament yarn will affect the fabric and its parameters.

6. Proposal for further studies

6.1 Cross-sectional shape of fiber to improve wicking

When it comes to the wicking properties of the spacer fabrics only polyester is relevant for the purpose of this study since it is the material that Thule wants to use in their product. Therefore, it could also be more relevant to look on the construction of the fabric rather than the actual fibers. There could also be different polyester yarns which have specific cross-sectional shapes to achieve a bigger area for the moisture to be transported by. This is however not included in this study because of lack of information (not allowed to specify) but could be further studied in the future to see the effects on the spacer fabrics surface structure and thickness etc. with the use of yarn with different cross-sectional shapes and their effects on comfort properties. Changing the cross- sectional shape of the yarn is possible when working with monofilament, if it however is not possible to use the monofilaments in this type of product because of guideline CEN/TR 13387-1:2018 the effects of the surface structure of the spacer fabrics could be further investigated and focused on the other parameters affecting moisture management and wicking.

6.2 Objective testing of handle properties

It would also be interesting to test the fabric samples handle objectively which was not possible in this study because of lack of machine equipment and the fabric samples were therefore evaluated subjectively by touch and feeling. This may however not be the most correct scale and can give biased results based on human error and each person may not evaluate or have the same opinions about a specific fabrics softness.

6.3 Explore further possibilities with multifilament as spacer yarn

Because of guideline CEN/TR 13387-1:2018 that suggests no use of monofilament in baby products it would be interesting to further investigate how multifilament can be used to create spacer fabrics that are safer for children.

6.4 Examine washability

A request from Thule was to examine the washability of the spacer fabrics since this is an important property in a baby product.

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Appendix I.

WORKSHEET 2

One-way ANOVA: WK4 front; WK4 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK4 front; WK4 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	6182720	6182720	2060,91	0,000
Error	18	54000	3000		
Total	19	6236720			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
54,7723	99,13%	99,09%	98,93%

Means

Factor	N	Mean	StDev	95% CI
WK4 front	10	5396,0	70,0	(5359,6; 5432,4)
WK4 back	10	6508,0	33,3	(6471,6; 6544,4)

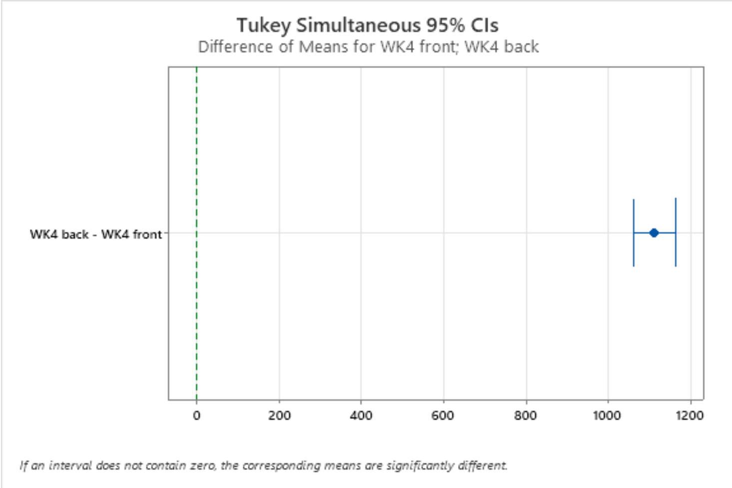
Pooled StDev = 54,7723

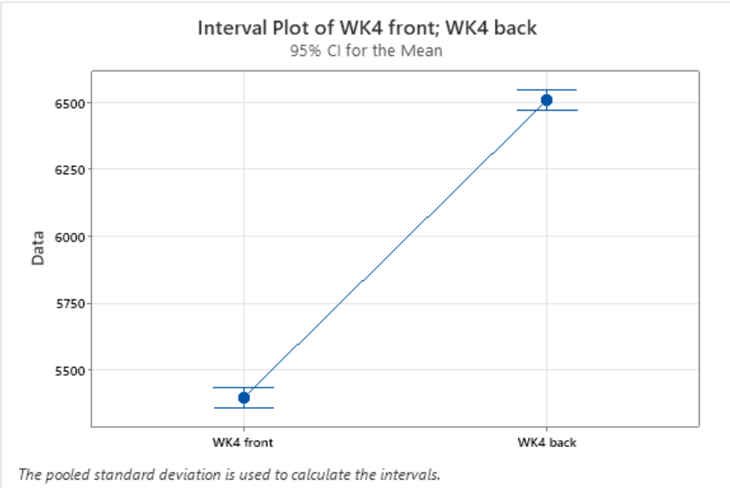
Tukey Pairwise Comparisons

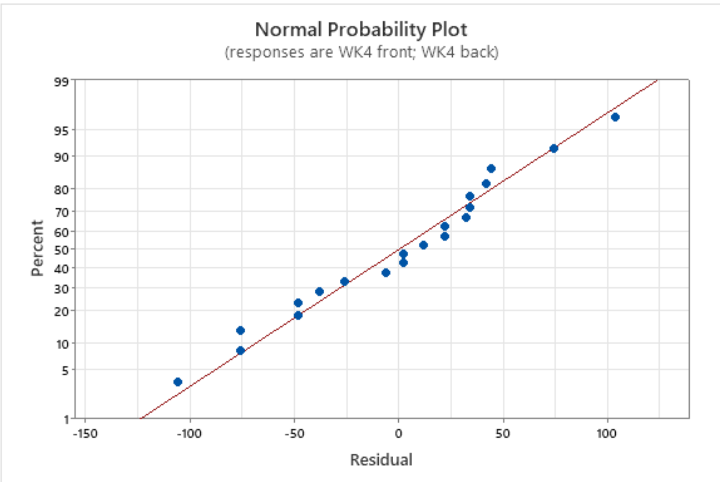
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
WK4 back	10	6508,0	A	
WK4 front	10	5396,0		B

Means that do not share a letter are significantly different.







WORKSHEET 3

One-way ANOVA: WK5 front; WK5 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK5 front; WK5 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	92480	92480	2,69	0,119
Error	18	619500	34417		
Total	19	711980			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
185,517	12,99%	8,16%	0,00%

Means

Factor	N	Mean	StDev	95% CI
WK5 front	10	4699,0	190,9	(4575,7; 4822,3)
WK5 back	10	4563,0	180,0	(4439,7; 4686,3)

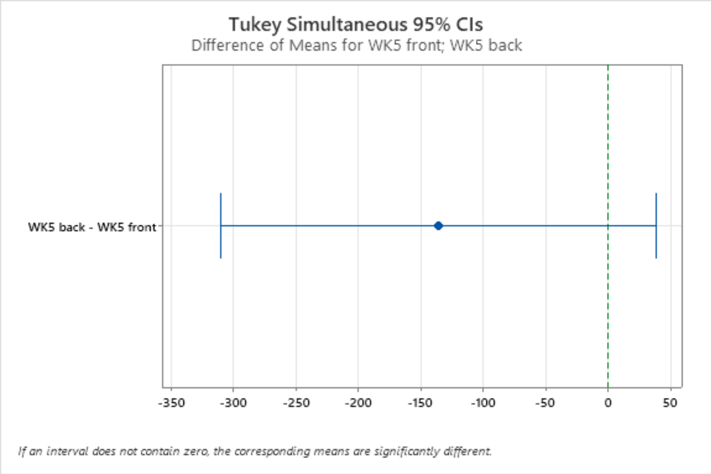
Pooled StDev = 185,517

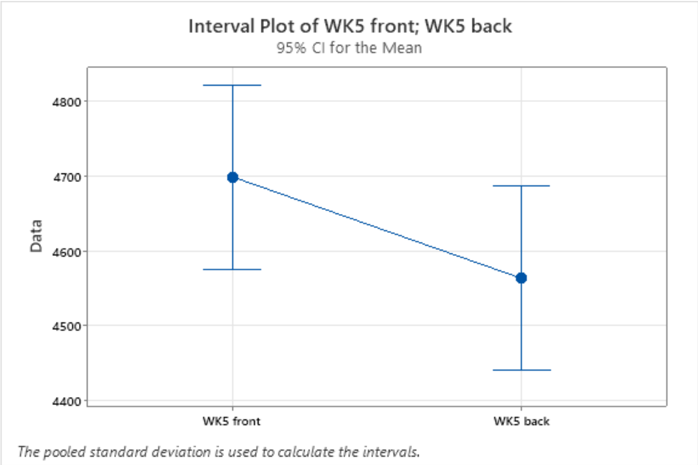
Tukey Pairwise Comparisons

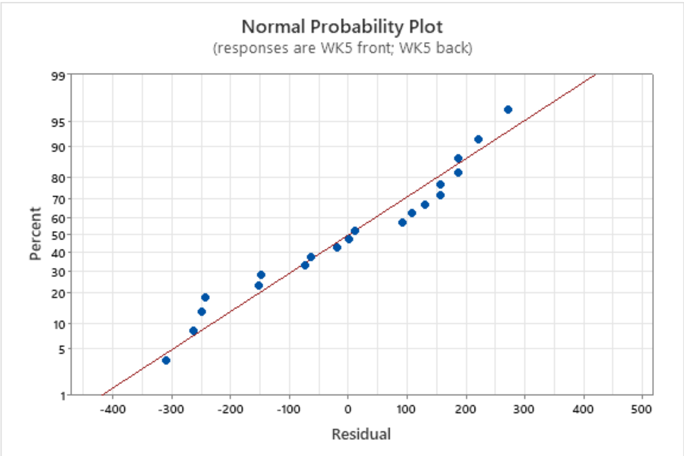
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
WK5 front	10	4699,0	A
WK5 back	10	4563,0	A

Means that do not share a letter are significantly different.







WORKSHEET 4

One-way ANOVA: RF front; RF back

Method

Null hypothesis	All means are equal

Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	RF front; RF back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	28880	28880,0	53,59	0,000
Error	18	9700	538,9		
Total	19	38580			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
23,2140	74,86%	73,46%	68,96%

Means

Factor	N	Mean	StDev	95% CI
RF front	10	1769,00	23,78	(1753,58; 1784,42)
RF back	10	1693,00	22,63	(1677,58; 1708,42)

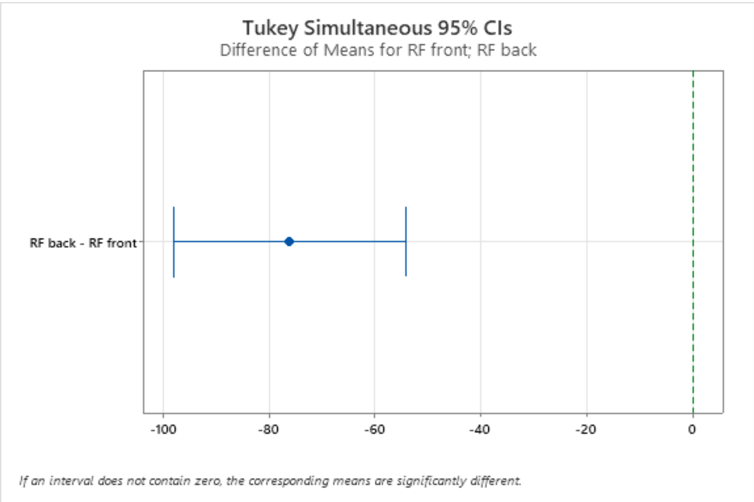
Pooled StDev = 23,2140

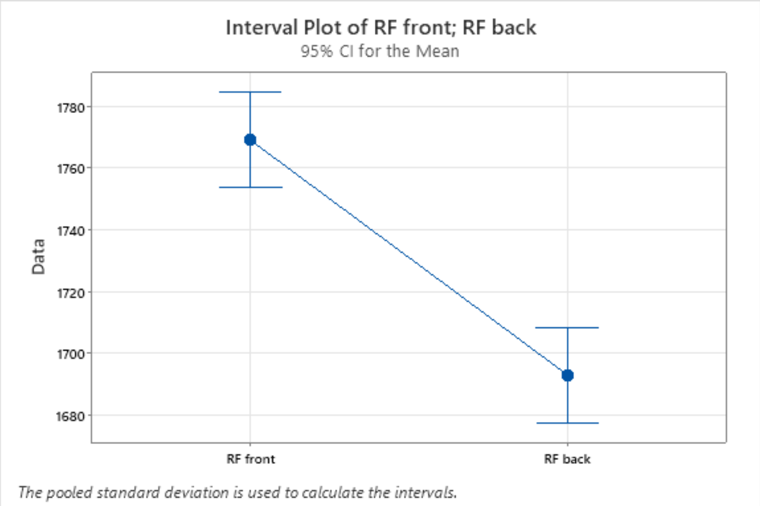
Tukey Pairwise Comparisons

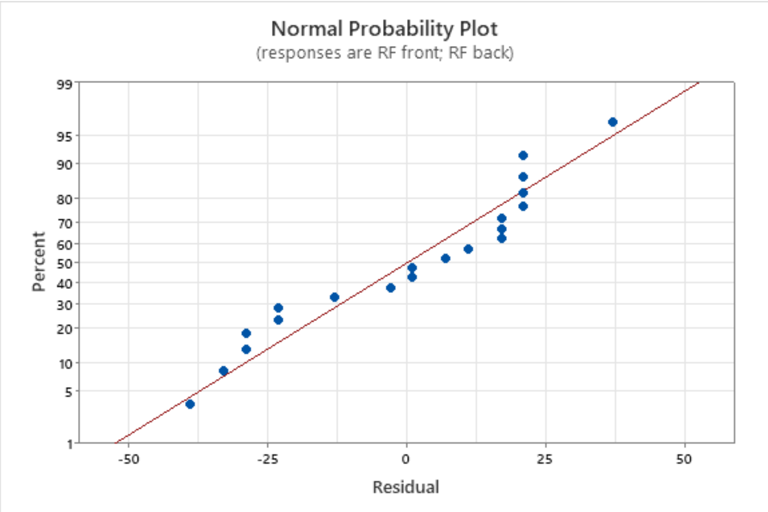
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
RF front	10	1769,00	A	
RF back	10	1693,00		B

Means that do not share a letter are significantly different.







WORKSHEET 5

One-way ANOVA: WK6 front; WK6 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK6 front; WK6 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Factor	1	524880	524880	249,94	0,000
Error	18	37800	2100		
Total	19	562680			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
45,8258	93,28%	92,91%	91,71%

Means

Factor	N	Mean	StDev	95% CI
WK6 front	10	3688,0	45,7	(3657,6; 3718,4)
WK6 back	10	3364,0	46,0	(3333,6; 3394,4)

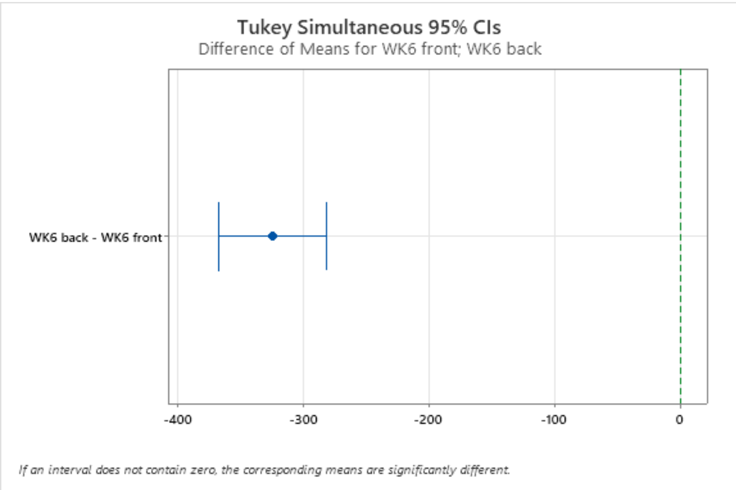
Pooled StDev = 45,8258

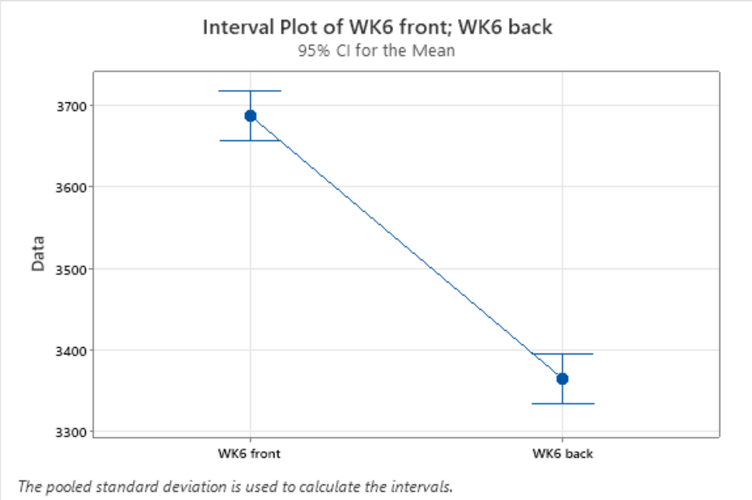
Tukey Pairwise Comparisons

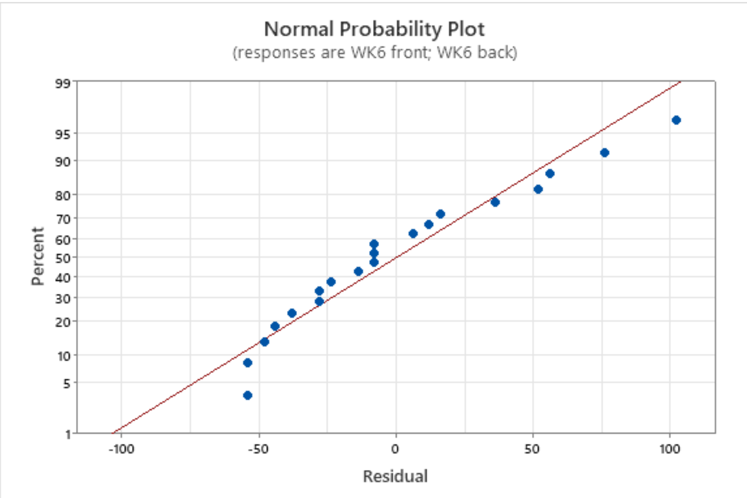
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
WK6 front	10	3688,0	A	
WK6 back	10	3364,0		B

Means that do not share a letter are significantly different.







WORKSHEET 6

One-way ANOVA: WK3 front; WK3 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK3 front; WK3 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Factor	1	1095120	1095120	15,52	0,001
Error	18	1269960	70553		
Total	19	2365080			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
265,619	46,30%	43,32%	33,71%

Means

Factor	N	Mean	StDev	95% CI
WK3 front	10	4862,0	74,5	(4685,5; 5038,5)
WK3 back	10	5330	368	(5154; 5506)

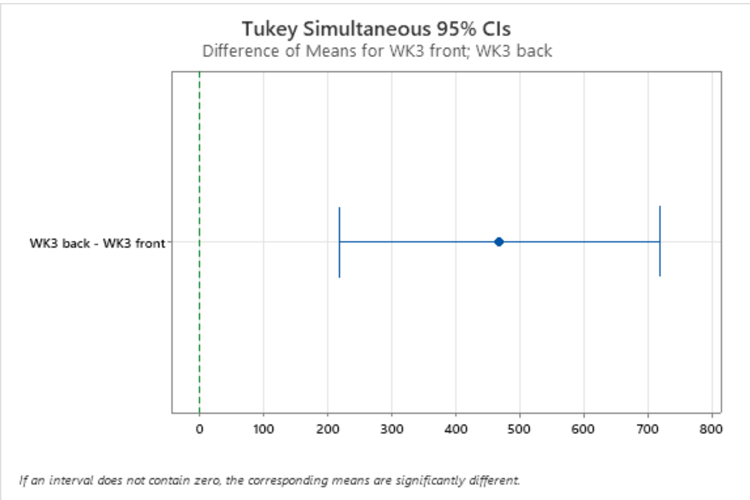
Pooled StDev = 265,619

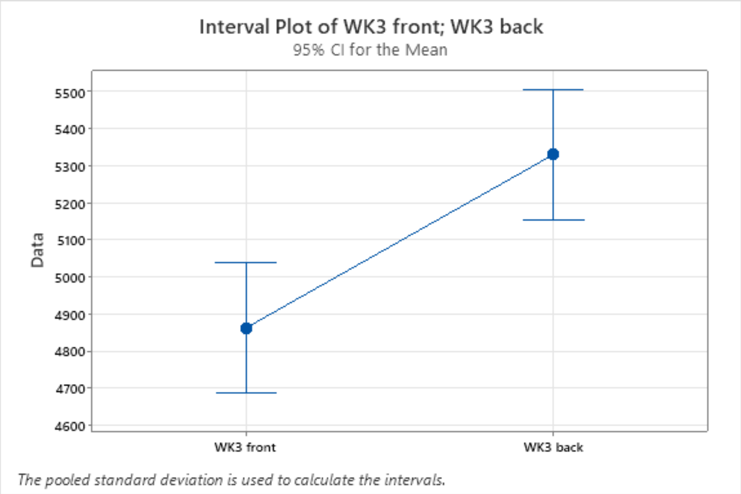
Tukey Pairwise Comparisons

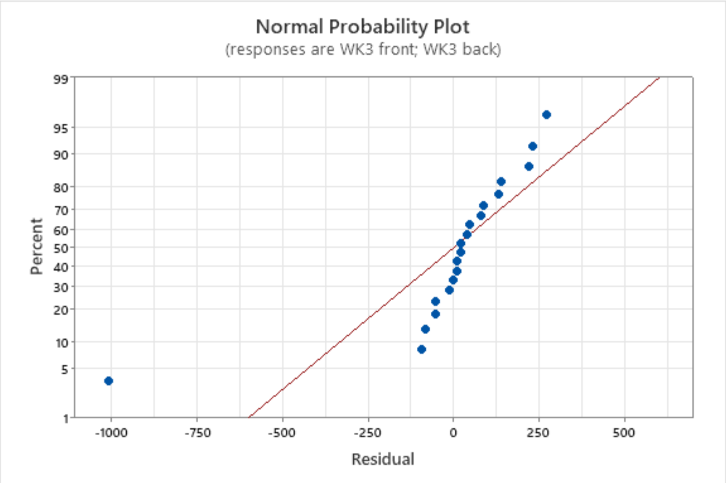
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
WK3 back	10	5330	A	
WK3 front	10	4862,0		B

Means that do not share a letter are significantly different.







WORKSHEET 7

One-way ANOVA: WK2 front; WK2 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK2 front; WK2 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Factor	1	720,0	720,0	0,43	0,519
Error	18	29900,0	1661,1		
Total	19	30620,0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
40,7567	2,35%	0,00%	0,00%

Means

Factor	N	Mean	StDev	95% CI
WK2 front	10	3993,0	40,0	(3965,9; 4020,1)
WK2 back	10	3981,0	41,5	(3953,9; 4008,1)

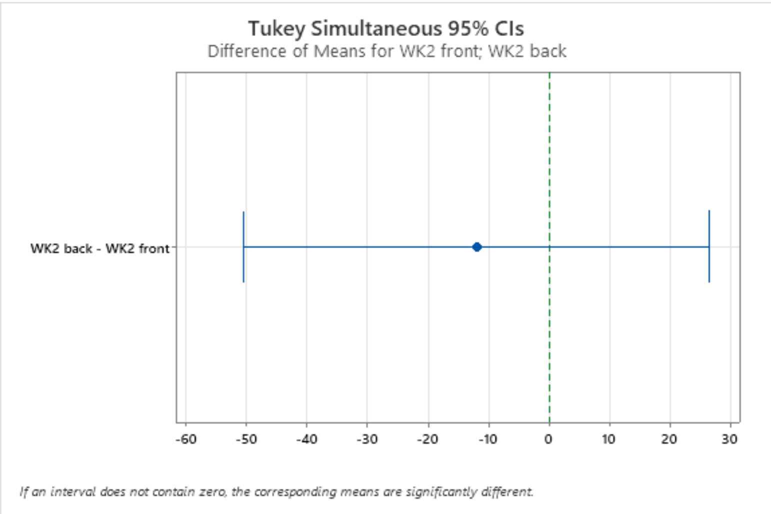
Pooled StDev = 40,7567

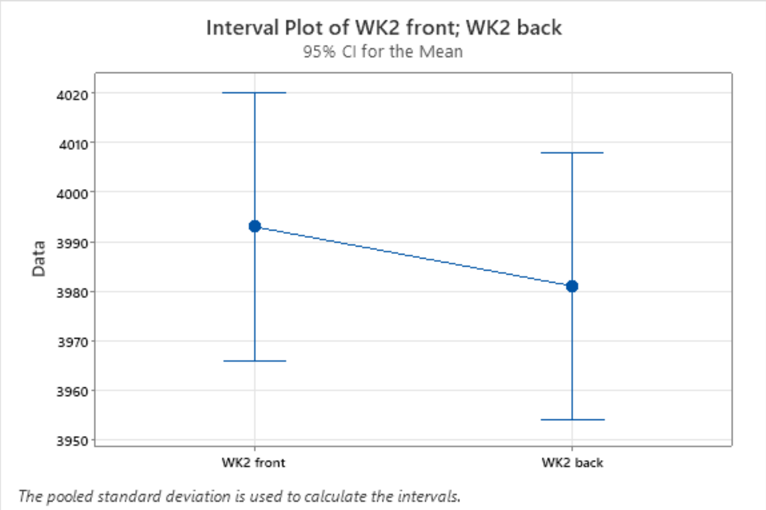
Tukey Pairwise Comparisons

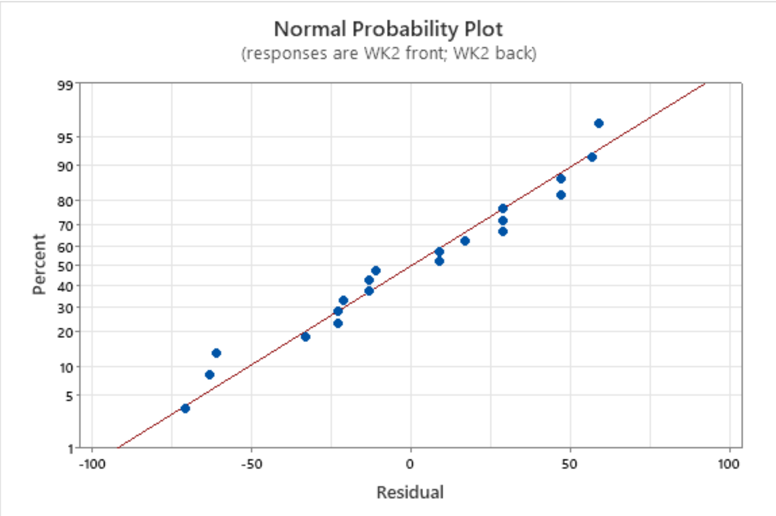
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
WK2 front	10	3993,0	A
WK2 back	10	3981,0	A

Means that do not share a letter are significantly different.







WORKSHEET 8

One-way ANOVA: WK1 front; WK1 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	WK1 front; WK1 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Factor	1	5780	5780	2,65	0,121
Error	18	39320	2184		
Total	19	45100			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
46,7380	12,82%	7,97%	0,00%

Means

Factor	N	Mean	StDev	95% CI
WK1 front	10	3822,0	55,5	(3790,9; 3853,1)
WK1 back	10	3788,0	35,8	(3756,9; 3819,1)

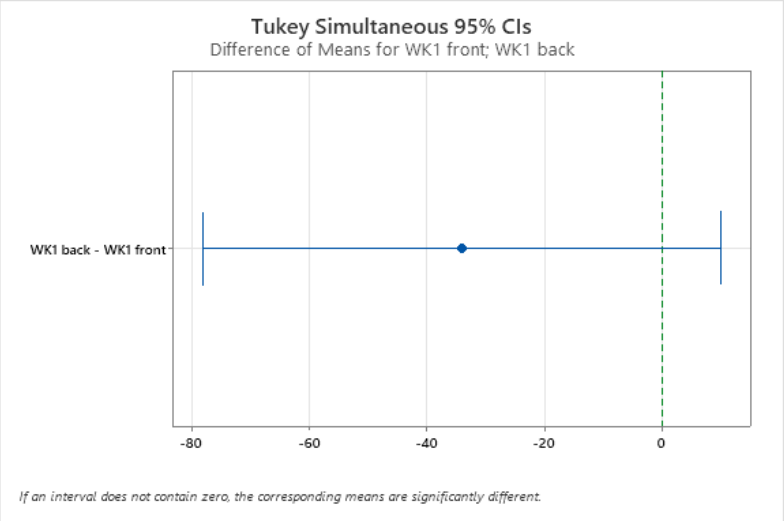
Pooled StDev = 46,7380

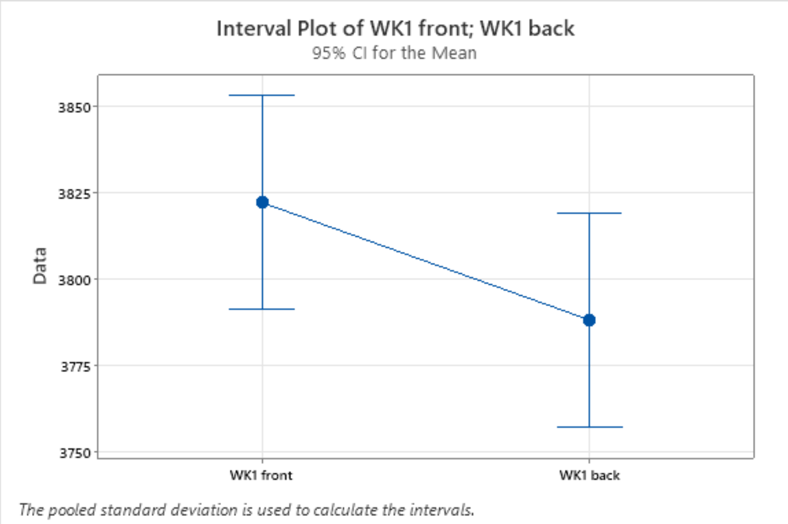
Tukey Pairwise Comparisons

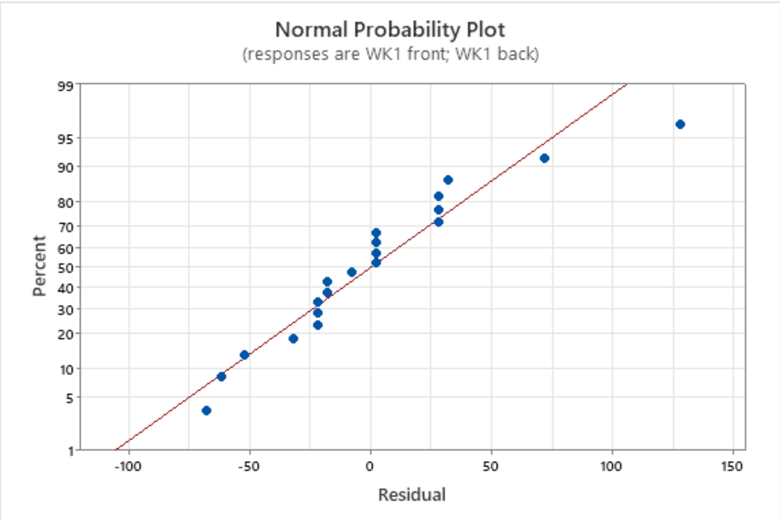
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
WK1 front	10	3822,0	A
WK1 back	10	3788,0	A

Means that do not share a letter are significantly different.







WORKSHEET 9

One-way ANOVA: CK1 front; CK1 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	CK1 front; CK1 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	37845	37845	13,84	0,002
Error	18	49210	2734		
Total	19	87055			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
52,2866	43,47%	40,33%	30,21%

Means

Factor	N	Mean	StDev	95% CI
CK1 front	10	3255,0	60,4	(3220,3; 3289,7)
CK1 back	10	3342,0	42,6	(3307,3; 3376,7)

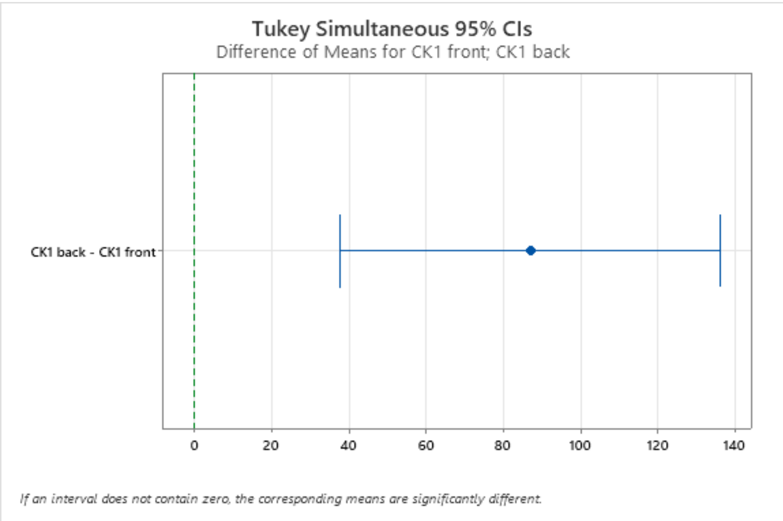
Pooled StDev = 52,2866

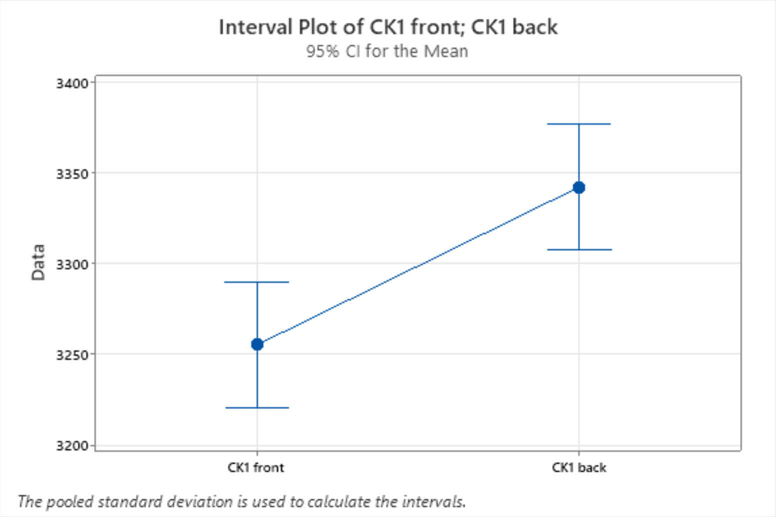
Tukey Pairwise Comparisons

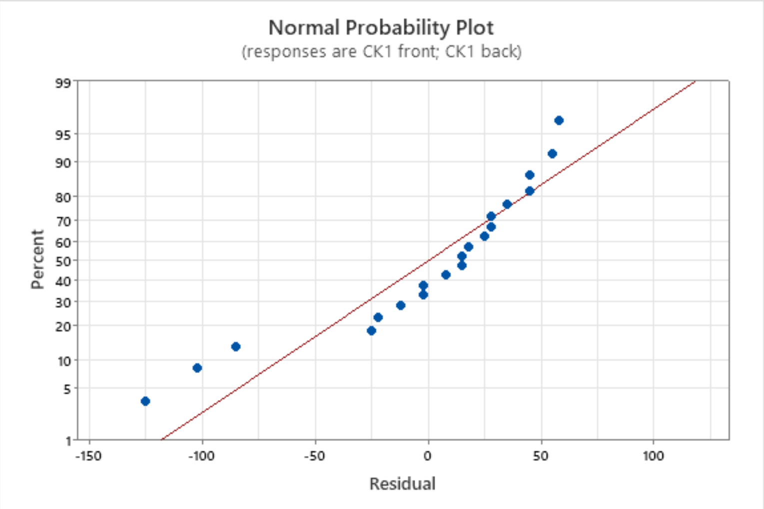
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
CK1 back	10	3342,0	A	
CK1 front	10	3255,0		B

Means that do not share a letter are significantly different.







WORKSHEET 10

One-way ANOVA: CK2 front; CK2 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	CK2 front; CK2 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Factor	1	180,0	180,0	0,34	0,569
Error	18	9619,8	534,4		
Total	19	9799,8			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
23,1178	1,84%	0,00%	0,00%

Means

Factor	N	Mean	StDev	95% CI
CK2 front	10	544,90	24,52	(529,54; 560,26)
CK2 back	10	538,90	21,63	(523,54; 554,26)

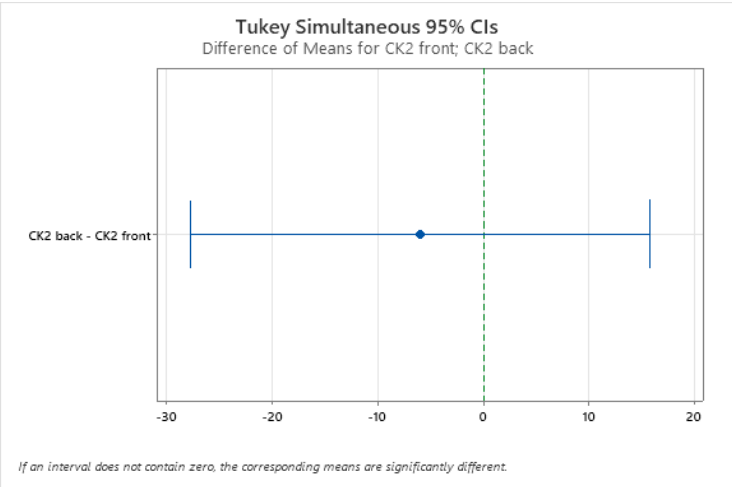
Pooled StDev = 23,1178

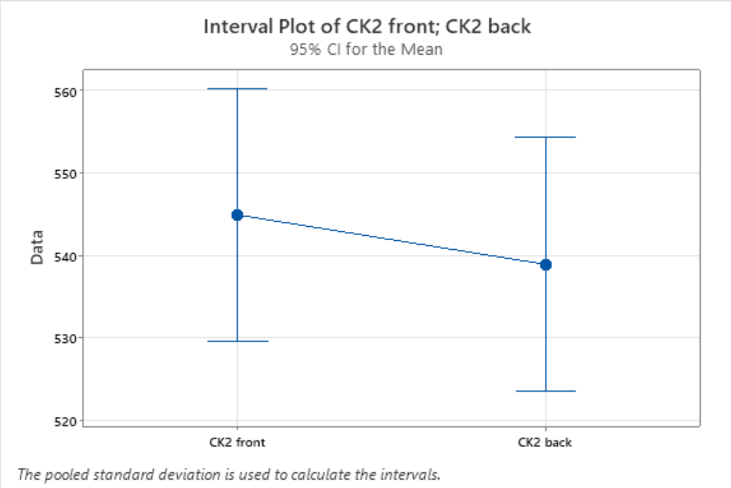
Tukey Pairwise Comparisons

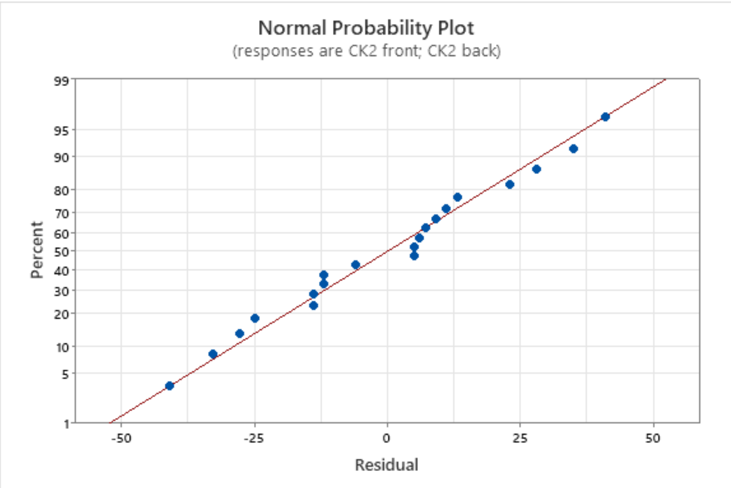
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
CK2 front	10	544,90	A
CK2 back	10	538,90	A

Means that do not share a letter are significantly different.







WORKSHEET 11

One-way ANOVA: CK3 front; CK3 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	CK3 front; CK3 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	3538	3537,8	3,80	0,067

Error	18	16768	931,6
Total	19	20306	

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
30,5214	17,42%	12,83%	0,00%

Means

Factor	N	Mean	StDev	95% CI
CK3 front	10	451,40	25,71	(431,12; 471,68)
CK3 back	10	424,8	34,7	(404,5; 445,1)

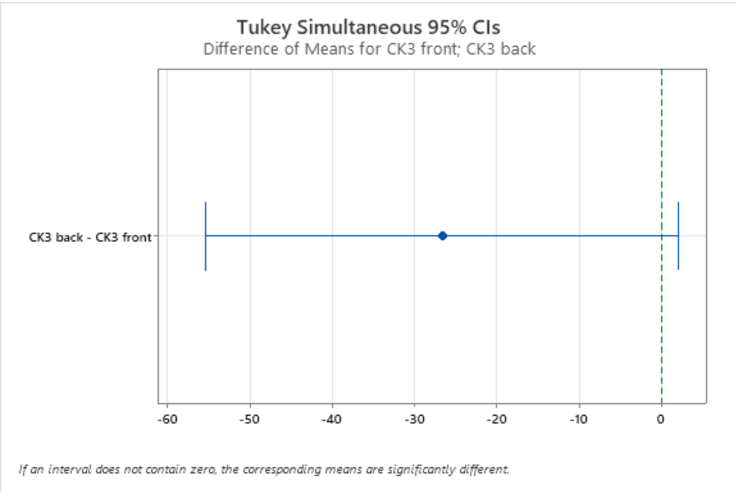
Pooled StDev = 30,5214

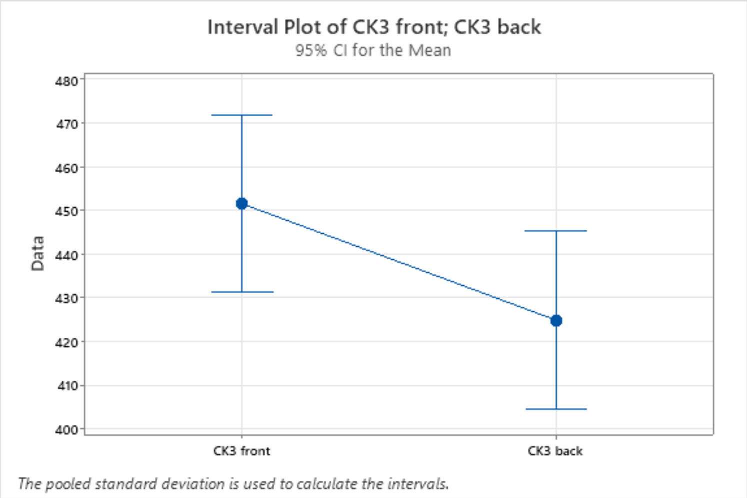
Tukey Pairwise Comparisons

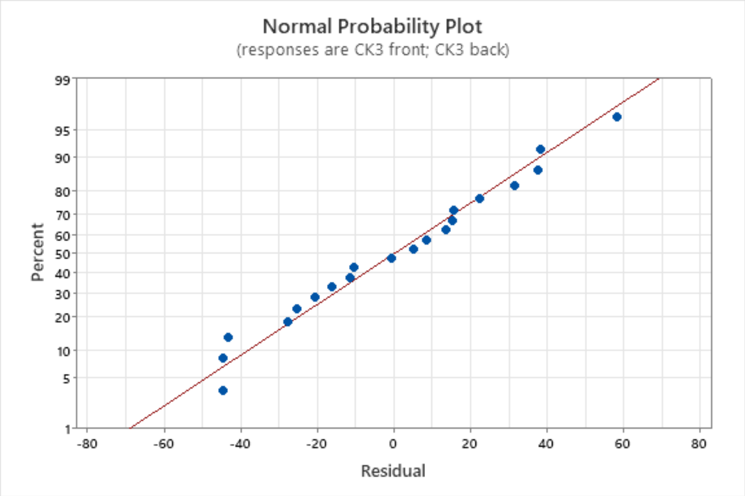
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
CK3 front	10	451,40	A
CK3 back	10	424,8	A

Means that do not share a letter are significantly different.







WORKSHEET 12

One-way ANOVA: CK4 front; CK4 back

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	2	CK4 front; CK4 back

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	288000	288000	352,17	0,000

Error	18	14720	818
Total	19	302720	

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
28,5968	95,14%	94,87%	94,00%

Means

Factor	N	Mean	StDev	95% CI
CK4 front	10	3268,0	36,1	(3249,0; 3287,0)
CK4 back	10	3028,00	18,14	(3009,00; 3047,00)

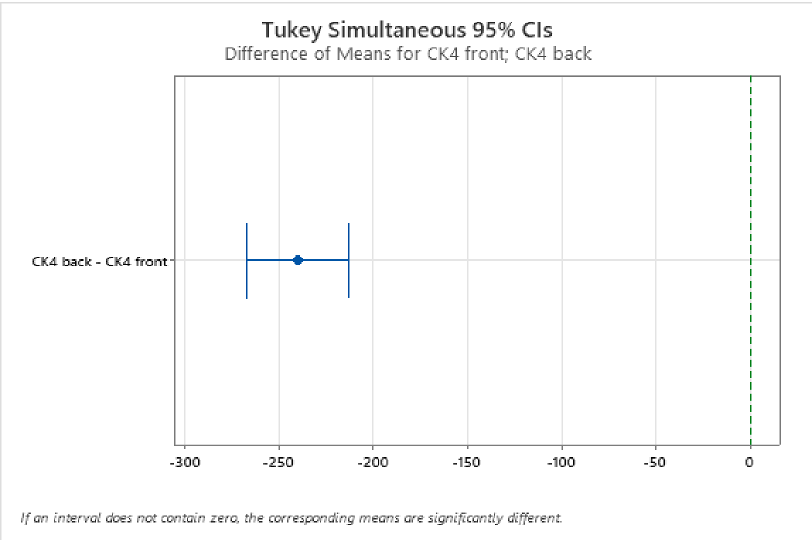
Pooled StDev = 28,5968

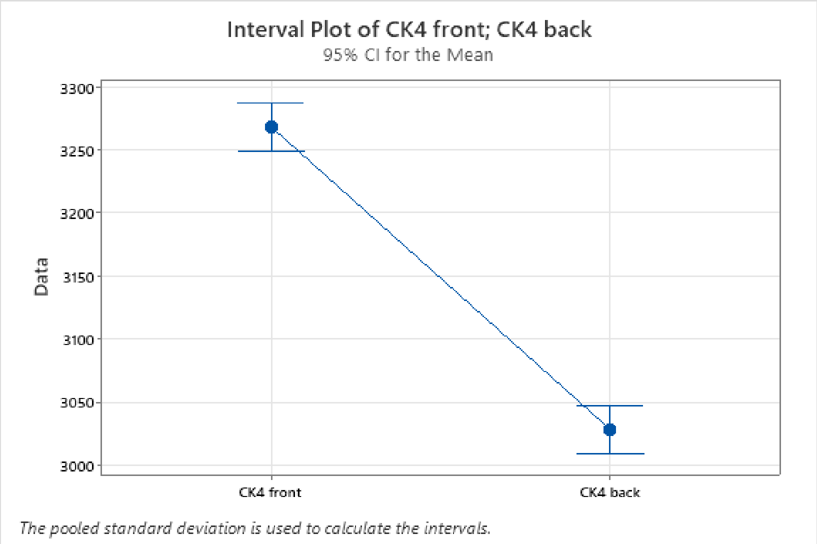
Tukey Pairwise Comparisons

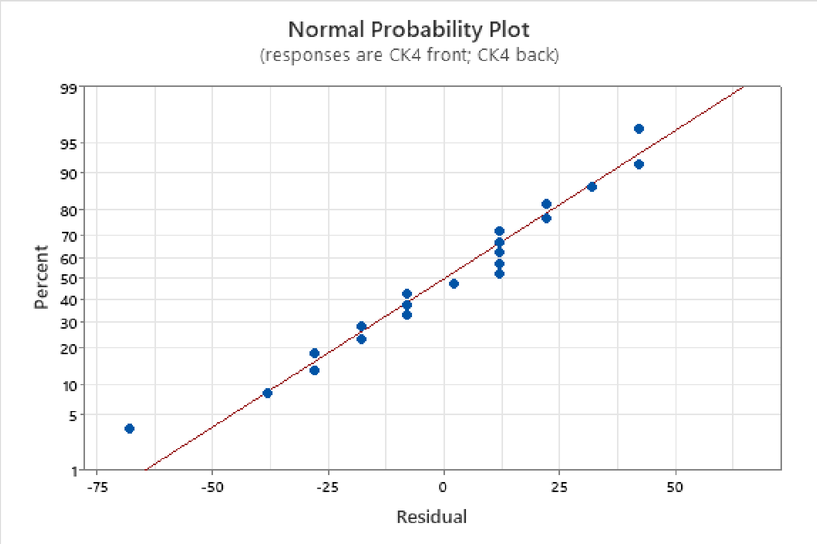
Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
CK4 front	10	3268,0	A	
CK4 back	10	3028,00		B

Means that do not share a letter are significantly different.




Interval Plot of CK4 front; CK4 back
95% CI for the Mean
Data
3300
3250
3200
3150
3100
3050
3000
CK4 front
CK4 back
The pooled standard deviation is used to calculate the intervals.


Normal Probability Plot
(responses are CK4 front; CK4 back)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-75
-50
-25
0
25
50
Residual