Piezoelectric behaviour of woven constructions based on poly(vinylidene fluoride) bicomponent fibres

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**Title:** Piezoelectric behaviour of woven constructions based on poly(vinylidene fluoride) bicomponent fibres

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Abstract
During this project it was investigated how the newly developed piezoelectric PVDF bicomponent fibre behaved when integrated in different weave constructions. The possibility to integrate conductive yarns as outer electrode was studied in order to see if it was possible to create a fully textile piezoelectric sensor. The piezoelectric properties of the bicomponent fibre is given by the sheath material, which is a polymeric material known as poly(vinylidene fluoride) (PVDF). Today only piezoelectric film made by PVDF is commercially available, but with a flexible PVDF bicomponent fibre it improves the possibility to integrate piezoelectric material into a textile construction.

In this study the PVDF bicomponent fibre was integrated in the warp direction into weave constructions, such as plain weave, twill and weft rib. All the woven bands included 60 PVDF bicomponent yarns, with 24 filaments in each bundle and the average width of the bands produced was 30 mm. Different conductive materials and fibres, acting as outer electrode, were coated or integrated together with the PVDF fibre and the behaviour of the PVDF fibres was analysed. All the woven samples went through corona poling with a voltage of 7 kV in 70 °C for 3 min. The weave construction that gave highest piezoelectric output signal was twill with weft that has low tex. The twill construction gave a range amplitude of 1.5-3.3 V when subjected to a dynamic strain of about 0.25% at 4 Hz.

It was shown that different conductive materials influenced the PVDF fibre in different ways, due to the resistance of the material. It was also shown that it was possible to integrate piezoelectric bicomponent fibre into a textile construction and that a fully textile piezoelectric sensor could be produced by using conductive yarns as outer electrode.

Key words: Piezoelectricity, poly(vinylidene fluoride) (PVDF), bicomponent fibre, conductive fibres, textile sensor, tensile sensor, weaving.
Popular Abstract

The prefix *piezo* comes from the Greek word *Piezin*, which means press or squeeze. Materials with piezoelectric properties are able to generate voltage when they are pressed or squeezed. Poly(vinylidene fluoride) (PVDF) is a polymeric material, which has the piezoelectric properties. Today piezoelectric film made out of PVDF is commercially available and can be found in various applications, such as speakers, underwater microphones and measuring devises for pressure, vibration and impact. Now there exist a piezoelectric fibres created by Swerea IVF and Swedish School of Textiles and in this study it is investigated if they could be used in production of textiles.

In this study the PVDF bicomponent fibres were integrated into different weave constructions, such as plain weave, twill and weft rib. Different conductive materials were integrated together with the PVDF bicomponent fibre and the behaviour of the PVDF fibre was analysed. It was shown that it was possible to extract a voltage signal when the samples were subjected to a mechanical stress. A fully textile piezoelectric sensor can be produced for e.g. medical devices, such as health monitors measuring electrocardiogram (ECG) and respiratory signals.

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1. Introduction
Textiles that can sense and respond to changes in their environment are known as smart textiles. A lot of research has been made integrating electronics into textile constructions, called electronic textiles (E-textiles). The textile based electronic solutions and functions, that are integrated in a textile structure makes it more wearable and increases the comfort for the wearer, due to that it is lightweight (Tao X., 2005). Materials that are piezoelectric can generate voltage when subjected to a mechanical stress (Tichý J. et al., 2010). The piezoelectric effect has found its way into the development of smart textiles, in applications such as energy harvesting and medical devices.

1.1 Background description
In the late 19th century the brothers Pierre and Jacques Curie discovered that certain crystals could generate a charge which was proportional to the applied mechanical stress (Ueberschlag P., 2001). The brothers had discovered the piezoelectric effect. In 1969 Kawai discovered the piezoelectric properties in poly(vinylidene fluoride) (PVDF) (Kawai H., 1969) and it has found its way into smart textile applications (Lund A. and Hagström B., 2010). The PVDF polymer is a flexible polymer with properties such as high resistance to chemicals, high mechanical strength and toughness (Esterly D.M., 2002).

Today PVDF film and coaxial cables with piezoelectric properties are commercially available (Measurement specialties, 2013) and can be found in various applications and devices, such as in resonators, speakers and underwater microphones, measuring pressure, vibration, acceleration, stress and strain gauge, impact detector and position sensor (Tichý J. et.al., 2010). Many attempts have been made to develop health monitoring devices, such as collecting electrocardiogram (ECG) and respiratory signals, by using piezoelectric PVDF (Choi S. et.al., 2008) (Chiu Y.-Y. et.al., 2013). But most of them have used the commercially available PVDF film.

The piezoelectric PVDF can be used for energy harvesting, due to that the material can convert mechanical energy into electrical energy. Research has been made by embedding piezoelectric material in a shoe (Shenck N.S. and Paradiso J.A., 2001), and in this way it is possible to generate power when walking. From a PVDF stave, made out of several layers of PVDF film, Shenck and Paradiso (2001) were able to extract an average power of 1.3 mW when subjected to an average power in a 250kΩ load at a frequency of 0.9 Hz.

A lot of research has been made to get piezoelectric PVDF in fibre form, but it has mostly been focused in production of nanofibres, which is produced by the electrospinning process. The interest in the electrospinning PVDF polymer is due to that the fibres goes through an electrical field during production. The electrical field given by the electrospinning technique is poling the PVDF fibre when
produced and they obtain the β-phase crystallinity, which is the phase that gives the highest polarity and the best piezoelectric effect (Chang C. et. al., 2010). There have also been attempts made producing piezoelectric PVDF fibres by traditional melt spinning, in order to make it more suitable in fibre and textile production. Magniez K. et al., (2013) produced a pure PVDF fibre by melt spinning and integrated the fibre into different weave constructions, such as plain weave and twill 2/2. It was shown that they could get a voltage output of average 3-4 V when the woven samples was exposed to a force of 70N with a frequency of 1 Hz.

From a successful research project in cooperation of Swerea IVF, Chalmers University of Technology, Swedish School of Textiles and Swedish ICT ACREO a newly developed bicomponent fibre was produced by melt spinning. The fibre has PVDF as sheath material and a mixture of carbon black (CB) and high density polyethylene (HDPE) in the core, acting as inner electrode. To be able to collect the generated charges from the piezoelectric PVDF another conductive layer had to be applied on the surface of the fibre, called outer electrode. The bicomponent fibre could generate a voltage output up to 20 mV N^{-1} when subjected to a lateral compression. (Lund A. et al., 2012)

In a more recent project with the same piezoelectric bicomponent fibre the most suitable poling technique was investigated. It was shown that the contact poling technique gave highest piezoelectric response, but corona poling was more gentle to the fibres and was more suitable considering continuous fibre production. During the project a textile sensor was produced by incorporating the developed PVDF bicomponent fibre as weft in a woven structure. After the fabric had gone through the poling process a conductive coating, (Elastosil LR 3162) was applied, acting as outer electrode. It was suggested that it was possible to harvest energy out of the textile sensor which was enough to supply energy to low power electronics. It was theoretically calculated that from the 15×100 mm sensor textile that was produced they expect to get 1 mW when subjected to strain of 1%. (Nilsson E. et al., 2013)

The development of the new piezoelectric bicomponent fibre has come to the point where the piezoelectric behaviour of the fibre should be investigated when integrated in a textile construction. The possibility to use conductive fibres as outer electrode should also be explored. If successful, this would increase the possibility to incorporate piezoelectric sensors in textile applications, such as health care and sportswear applications.
1.2 Aim
The aim with this study is to investigate how the piezoelectric bicomponent fibre will behave when it is incorporated in different weave constructions and investigate the possibilities to integrate different conductive yarns as outer electrode, in order to create fully textile piezoelectric sensors.

1.2.1 Research questions
- Is it possible to create a fully textile sensor with PVDF bicomponent fibres in the warp direction and a conductive fibre as outer electrode in the weft direction?
  - How will the conductive yarn influence the piezoelectric behaviour?
- Which weaving process and construction is most suitable in order to create a fully piezoelectric textile sensor with PVDF bicomponent fibres?
  - Is it possible to have the PVDF bicomponent fibre alone in the warp direction?
  - How will the weave construction influence the piezoelectric properties of the PVDF bicomponent fibre?

1.3 Delimitations
This master thesis is limited to only use PVDF bicomponent fibre, with a core of CB and HDPE, as piezoelectric material. The piezoelectric fibre will only be incorporated into basic weave constructions, such as plain weave and twill. Corona poling of the PVDF bicomponent fibre will be performed after it has been incorporated into a woven structure. The size of the woven samples can only be in the range of 40×300 mm, due to the dimensions of the poling apparatus. The materials used in the samples produced should manage temperatures of 135 °C, due to the high temperature during poling and when the connection with the core of the fibre is laminated on the fibre ends. The tensile test machine, model 66-21B-01, MTS systems, will be used during the characterisation of the piezoelectric properties of the woven samples and is limited to a load-cell of 2.5 kN.
2. Theory
In this chapter important aspects that are taking part in this project are presented, such as what piezoelectricity is and the steps in a weaving process.

2.1 Smart textiles
A smart material can be defined as a material or structure that can sense and react to the environmental conditions or to stimuli, such as thermal, chemical and mechanical. Smart materials can also be divided into three categories, passive smart, active smart and very smart materials. The passive smart material only has the ability to sense the surrounding conditions or stimuli, the active smart material can sense and also react to the stimuli. While the very smart material can sense, react and adapt. (Tao, 2001) Introducing textiles into medical applications can increase the comfort, due to the flexibility of the textile construction and also the softness of the fabric (Van Langenhove L., 2007). A smart textile device, that is monitoring a patient, can transmit information wireless to the hospital, which watches the data received. In this way people with chronic diseases and elderly with specific needs, can stay home and feel safe, even if they have health issues that require watching several times a day. (Gupta S., 2010)

The manufacturing processes used creating textiles, such as weaving and knitting, have been developed during a long time. By using this traditional techniques with new materials something interesting and unforeseen can be revealed. (Van Langenhove L., 2007)

Creating textile based sensors is a large part of the smart textile development, especially towards the medical field. Research has been made where textile based sensors were integrated in clothing or devices in order to monitor heart rate (ECG) and respiration (Choi S. et al., 2008) (Chiu Y.-Y. et al., 2013). Sensors can be divided into active and passive sensors. The passive sensors require an external power source to be able to convert the input energy into a measurable difference of potential. The active sensor can convert the input energy, without an external power source. (Carpi F. and Rossi D.D., 2005) This means that passive sensors are usually made from conductive fibres and the active sensors can be based on piezoelectric effect (Van Langenhove L., 2007).

2.1 Piezoelectricity
The prefix piezo comes from the Greek word Piezin which means press or squeeze (Kutz M., 2002). Piezoelectricity or press electricity can be defined as changes in electric polarisation which is proportional to the applied strain (Tichý J. et al., 2010). Depending on the structure of the crystalline units a material can have the piezoelectric property. When the atomic structure of the crystalline units are arranged in a non-symmetrically arrangement, it causes the crystal’s to act as dipoles. (Lund A. et al., 2012) If a material is piezoelectric the dielectric displacement will increase in response to mechanical stress (Tichý J. et al., 2010).
This phenomenon is called *direct effect*, seen in fig. 2.1a, and can be directed the other way around, where a mechanical deformation is created due to applied electrical charge. This is called *converse effect*, seen in fig. 2.1b. (Harrison J.S and Ounaies Z., 2001) The direct effect is ideal for sensor applications and the converse for actuator applications (Daraville T. R. et al., 2005). The Piezoelectric effect can also react on other stimuli, such as temperature. In this case the phenomenon is called *pyroelectric effect* (Harrison J.S and Ounaies Z., 2001) (Vassiliadis S., ed., 2011). *Ferroelectricity* is a property for some dielectric materials. It is when the crystalline regions in a material exhibit a spontaneous separation of negative and positive charges and makes the materials crystals positive on one side and negative on the other. Piezoelectric properties can be found in ceramics, polymers and in biological systems (Harrison J.S and Ounaies Z., 2001), such as bones and silk (Vassiliadis S., ed., 2011).

![Figure 2.1: a) Direct piezoelectric effect, b) Converse piezoelectric effect. The direction of the polarisation is indicated by the arrow, P](image)

The piezoelectric properties of a material can be characterised with aid of two piezoelectric coefficients. One of them is the strain constant, $d$, which is related to the mechanical strain that is produced due to the applied electrical charges. The other one is the voltage constant, $g$, which relates to electrical charges produced due to mechanical stress that is applied. (Lund A., 2010)

When using piezoelectric material in a sensor it is no use to measure static load, due to that there is a leakage of current. During load of a piezoelectric material it will be an output at first and then after a while the response will decrease and become zero again (Ashruf C.M.A., 2002). Therefore piezoelectric material is more suitable for dynamic strain measurements.

### 2.2 Piezoelectric polymers

Piezoelectricity is not natural in polymer materials, but polymers such as PVDF, polypropylene (PP), polyethylene terephthalate (PET) and the odd numbered polyamides (PA11, PA9, PA7, PA5) can be made piezoelectric (Vassiliadis S., ed., 2011). Polymers has lower piezoelectric strain constant compared to ceramics, such as lead zirconate titanate (PZT), but piezoelectric polymers has higher piezoelectric voltage constant. This makes the polymers more suitable as
sensors than ceramics. Sensors and actuators made out of piezoelectric polymers are also more flexible in production, compared to ceramics which is brittle. Polymers have low dielectric constant, low density and low elastic stiffness. These properties result in that the piezoelectric polymer has high voltage sensitivity which is preferred for sensors. (Harrison J.S and Ounaies Z., 2001)

2.2.1 PVDF- Poly(vinylidene fluoride)
PVDF is a polymer that consist out of long chains with the repeating monomer [CH2 = CF2]. The hydrogen (H) atoms in the polymer chain are positively charged and the fluorine (F) atoms are negatively charged in regard to the carbon (C) atoms. This charge of the different atoms gives each monomer unit an inherent dipole moment. (Sirohi J. and Chopra I., 2000) PVDF is a polymorphic material, which means that it can crystallize into different phases. These phases are known as α-, β-, γ-, and δ-phase. It is the β-phase also called Form I that gives the best piezoelectric effect, due to its high polarity. The β-phase has an orthorhombic unit cell where the chains are in trans conformation, seen in fig. 2.2. When PVDF crystallize it wants to take the shape of α-phase, also called Form II, because it is most energetically favourable. The α-phase is non-polar and has a monoclinic unit cell, where the chains are in a conformation of alternate trans and gauche. (Lund A. et al., 2012)

![Figure 2.2: Conformation of PVDF in α-phase (left) and β-phase (right)](image)

In order to convert an α-phase PVDF into β-phase mechanical stretching has to be applied at a certain temperature. After the mechanical stretching the β-phase crystallites are randomly orientated (Bharti V., et al., 1997) and to get them aligned the PVDF material has to go through a poling process. The position of the crystals before and after poling can be seen in fig. 2.3. When poling a material it goes through a high electrical field (Lund A. et al., 2012). It is not fully clear what happens during the poling process, but it is known that the crystals in the polymer are influenced by the electrical field which creates a net polarisation. This net polarisation will align the crystals collectively due to the response of the surrounding. (Esterly D.M., 2002)
When the piezoelectric PVDF material is subjected to a tensile stress, charges will be developed on the surface of the material (Daraville T. R. et al., 2005). Due to that the crystals in the material will come closer together, which gives an increased charge density. In order to be able to register the charges that the piezoelectric material generates electrodes has to be applied on each side of the material (Lund A. et al., 2012). However, the PVDF polymer has a low coefficient of friction and this makes it difficult to get anything to stick onto the surface of the fibre (Solvay, 2012).

2.3 Poling

It has been shown that when poling the stretched PVDF the polar crystallites will become aligned and this will provide the piezoelectric properties (Gerliczy G. and Betz R., 1987). The principle of poling is that a material is exposed to an electrical field and it can be performed in a contact mode and non-contact mode. Contact mode means that there are two electrodes on both sides of the material and the electrodes are connected to a high voltage supply. Non-contact mode, which also can be called corona poling, is when a material is placed between a high potential electrode and grounded counterpart.

2.3.1 Corona poling

In corona poling the high potential corona discharges will ionize the air which become conductive and charging the materials surface and thus creating an electrical field in the material. The electrical field that is created will orient the molecule dipoles in a more aligned position. One way to apply corona discharge onto a material is by a needle electrode. (Nilsson E., et al., 2013)

The corona poling method has some advantages compared to contact poling. For example corona poling only needs one electrode in order to polarise the material and the electrical field created in the corona poling can come closer to the dielectric breakdown of the material. Another advantage is that when using the corona poling method the outer electrode can be applied after the poling process. This enables post-treatment on the fibres. The corona poling method is also less sensitive to defects on the fibre. (Nilsson E., et al., 2013)

To get the ions in the electric field to be evenly distributed over the surface of the material corona needles are used (Miller T., 2011). The corona needle is placed a few centimetres over the PVDF material. (Nilsson E., et al., 2013) When the tip of
the needles reaches the required potential, which is in the range of 5-10 kV (Miller T., 2011), the air around becomes ionized. The surface of the material becomes charged and an electrical field is created between the surface of the fibres and the grounded inner electrode. This electrical field will polarize the PVDF material, which makes the polymer chains to reorganize and the dipoles will become aligned. The voltage that is applied has to be adjusted to avoid breakdowns. It has been shown that when poling with low electrical field the piezoelectric properties can be increased by poling with higher temperature and during a longer time. (Nilsson E., et al., 2013)

2.4 Inner and outer electrode
For a commercial PVDF film, the polymeric layer has thin electrically conductive material, which is fixed on each side of the film and acts as electrodes. The conductive material that is often used is some sort of metal alloy. The metal surfaces are connected with metal wires in order to be able to register the output voltage generated by the piezoelectric film (Images, 2007). It is important that the electrode covers as much area of the piezoelectric material as possible. The larger the overlapping area is the higher the piezoelectric output will become. (Lund A. et al., 2012) For a piezoelectric PVDF fibre, electrodes is also needed and they can be added as a top and bottom layer of a fibrous sheath, (Wang Y.R., et al., 2010) but the electrodes can also be integrated into the fibre structure by melt spinning a bicomponent fibre (Lund A. et al., 2012). For a PVDF bicomponent fibre that has an integrated core electrode, also known as the inner electrode, it is preferred to place it along the fibre length in the core of the fibre structure. CB is used as electrical conductive material in the inner electrode in the specific PVDF fibre of this study. After the bicomponent fibre has been poled the dipoles will be arrange so that one charge is closer to the inner electrode of the fibre and the other charge is closer to the surface. A cross-section of the bicomponent with the arranged charges can be seen in fig. 2.4.

To be able to collect the generated charges from the PVDF sheath material of the bicomponent fibre an outer electrode has to be applied. (Lund A. et al., 2012) In recent studies different conductive materials has been used, such as CB blended with HDPE and conductive silicon rubber (Nilsson E., et al., 2013) (Lund A. et al., 2012). By applying conductive coatings onto a woven structure or incorporate the fibres into a composite matrix it will affect the flexibility of the material. There are some disadvantages by using non-metal material in the electrodes instead of metals, such as their higher resistance. Using a material with higher resistance as electrode will lead to a decreased piezoelectric output voltage. (Nilsson E., et al., 2013)
2.5 Weaving processes
In this part the different steps in the weaving process and the different weave constructions used during the project are presented below.

2.5.1 Winding
Winding is the first step for yarn preparation before weaving. This is made in order to get a yarn package that is suitable for further processes. The winding can be made with different methods, such as side withdrawal and over-end withdrawal. During the side withdrawal the yarn is removed from a rotating spool. A large advantage with this method is that it prevents the yarn from rotation during withdrawal, which makes the twist of the yarn constant. The downside is that it might give tension variation, due to inertia of the spool during high speed winding. For the over-end withdrawal method the yarn package is not rotating, instead the yarn is pulled over the end of the package. This method is most common, due to that it is simple. There are some drawbacks with this method and one of them is ballooning of the yarn when it is unwound from the package, which is caused by centrifugal forces and leads to uneven tension. The other drawback is that it gives the yarn extra twist when the yarn is winded. (NIIR Board, 2003)

2.5.1 Warping
There should be one yarn supply package for each warp yarn, which is winded in a parallel position around a warp-beam with uniform tension. The yarn packages are held by a creel that supplies the warp yarns in their correct position onto the warp beam. (NIIR Board, 2003)

2.5.3 Weaving
The definition of conventional weaving is when two set of yarns/fibres are running orthogonally to one another and interlacing. The yarns running in the width direction in a woven structure are known as weft and the yarns running in the length direction are known as warp. There are four primary motions that have to be made in order to be able to continuously produce a woven fabric. These four primary motions are: (Schwartz P., et al., 1982)

1. Shedding
2. Weft insertion
3. Beat-up motion
4. Warp and fabric control
The first primary motion, *shedding*, is the movement of the warp yarns that gives an insertion path for the weft insertion. When setting up the weaving machine all the warp yarns have their specific position and therefore each yarn is threaded through a heddle eye. The heddle eyes are positioned onto heald frames. To be able to produce a woven fabric, at least two heald frames with threaded heddles have to be used. It is the alternate lowering and lifting motion of the heald frames that creates the shed. There are three kinds of shedding systems, and those are cam, dobby and jacquard. The cam system is the simplest one which also means that it has its limitations in variety of pattern designs. It is the shape or profile of the cams that sets the heald frames in motion and that controls the design of the fabric. With the dobby system the numbers of pattern designs are increased compared to the cam system. This is due to that the dobby system is capable to separate the pattern control and the movement of the healds. The jacquard system is similar to the dobby system, but instead of controlling a whole heald frame the jacquard system controls all the heddle eyes individually. This way of controlling the shed gives endless repeating size of a weaving pattern. (Schwartz P., et al., 1982)

*Weft insertion* also called picking motion, due to the one weft yarn that is inserted into the fabric is known as a *pick*. The weft insertion is simply the insertion of weft yarn through an open shed. The weft yarn can be inserted by different kinds of yarn carriers, such as the traditional shuttle, rapier grippers, projectile grippers, air- and water- jet. The four last yarn carriers are categorised as shuttleless systems. (Schwartz P., et al., 1982)

The different weft insertions systems give different selvages. The shuttle gives a hairpin selvage due to that the shuttle carries the weft package through the shed. The shuttleless looms can give different selvages, but generally the weft ends are always cut, due to that the length of the weft has to be cut before every pick. (Horrocks A.R. and Anand S.C., (ed), 2000)

After weft insertion the yarn has to be incorporated into the body of the fabric and this is made by the *beat-up* motion. The beat-up is made by a reed. All the warp yarns are threaded through the spaces between the wires of the reed, which are known as dents. The reed has a backward and forward motion during the weaving cycle. During the weft insertion the reed is in the backward position. When the weft insertion is finished the reed will go into its forward position where the wires on the reed will engage the weft yarn to the fell of the fabric. (Schwartz P., et al., 1982)
To get a continuous production of woven fabrics the weaving machine has to be able to continuously supply warp yarn and remove finished fabric. The supply of warp yarns is made by a let-off system that makes the feeding in a uniform tension and rate, which is given by a breaking motion. The take-up system removes the finished fabric. One way to do this is that the fabric is winded and stored onto a beam, also called cloth roll. To maintain the full width of the finished fabric at the fell temples can be used. They also ensure that the weft yarns are incorporated as straight as possible across the width of the fabric during beat-up, so that the reed doesn’t break the outer warp yarns. (Schwartz P., et al., 1982)

2.5.4 Mechanical wear of yarns

Winding of the yarns is made in order to divide the yarn into smaller spools to be used during warping. In this step of the process the yarn goes through several guides and breaks, which subjects the yarn to abrasion, due to friction. (NIIR Board, 2003)

During warping the yarns are going through breaks or tension devices, which are placed on the warp creel. These tension devices gives the warp yarns the uniform tension when they are winded onto the warp beam, but they also subject the yarns to friction. (NIIR Board, 2003)

The warp yarns during the weaving process are subjected to a lot of friction against the metal of the weaving machine when they are threaded through the heddles and reed. The yarns always have contact with the metal during shedding and therefore they are constantly being rubbed, which creates friction. At the same time the yarns are also subjected to a high tension, due to the let-off and take-up system. Due to this high tension and friction there is a large possibility that the yarns will break, which should be avoided. One solution can be to use lubrication in order to decrease the friction that is created between the surface of the yarns and the metal of the machine. (NIIR Board, 2003) The yarn lubrication mostly used is water-based and made from oils and surfactants. The surfactants are introduced to make the lubricant easier to wash away before further finishing of the produced textiles. (Gupta V.B. and Kothari V.K., 1997)

Broken filaments in a multifilament yarn or fibres in a staple fibre yarn that sticks out of the surface of the yarn can cause problems. During shedding the yarns will rub against each other and the filaments that stick out will start to entangle with each other or with themselves. A damaged PVDF bicomponent fibre can be seen in fig. 2.5. This can cause the whole yarns to entangle with each other and lead to breakage or fabric defects. In this case lubrication can also be used, in order to make the surface of the yarns smoother. (NIIR Board, 2003)
2.5.5 Weave constructions

A woven fabric is where the warp and weft yarns are interlacing in a specific pattern. The repeat of a weave construction is the smallest unit of the construction and when it is repeated it produces the design of the fabric. (Schwartz P., et al., 1982) In weaving there are three basic weave constructions, plain weave, twill and satin. All the other weave constructions are derived from these three basic weave constructions. (Vassiliadis S., (ed.), 2011)

The weave construction has large influences on the appearance and the mechanical properties of the produced fabric (NE, 2013). Therefore different weave constructions are suitable for different applications. It all depends on what is wanted out of the material and what the fibres used can endure. A flexible fibre manages to be bent with a high angle in the fabric, but a stiff fibre will break easily when exposed to the same bending angle.

**Plain weave**
This weave construction has the smallest repeat, which makes the number of intersections in the weave higher compared to all other constructions. Due to the high number of intersections the plain weave gives high stability to the woven textile and also high crimp. In fig. 2.6a a plain weave construction can be seen.

**Weft rib**
This weave construction is derived out of the plain weave. For this construction the weft yarn floats over two warp yarns in a repeat of two picks. The weft rib only show the weft on the surface on the textile and therefore gives a bar like structure, which run in the warp direction. In the weft rib the warp yarns are running through the construction almost completely straight with a low crimp. In fig. 2.6b a weft rib construction can be seen.

**Twill**
Twill weave gives the characteristic diagonal lines in the textile structure. This weave is more flexible compared to the plain weave and this makes it easier to drape. Due to that there are floatations of the warp yarns in the construction the twill gives lower crimp compared to plain weave, but higher than the weft rib. In fig. 2.6c a twill construction can be seen.
2.5.6 Crimp

Crimp can be defined as the change in percentage of the length of the yarn woven into a fabric. This percentage is estimated as a comparison to the length and width of the fabric corresponding to the warp crimp and the weft crimp respectively. If $L$ represents the length of the yarn before it is incorporated into a woven fabric and $X$ represents the yarn length when it is in a woven fabric, which can be seen in fig. 2.7. The crimp $R$ is given by this formula below: (Schwartz P., et al., 1982)

$$R = \frac{L - X}{X} \times 100$$

Eq.1

![Figure 2.7: Crimp, change in percentage of the length of the yarn woven into a fabric. X is the length of the fabric and L is the length of the yarn before integrated into the fabric.](image)

The crimp depends on the characteristics of the yarns, such as diameter and it also depends on the tensions applied and cover factor of the warp and weft. (Horrocks A.R. and Anand S.C., 2000)

2.5.7 Cover factor

The cover factor can be defined as the area of a fabric that is covered by one set of yarns. For woven fabrics there are two cover factors, warp and weft cover factor. To get the total cover factor of the fabric the warp and weft cover factor are added together. (Horrocks A.R. and Anand S.C., 2000)

The cover factor can be calculated with the equation below:

$$\text{Cover factor} = \frac{\text{Threads/cm}}{10 \times \text{tex}}$$

Eq.2
2.6 Washability
In hospital environments the hygiene is an important aspect and therefore the possibility to wash the textile sensor device is crucial. The function of the textile sensor must also be unaffected by the washing process. (Van Langenhove L., 2007)

To be able to say that a material can be washed or not it has to be resistant to detergents and moisture, but also physical resistance against the high temperature and mechanical stresses is important. (Suh M., 2010) When using metal based conductive fibres there is a large risk of corrosion and oxidation when washing, but this can also come from sweat during regular use. (Van Langenhove L., 2007) The corrosion and oxidation of the pure metal fibres will increase the electrical resistance of the yarns. (Suh M., 2010)
3. Materials used
In this chapter the different materials used during the project are presented more carefully.

3.1 Bicomponent fibre
The bicomponent fibre was used in the warp direction in woven bands. The sheath material was made out of PVDF homopolymer, Solef 1008. The core material was carbon black (CB), with the commercial name Ketjenblack EC-600JD mixed with high density polyethylene (HDPE), ASPUN 6835 A. Thus, the core material of the integrated inner electrode of the fibre was electrically conductive. During the melt spinning the PVDF fibre was drawn in the solid state with a solid state draw ratio, (SSDR) of 4. (Lund A. et al. 2012)

The bicomponent yarn includes 24 filaments, each with the diameter of about 60 µm, where the core diameter is about 24 µm and the thickness of the PVDF sheath is 18 µm, seen in fig. 3.1. The yarn has a tex of 860 tex which means that each filament was about 36 dtex. The elastic modulus of the fibre was 181 cNtex⁻¹ and elongation at break was 60.7%. The tenacity of the bicomponent fibre was 24.8 cNtex⁻¹. (Lund A. et al. 2012) According to Haagensen D. (2010) a bundle with 24 filaments can endure 6% strain without reaching the plastic deformation.

In this study the 24 filaments in the PVDF bicomponent yarn bundle were twisted together with a twist of 80 turns/m.

![Cross-section of bicomponent fibre](image)

Figure 3.1: Cross-section of bicomponent fibre

3.2 Polyester
The polyester materials used in this project was two types of fibres, mono- and multifilament with 15.6 tex and 130 tex respectively. These fibres were integrated as weft in both plain weave and in the twill construction. The high difference in tex was decided due to that it gives high difference in thickness of the yarn. The thicker the yarn is the crimp will become higher on the warp yarn. By using these polyester yarns with different tex a comparison can be made between different
crimp. The material polyester was chosen due to that it endures high temperatures with a melting temperature of 220-267 °C (Harper C.A., 1996).

3.3 Conductive material
Different conductive materials were used during this project in order to create an outer electrode or to get a connection to the inner electrode. The conductive materials used are presented below.

3.3.1 Bekaert Bekintex, BK 50/2
The BK 50/2 is a composite fibre produced by Bekintex (Bekaert, Belgium). The fibre contains 20% short steel fibres in combination with 80% polyester fibres. (Bekaert, 2012) Because of the construction of the fibre it is as easy to handle as ordinary polyester threads. (Post E.R., et al., 2000) The value of the tex and resistance of the fibre can be seen in table 5.1. This fibre will be named Bekintex throughout the report.

3.3.2 Statex
The Statex fibre (Statex, Germany) is a metalized polyamide that is plated with 99% of pure silver. These fibres have high conductivity and are often used in medical, anti-static, and military applications. (Statex, 2012) The value of the tex and resistance of the fibre can be seen in table 5.1. This fibre will be named Statex throughout the report.

3.3.3 Shakespeare F9416
Shakespeare (Resistat, United States) is a conductive fibre which is a polyamide 6.6 fibre with an outer skin covered by carbon particles. The carbon particles are saturated onto the polyamides surface by a suffusion process. (Resistat, 2012) The value of the tex and resistance of the fibre can be seen in table 5.1. This fibre will be named Shakespeare throughout the report.

3.3.4 Elastosil LR 3162 A/B
For the woven samples that do not have a conductive yarn as an outer electrode a thin layer of a conductive coating has to be applied on the surface. Elastosil LR 3162 is an electrically conductive two component silicone rubber and by mixing an A and B component of the rubber a less sticky material is received due to crosslinking during vulcanisation. (Wacker Chemie AG, 2013) The conductivity of the silicone rubber according to the supplier is 0.09 S/cm.

3.3.5 LDPE with CB
To get a connection to the inner electrode of the bicomponent fibre a thin conductive sheath, made out of low density polyethylene (LDPE) and 10 wt% of carbon black (CB) was produced. Granulates were compression moulded to a thickness of about 1 mm. The pressure moulding was performed in 135 °C, which is above the melting point of LDPE.
4. Methods
This chapter is divided into different parts, method of sample production and characterisation. The different methods are presented below.

4.1 Sample production
All the samples produced were in the size of about 30×1000 mm, which then were divided into three samples. The samples were named with a specific system, for example, sample 6.1, where the first number in the name refers to the woven band with its specific weft material and weave construction and the second refers to sample number. The numbers of the woven band can be seen in table 5.1. The PVDF bicomponent fibre was in the warp direction with 20 warp yarns/ cm.

4.1.1 Preparation of the PVDF warp yarns
The PVDF yarn was supplied on one cone and therefore the yarn was divided onto 60 smaller spools, by winding with the winding machine, Schweiter MC 764/54. The smaller spools were then put onto a platform with spikes on it to hold the spools in place close to the warp creel. The 60 yarns were then threaded in the warp creel and pulled through a reed which gathered the yarns and then through another reed which determined the warp width. The yarns are then uniformly spread over 100 mm width warp beam and attached with tape. The winding onto the warp beam was made by hand.

4.1.2 Weaving
The weaving was performed on a band weave machine, Saurer 60B 1-2, with the cam shedding system. All the warp yarns were threaded with one yarn in each heddle eye. The reed had the size of 10 dents/ cm and the reed was threaded with 2 yarns/ dent. The average speed was 180 picks/min. The density of weft was registered.

4.1.3 Evaluation of the mechanical abrasion
The samples produced were photographed with an optical microscopy, model Nikon SMZ-U zoom 1:10, to see the damage on the samples. An evaluation was made where the last 200 mm on the samples were investigated more thoroughly and the number of damaged fibres was counted. The result can be seen in appendix A.

4.1.4 Resistance of the conductive fibres
The resistance of the conductive fibres was measured over two different distances, 0.5 meter and 1 meter. The measurements were made at least 3 times for each distance to get an average. The resistance was measured with a multimeter, FLUKE 114 true RMS multimeter.

4.1.5 Prepare connection
To get a connection with the conductive core which is the inner electrode of the fibres, the ends of the PVDF bicomponent fibres of the weave were cut with a scalpel. The ends were then placed between two thin sheaths of LDPE mixed with
10 wt% of CB. It was then compression moulded in a heat press at 135 °C. For the samples that had a woven integrated outer electrode about 20 mm of the conductive weft was removed to be sure that only the ends of the PVDF fibre was connected.

4.1.6 Corona poling
The woven sample was stationary positioned in the middle between two flat needle boards with 45 needles on each board. The distance between the needles and the sample was about 25 mm and the poling area was about 30×100 mm. The sample was clamped on each side of the corona poling device, to keep stretched. The needle boards were connected to the high voltage power supply, ES50R-10W (Gamma High Voltage Research, Ormond Beach, FL) and the core of the PVDF fibres was connected to the electrical ground. The poling was performed in an oven at a temperature of 70 °C and the applied voltage was set on 7 kV. The samples were subjected to the electrical field for 3 min. The heat was turned off and the sample was cooled down for 5 min before the voltage was removed. The setup of the corona poling can be seen in fig. 4.1. For every sample the leakage of current during poling was monitored and the registered current levels can be seen in appendix B.
4.1.7 Measurement of the electrical field

The electrical field was measured with a high voltage probe, FLUKE 80K-40 HV. The measurement was made during the last 5 min of the corona poling while the sample cooled down to room temperature and the 7 kV voltage still is on. The electrical field was measured at four positions, on the needles, on the textile surface, in the middle between the textile and the needles and on the textile about 10 cm away from the exposed area. The positions can be seen in fig. 4.2.

The electrical field strength is calculated according to:

\[
\text{Electrical field strength} = \frac{\text{Voltage (V)}}{\text{Thickness of the PVDF sheath (m)}} \tag{Eq.3}
\]

![Figure 4.2: Measurement of the electrical field. (1) on needles, (2) on textile at exposed area, (3) in the middle between the needles and textile and (4) on textile 10 cm from exposed area](image)

4.1.8 Coating of the outer electrode

The samples which were produced without a woven outer electrode must be coated with a conductive coating after the poling process. The coating applied was the conductive silicone rubber, Elastosil LR 3162 (Wacker Chemie AG, München, Germany). The A and B compounds of the rubber was weighed equally and then mixed carefully together. A thin layer of the mixture was applied onto about 150 mm on both sides of the sample with a scraper in order to get high coverage of the coating onto the fabric. The coating was cured in an oven at 110 °C for about 60 min.

4.1.9 Pre-control of the piezoelectric effect

In order to test that each samples was successfully made showing piezoelectric properties the inner and outer electrode of the woven sample were connected to an oscilloscope. The sample was subjected to a mechanical stress performed by hand, seen in fig. 4.3.
4.1.10 Mechanical properties
In order to test the mechanical properties the sample was fixed between the clamps of the tensile tester, Instron 5966, with a distance of 100 mm. The settings on the tensile tester were made with the Instron Bluehill software (Bucks, England). A pre-load was set to 0.5 N. The sample was subjected to three cycles with different elongation. At first it was elongated up to 1.5% and returned to zero, then 3% and returned to zero and at last 5% and returned to zero. The speed of the elongation was set on 360 mm/min and the force needed to elongate the sample was registered, see appendix C.

4.2 Methods for characterisation
The woven samples were subjected to a dynamic strain created by the tensile testing machine, model 66-21B-01, MTS systems. The setup of the characterisation methods can be seen in fig. 4.4. The MTS machine was servo-hydraulic, which was needed in order to tests at high frequencies and register a voltage output, seen in fig. 4.5. The load cell on the MTS machine was 2.5 kN and the samples was placed in the clamps between two rubber sheaths, to prevent sliding and as electrical isolation. The starting distance between the clamps was set on 100 mm and after the sample was secured between the clamps a pre-tension was applied by further increasing the distance between the clamps. This was made in order to prevent slack in the sample during measurement and the new distance was registered. The voltage signal from the samples electrodes was connected to data acquisition device, NI DAQPad-6016, from National Instrument, which was connected to a computer running the LabVIEW software to record the measurements. The force and strain from the tensile tester were collected as analog signals.
4.2.1 Frequency sweep
The lower cut-off frequency ($f_c$) is a key characteristic of the woven samples as it tells how the sensor can be applied. One of the three samples of the different woven bands was subjected to a frequency sweep with the MTS tensile testing machine. A sinusoidal strain was applied with an amplitude value of about 0.1%. The frequency sweep was performed from 0.1 Hz to 10 Hz. The pre-load during measurement was set to 30 N. The voltage at the cut-off frequency can be calculated with the equation below:

$$V_f = \frac{V_0}{\sqrt{2}}$$  \hspace{1cm} \text{Eq.4}

Where $V_f$ is the voltage at the cut-off frequency, $V_0$ is the highest voltage generated during the frequency sweep. Using equation 4 the cut-off frequency can be estimated.
4.2.2 Constant strain
The samples were subjected to a specific strain of about 1% and then the strain was held until the voltage output signal returned to zero. The measurements were made with the MTS tensile tester machine. The pre-load was set to 30 N. This test was made in order to compare how the samples voltage output behaves when subjected to a constant strain. All three samples of the woven band were tested with this test.

An alternative way to determine the cut-off frequency of the piezoelectric sensor is to expose the sample to a step function. Equation 5 can be used to calculate the cut-off frequency. Where τ is the time it takes for the initial voltage signal to get down 1/e after a strain or step is applied. The longer time it takes the lower the cut-off frequency will be.

\[ f_c = \frac{1}{2\pi \tau} \]  
**Eq.5**

4.2.3 Dynamic strain
The samples were also subjected to a dynamic strain with amplitude of 0.25 mm with a frequency of 4 Hz, which was shown to be over the cut-off frequency. The sample was fixed between the clamps in the MTS tensile machine with a distance of 100 mm. A pre-load of about 30 N was then put on the sample and the new distance between the clamps was registered and the new strain % was calculated. This test was made in order to compare the voltage output with a ratio of voltage and strain %. All three samples of the woven band were tested with this method.

4.2.4 Power output
A model where the power that is generated from a PVDF beam subjected to a bending model has been developed by Sodano H.A. et al., 2004. According to Nilsson E. et al., 2013 the model could be applied to calculate the power generated by fibres when subjected to an axial tension, with the equation:

\[ P = \frac{V_0^2}{2} \frac{nf}{C_p} \]  
**Eq.6**

Where \( P \) is the generated power, \( V_0 \) is the generated voltage at a specific tension amplitude, \( f \) is the frequency of the tension that is applied and \( C_p \) is the capacitance of the sample. The measurements of the \( C_p \) were provided by ICT ACREO as presented in appendix E.
4.2.5 Washing

A test was made on one of the samples to see how it performed before and after washing. The washing and drying was performed according to SS-EN ISO 6330-2012, in 40 °C. The detergent used was ECE A, which is without perborate. The dosage of the detergent was 20 g/wash cycle and the sample was washed one time. During the washing no loading of the fabric was used. The sample was washed in a laundry bag and after the wash it was hang dried.
5. Result
The results are divided into two parts, results from the sample production of the different woven bands and the results from characterisation of the piezoelectric properties of the weaves. In the results the main findings are presented and some of the results are given in the appendix A, B, C, D, E and F to complete the presentation.

5.1 Sample production
To be able to study the effect of the PVDF bicomponent fibre used as warp in combination with different weft material and weave constructions, 18 samples were produces as shown in table 5.1. Pictures taken by microscope, with a zoom of 1:10, with different combinations of the weave construction and weft material are shown in fig. 5.1. The fibres seen in the vertical direction is the PVDF bicomponent fibre and the fibres in the horizontal direction are the different weft yarns. The samples in fig. 5.1 are also the samples chosen to continue with for the measurements of characterisation.

<table>
<thead>
<tr>
<th>Weft construction</th>
<th>Weft material</th>
<th>Weft material</th>
<th>Weft material</th>
<th>Weft material</th>
<th>Weft material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poly 15.6 tex</td>
<td>Poly 130 tex</td>
<td>Bekintex</td>
<td>Statex</td>
<td>Shakespeare</td>
</tr>
<tr>
<td>Twill 3/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain weave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weft rib</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: The samples produced with different weft
<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Weave construction</th>
<th>Warp material</th>
<th>Weft material</th>
<th>Density of weft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Cotton</td>
<td>15 yarn/cm</td>
</tr>
<tr>
<td>2.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>PVDF bicomponent fibre</td>
<td>13 yarns/cm</td>
</tr>
<tr>
<td>3.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>PVDF bicomponent fibre</td>
<td>13 yarns/cm</td>
</tr>
<tr>
<td>4.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>PVDF bicomponent fibre</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>5.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Polyester monofilament, 15.6 tex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>6.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Polyester multifilament, 130 tex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>7.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Statex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>8.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Bekintex, 50/2</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>9.</td>
<td>Plain weave</td>
<td>PVDF bicomponent fibre</td>
<td>Shakespeare</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>10.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>PVDF bicomponent fibre</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>11.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Polyester monofilament, 15.6 tex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>12.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Polyester multifilament, 130 tex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>13.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Statex</td>
<td>10 yarns/cm</td>
</tr>
<tr>
<td>14.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Bekintex</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>15.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Bekintex</td>
<td>17 yarns/cm</td>
</tr>
<tr>
<td>16.</td>
<td>Twill, 3/1</td>
<td>PVDF bicomponent fibre</td>
<td>Shakespeare</td>
<td>11 yarns/cm</td>
</tr>
<tr>
<td>17.</td>
<td>Weft rib</td>
<td>PVDF bicomponent fibre</td>
<td>Statex</td>
<td>21 yarns/cm</td>
</tr>
<tr>
<td>18.</td>
<td>Weft rib</td>
<td>PVDF bicomponent fibre</td>
<td>Shakespeare</td>
<td>19 yarns/cm</td>
</tr>
</tbody>
</table>
5.1.1 Properties of the conductive fibres
The value of the dtex and Ω/cm for the different conductive fibres, which was used as weft material, can be seen in table 5.2.

Table 5.2: Conductive fibres

<table>
<thead>
<tr>
<th>Conductive yarn</th>
<th>Dtex</th>
<th>Resistance Ω/cm, according to manufacture</th>
<th>Measured Ω/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statex</td>
<td>612</td>
<td>-</td>
<td>0.77</td>
</tr>
<tr>
<td>Bekaert Bekintex</td>
<td>396</td>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td>Shakespeare</td>
<td>818</td>
<td>5000</td>
<td>4520</td>
</tr>
</tbody>
</table>

5.1.2 Weft cover factor
The weft cover factor on the different weave constructions and weft material was calculated with equation 2 and the result can be seen in table 5.3.

Table 5.3: The cover factor of the weft in the different weave constructions

<table>
<thead>
<tr>
<th>Weft material</th>
<th>Plain weave</th>
<th>Twill 3/1</th>
<th>Weft rib</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statex</td>
<td>27 %</td>
<td>25 %</td>
<td>52 %</td>
</tr>
<tr>
<td>Bekintex</td>
<td>22 %</td>
<td>22 %</td>
<td>-</td>
</tr>
<tr>
<td>Shakespeare</td>
<td>31 %</td>
<td>31 %</td>
<td>54 %</td>
</tr>
</tbody>
</table>

5.1.3 Mechanical properties
The samples had a pre-load of 0.5 N and were subjected to a force producing a 5% extension of the samples, with a speed of 360 mm/min and then the force was released.

As can be seen in fig. 5.2 the sample with integrated Bekintex fibres require higher force to be extended 5% compared to Statex and Shakespeare. Fig. 5.2 was chosen to be shown in the results as it was a good example representing this measurement. The complete description of the different samples mechanical properties are shown in appendix C.
5.1.4 The strength of the electrical field during corona poling
During the corona poling of the samples the electrical field was measured. The electrical field was registered at four points, (1) on needles, (2) on textile at exposed area, (3) in the middle between the needles and textile and (4) on textile 10 cm from exposed area. The result can be seen in table 5.4 and it shows that all the samples were subjected to an electrical field, which verifies that the corona poling process is suitable to use. An estimation of the electrical field strength over the thickness of the PVDF sheath, (18 µm) has been calculated according to equation 3.

Table 5.4: Measurement of the electrical field

<table>
<thead>
<tr>
<th>Sample</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>Electrical field strength on textile surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3 Plain weave, Statex</td>
<td>7.4 kV</td>
<td>0.7 kV</td>
<td>2.5 kV</td>
<td>0.6 kV</td>
<td>38.9 MV/m</td>
</tr>
<tr>
<td>8.3 Plain weave, Bekintex</td>
<td>7.7 kV</td>
<td>0.8 kV</td>
<td>2.5 kV</td>
<td>0.8 kV</td>
<td>44.4 MV/m</td>
</tr>
<tr>
<td>9.1 Plain weave, Shakespeare</td>
<td>7.7 kV</td>
<td>0.6 kV</td>
<td>3.3 kV</td>
<td>0.3 kV</td>
<td>33.3 MV/m</td>
</tr>
<tr>
<td>3.1 Plain weave, PVDF</td>
<td>7.6 kV</td>
<td>1.6 kV</td>
<td>2.5 kV</td>
<td>0.001 kV</td>
<td>88.9 MV/m</td>
</tr>
<tr>
<td>17.3 Weft rib, Statex</td>
<td>7.7 kV</td>
<td>0.4 kV</td>
<td>3.3 kV</td>
<td>0.3 kV</td>
<td>22.2 MV/m</td>
</tr>
</tbody>
</table>

5.1.5: Coating of conductive silicone rubber
After the corona poling process the woven bands with polyester as weft had to be coated with thin a layer of conductive silicone rubber, Elastosil LR 3162. A woven band before and after the coating can be seen in fig. 5.3.

Figure 5.3: Before (left) and after the conductive coating was applied (right)
5.2 Characterisation of the piezoelectric properties of the woven samples
In this part the results of the piezoelectric properties of the woven bands are presented.

5.2.1 Frequency response of the woven samples
The different samples were subjected to a frequency ramp from 0.1 Hz to 10 Hz with a dynamic strain with an amplitude of 0.1% and a pre-load of 30 N. The result can be seen in fig. 5.4 – 5.7.

![Figure 5.4: Frequency response for the coated bands](image)

The woven bands with the coated silicone rubber, Elastosil LR 3162, as outer electrode show a cut-off frequency of an average of about 1.2 Hz, as can be seen in table 5.5. The cut-off frequency was estimated using equation 4.

<table>
<thead>
<tr>
<th>Coated sample</th>
<th>Cut-off frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1 Twill 15.6 tex</td>
<td>1 Hz</td>
</tr>
<tr>
<td>12.1 Twill 130 tex</td>
<td>0.8 Hz</td>
</tr>
<tr>
<td>5.1 Plain weave 15.6 tex</td>
<td>1.2 Hz</td>
</tr>
<tr>
<td>6.1 Plain weave 130 tex</td>
<td>1.7 Hz</td>
</tr>
</tbody>
</table>

Table 5.5: The cut-off frequency for the coated samples
Figure 5.5: Frequency response for the woven bands with integrated Bekintex fibre

Figure 5.6: Frequency response for the woven bands with integrated Statex fibre

Figure 5.7: Frequency response for the woven bands with integrated Shakespeare fibre
5.2.2 Constant strain

All the samples were measured with a pre-load of 30 N and then subjected to a constant strain of about 1%. The cut-off frequency was calculated with equation 5. The results can be seen in fig. 5.8- 5.11.

The pre-load of 30 N in fig. 5.8 gave a starting strain of 0.9%. A constant strain was then applied of 1%, which gave a total strain of 1.9% creating a voltage output of 8.9 V. The cut-off frequency was calculated to 3.18 Hz.

The pre-load of 30 N in fig. 5.9 gave a starting strain of 1%. A constant strain was then applied of 1%, which gave a total strain of 2% creating a voltage output with amplitude of 10 V. The cut-off frequency was calculated to 0.02 Hz.

Figure 5.8: Plain weave with polyester 15.6 tex as weft and coated with conductive silicon rubber. Subjected to a square wave at 0.1 Hz

Figure 5.9: Plain weave with Bekintex as weft
The pre-load of 30 N in fig. 5.10 gave a starting strain of 1.8%. A constant strain was then applied of 1%, which gave a total strain of 2.8% creating a voltage output with amplitude of 5.6 V. The cut-off frequency was calculated to 0.14 Hz.

The pre-load of 30 N in fig. 5.11 gave a starting strain of 1.7%. A constant strain was then applied of 1%, which gave a total strain of 2.7% creating a voltage output of 3 V. The cut-off frequency was calculated to 0.03 Hz.
5.2.3 Dynamic strain

All the samples were subjected to a dynamic strain of about 0.25% with a frequency of 4 Hz and a pre-load was set of about 30 N. Due to that a pre-load was applied, the samples get different distance between the clamps at the starting point. The frequency was decided to be 4 Hz in order to be sure that the tests were performed over the cut-off frequency. The average voltage-strain ratio of the samples was calculated and the variation between the different results of the woven bands can be seen in fig. 5.12 - 5.15.

Figure 5.12: Voltage – strain ratio for the coated samples when subjected to a strain of about 0.25% at 4 Hz

Figure 5.13: Voltage – strain ratio for the samples with Bekintex, when subjected to a strain of about 0.25% at 4 Hz
Figure 5.14: Voltage – strain ratio for the samples with Statex, when subjected to a strain of about 0.25% at 4Hz

Figure 5.15: Voltage – strain ratio for the samples with Shakespeare, when subjected to a strain of about 0.25% at 4Hz

The average amplitude voltage output of the twill construction with different outer electrode, coating (Elastosil LR 3162), Bekintex, Statex and Shakespeare, when subjected to a strain of about 0.25% with a frequency of 4 Hz and a pre-load of 30 N, can be seen in table 5.6.

<table>
<thead>
<tr>
<th>Conductive material</th>
<th>Average amplitude voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating (Elastosil LR 3162)</td>
<td>2.6 V</td>
</tr>
<tr>
<td>Bekintex</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Statex</td>
<td>3.2 V</td>
</tr>
<tr>
<td>Shakespeare</td>
<td>1.5 V</td>
</tr>
</tbody>
</table>

The amplitude of the piezo-signal for the twill construction with conductive silicone rubber as coating and polyester 15.6 tex as weft, can be seen in fig. 5.16. In appendix D the amplitude of the piezo-signal for the other weft materials used in a twill construction are presented.
The amplitude of the piezo-signal for the twill construction with conductive silicone rubber as coating and polyester 15.6 tex as weft, is 2.9 V, subjected to strain amplitude of about 0.25%.

### 5.2.4 Power generated

The measurement of the resistance and capacitance of two samples woven with twill 3/1 and integrated Statex and Shakespeare fibres can be seen in appendix E. The numbers given in table 5.7 of the $V_0$ and $f$ are estimated from fig. 5.6, 5.7 and appendix E.

#### Table 5.7: Needed numbers for calculation of power generation

<table>
<thead>
<tr>
<th>Statex, twill 3/1</th>
<th>Shakespeare, twill 3/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0 = 1.49$ V</td>
<td>$V_0 = 0.92$ V</td>
</tr>
<tr>
<td>$f = 0.71$ Hz</td>
<td>$f = 2.04$ Hz</td>
</tr>
<tr>
<td>$C_p = 5.6$ nF</td>
<td>$C_p = 3.2$ nF</td>
</tr>
</tbody>
</table>

At the specific tension amplitude of 0.1% the generated power from the samples was calculated with equation 6. The sample with Statex as weft material gave a power of 14 nW and Shakespeare gave a power of 9 nW.
5.2.5 Result after wash
A test was made on the sample with Shakespeare as weft to see how it performed before and after washing. This sample was chosen, due to that this sample seemed to withstand a wash. The washing and drying was performed according to SS-EN ISO 6330-2012, which is described in the method.

The pre-load of 30 N in fig. 5.17 gave a starting strain of 2.4%. A constant strain was then applied of 1%, which gave a total strain of 3.4% and creates a voltage amplitude of 2 V.

The pre-load of 30 N in fig. 5.18 gave a starting strain of 1.9%. A constant strain was then applied of 1%, which gave a total strain of 2.9% and creates voltage amplitude of 1.2 V.
6. Discussion
In this chapter the results that are given throughout the report will be discussed.

6.1 The construction of the woven bands
Weaving is the most suitable technique to use for a textile sensor based on piezoelectric fibres. Due to that it is the stretch of the piezoelectric material that creates the voltage output and in a woven construction the fibres are kept in a more straight position compared to knitting. When a woven band is subjected to a tensile strain in the warp direction it is the warp yarns that take up most of the load. Therefore the PVDF fibre was chosen to be alone in the warp direction to maximise the piezoelectric effect. One other large advantage to have the PVDF fibres in the warp direction is that the length of the band or fabric is not limited to the width of the loom. In the beginning of the thesis it was stated that the width of the woven band was limited to maximum 40 mm, so the width had to be in that range. There was also a limited supply of material. Therefore it was decided to have 60 warp yarns in the woven band with two yarns / dent in the reed, which gives a woven band with the width of about 30 mm.

When incorporating conductive fibres in the weave acting as the outer electrode it is important that the fibre is continuously laid in the weave construction to enable the voltage output. This is why the hairpin selvage, which is created when using a shuttle as weft insertion system, is an ideal choice.

6.1.1 Sample selection
The weave constructions selected were plain weave, twill 3/1 and weft rib. Plain weave and twill are two of the basic weave construction and many other weave constructions are derived from these two. The plain weave was chosen due to that it is a stable construction which has high crimp. Twill was used as it has a more loose construction which gives good drapability and lower crimp compare to plain weave. Weft rib was only used when the conductive fibres were integrated as weft, due to that the weft will cover the warp yarn too much. Therefore polyester yarns would not be used as weft in the weft rib construction due to that it would only prevent the conductive coating from getting a connection to the PVDF fibre and the voltage output would become low. The weft rib gives a higher cover factor compared to the plain weave and twill and the warp yarns in the weft rib will lay almost straight in the construction which gives low crimp.
6.1.2 Material selection

To see if it was possible to have conductive fibres as outer electrode different yarns were tested, Statex, Bekintex and Shakespeare. Statex was chosen due to the high conductivity as it is coated with silver. Bekintex or BK 50/2 was tested as it has less risk for oxidation when exposed to moisture and it also has much lower conductivity compared to Statex. The Shakespeare fibre is interesting as it has CB on the outside, i.e. the same material used in the core of the PVDF fibre.

The conductive silicone rubber, Elastosil LR 3162, was used as outer electrode for the samples without integrated conductive fibre. The silicone rubber was supplied by Swerea IVF and it had been successfully used and tested as outer electrode in previous experiments. It was used in order to be able to compare the samples with a coating to those having an integrated conductive fibre as outer electrode.

The different polyester fibres that were used had different tex. The monofilament had 15.6 tex and the multifilament fibre had 130 tex. This was made to see if there was a difference in the voltage output due to the difference in crimp, as higher tex gives higher crimp.

6.2 Mechanical abrasion

The mechanical abrasion was a big problem both during the preparation of and also during weaving. It was important that the PVDF yarns were free from damages before they were used in the weaving processes. When the PVDF yarn was winded on to smaller spools it could damage the filaments and if one filament was broken it started to entangle and break other filaments as well. The winding process could be gentler to the yarn by avoiding high abrasion breaks and tension devices. During warping the filaments broken in the winding process could also start to entangle more when it went through the yarn breaks.

During weaving there were high mechanical abrasion in the heddle eyes and the reed which went back and forward. Abrasion could also be seen between the fibres in the same dent. The first sample produced had a lot of damaged filaments, as can be seen in appendix B. It was clear that the problem was the heddle eyes, due to that broken filament was seen in front and behind the heddle eyes. The heddle eyes used were blade heddles which have sharp edges that easily can cut the filaments when strain is applied. Therefore the heddles were replaced by heddles which were gentler to the fibres. The shape of the different heddle eyes can be seen in fig. 6.1.
After the change of heddles a large improvement was seen, no filament was cut off by the edges of the heddle eyes. But the abrasion of the reed and fibre on fibre was still a problem. Lubrication was used to hold the filaments together and to decrease the friction of the movement of the reed. As can be seen in appendix B the number of damage fibres was quite similar for the plain weave and the twill, but for the weft rib more filaments was damaged. This is due to that the weft rib samples were woven with a different set of warp. The PVDF yarns in the second warp were more damaged before it went through the weaving process, probably due to damages occurring already during the melt spinning process. The weft rib weave construction also has more weft yarns /cm compare to the other weave constructions. This leads to that the reed will be in contact with the warp yarns for a longer time and give higher mechanical abrasion.

6.3 Mechanical properties

It can be seen in fig. 5.2 that the samples with Bekintex fibres in the weft direction requires a higher force to extend 5%, compared to the other conductive fibres. The explanation for this is that the thickness of the Bekintex fibre is the lowest of the three, due to that it has the smallest tex. Thinner fibres give lower crimp and therefore lower elasticity. The samples with Shakespeare, which has the highest tex, are the most elastic samples and require less force to extend 5%.

It can also be seen that the plain weave construction require a higher force compared to the twill construction for the same extension. This is probably due to that the plain weave has more intersections, which gives a stable and stiff construction. The twill construction is looser; it has less intersections, due to that the PVDF fibre in the construction floats over three weft yarns and therefore are laid straighter in the structure. This means that the PVDF fibres in the warp direction will be less influenced by the weft yarn when subjected to a tensile strain.

The curves in fig. 5.2 also show that all samples require more force in the loading phase compared to the unloading phase. This is evident from the fact that the extension is not immediately decreased as the force is decreased. Another crucial
observation is that the loading curve starts to increase slowly up to about 2%. This is due to that the crimp in the material straightens out. And then the loading curve turns into a straight and steeper line, which indicates that the actual material is subjected by the load. No samples showed that they crossed over the plastic deformation when extended 5%, which was expected due to that a single yarn endures 6% extension without reaching the plastic deformation.

6.4 Corona poling

During the corona poling a difference in behaviour between the samples were observed. The samples with integrated conductive yarns did not leak as much current during poling as for the samples without conductive yarns in the weft direction. The samples with conductive yarns were more stable, while the other samples showed a low current leakage in the beginning, but after a while the current started to increase drastically over the whole poling process, appendix B. The electrical field during poling was measured, see table 5.4. It was shown that the electrical field at the surface of the textile was higher for samples without integrated conductive yarns compared to the other samples. This might be due to that the yarns with integrated conductive fibres affect the electrical field over the whole length of the woven band. The PVDF fibre in the warp direction will then be subjected to lower electrical field strength.

Another difference in behaviour could also be seen after the corona poling. It was possible to get a voltage output from the whole sample length when a conductive thread was integrated, while from the other samples without conductive fibres a voltage output could only be achieved from the 100 mm that was poled. This might be due to that the conductive fibres were transferring the electrical field during the corona poling process.

6.5 Piezoelectric characterisation

To get higher quality signals from the load put on the samples a high pre-load of 30 N had to be used. This was due to the limitations of the measuring machine, which only had a load-cell of 2.5 kN. The MTS tensile machine had to be used to generate the frequency sweep to determine the cut-off frequency of the samples.

6.5.1 Frequency response

In fig. 5.4 it could also be seen that the samples have different value on the output voltage when exposed to the same frequency and elongation. For the samples woven with twill and also for the samples woven with a weft that has lower tex the output voltage is higher. This is probably due to that the PVDF yarns are straighter in the twill construction compare to the plain weave and also that the weft with lower tex gives lower crimp.

All the samples with integrated conductive fibres as weft do not start at zero during the frequency sweep measurements, in fig. 5.5-5.7 as for the coated samples, in fig. 5.4. This might be due to that the conductive fibres has high
resistance and therefore gets lower connection to the PVDF fibres. The conductive coating and fibres have different coverage on the textile surface, seen in fig. 6.2. Due to the distance to the intersection it takes longer time for the conductive fibres to collect the generated charges compared to the coating, which covers the whole area. It is observed that the samples woven with the twill construction with different conductive fibres in weft do not become stable the higher the frequency gets, they continue to decrease. This behaviour might be connected to the mechanical properties of the woven band, where a hysteresis could be seen in fig. 5.2. The delay of the recovery becomes visual at higher frequencies and therefore the twill curves in fig. 5.5-5.7 are decreasing.

**Figure 6.2: The difference in coverage for the different outer electrodes**

### 6.5.2 Cut-off frequency

In fig. 5.4 the cut-off frequencies of the coated bands could be calculated with equation 4. All the coated samples have a similar cut-off frequency of about 1.2 Hz, and the output voltage starts to be more or less constant at 4 Hz. The frequency response was not as clear for fig. 5.5-5.7 as for the coated bands and therefore the estimation of the cut-off frequency had to be made in another way. By subjecting the samples to a constant strain, as in fig. 5.8-5.11, equation 5 could be used to calculate the cut-off frequency. When comparing the results of the cut-off frequency for the coated bands that are calculated form the different methods there is a difference. This difference can depend on the sensitivity of the measurements. The real peak value of the piezo-signal generated when the sample is subjected to an immediate change in constant strain might be missed, due to the limited time resolution of the measuring device. Probably the real peak value is somewhat higher than the measured peak value, and this uncertainty may explain the somewhat higher estimated cut-off frequency using this method.

From fig. 5.9 and equation 5 the cut-off frequency of the woven bands with Bekintex as weft can be estimated to 0.02 Hz. It can be seen that the cut-off frequency is lower compared to the coated bands. This might be due to that the resistance of the Bekintex fibre is high and therefore it takes longer time for the voltage signal to return to zero.
6.5.3 Constant strain
The sample with integrated Statex fibres takes shorter time to discharge compare
to the samples with Bekintex and Shakespeare, which indicate a higher cut-off
frequency. Again this might be due to the differences in resistance of the
conductive fibres. Statex had lower resistance and therefore it took shorter time to
discharge. For the sample with Shakespeare in fig. 5.11 it can be seen that the
material is charging after it has been subjected to the strain. This behaviour is
inexplicable, but may be due to some sort of contact problem between the PVDF
and the conductive fibre. Another suggested explanation is that friction between
the fibres may generate static electricity.

6.5.4 Dynamic Strain
All the samples were subjected to a dynamic strain of about 0.25% extension
amplitude with a frequency of 4 Hz, as can be seen in fig. 5.12-5.15. The samples
woven with twill gave a larger voltage–strain ratio compared to the other
samples. This can be due to that the PVDF fibres are straighter in the structure
compare to the plain weave and therefore the piezoelectric fibres were subjected
to a higher load.

The voltage output extracted from the weft rib construction became lower than
expected and gave the lower result of the voltage–strain ratio. Before the
characterisation of the samples was made a higher value of the voltage output was
expected due to that the PVDF fibres was more or less straight in the weave
construction and that the value of the cover factor of the conductive weft yarn was
high. A theory why this could not be seen is that the high cover factor of the
conductive weft yarn in the weft rib construction transfers the electrical field from
the PVDF warp yarns during the poling process. Therefore the PVDF will be
subjected to a lower electrical field which result in a lower piezoelectric effect of
the finalised sample. The results from the measurement of the electrical field on
the plain weave and weft rib with integrated Statex yarns as weft are shown in
table 5.4. The weft rib, with higher cover factor, is subjected to a lower electrical
field compared to the plain weave.

The samples with Shakespeare fibres as weft gave the lowest voltage output for
all the different weave constructions. Shakespeare was the conductive fibre that
had the highest resistance of about 5000 Ω/cm. The high resistance limits the
conductive fibre to collect the generated charges created by the PVDF fibre when
it is subjected to a mechanical stress. The electrical field strength during the
corona poling gave the lowest result of 33.3 MV/m. The low electrical field would
have given lower piezoelectric effect.

Some of the samples had a large difference in the result of the voltage–strain ratio,
as can be seen in fig. 5.12 - 5.15. This difference can be due to many aspects, such
as damages of the PVDF bicomponent fibres during weaving, variations in the
poling process, contact with the outer electrode and different tension supplied over the sample during the piezoelectric measurements. It would be ideal if it was possible to use piezoelectric fibres that have been poled before they are integrated into a woven structure, as fewer factors will influence the poling process and the result might be a more uniform effect. It would also make it easier if the whole textile not need to go through the poling process.

6.6 Washability
As can be seen in fig. 5.17 and 5.18 the material is affected when being washed. The washed sample discharge faster compared to the unwashed. This can be due to that the conductive fibres and the PVDF fibres have come closer together after the washing and drying, as can be seen in fig. 6.3.

![Unwashed vs Washed](image)

**Figure 6.3:** Difference in the cross-section of unwashed and washed sample

The faster discharge after the sample has been washed can also be due to that something that hindered the connection between the PVDF and conductive fibre has been washed away. It can be the spin finish and lubrication that was used during melt spinning and weaving. It was also tested to only hand wash the Shakespeare fibre, to see if there was a change. It was shown that the resistance had decreased with 700 Ω/cm.

6.7 Application discussion
The conductive fibres integrated in the textile structure influences the properties of the piezoelectric effect when poled as a finalised weave. However the conductive fibre gave the samples lower cut-off frequency, which makes it possible to use the material when measuring dynamic strain at low frequencies.

The energy harvesting aspect of the produced samples were not investigated in detail. However, from the 30×100 mm sample with Statex as weft it was estimated that about 14 nW could be generated at a tension amplitude of 0.1%. As this tension amplitude is considered to be low the power output of the samples when subjected to higher tension amplitude needs to be further investigated especially as it is not expected to be linear relationship.

There are still much that have to be investigated in order to understand how the different conductive fibres influences the piezoelectric bicomponent fibre, but it has been shown that it is possible to extract a signal when the samples are subjected to a mechanical stress.
At the moment it is difficult to estimate the cost to produce a piezoelectric textile sensor based on the current bicomponent fibre, but the materials used are not that expensive. The cost is in the poling process, but if there is a possibility to develop a continuous poling process that can be performed together with the fibre spinning process the cost could be reduced. The possibility to have the outer electrode integrated in a woven structure with the bicomponent fibre also decreases the number of steps in the process to produce piezoelectric textile sensors. Due to that the conductive coating does not need to be applied as outer electrode. Such improvements of the production process would improve the possibility to integrate textiles sensors in clothes, which would enable e.g. measuring ECG and respiratory signals in sportswear and medical applications.
7. Conclusion
In this report it has been shown that it was possible to create a fully piezoelectric textile sensor with PVDF bicomponent fibre alone in the warp direction with integrated conductive fibres as outer electrode. With few adjustments the weaving process could be improved, to avoid fibre breakage of the PVDF bicomponent fibre and the choice of the weave construction was important for the final result. Some of the weave constructions were clearly unsuitable for the application, due to the cover factor, while some were more suitable, but the effect of the crimp has to be considered.

However there is an uncertainty how the bicomponent fibres are influenced by the integrated conductive fibres and this has to be further investigated. But it can be stated that the resistance and the coverage of the conductive fibres have a large influence.

The weave construction that gave highest piezoelectric output signal was twill with weft that has low tex. The twill construction gave a range amplitude of 1.5-3.3 V when subjected to a dynamic strain of about 0.25% at 4 Hz.

8. Further Research
A continuous fibre poling process should be developed in order to reduce the number of steps in the production of textile sensors based on piezoelectricity. This would decrease the variation in the piezoelectric voltage output for the woven samples, due to that the number of factors that influences the result would be decreased. The possibility to develop prototypes which can lead to a real product would be improved with this rationalization of the processes.

More research is needed to understand how the different conductive yarns influence the PVDF fibres piezoelectric effect. Further, how much does the spin finish that is applied during melt spinning and weaving influence the piezoelectric effect, due to the decreased contact between the PVDF bicomponent fibre and conductive material?

The washability of the piezoelectric textile has to be thoroughly investigated, especially for applications in health care and sportswear. This is not only concerning the hygienic aspect of the textile but also that the developed textile sensors should continue to provide reliable data after several washes.

Energy harvesting is an interesting application and it has to be further investigated how higher tension amplitudes than were used in this study will influence the generated effect.
9. Acknowledgement

I would like to give a huge thanks to all that have taking part in this thesis work and that made it possible to complete. A special thanks to my kind supervisors, Leif Sandsjö, Erik Nilsson and Anja Lund, which have guided and helped me throughout the thesis work. I would like to thank Swerea IVF, for providing material and opportunity to perform my measurements. Thanks Bengt Hagström for your valuable support throughout the project. During the weaving process I got appreciated support and some good laughs to from Fredrik Wennersten, Roger Högberg and Hanna Lindholm at the Swedish School of Textiles. I would also like to thank Swedish ICT ACREO which helped me with some of my measurements.

I want to give a huge thanks to my family and friends, which have supported and made me stay positive.

Karin Rundqvist
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### Appendix A

**Table A.1: Evaluation of the mechanical abrasion**

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Number of damage on the textile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>no visual damages</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>no visual damages</td>
</tr>
<tr>
<td>6</td>
<td>no visual damages</td>
</tr>
<tr>
<td>7</td>
<td>no visual damages</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>no visual damages</td>
</tr>
<tr>
<td>13</td>
<td>no visual damages</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>no visual damages</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>no visual damages</td>
</tr>
<tr>
<td>18</td>
<td>no visual damages</td>
</tr>
</tbody>
</table>
Appendix B

Leakage of current during corona poling

The registered leakage of current during the corona poling of the woven samples can be seen in table B1-B3.

Table B.1: Current leakage during corona poling for weft rib

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Weave construction</th>
<th>Weft material</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Weft rib</td>
<td>Statex</td>
<td>~33 - 43</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Shakespeare</td>
<td>~40</td>
</tr>
</tbody>
</table>

Table B.2: Current leakage during corona poling for plain weave

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Weave construction</th>
<th>Weft material</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Plain weave</td>
<td>PVDF</td>
<td>~40 – 130</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Polyester, monofilament, 15.6 tex</td>
<td>~40 – 120</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Polyester, multifilament, 130 tex</td>
<td>~40 - 147</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Statex</td>
<td>~47 - 53</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Bekintex</td>
<td>~127 - 132</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Shakespeare</td>
<td>~40 - 42</td>
</tr>
</tbody>
</table>

Table B.3: Current leakage during corona poling for twill 3/1

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Weave construction</th>
<th>Weft material</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Twill 3/1</td>
<td>PVDF</td>
<td>~40 - 120</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Polyester, monofilament, 15.6 tex</td>
<td>~40 - 173</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Polyester, multifilament, 130 tex</td>
<td>~40 - 100</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Statex</td>
<td>~40 - 50</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Bekintex</td>
<td>~137 - 153</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Shakespeare</td>
<td>~30 - 37</td>
</tr>
</tbody>
</table>
Appendix C

Figure C.1: Twill construction with different conductive fibres as weft material subjected to a 1.5% extension

Figure C.2: Twill construction with different conductive fibres as weft material subjected to a 3% extension

Figure C.3: Twill construction with different conductive fibres as weft material subjected to a 5% extension
Figure C.4: Plain weave construction with different conductive fibres as weft material subjected to a 1.5% extension

Figure C.5: Plain weave construction with different conductive fibres as weft material subjected to a 3% extension

Figure C.6: Plain weave construction with different conductive fibres as weft material subjected to a 5% extension
Figure C.7: Plain weave construction with different conductive fibres as weft material subjected to a 1.5% extension

Figure C.8: Plain weave construction with different conductive fibres as weft material subjected to a 3% extension

Figure C.9: Plain weave construction with different conductive fibres as weft material subjected to a 5% extension
Appendix D

Figure D.1: The amplitude of the piezo-signal for the twill 3/1 with conductive silicone rubber as coating and polyester 15.6 tex as weft, is 2.9 V, subjected to strain amplitude of about 0.25%.

Figure D.2: The amplitude of the piezo-signal for the twill 3/1 with Bekintex is 3.8 V, subjected to strain amplitude of about 0.25%. In the diagram it can be seen that the piezo-signal is not stable around the zero line.
Figure D.3: The amplitude of the piezo-signal for the twill 3/1 with Statex is 2.5 V, subjected to strain amplitude of about 0.25%. In the diagram it can be seen that the piezo-signal is not stable around the zero line.

Figure D.4: The amplitude of the piezo-signal for the twill 3/1 with Shakespeare is 1.6 V, subjected to strain amplitude of about 0.25%. In the diagram it can be seen that the piezo-signal is not stable around the zero line.
Appendix E

Figure E.1: Resistance and capacitance of the twill 3/1, with Shakespeare as weft

Figure E.2: Resistance and capacitance of the twill 3/1, with Statex as weft