Czech University of Life Sciences Prague

Faculty of Forestry and Wood Sciences

Department of Wood Products and Wood Constructions

Diploma Thesis

Optimization process of natural-fibre nonwovens

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DIPLOMA THESIS ASSIGNMENT

Bc. Štěpán Hýsek

Wood Engineering

Thesis title

Optimization process of natural-fibre nonwovens

Objectives of thesis

The objective of this study is the processing of air-laid nonwovens using the natural fibres hemp and flax. The main goal is the improvement of properties of nonwovens manufactured with a small-size air-laying nonwoven machine and optimization of nonwoven fabrication with this air-laying machine.

Methodology

In the first part of the study is worked out a literary research about nonwoven fabrication. In the practical part of the study experiments are carried out with the SPIKE® air-laying machine from the Formfiber Denmark APS company and properties of nonwovens are observed. On the ground of these observations the nonwoven fabrication process can be optimized.

The proposed extent of the thesis

60-80 pp

Keywords

air-laying, flax, hemp, natural-fibre, nonwoven

Recommended information sources

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Declaration

I declare that I have worked on my diploma thesis titled "Optimization process of natural-fibre nonwovens" by myself and that I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not violate the copyrights of any third party.

In Prague, on 20th April 2016 ______________________________

Štěpán Hýsek

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Optimalizace výroby netkaných textilií z přírodních vláken

Optimization process of natural-fibre nonwovens

Abstrakt

Tato diplomová práce se zabývá výrobou netkaných textilií z přírodních vláken (konopí a lnu) pomocí aerodynamické vrstvící technologie. Práce je rozdělena na část teoretickou a praktickou. První část práce pojednává o problematice přírodních vláken a výrobě netkaných textilií a v navazující experimentální části jsou popsány prováděné experimenty týkající se optimalizace vlastností netkaných textilií z přírodních vláken. Pro vrstvení vlákenného rouna byla použita aerodynamická vrstvící technologie SPIKE®, kterou dodává firma Formfiber Denmark ApS. Vlastnosti netkaných textilií byly sledovány před i po zpevňování vlákenného rouna, k němuž byla použita vpichovací technologie. Rovněž byl hodnocen proces formování vlákenného rouna. Z výsledků plyne, že nastavení vrstvícího stroje má vliv na formování vlákenného rouna a vlastnosti netkaných textilií. Na základě rozsáhlých experimentů bylo definováno několik nastavení vrstvícího stroje, která jsou vhodná pro výrobu netkaných textilií s vysokou hustotou, s dobrými tahovými vlastnostmi nebo která zvyšují produktivitu vrstvení. Některé výsledky jsou negativně ovlivněny velkým rozptylem plošné hmotnosti netkaných textilií. Pro snížení rozptylu plošné hmotnosti vyráběných textilií byla linka pro výrobu netkaných textilií v dané laboratoři modernizována.

Abstract

The presented diploma thesis deals with the processing of air-laid nonwovens using the natural fibres of hemp and flax. Firstly, a literary search dealing with natural fibres and nonwoven fabrication was obtained. Secondly, extensive investigations of natural-fibre nonwoven optimization were designed. SPIKE® air-laying technology from the Formfiber Denmark ApS Company was used. The web-formation processes and the properties of the fibre-webs were evaluated. After needle-punching, the properties of the reinforced fibre-mats were evaluated. The investigations have clearly revealed that the settings of the air-laying machine affect web-formation process and nonwoven properties. On the grounds of monitoring of web-formation processes and evaluating of fibre-web or fibre-mat quality, several machine settings that can be used to enhance productivity of the machine, or settings that are suitable for fabricating nonwoven fabric with high density or great tensile properties were defined. Some results are negatively influenced by fluctuations of fabric basis weight, and in order to eliminate these fluctuations the nonwoven production line in the laboratory was modernized.

Klíčová slova: vzdušné vrstvení, len, konopí, přírodní vlákna, netkaná textilie

Keywords: air-laying, flax, hemp, natural-fibre, nonwoven

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1 Introduction

1.1 Introduction

In recent years, environmental legislation and consumer pressure have increased pressure on manufacturers of materials and end-products to consider the environmental impact of their products during all stages of their life-cycle. Eco-design is currently becoming a philosophy that is applied to more and more materials and products. In view of this, natural fibres based on lignocellulose, such as flax, hemp, jute, sisal, abaca, cotton, coir, or kapok have received considerable attention as an environmentally-friendly alternative for the use of glass fibres in engineering materials, especially as reinforcement in composites (Garkhail *et al.*, 1999; Maity *et al.*, 2014; Yan *et al*., 2014). The usage of natural fibres in nonwovens has increased remarkably during the last few years, but the overall market share of these fibres is lower than that of man-made fibres. Natural fibres can be utilized in many industries, for example in the automotive, construction, marine, acoustic and electronic applications industries. Some natural fibres are cheaper than conventional synthetic fibres, and since they have the potential to be recycled and are eco-friendly through their biodegradability, renewability and lower energy consumption from fibre growing into finished products, they also find application due to these added advantages (Das *et al*., 2012; Maity *et al.*, 2014; Sgriccia, 2008). However, there are problems with natural fibres, and these often relate to their non-uniformity in physical properties, quality variation based on region of origin, deterioration of physical properties from exposure to moist conditions and lower resistance to microbial attack (Anandjiwala and Blouw, 2007; Das *et al.*, 2012).

This study is concerned with air-laying nonwoven fabrication and evaluation of nonwoven properties. The main aim of the study is to improve nonwoven properties via air-laying machine optimization. The SPIKE® air-laying technology from the Formfiber Denmark ApS Company was used. The technology is based on dry forming of a fibre web in a forming box. Fibre-separating rollers (spike rollers) singularise fibres from fibre clumps (Andersen, 2009). The technology can produce mats from natural fibres, as well as synthetic fibres or recycled fibres.

1.2 Objectives of the thesis

The presented thesis deals with the processing of air-laid nonwovens using the natural fibres hemp and flax. The main goal of this research is to improve the properties of nonwovens manufactured with a small-size air-laying nonwoven machine and optimization of nonwoven fabrication with this air-laying machine. In order to achieve the target of the study, partial questions must be answered: how do the particular machine components affect nonwoven properties? What function do the particular machine components have? What is the fibre trajectory and process time in the machine? There are two kinds of machine settings parameters that affect web quality: velocity and direction parameters. These parameters should be optimized. The working hypothesis can be defined in the following form:

$$H^*: Machine\ settings\ affect\ nonwoven\ quality.$$

2 Theoretical part

2.1 Materials for nonwoven fabrics – natural fibre

Nonwovens can be fabricated from natural fibres as well as synthetic fibres. This study is concerned with natural fibres, and therefore the category of natural fibres is described further. Natural fibres are generally classed as either of vegetable or animal origin. Vegetable fibres are composed of cellulose, whilst animal fibres are composed of proteins (Dicker *et al.*, 2014). In his Handbook of Textile Fibres, J. Gorgon Cook states natural fibres of mineral origin as well. Natural fibre of vegetable origin can be defined as fibrous plant material produced as a result of photosynthesis. Another general term used for natural fibres of vegetable origin is lignocellulosic fibres. There are two general classifications of plants producing natural fibres: primary and secondary. Primary plants are grown for their fibre content while secondary plants are those where the fibres come as a by-product from some other primary utilization. Jute, hemp, kenaf, sisal and cotton are typical primary plants, while pineapple, cereal stalks, agave, oil palm or coir are examples of secondary plans. However, categorization of some plants into the classes can be dual (Pickering, 2008).

2.1.1 Fibre types

The most common classification for natural fibres of vegetable origin is by botanical types. Using this system, there are six basic types of natural fibres:

- bast fibres
- leaf fibres
- seed fibres
- core fibres
- grass and reed
- all other types such as wood and roots

Some duals can also arise by this classification – some plants yield more than one type of fibre. For example jute, flax, hemp and kenaf have both bast and core fibres, whiles agave, coconut and oil palm have both fruit and stem fibres (Pickering, 2008).

Bast fibres such as jute, flax, hemp, ramie and kenaf come from the inner bark or phloem of dicotyledonous plants. These fibres lay under a thin bark and exist as fibre bundles and run parallel to the stem. Leaf fibres run lengthwise through the leaves of monocotyledonous plants, for example banana, sisal, agave and pineapple. Seed or fruit fibres are such as coir, cotton and kapok are widely used in the textile industry, one of them – cotton has become the most important textile fibre in the world. Core fibres such as kenaf, hemp and jute have bundles of fibres in the core of the stem. For example wheat, corn and rice belong to the grass and reed group (Cook, 2003; Pickering, 2008).

Flax

Flax (*Linum usitatissimum* L.) is one of the most widely utilised natural fibres. Flax is also one of the first to be extracted, spun and woven into textiles. In recent years, the use of flax fibres has gained popularity due to an increasing requirement for developing sustainable materials. Flax fibres are cost-effective and offer specific mechanical properties comparable to those of man-maid fibres. Fine and regular long flax fibres are usually spun into yarns for linen textiles. Linen fabric maintains a strong traditional niche among high quality household textiles (bed linen). Shorter flax fibres produce heavier yarns suitable, for example, for sails, tents and canvas. Even lower fibre grades are used as reinforcement and filler in composites mainly in automotive interior substrates and furniture (Yan *et al*., 2014). Linen is about 20% stronger when wet than dry, which helps it to withstand mechanical treatment in laundering (Cook, 2003).

Like cotton, flax fibre is formed from a cellulose polymer, but its structure is more crystalline, making it stronger, crisper and stiffer to handle and more easily wrinkled. Flax plant ranges in length up to 90 cm and possesses strong fibres all along its stem with a fibre diameter of 12–16 μm. At the macroscopic level a flax stem is composed of bark, phloem, xylem and a central void. At the meso-scopic level of the cross-section of a bundle contains 10 – 40 fibres which are linked together mainly by pectin. In Fig. 1 is shown a section of a stem of a flax plant. Bundles of fibre cells lie below the surface layer (Cook, 2003; Yan *et al*., 2014).

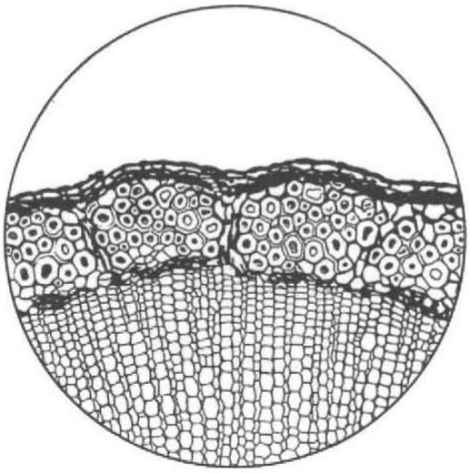

Figure 1 Section of a stem of a flax plant, Cook 2003

The flax fibre on the microscopic scale is displayed in Fig. 2. Each elementary fibre is made of concentric cell walls. At the centre of the fibre are concentric cylinders with a small open channel in the middle called the lumen, which contributes to water uptake. The outer cell wall, designed as the primary cell wall, is only 0.2 µm thick. This cell wall coats the thicker secondary cell wall, which is responsible for the strength of the fibre and encloses the lumen. The secondary cell wall (S2) contains numerous crystalline cellulose micro-fibrils and amorphous hemicellulose which are oriented at 10° with the fibre axis and give fibre its high tensile strength (Yan *et al*., 2014).

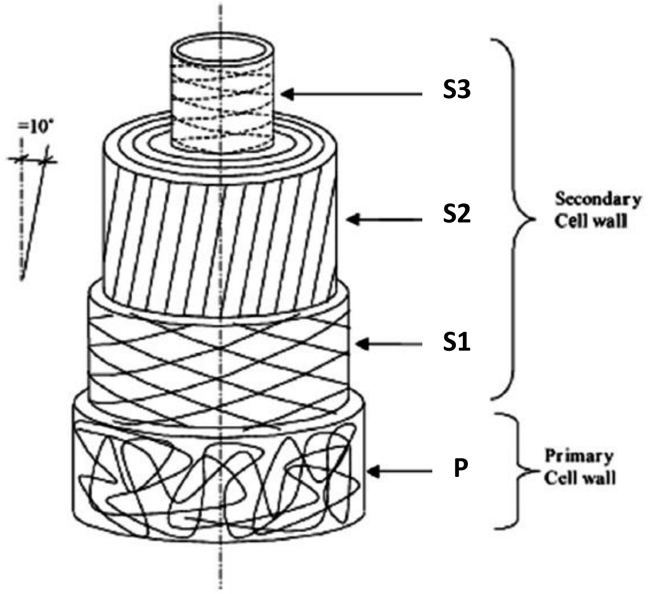

Figure 2 The microstructure of a flax cell, Yan *et al*. 2014

Hemp

Canabis sativa L. subsp. *sativa* var. *sativa* is the variety grown for industrial fibre. It is an annual plant that is grown in temperate climates mainly in Europe, Canada and China. The plant has become very popular because it grows fast, produces very strong fibres and fibre yield can be as high as 900 – 2600 kg/ha. It has a long traditional use as a textile fibre and for canvas or ropes. There is a small market for hemp paper, used for cigarette paper (Pickering, 2008). The high strength and stiffness of hemp fibres also makes them a useful material to be used as reinforcement in composite materials. There has been an exponential increase in the use of hemp for various applications in recent years. In hemp plant, fibres are contained within the tissues of the stem which help to hold the plant erect. These fibres impart strength and stiffness to the tree. Fig. 3 shows a hemp stalk where the outer bast fibres are separated from the inner core (Shahzad, 2012).

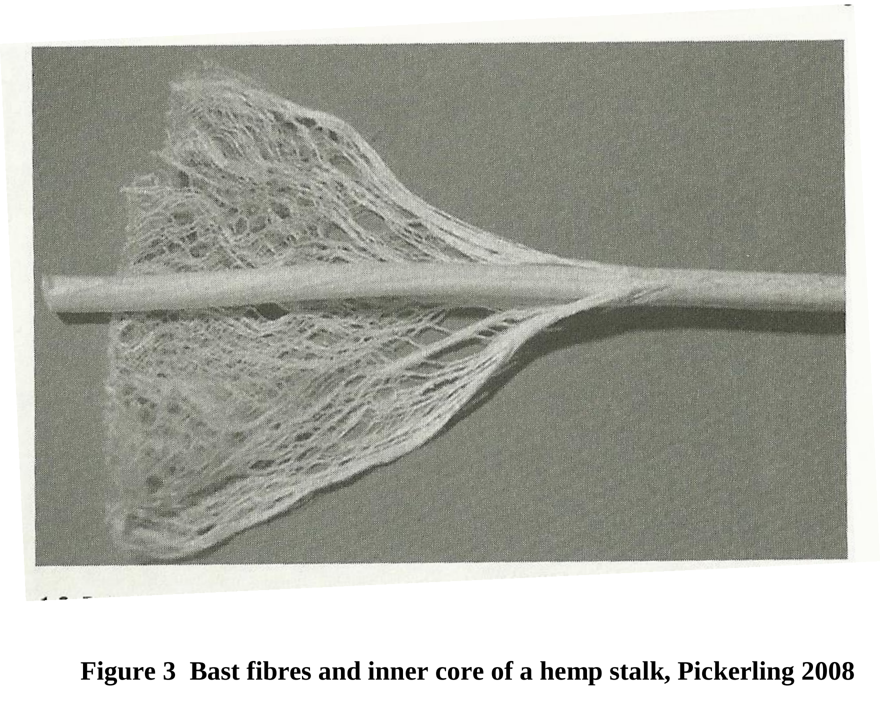

Figure 3 Bast fibres and inner core of a hemp stalk, Pickerling 2008

Hemp has coarser fibres than flax. The fibres are dark in colour and difficult to bleach, and they are strong and durable. Strands of hemp fibre may be 2 m in length; the individual cells are 13 – 26 mm long. They are cylindrical in shape, with joints, cracks or swellings on the surface. Like flax, the cells of hemp fibre are thick-walled and polygonal in the cross-section (Fig. 4). The lumen is broader than that of flax. Hemp fibres are more lignified than flax, and are consequently stiffer (Cook, 2003). The chemical composition of both hemp and flax fibres is presented in Table 1.

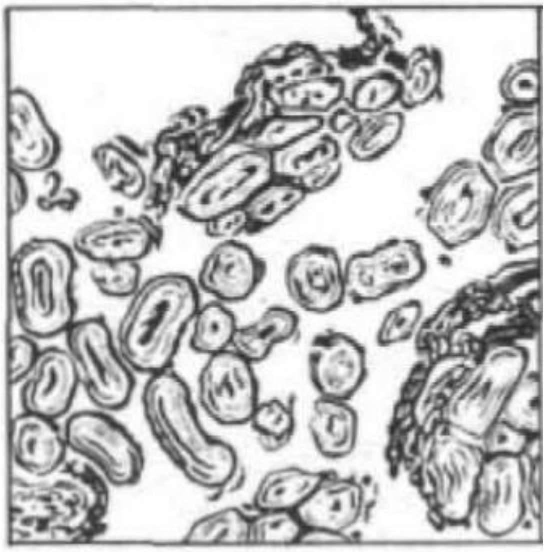

Figure 4 Cross-section of hemp fibres, Cook 2003

Table 1 Chemical composition of flax and hemp fibres, Shahzad 2012; Yan *et al*. 2014

Type of fibre	Cellulose [%]	Hemicellulose [%]	Lignin [%]	Pectin [%]
Flax	65 - 75	11 - 21	2 - 5	2
Hemp	55 - 78	11 - 22	3 - 8	1 - 2

2.1.2 Advantages and disadvantages of natural fibres

Lignocellulosic natural fibres such as sisal, coir, jute, ramie, pineapple leaf and kenaf have the potential to be used as a replacement for glass or other traditional materials. These fibres have many properties which make them an attractive alternative to traditional materials; they have high specific properties such as stiffness, impact resistance, flexibility and modulus. The comparison between some material and mechanical properties of E-glass and natural fibres is listed in Table 2. The densities of a variety of materials are plotted against Young's modulus using Ashby plots on Fig. 5.

Natural fibres are also available in large amounts and are renewable and biodegradable. Compared to traditional materials, other desirable properties are low cost, low density, biodegradability, renewability, non-toxicity, less equipment abrasion, less skin and respiratory irritation, vibration damping, enhanced energy recovery and low embodied energy and CO_2 emissions. Fig. 6 plots the production cost of a variety of materials against tensile strength (Dicker *et al.*, 2014; Sgriccia *et al.*, 2008). Disadvantages include low degradation temperatures (ca. 200 °C), which make them incompatible with thermosets that have high curing temperatures. There are several other challenges presented by natural fibres such as large variability of mechanical properties (discussed below in this paper), lower ultimate tensile strength, lower elongation, problems with nozzle flow in injection moulding machines, problems with storing of raw material, bubbles in the product and poor resistance to weathering (Anandjiwala and Blouw, 2007; Sgriccia *et al.*, 2008).

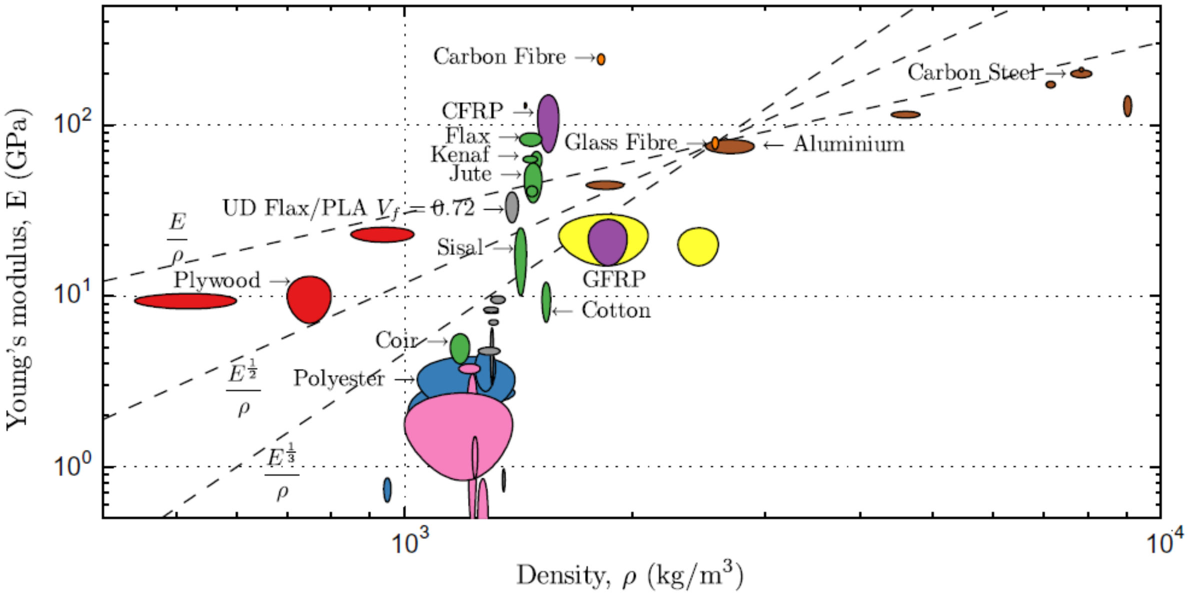

Figure 5 Ashby plots of Young's modulus compared to density of a variety of materials, Dicker *et al.* 2014

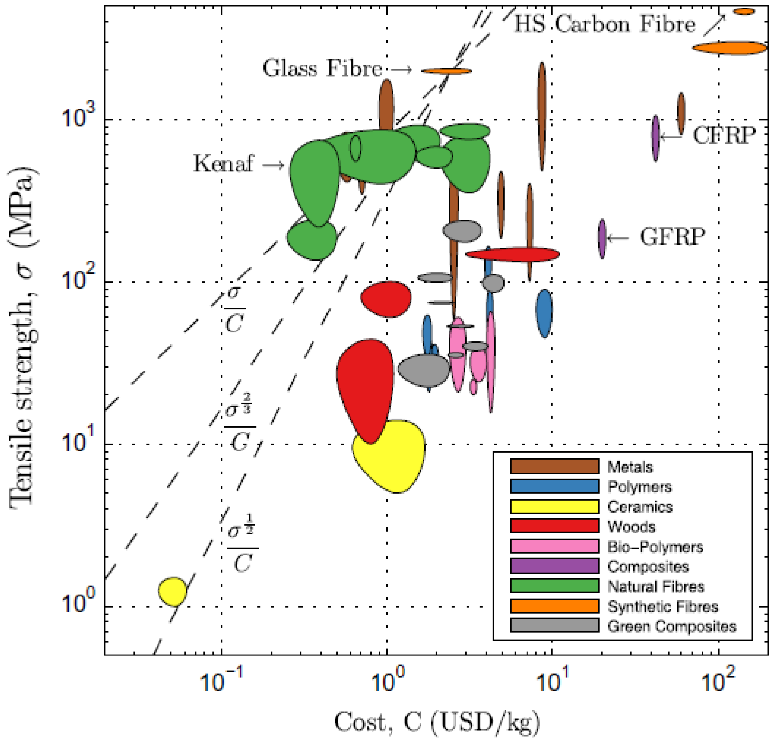

Figure 6 Ashby plots of tensile strength compared to costs of a variety of materials, Dicker *et al.* 2014

Table 2 Properties of E-glass and other natural fibres, Cheung 2009; Yan *et al.* 2014

Properties/fibres	E-glass	Hemp	Jute	Ramie	Coir	Sisal	Flax	Cotton
Density[g·m^{-3}]	2.55	1.48	1.46	1.5	1.25	1.33	1.4	1.51
Tensile strength [MPa]	2400	550-900	400-800	500	220	600-700	800-1500	400
Tensile modulus [GPa]	73	70	10-30	44	6	38	60-80	12
Elongation at break [%]	3	1.6	1.8	2	15-25	2-3	1.2-1.6	3-10
Diameter [µm]	< 17	25-600	20-200	20-80	10-460	8-200	12-600	10-45
Moisture absorption [%]	-	8	12	12-17	10	11	7	8.25

2.2 Definition of nonwovens

Nonwovens can be described as three-dimensional anisotropic structures made from fibres orientated in preferential or random directions and bonded by thermal, chemical, mechanical entanglement, or a combination of these techniques (Rawal et *al*., 2010). They are unique, high-tech, engineered fabrics which are used across a wide range of applications and products (EDANA, 2015). In the international standard ISO 9092:2011, nonwovens are defined as structures of textile materials such as fibres, continuous filaments, or chopped yearns of any nature or origin that have been formed into webs by any means, and bonded together by any means, excluding the interlacing of yearns as in woven fabric, knitted fabric, laces, braided fabric or tufted fabric. There are three major methods of nonwoven fabrication, and according to these three fabrication methods, nonwovens can be divided into three areas: dry-laid, wet-laid and polymer-laid. It can be stated in a simplified way that dry-laid nonwovens have their origin in textiles, wet-laid materials in papermaking and polymer-laid in polymer extrusion and plastics (Russell, 2007).

2.3 Processes for nonwovens

2.3.1 Opening and mixing of fibres

The goal of this manufacturing step is to maximise the degree of opening at a particular opening device whilst minimising the associated fibre damage, particularly fibre breakage. Bale breakers are used as the first step in a nonwoven process line. These devices break down big and very dense bales into manageable clumps, and they pneumatically feed these at a relatively consistent flow rate to the opening machine. A bale opener is shown in Fig. 7.

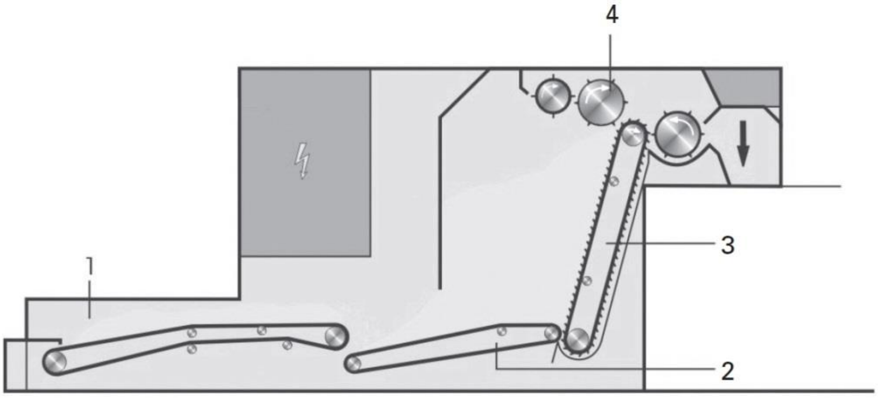

Figure 7 Bale opener, Russell 2007
1 – feed table, 2 – feed lattice, 3 – spiked lattice, 4 – evener roller

Another system of initially treating bales is the utilization of bale pickers. Rows of bales are positioned in line formation and a mechanical picking device traverses across the top of bales and removes uniform small tufts. Rotating spiked rollers set on a pivot arm inside the bale picker head are used. This device can produce a well-distributed mix of fibre tufts (Batra and Pourdeyhimi, 2012; Russell, 2007). The fibre opening process is required to gradually reduce the size of the fibre tufts that are produced by bale openers or bale pickers. Spiked, pinned or saw-tooth metallic clothing is used to open the fibres gradually. Both mechanical and aerodynamic forces of action are involved in opening of fibres (Das e*t al*., 2012). A schematic view of a fibre opener with pneumatic doffing is shown in Fig. 8.

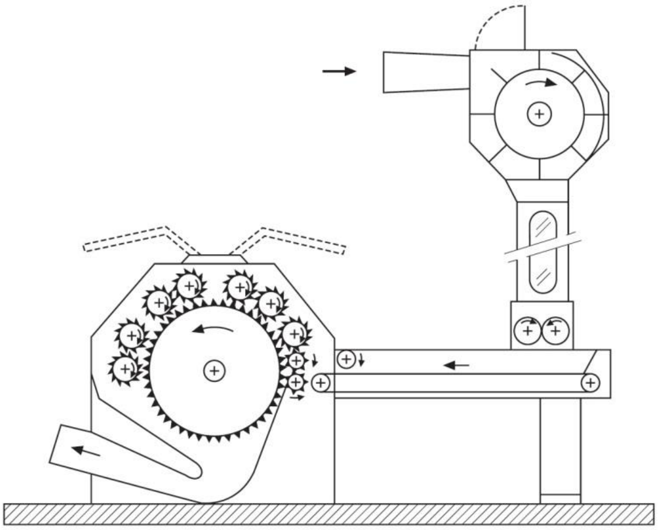

Figure 8 Fibre opener, Russell 2007

After these processing steps, different fibre types, grades or dimensions can be blended to obtain a particular combination of physical properties in the final fabric. The properties of nonwoven fabric are fundamentally a function of the blend composition, and poor blending leads to various processing and quality problems. Multi-hopper systems can be used for blending purposes. These machines weigh fibres and subsequently batch them on the conveyor, as show in Supplement 1 (Russell, 2007).

2.3.2 Web-formation processes

Carding process

Parallel-laid webs in which the fibres are preferentially oriented in the machine direction are produced directly from carding and related processes. The purpose of carding is to disentangle and mix fibres to form a homogeneous web of uniform basis weight. Generally, every roller card has a central cylinder or swift that is the largest roller. Smaller satellite rollers, called workers and strippers, are situated around the cylinder, and they carry out the basic function of working and stripping. A card configuration is shown in Fig 9.

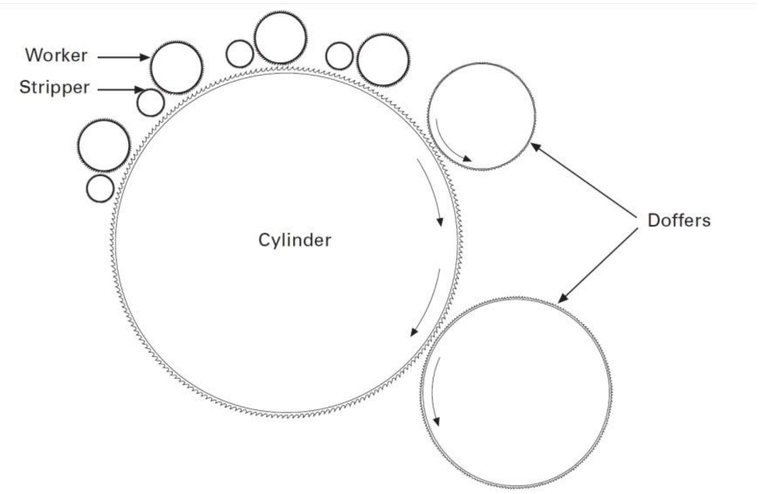

Figure 9 Card configuration, Russell 2007

The cylinder is the central distributor of fibres during the process. The worker-stripped pairings around the perimeter of the cylinder have both a carding and mixing function. The doffer rollers condense and remove fibre from the cylinder in the form of a continuous web. A detailed schema of the interaction between card rollers is shown in Fig 10. The cylinder conveys fibres towards the worker, and as the fibre passes the worker teeth, some of it is trapped on the worker teeth, whose surface speed is slower than that of the cylinder. Before the worker teeth get back to the cylinder, the fibre must be removed; otherwise the worker will continue to collect fibre until it becomes full. The role of the stripper is to remove fibre from the worker and to re-present the fibre back onto the cylinder. This series of actions represents the fundamental function of a carding machine. Fibres are worked and stripped within a carding machine until the fibres are so uniformly distributed and individualised that a homogenous web can be formed. The function of a doffer is than to remove fibre from the cylinder and to produce a continuous web (Batra and Pourdeyhimi, 2012; Russell, 2007). The challenge in carding is to achieve high production speeds whilst simultaneously maintaining uniformity. The roller speed cannot be increased much; otherwise there will be unacceptable fibre damage. However, multiple doffers and increasing the number of worker-stripper rollers can be used to enhance the transfer efficiency and carding action, resulting in a higher production rate (Das *et al*., 2012).

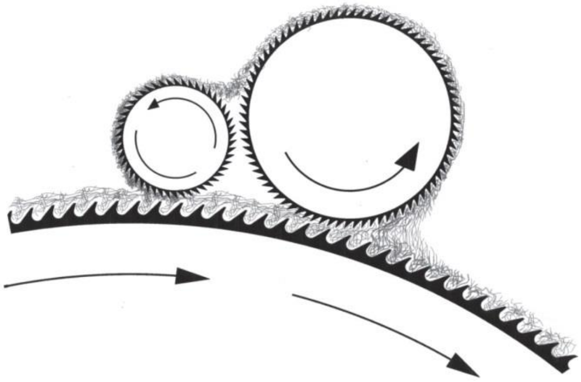

Figure 10 Interaction between card rollers, Russell 2007

Air-lay process

Air-laying (aerodynamic or air-laid web formation) refers to a family of dry-laid web formation processes. A characteristic feature of air-laid webs is their isotropicity - air-laid webs are frequently referred to as random-laid. Air-lay processes are highly versatile in terms of their compatibility with different fibre types and specifications. This versatility partly arises from the principles of fibre transport and deposition, as well as the variety of machine designs (Russell, 2007). Furthermore, using air-lay technology, it is possible to produce soft, voluminous and high-loft structures. Through this technology, isotropic nonwovens can be produced at lower basis weight, and the webs also have good compressibility (Das *et al*., 2012). However, fabric uniformity is highly dependent on fibre opening, and individualisation prior to web forming and fibre entanglement in the air stream can lead to web faults (Russell, 2007). There is no such thing as a standard air-laying machine; the following text describes some representative kinds. Cleaned, opened or individualised fibres are transported to the web forming section by free fall, compressed air, air suction, closed air circuit or a combination of compressed air and air suction systems. The principle of web formation using a suction assisted lending area is schematically shown in Fig. 11. Fibres are fed into a pair of feed rollers which are designed to grip the fibre and prevent large clumps from being drawn into the system. The rotating drum removes fibres from the fringe presented by the feed rollers and the fibres are transported by hooking around the wire teeth on the drum and are subsequently removed via a high-velocity airstream. The air is separated on the air permeable conveyor and the fibres are deposited to form the web structure (Russell, 2007).

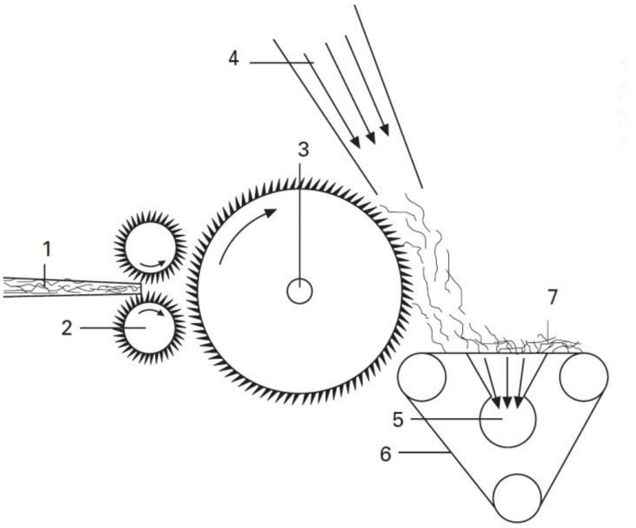

Figure 11 Principle of air-laying, Russell 2007
1 – pre-made batt, 2 – feed roll, 3 – main cylinder, 4 – air blower, 5 – suction, 6 – conveyor belt, 7 – air-laid web

The Rando-webber aerodynamic web forming methods are shown in Supplements 2 and 3. Webs of 10 – 3000 g·m^{-2} can be produced by model A, and model B is used to form webs with very low to zero crimp. Fig. 12 shows an apparatus for producing air-laid structures composed of two or more separated layers of different randomly orientated fibres (Russell, 2007). Spike air-laying technology from the Formfiber Denmark ApS company is described below in this thesis.

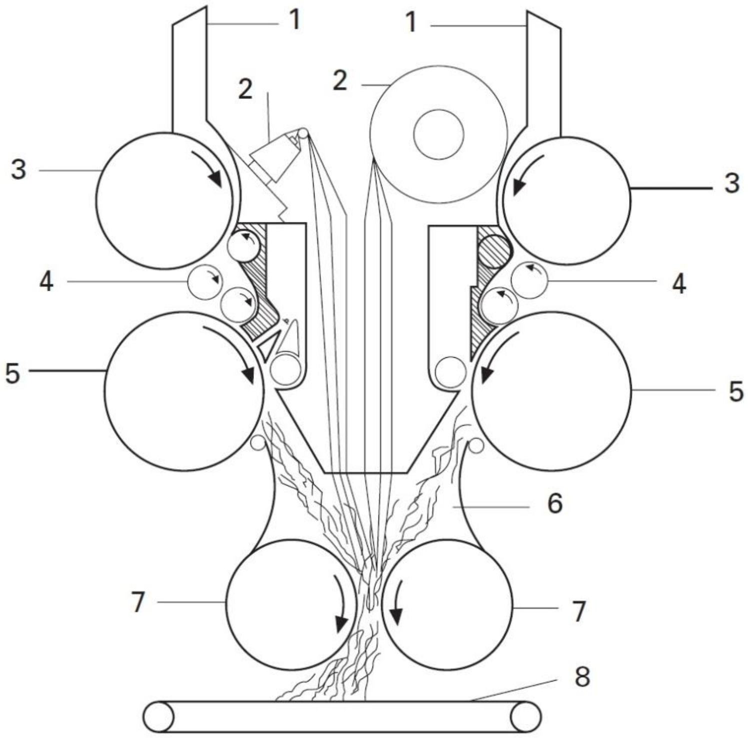

Figure 12 Apparatus for producing composite web structure, Russell 2007
1 – feeding chutes, 2 – filament supply unit, 3 – condenser rolls, 4 – feed rolls, 5 – conventional licker-in, 6 – fibre transport chamber, 7 – condenser rolls, 8 – landing conveyor

Wet-lay process

In the wet-lay process, individual fibres or clusters of fibres are integrated to a continuous form in water as a medium. Any fibre able to be dispersed in water can be used, but short to medium length fibres are preferred. The fibres are first homogeneously dispersed in water by means of strong agitation, and then they are collected over a moving perforated plate in consolidated form by separating them from water through filtration and drainage. Although water is mainly removed by gravity, suction or pressure systems are used to ensure better water extraction from the fibre aggregate, followed by heating. The main characteristics of the wet-lay process lie in very high production rates coupled with an extremely uniform fabric. The main disadvantage is the requirement of huge quantities of water and high energy consumption during drying (Das e*t al*., 2012). Early attempts by companies to enter the wet-laid nonwovens sector were based on use of old, fully depreciated paper machines (Russell, 2007). However, nonwovens that are produced from synthetic fibres and from difficult to disperse furnishes are produced at higher levels of dilution, and by machines specially designed for this purpose. These wet-laid machines operate at much lower consistencies than traditional paper machines. Paper machines operate at consistencies in the range of 0.3 – 0.8% fibres by weight. The wet-laid nonwoven machines can operate at consistencies below 0.1% in order to get good dispersion of the fibres. Fig. 13 shows this kind of wet-laid machine (Hutten, 2007).

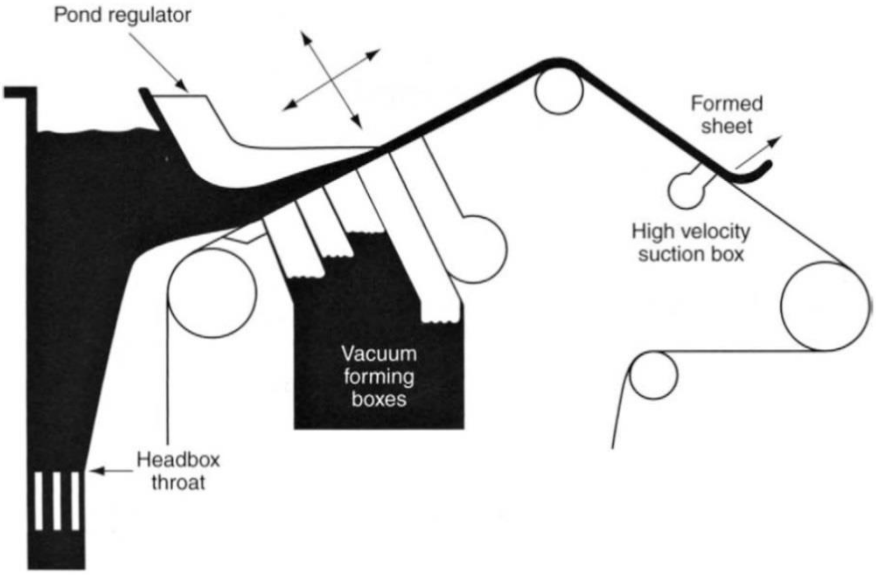

Figure 13 Headbox for wet-laying, Hutten 2007

Polymer-lay process

Polymer-laid nonwovens are produced by extrusion spinning processes, and filaments are directly collected to form a web instead of being formed into tows or yarns as in conventional spinning. Due to the elimination of the intermediate steps, these processes are the most efficient methods of producing fabrics. There are two main polymer-laid processes: spunbonding and meltblowing (Russell, 2007). The spunbonding process consists of the following basic stages: filament extrusion of molten polymer through a spinneret, drawing by rollers, laying down over a forming screen and bonding (Das e*t al.*, 2012). The basic stages in the production of spunbond fabrics are shown in Supplement 4. Meltblowing is a one-step process for converting polymer granules into nonwoven materials. In this process, the polymer is extruded through die into a high-velocity stream of hot air, which draws the emerging polymer into fine and relatively short fibres. When the fibres reach the collector screen they are solidified, randomly deposited and self-bonded (Das *et al.*, 2012). This process is schematically shown in Fig. 14.

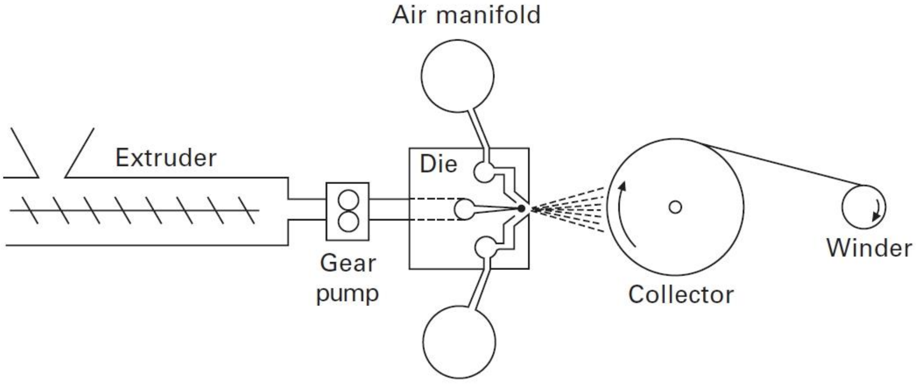

Figure 14 Scheme of meltblowing process, Russell 2007

2.3.3 Web-bonding processes

Needle-punching process

In this process, fibres are mechanically entangled in a web in order to produce a fabric by reciprocating barbed needles, called felting needles. The needle-punching machine is illustrated in Fig. 15. The barbed needles are clamped into a board which oscillates vertically between two fixed plates; each plate is drilled with corresponding holes through which the needles move. As the web moves through the loom, more fibres are progressively entangled and a coherent fabric is formed. The action of a barbed needle is shown in Supplement 5. There are single-board or multi-board needle-punching machines. Some common sequences of needle-punching machines are shown in Supplement 6 (Russell, 2007). An important factor that characterizes the needle-punching process is punch density. Higher punch densities result in denser fabrics with higher tensile strength and other properties such as abrasion resistance, bursting strength and tear resistance, but also results in greater amounts of fibre damage and fibre breakage. With increasing punch density, the strength of nonwoven fabric reaches its maximum and then falls (Das *et al*., 2012). Needle-punching is the second most popular technique after spunbonding and is widely used in various engineering applications (Midha and Mukhopadyay, 2005).

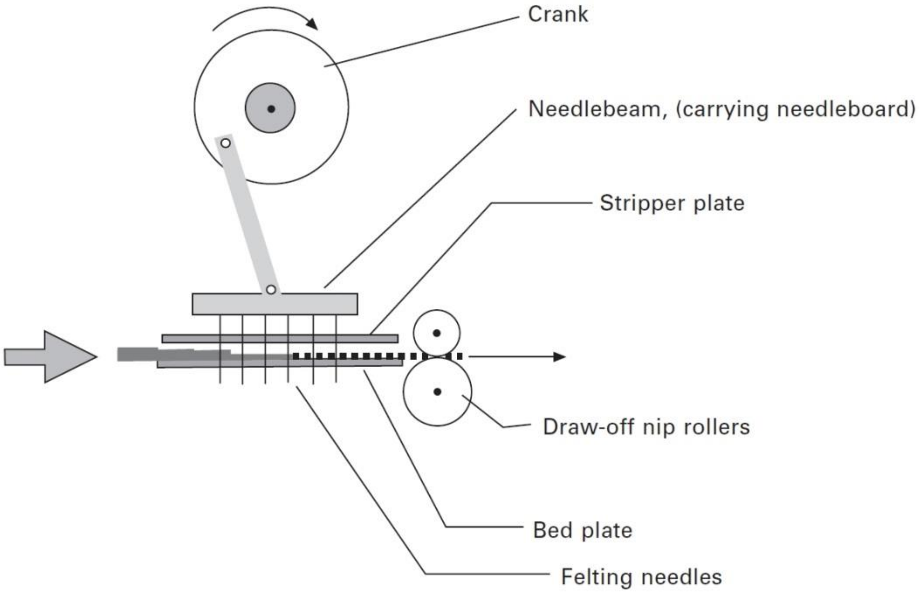

Figure 15 Scheme of needle-punching machine, Russell 2007

Hydroentanglement process

The hydroentanglement process uses water jets to create entanglement among fibres and provides integrity to the structure in place of needles in needle-punching technology. Any type of web can be used. Dry-laid webs such as carded and air-laid and wet-laid webs are mostly used as feed materials, but spunbond and meltblown structures are also used (Das e*t al*., 2012). The principle of hydroentanglement is shown in Fig 16. A curtain of multiple high-pressure columnar water jets is produced by pumping water through capillary cone-shaped nozzles in a jet strip. These jets are directed at a web supported on a moving conveyor, which may be a flat bed or cylindrical surface. Fibre entanglements are introduced by the combined effects of the incident water jets and the turbulent water created in the web. De-energised water is drawn into the vacuum box for recycling and reuse. Some of the remaining process water continues with the web, and this has to be removed and dried up. Removing water via suction is very effective for synthetic fibres and reaches values well below 100%. For hygroscopic fibres, the water content is much higher after mechanical extraction, which places a high demand on the subsequent drying process (Russell, 2007). The hydroentangled fabric possesses excellent flexibility, absorbency and high strength. The drawbacks of the process are related to vacuum extraction, filtration of water, recirculation of water and web drying, which result in high-energy consumption (Das *et al*., 2012).

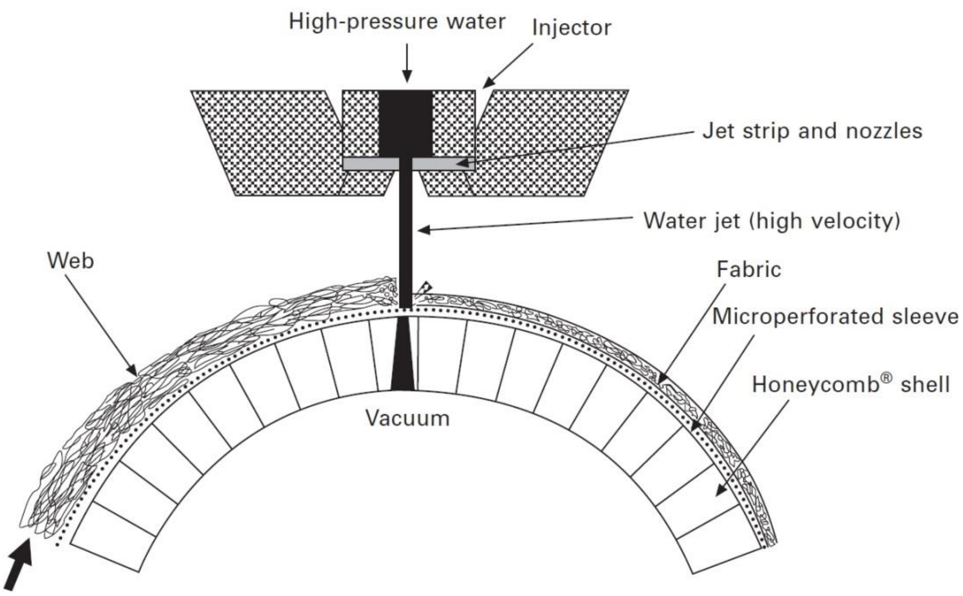

Figure 16 Principle of hydroentanglement, Russell 2007

Thermal-bonding process

Thermal bonding requires a thermoplastic component to be present in the web. Heat is applied until the thermoplastic component becomes viscous or melts, and the polymer flows via surface tension and capillary action to fibre crossover points where bonding regions are formed. Bonds are fixed by subsequent cooling. Thermally bonded fabrics are produced both from thermoplastic materials and from fibres that are not intended to soften or flow on heating. The binder fibre component ranges from 5 – 50%, the percentage depends on the physical property requirements of the final product. There are different methods of applying heat energy to the web. Widely used methods are calendar bonding, which is contact bonding, through-air bonding and thermal radiation bonding (Russell, 2007).

Chemical-bonding process

In chemical-bonding, adhesive materials (binder polymers) are used to bind and hold the fibrous materials together. An adhesive or a binder is applied by saturation, foam, spraying, coating or printing. After applying the adhesive, the next step is the removal of the solvent, coagulation of the adhesive and drying and acceleration of bond formation between the binder and web through curing. It is very difficult to get uniform bonding across the thickness of fibrous webs. Even during drying, the binder tends to move towards the surface of the fabric, resulting in lower binder levels in the core layer of the nonwoven (Das *et al*., 2012). Saturation bonding involves the complete immersion of the web in a binder bath, or by flooding the nonwoven as it enters the nip of a pair of rolls. A basic principle of applying a binder by this method is illustrated in Fig. 17. Foam bonding seams similarly to saturation; only foamed polymer is used. In spray bonding, binder is sprayed onto moving web in fine droplet form. This technique is used to make highly porous and bulky products. Binder systems are applied at levels from 5 – 150% on dry weight of fabric. A low binder addition is often sufficient to bond fibres at the surface, while high binder addition is used to make stiff reinforcement components (Russell, 2007).

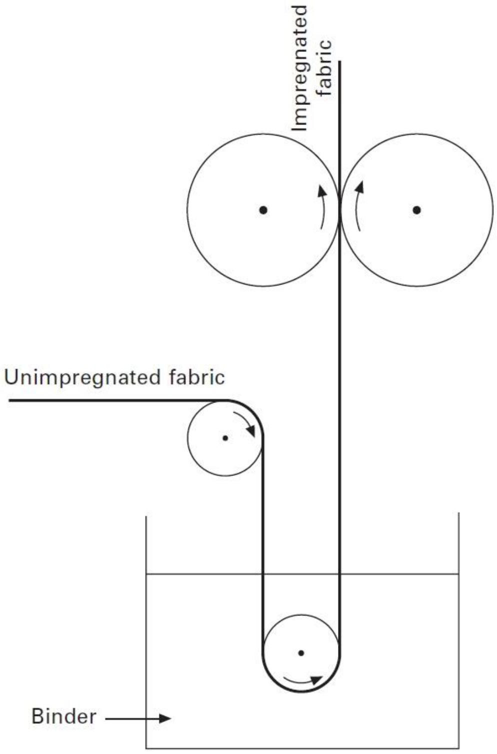

Figure 17 Principle of chemical-bonding, Russell 2007

3 Practical part

According to the hypotheses that are defined below, the experimental part is divided into two subsections. In the first section, various combinations of the direction of rotation of spike rollers were adjusted. In the second section, various combinations of the frequency of rotation of spike rollers were adjusted, and this section proceeds from the results of the first section. In the second section, only the machine settings, which gave satisfactory results in the first section, are further optimised.

3.1 Machine description

In order to form a web of fibrous material, Formfiber spike air-laying technology was used, namely the machine FORMFIBER SPIKE 500. A schematic side view of a forming box is shown in Fig. 18. The forming box is comprised of a transparent housing into which fibres are supplied from an inlet. In the described layout, a manual input of fibre clumps into a suction pipe is used. The suction pipe drains into the forming box via the inlet. Suction speed can be changed depending on the fibre mass. A vacuum box is positioned beneath a forming wire on which the fibres are air-laid to form fibreboard in a dry forming process. In Fig. 18, the forming box is shown with interior elements. Inside the forming box, several spike rollers are provided in four rows. The spike rollers are fibre-separating rollers employed to separate clumps of fibres. For this purpose, the rollers have radially outward projecting fingers or spikes for contacting the fibre clumps. There are five spike rollers in each row. Following convention is used in order to distinguish component spike rollers. From top to bottom the rows of spike rollers are numbered in ascending order. In Fig. 18, some of the spike rollers are gathered with a dotted line. This line symbolizes groupings of spike rollers that are manipulated by one motor. On a machine control panel and in Fig. 18, groupings of spike rollers on the left side are marked with the symbol A, and on the right side they are marked with the symbol B. An endless belt screen is also provided inside the forming box. This endless belt screen, also called a fibre catcher, includes an upper run, a vertical section where the belt screen moves in a downward direction, a lower run where the belt travels parallel with the underlying forming wire and an upwardly oriented run. Each motor of spike rollers can be driven in two directions and revs can be set from the interval 0 – 90 s^{-1}. In addition, the revs of the motor of the fibre catcher can be set from this interval; however, the rotation direction of this belt can only be in the production direction. This means that the lower run of the fibre catcher is moved in the same direction as the forming wire (Andersen, 2009).

Big clusters of fibres are blown into the upper part of the forming box via the inlet. After crossing through the first two rows of spike rollers, in the space between second and third row of spike rollers the clusters of fibres are smaller than in the upper part. After crossing through the third and fourth rows of spike rollers the fibres should be fully opened and be single. The endless belt screen runs in the upper part between the first and second, and in the lower part between the third and fourth row of spike rollers. The fibre catcher includes closed portions and openings provided in a predetermined pattern. If, after crossing the third row of spike rollers some of the fibre clusters are not fully disintegrated, these oversized fibres and fibre clumps are retained on the belt screen and are returned to the upper section of the forming box for further disintegration and shredding. The retained fibre clusters are captured on the upper surface of the lower run of the fibre catcher, which then becomes the lower surface of the upper run. The fibres are sucked downward via spikes from the fibre catcher, and the clumps of fibres are shredded an additional time. In order to ensure efficient shredding of fibres from the fibre catcher, the first three spike rollers in the second row (2B) are provided with different, decreasing distances between their respective axes of rotation and the upper run of the fibre catcher. The first spike roller in the row is positioned with the largest distance and the subsequent spike rollers are positioned with graduated closer distance. This layout enables the returned fibre clumps to be gently peeled off, shredded and disintegrated. It is assumed that the first three rows of spike rollers disintegrate the fibre clumps and that the main function of the fourth row of spikes is to layer the fibres on the forming wire. Another important element to ensure the trouble-free operation of the entire system is the vacuum box. The forming wire is made up of a sieve. This perforated belt enables a suction stream to be created by which the fibres are sucked downwards and the fibre web is gradually layered. The vacuum fan decreases leakage of fibres from the housing and increases the friction force between the fibres and the forming wire so that the fibre web can be carried away from the forming box. The fibre web can be made from natural fibres, synthetic fibres or any combination thereof, as well as granular material. The length of fibres can be (1 – 75) mm (Andersen, 2009; SPIKE - Formfiber Denmark ApS).

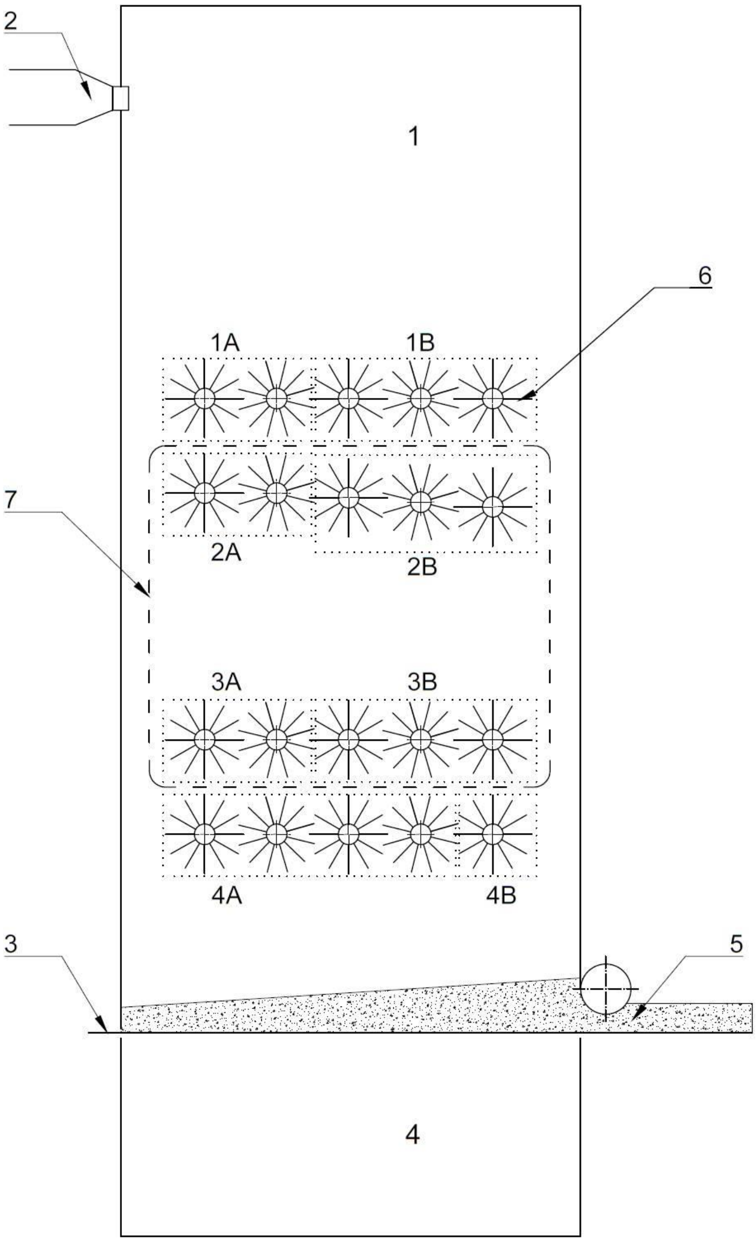

Figure 18 Schematic side view of the forming box
1 – forming box, 2 – inlet, 3 – forming wire, 4 – vacuum box, 5 – fibre-web, 6 – row of spike rollers, 7 – belt screen

3.2 Materials and methods

3.2.1 Materials

Raw flax and hemp fibres were used for the preparation of air-laid and needle-punched nonwoven fabric. Hemp fibres were supplied by Waldland Company and the hemp plants were grown in Austria. These plants were grown as seed hemp plants. Supplied fibres included many shives. It can be stated that the used hemp fibres were harvesting rests. Commercial pure-clean flax fibres were supplied by a French provider.

3.2.2 Opening and cleaning

The raw materials included many foreign particles. Tufts of fibres were manually put into the opening-roller from bales to reduce the size of the fibre tufts and remove foreign particles as rests of stems (Das *et al.*, 2012). The more times the raw fibres are treated in the opening-roller, the more foreign particles are removed. However, the more times the fibres are treated in the opening-roller, the more they are destroyed. As particles from stems were mainly in the hemp bales, the separation process was done three times. Flax fibres were treated in the opening-roller only one time.

3.2.3 Air-laying

Opened, separated and cleaned fibres were manually fed into the suction pipe of the air-laying machine. Feeding was done as continually as possible. The speed and direction of rotation of the rotating spiked wheels were adjusted to various combinations. The exact initial values are listed in Table 3 and are equivalent to previous use of the machine. Nine combinations of spike rotation were chosen, and these combinations are schematically shown in Fig. 19. Plus or minus signs symbolize the direction of rotation of the group of spike rollers (connected with a belt) according to Fig. 18. The plus sign symbolizes the positive mathematical direction of rotation (opposite to the rotating hands of a clock), and minus sign symbolizes the negative direction. The fibre webs of a nominal length 200 cm, nominal width of 50 cm and nominal height of 12 cm were produced.

The spike rollers are the main part of the air-laying machine. They singularize fibres, determine fibre trajectory, fibre process time and fibre alignment. Apart from the spike rollers, other machine elements also determine fibre flows in the machine, the settings of these machine elements are dependent on the types of fibres and the settings of the spike rollers. The fibre transport fan can be adjusted to various intensities. The intensity of the transport fan depends on the bulk of fibres. Large, heavy fibres require higher transport fan intensity for their transport. Small and lightweight fibres must be transported with lower transport fan intensity; otherwise they will be blown through the entire forming box and they will fly out of the output into the air without forming a web. The vacuum fan helps keep the flying fibres in the forming box, and to make fibre sediment. In addition, this fan enhances the friction between the fibre web and the forming wire. The speed of the forming wire depends on the productivity of the entire air-laying machine. In the current organization of devices in the nonwoven production in the described laboratory, the speed of the forming wire is limited by the speed of the mobile conveyor of the fibre webs. The frequency of rotation of the fibre catcher can also be regulated. The fibre catcher returns large fibre clumps to the upper section of the forming box for further disintegration, and therefore the frequency of rotation of this belt screen depends on the amount of fibres that are treated in the forming box. In this research, only the parameters of the spike rollers are adjusted to various combinations on the basis of the functions of the particular machine elements.

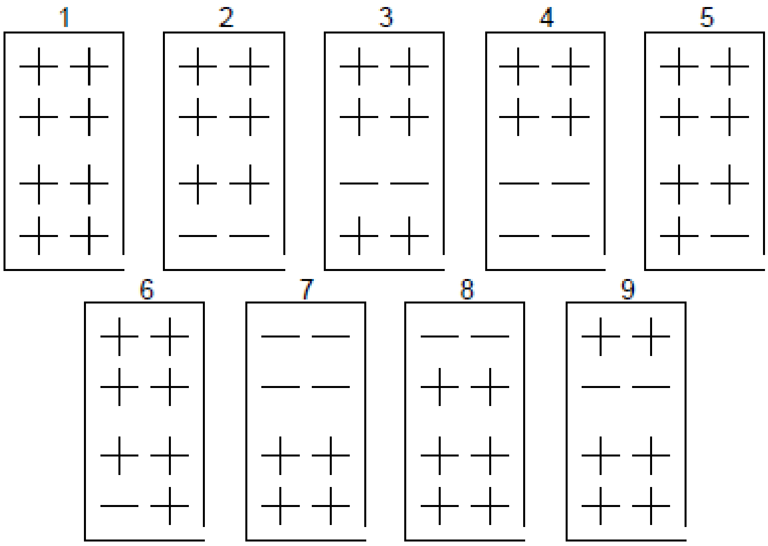

Figure 19 Directions of spike rotations

Table 3 Values of speed parameters

Type of Motor	Frequency [s^{-1}]
Motor 1A	65.6
Motor 2A	77.8
Motor 3A	49.8
Motor 4A	41.3
Motor 1B	73.3
Motor 2B	71.3
Motor 3B	48.3
Motor 4B	42.7
Fibre Catcher	30.0
Fibre Transport Fan	19.0
Wire Run	5.0
Vacuum Fan	30.0

On the basis of results from the first phase, some spike rotation settings were chosen in order to further optimize the process. The criteria were tenacity of nonwovens and quality of webs. Two spike rotation settings were chosen, namely numbers 1 and 5. In this part, the influence between velocity parameters of the machine elements and the nonwoven properties was observed. Two levels of velocity of spike rollers were chosen and the combinations are listed in Table 4, or Table 5. The higher velocity is twice as high as the lower velocity. Given the assumption that the upper two rows of spikes work together, these two rows of spike rollers were always turned on with the same velocity, as well as the two lower rows of spike rollers. Additionally, two combinations for spike rotation 5 (Table 5) were added. These combinations distinguish the frequency of rotation of the spike rollers in the fourth row.

Table 4 Combination of velocity parameters for spike rotation settings 1 and 5

Marking of a combination	Frequency of spikes 1A, 1B, 2A, 2B [Hz]	Frequency of spikes 3A, 3B, 4A, 4B [Hz]
A	40	40
B	80	40
C	80	80
D	40	80

Table 5 Additional combination of velocity parameters for spike rotation setting 5

Marking of a combination	Frequency of spikes 1A, 1B, 2A, 2B [Hz]	Frequency of spikes 3A, 3B, 4A [Hz]	Frequency of spike 4B [Hz]
E	40	80	40
F	40	40	80

During air-lying, the fibre process time in the machine was measured. Measurements were carried out with ball-shaped clusters of hemp fibres; the weight of each cluster was 10 g. The fibres were coloured for high visibility. The fibre process time was defined as the time between a cluster entering into the forming box and the deposition of all fibres from the cluster on the forming wire. Each measurement was repeated three times and the time was measured with accuracy to a tenth of a second.

3.2.4 Needle-punching

The needle-punching process was applied in order to intensify mechanical-bonding between fibres. The feeding speed for needle-punching was set to 0.45 $m \cdot min^{-1}$ and the punching rate at 118 $strokes \cdot min^{-1}$. The needle-head held 442 needles of 125 x 490 mm in dimension. After needle-punching, the fibres in the nonwoven felts were fully entangled and interacted. Fig. 20 shows a reinforced mat and punctures caused by the barbed needles are visible on the section.

Figure 20 Section of a reinforced mat

3.2.5 Nonwoven quality evaluation

Various parameters of nonwoven properties were measured after air-laying and after needle-punching in order to evaluate the quality of air-laid nonwovens. Before needle-punching, the following properties of webs were verbally evaluated: surface waviness along and across the production direction, low-dense areas in the surface and the size and frequency of fissures. A four-tier scale of web quality was defined, and the webs were categorized into this quality scale on the basis of a verbal evaluation. After needle-punching, the tenacity and stretch of mats along and across the production direction was measured. The basis weight of the fabrics was also measured. Fibre trajectories and fibre process time were observed in order to evaluate fibre deposition dynamics.

Determination of tenacity and stretch

Firstly, the following terms must be defined: elongation is deformation in the direction of the load caused by a tensile force. Elongation is generally expressed as a percentage of the length of the stretched material to the length of the un-stretched material. It can be determined by the degree of stretch under a specific load, or by the point where the stretched material breaks. In this study, elongation was measured at a maximum load, called stretch. Breaking force is defined as the maximum force applied to a material when it is carried to rupture (Fig. 21) (EN ISO 9073-18:2007). Tenacity can be calculated from breaking force (Sengupta *et al.*, 2008).

$$Tenacity\ (\frac{cN}{tex}) = \frac{Breaking\ force\ (cN)}{Specimen\ width\ (mm) \cdot Fabric\ basis\ weight\ (\frac{g}{m^2})}$$

According to EN ISO 9073-18, from each nonwoven sample, five specimens in the machine direction (MD) and cross direction (CD) were prepared. A die was used for specimen preparation to ensure the same dimensions of all of the specimens. The first specimen was cut 100 mm from the edge of the nonwoven sample in order to avoid changing the natural state of the test area of the material. The length of each specimen was 340 mm and the width was 50 mm. The specimens were conditioned in the standard atmosphere at temperature (20 ± 2) °C and relative air humidity of 65%. A tensile testing machine with a constant rate of extension was used. The distance between clamps (gauge length) was set at 200 mm and the extension rate at 100 $mm \cdot min^{-1}$. Specimens were mounted in the clams so that all of the slack in the material was removed and pretension 2 N was simultaneously applied to the specimens. If a specimen was broken at the edge or in the jaws, the result was discarded and another specimen was taken until the required number of acceptable breaks was obtained (EN 29073-3:1992; EN ISO 9073-18:2007).

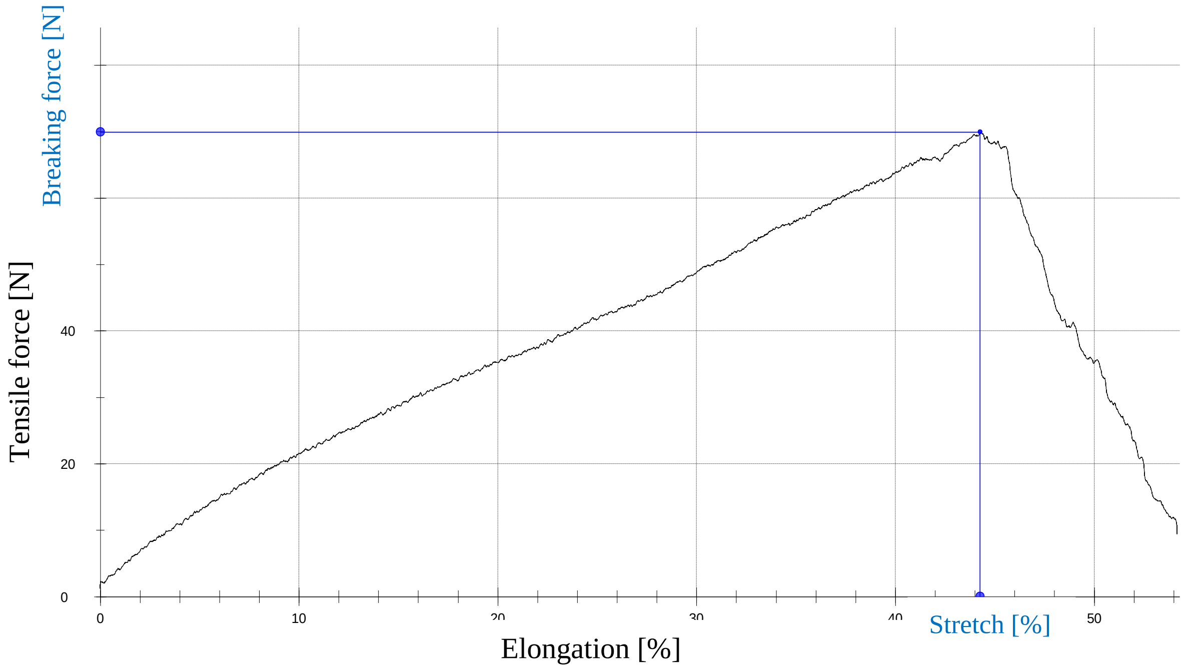

Figure 21 Explanation of terms

3.2.6 Statistical methods

The following descriptive statistics were calculated to describe the measured data: minimum, maximum and sample mean, which is calculated according to the following formula:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

The variability in the data is described by the sample standard deviation

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

and by the coefficient of variation

$$\hat{c}_v = \frac{s}{\bar{x}} \cdot 100\%$$

(Motgomery *et al*., 1998).

Extreme values and values that lied outside the interval $(\bar{x} \pm 3 \cdot s)$ were not discarded from the results, because as discussed in the discussion, the fabric basis weight affects its tenacity and stretch. In the case of varying basis weight, the tenacity and stretch also scatter.

At the beginning of this research, a working hypothesis in the following form was defined:

$$H^{*}: Machine\ settings\ affect\ nonwoven\ quality.$$

In this part, it can be estimated whether the settings of spike rollers have any influence on the stretch and tenacity of webs. Statistical hypothesises that put equalities between means of tenacity and stretch of nonwovens produced by various machine settings are formulated for this purpose. In terms of adjusting the direction of rotation of spike rollers, 288 null hypothesises are stated:

$H_{01,i}: \bar{x}_j^{m,d,c} = \bar{x}_j^{m,d,c}$ where $i \in \{1,2 \ldots 288\}$ – number of hypotheses

$j \in \{S1, S2 \ldots S9\}$ – number of machine setting

$m \in \{flax, hemp\}$ – material

$d \in \{MD, CD\}$ – machine or cross direction

$c \in \{tenacity, stretch\}$ – characteristic

In terms of adjusting the frequency of rotation of spike rollers, 360 null hypothesises are stated:

$H_{02,i}: \bar{x}_j^{m,d,c} = \bar{x}_j^{m,d,c}$ where $i \in \{1,2 \ldots 360\}$ – number of hypotheses

$j \in \{S1A \ldots S1D, S5A \ldots S5F\}$ – n. of m. setting

$m \in \{flax, hemp\}$ – material

$d \in \{MD, CD\}$ – machine or cross direction

$c \in \{tenacity, stretch\}$ – characteristic

A one-way analysis of variance was used to determine whether any of the pairwise differences from the number of means are significant. A Tukey (HSD) test was employed to determine the significant differences between group means. This post hoc test is more conservative than the Fisher LSD test, but less conservative than Scheffe's test. According to EN ISO 9073-18, five specimens in the machine direction and cross direction were prepared from each nonwoven sample. The Tukey test should be used for a small amount of specimens in each group (StatSoft, 2015a; Winer *et al.*, 1991). Computations were carried out by Statistica software. A significance level α = 0.05 is selected, and rejection of the null hypothesis leads to accepting the alternative hypothesis:

$$A_{1\ or\ 2,i} = \bar{x}_j^{m,d,c} \neq \bar{x}_j^{m,d,c}$$

The influence between the machine settings and tenacity or stretch of fabricated nonwovens is represented by box plots. These box plots show us the properties of the measured parts of the nonwoven samples, whereas the properties of entire nonwoven samples can be estimated by an analysis of variance. The symbols that are used in the box plot visualisation in this work are explained in Fig. 22.

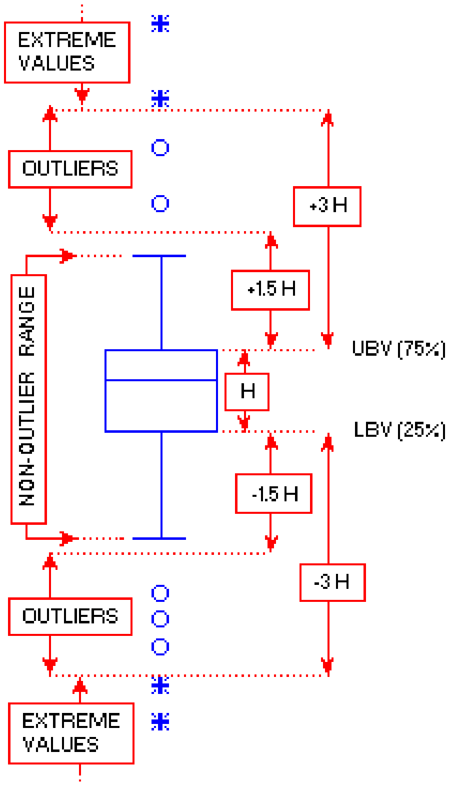

Figure 22 Explanation of box plot symbols, StatSoft 2015b

3.3 Results

3.3.1 Observed phenomenon during air-laying

Surface layer

The laid web is carried out from the forming box by forming wire and a pressure roller is positioned on the output from the forming box (see Fig. 18). The function of this roller is to form and even out a surface of webs. The drift of fibres before the pressure roller is higher than behind it. This roller compresses fibre webs and makes it possible to observe two layers on the vertical profile of the web. In the surface layer, the position of fibres is affected by pressure from the roller, and the fibres lay there in the horizontal position. This layer occupies approximately one third of the total height of the web. The lower layer is not affected by pressure from the roller, and the position of the fibres is determined there by the laying effect of spike rollers. There are mostly vertically oriented and tangled fibres. These thickness profiles are produced if settings numbers 1, 3, 5, 7, 8 and 9 are used. This profile with surface layer is shown in Fig. 23. An inverse thickness profile is created for settings 2, 4 and 6. Only a small amount of fibres is laid by the 4A spikes in the back part of the forming wire, and these are horizontally oriented. Most of the fibres are laid by the 4B spike in front of the pressure roller. These are vertically oriented and create a high drift. By comprising these vertically oriented fibres, a low consistent or inconsistent web with fissures is created. The thickness profile seems like an inverse profile compared to the previous case. The inverse profile is shown in Fig. 24.

Figure 23 Thickness profile, flax fibres

Figure 24 Inverse thickness profile, hemp fibres

Creation of fissures

Depending on the direction of the rotation of spike rollers in the two bottom rows, the fibres are blown into the front or into the back part of the forming wire. If fibres are blown into the front part, there is a very high drift of fibres before the pressure roller and the fibres must be extensively compressed. The more the fibres are compressed, the more they expand behind the roller. The expansion effect can be so huge that the consistency of a fibre web breaks. In the second case the fibres are blown into the back part of the forming wire; in front of the pressure roller is a low drift of fibres and no fissures are created on the surface of a web behind the pressure roller. The creation of fissures is shown in Fig. 25.

Figure 25 Creation of fissures, flax fibres

Fibre deposition dynamics – adjusting the direction of rotation

Fibre flows in the forming box that were observed during production of webs by changing the direction of rotation of particular machine elements are mentioned and described in the following chapter. Directions of spike-rotations fit the description in Fig. 19.

Setting no. 1 is the basic setting of the air-laying machine; all of the particular machine elements rotate in the production direction. Thus far, only this setting was used to produce webs via this machine. The fibre trajectory matching this setting is displayed in Fig. 26. The dotted-line represents the connections among the spike wheels, which are running in same direction at an identical rotation speed, and the arrows on these lines show the directions of rotations. Thin trajectory-arrows represent fibre flow. Good-quality webs from both flax and hemp fibres can be produced by using this adjustment. The same fibre trajectories can be achieved by setting no. 9.

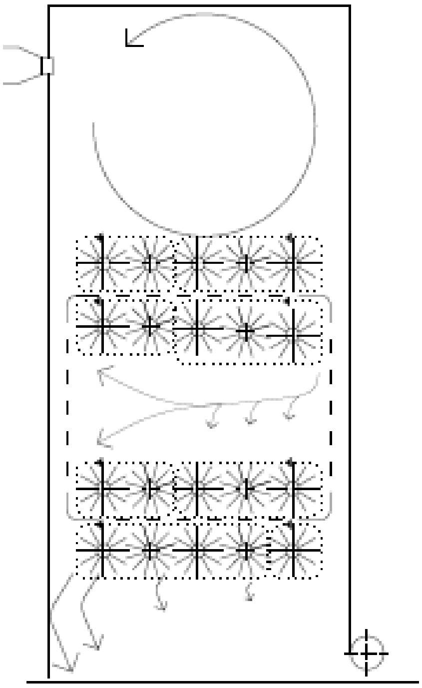

Figure 26 Fibre flow, setting 1

Setting no. 2 is displayed in Fig. 27. The bottom row of spikes rotates opposite to the production direction. Fibres are blown into the front part of the forming wire and there are very few fibres in the back part of the forming wire. This results in creating fissures in the web and a low consistent or inconsistent web. The same fibre trajectories can be achieved by setting no. 6. Settings nos. 2 and 6 are obviously unsuitable for web laying.

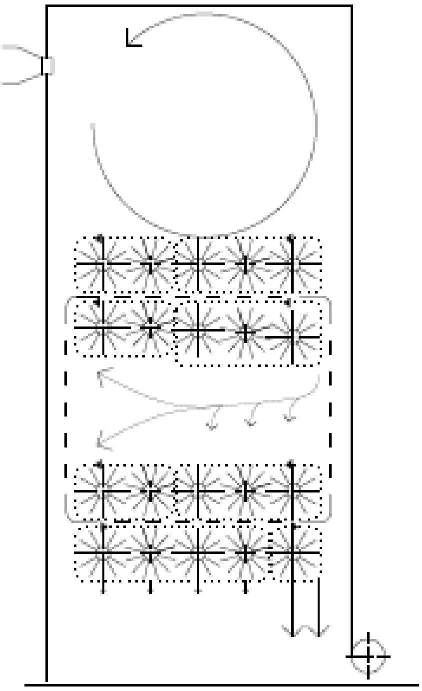

Figure 277 Fibre flow, setting 2

Fibre flow, which arises using setting no. 3, is displayed in Fig. 28. Here we see the different web qualities of flax and hemp fibres. Although webs from flax achieve good quality using this setting, webs from hemp achieve bad quality.

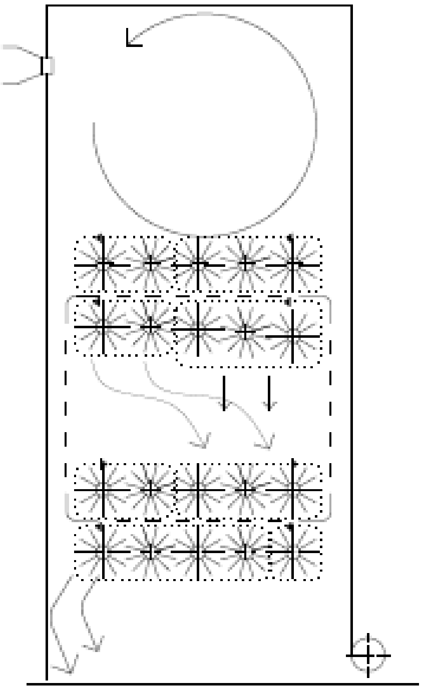

Figure 29 Fibre flow, setting 3

Setting no. 4 is determined by running the two bottom rows of spikes opposite to the production direction. The fibre flow is shown in Fig. 29. Usage of this setting results in overturned thickness profile of webs, inconsistent webs and the worst web quality from both flax and hemp fibres.

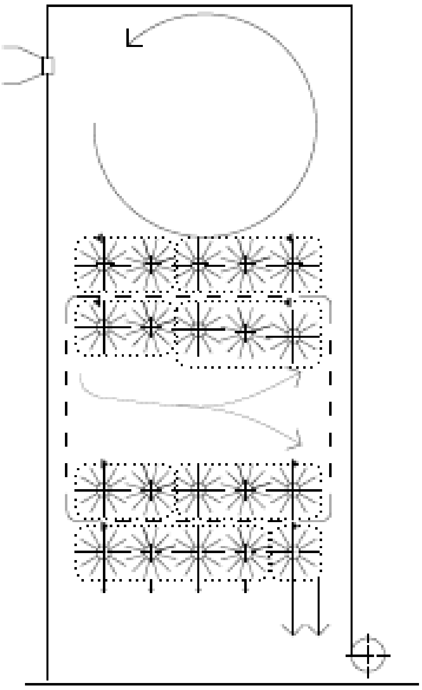

Figure 30 Fibre flow, setting 4

Setting no. 5 is determined by running spike 4B opposite to the production direction. The fibre flow is shown in Fig. 30. The last bottom spike blows fibres into the back part of the forming wire, which causes the fibres in the forming web to be comprised and the web is denser. Secondly, due to spike 4B rotating in the opposite direction, there is a low drift of fibres before the pressure roller and any fissures arise in the web. Webs of the best quality from both flax and hemp fibres were produced by using this adjustment. This adjustment should also be used to manufacture high-density webs.

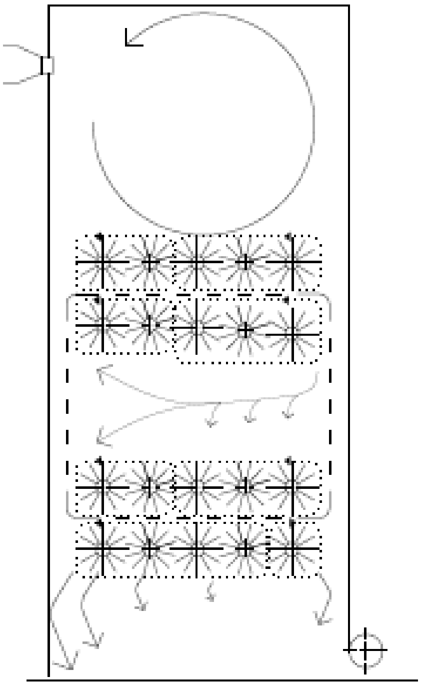

Figure 31 Fibre flow, setting 5

Setting no. 7 is displayed in Fig. 31. The upper two rows of spikes rotate opposite to the production direction. This adjustment causes the fibres from the inlet to be directly sucked into the space under the first two rows of spikes, and only a few fibres circulate in the upper part of the forming box. Good-quality webs from both flax and hemp fibres can be produced by using this adjustment. This setting should be used if high productivity of the machine is required. However, the fibres must be well opened; if they are not, there is a danger of seizure of fibre tufts within spikes, or between the belt screen and the decking of the belt screen.

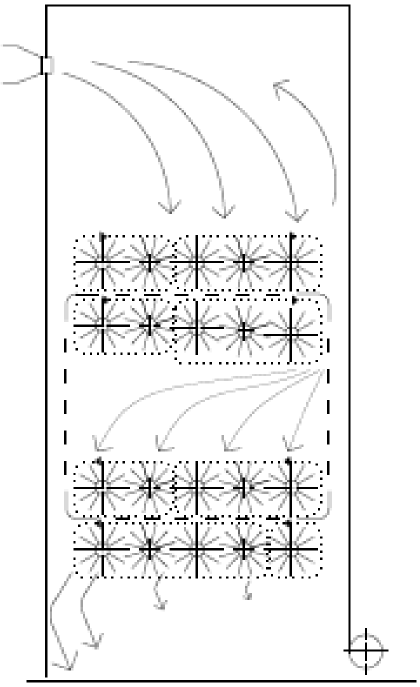

Figure 32 Fibre flow, setting 7

Fibre flow using setting no. 8 is displayed in Fig. 32; the upper row of spikes rotates opposite to the production direction. To a large extent the effects of this setting are the same as the effects of setting no. 7. The quality of the manufactured web is the same; only productivity is lower.

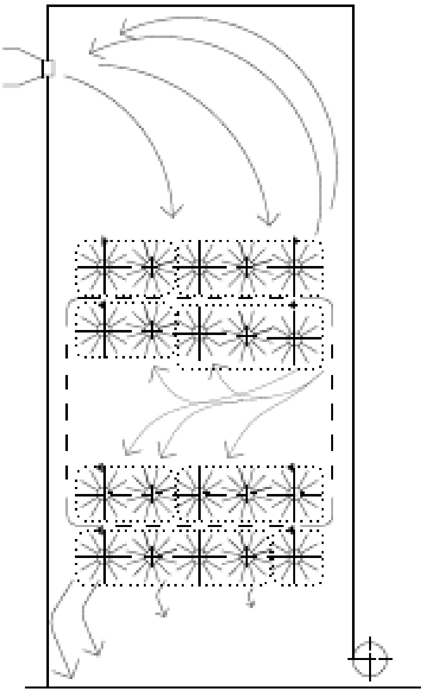

Figure 33 Fibre flow, setting 8

Fibre deposition dynamics – adjusting the frequency of rotation

The two lower rows of spike rollers form the fibre web, and it was observed that the faster they rotate, the more the drift of fibres on the forming wire is compressed. This is an important effect, because when the fibres are compressed during lying, they do not need to be compressed as extensively by the pressure roller on the output from the machine. Achieving a high web density using a high drift of fibres, which is consequently extensively compressed by the pressure roller, creates fissures in the web. Thanks to the effect of compressing fibres during lying, a good quality web can be made, and also with a higher density. This effect was observed for all of the settings when the lower two rows of spikes were rotating at a frequency level 80 Hz.

When laying a web from flax fibres and using setting number 5, undesirable fibre flow was observed when the opposite-rotating spike 4B was rotating at a high frequency level (settings 5C, 5D and 5F). In these cases the opposite-rotating spike 4B had such high suction effect that the fibres from the forming screen were sucked into the upper parts of the machine and/or blown from the output to the back part of the forming wire. No webs were created by using these settings. This phenomenon only occurred when flax fibres were used; lying of hemp fibres was problem-free and the quality of the hemp webs was good (only the surface was uneven). Flax fibres have a fluffier structure than hemp fibres, and they could therefore be sucked more easily than the hemp fibres. However, it is assumed that at an even higher frequency level than 80 Hz the hemp fibres would also be sucked back to the machine.

Fibre process time

The measurements of fibre process time in the machine were negatively affected by the long-lasting circulation of the rest of the fibres in the forming box. This small amount of fibres, which spent a longer time than the other fibres in the forming box, negatively affects the information value of the measured time. The results from these measurements must be understood only as approximate results. The average values are presented in Table 6; given the inaccuracy of the measurement, they are rounded to a unit of a second.

Table 6 Fibre process time in the machine

Settings	Process time [s]	Settings	Process time [s]
S1	8	**S1A**	8
S2	8	**S1B**	8
S3	8	**S1C**	8
S4	8	**S1D**	7
S5	8	**S5A**	8
S6	9	**S5B**	8
S7	5	**S5C**	8
S8	7	**S5D**	7
S9	14	**S5E**	7
		S5F	8

3.3.2 Evaluation of fibre-web quality

On the basis of a verbal evaluation, air-laid webs were categorized into a four-tier quality scale in order to classify web quality. The definitions of web properties in the quality levels are mentioned in Table 7, or in Table 8. Generally, flax fibres are more spacious, and the web surfaces from these fibres are inclined to create surface fissures more than the webs from hemp fibres. In order to better recognize the quality differences between the webs, quality levels are defined slightly distinctly for flax and hemp fibres. Pictorial documentation of web quality scale is enclosed in Supplements 7 – 10.

Table 7 Web quality scale for flax fibres

Quality level	Allowed errors of webs
1	surface waviness along and across the production direction, low-dense areas in the surface layer
2	surface waviness along and across the production direction, low-dense areas in the surface layer, fissures in the surface layer or rare fissures with a depth max. of one half of web high
3	low-dense areas in the surface layer, frequent fissures with a depth max. of one half of web high, low consistent web
4	frequent fissures with a depth higher than one half of web high, inconsistent web

Table 8 Web quality scale for hemp fibres

Quality level	Allowed errors of webs
1	low-dense areas in the surface layer
2	surface waviness along and across the production direction, low-dense areas in the surface layer, fissures in the surface layer
3	low-dense areas in the surface layer, fissures with a depth max. of one half of web high, low consistent web
4	frequent fissures with a depth higher than one half of web high, inconsistent web

The categorization of air-laid webs on the basis of a visual evaluation of quality is entered in Table 9 or Table 10.

Table 9 Quality of webs from flax

Spike rotation settings	Quality level
S1	2
S2	3
S3	2
S4	4
S5	1
S6	4
S7	2
S8	2
S9	2

Table 10 Quality of webs from hemp

Spike rotation settings	Quality level
S1	2
S2	4
S3	3
S4	4
S5	1
S6	3
S7	2
S8	2
S9	2

The quality of webs from flax and hemp made by the frequencies that are mentioned in Tables 4 and 5 was similar to the quality of the webs made by setting numbers 1 or 5 by using the basic frequencies. Only a few differences were observed and they are mentioned in the chapter *Fibre deposition dynamics – adjusting the frequency of rotation.*

3.3.3 Evaluation of fibre-mat quality

In Tables 11 and 13, or 12 and 14, are listed the values of basis weight, stretch and tenacity of flax, or hemp, and nonwovens for different machine settings with their descriptive statistics, namely: minimum, maximum, sample mean, standard deviation and coefficient of variation. We can see that flax nonwovens achieved higher tenacity and stretch than hemp nonwovens. The tenacity of both flax and hemp nonwovens is higher in the machine direction than in the cross direction; however, stretch is higher in the MD. Tenacity has a relatively high coefficient of variation (30% on average), whilst the coefficient of variation of the stretch of flax nonwovens is on average 15%, the coefficient of variation of the stretch of hemp nonwovens is almost as high as the coefficient of variation of tenacity.

In Supplements 19 – 34 are listed the graphic results from the analysis of variance and p-values (the smallest level of significance that would lead to rejection of the null hypothesis) of the Tukey test of tenacity of nonwovens. Red coloured values are values that are lower than the significance level 0.05, and in this case the null hypothesis is rejected and the alternative hypothesis is accepted. Black coloured values are higher than the significance level which leads to failing to reject the null hypothesis (Motgomery *et al.*, 1998, p. 158; Triola, 1989, p. 338). The graphical results from the analysis of variance plot 95% confidence intervals that are displayed by vertical columns and sample means displayed by dots.

Figs. 33 – 36 and 37 – 40 plot the influence between the settings of spike rollers and tenacity of nonwovens. Box plots for the stretch of nonwovens are listed in Supplements 11 – 18. The results from further analysis of stretch of nonwovens are not listed because no influence was found between machine settings and stretch. As discussed below, the variable basis weight makes the data of the stretch incomparable because stretch is highly affected by basis weight.

Table 11 Basis weight, stretch and tenacity of flax nonwovens for different machine settings – adjusting the direction of rotation

		MD			CD		
Settings		Basis weight [g/m^2]	Stretch [%]	Tenacity [cN/tex]	Basis weight [g/m^2]	Stretch [%]	Tenacity [cN/tex]
S1	$\bar{x}$	905	58,5	0,287	808	69,7	0,150
	Minimum	855	52,5	0,236	802	62,0	0,105
	Maximum	948	66,0	0,377	819	75,5	0,194
	s	35	5,6	0,063	7	5,6	0,034
	$\widehat{c_v}$	3,8	9,6	21,9	0,9	8,0	22,9
S2	$\bar{x}$	628	41,2	0,091	655	53,5	0,075
	Minimum	577	34,5	0,055	590	41,0	0,038
	Maximum	729	55,5	0,134	768	67,5	0,122
	s	63	8,9	0,030	70	10,3	0,032
	$\widehat{c_v}$	10,0	21,7	32,8	10,7	19,2	42,7
S3	$\bar{x}$	664	49,7	0,056	673	47,0	0,054
	Minimum	583	38,5	0,046	606	42,0	0,031
	Maximum	769	59,5	0,074	771	53,5	0,081
	s	79	10,1	0,011	67	4,8	0,023
	$\widehat{c_v}$	11,9	20,4	19,5	9,9	10,2	42,3
S4	$\bar{x}$	726	47,4	0,053	793	49,7	0,130
	Minimum	632	37,5	0,033	728	33,5	0,094
	Maximum	783	60,0	0,090	856	60,5	0,159
	s	64	10,5	0,023	59	10,1	0,025
	$\widehat{c_v}$	8,8	22,2	42,4	7,4	20,3	19,4
S5	$\bar{x}$	772	51,7	0,257	769	67,2	0,171
	Minimum	759	44,5	0,180	746	53,5	0,102
	Maximum	788	58,0	0,356	798	82,0	0,251
	s	12	5,5	0,065	24	10,1	0,057
	$\widehat{c_v}$	1,5	10,6	25,417	3,1	15,1	33,5
S6	$\bar{x}$	760	35,7	0,094	683	51,3	0,076
	Minimum	683	25,0	0,061	464	19,0	0,017
	Maximum	834	45,5	0,134	803	74,5	0,163
	s	61	8,7	0,031	148	21,7	0,054
	$\widehat{c_v}$	8,0	24,4	32,5	21,6	42,2	70,9
S7	$\bar{x}$	714	50,2	0,131	682	57,7	0,148
	Minimum	649	36,0	0,054	609	48,0	0,127
	Maximum	803	68,0	0,201	847	66,0	0,183
	s	57	13,2	0,062	98	7,8	0,024
	$\widehat{c_v}$	8,0	26,2	47,1	14,3	13,5	16,1
S8	$\bar{x}$	695	55,7	0,226	683	57,8	0,130
	Minimum	613	50,0	0,168	607	48,5	0,082
	Maximum	808	65,5	0,395	760	64,5	0,172
	s	73	6,3	0,095	64	6,9	0,032
	$\widehat{c_v}$	10,5	11,3	42,2	9,3	11,9	24,7
S9	$\bar{x}$	738	65,1	0,186	671	57,0	0,144
	Minimum	726	48,0	0,100	628	47,0	0,092
	Maximum	775	77,0	0,255	762	61,5	0,197
	s	21	11,1	0,059	54	5,8	0,038
	$\widehat{c_v}$	2,8	17,1	31,8	8,0	10,1	26,1

Note: MD = machine direction, CD = cross direction, $\bar{x}$ = sample mean, s = sample standard deviation, $\widehat{c_v}$ = coefficient of variation

The highest average value of tenacity of flax nonwovens in the MD (0,287 cN/tex) was achieved by setting no. 1, but these nonwovens had a strongly higher basis weight than the other nonwovens. The second highest average value of tenacity (0,257 cN/tex) was achieved by setting no. 5, however, the basis weight of these samples is close to the average basis weight of the group of flax nonwovens measured in the MD

(734 g/m^2). Nonwovens made by settings nos. 2, 3, and 4 achieved very low tenacity, whilst nonwovens produced by settings nos. 2 and 3 had very low basis weight (628, or 664 g/m^2). The nonwovens produced by setting no. 4 had an average value of basis weight of 726 g/m^2. In the CD, nonwovens made by S5 achieved higher average value of tenacity than nonwovens made by S1 despite the lower average value of basis weight of S5 samples.

Table 12 Basis weight, stretch and tenacity of hemp nonwovens for different machine settings – adjusting the direction of rotation

		MD			CD		
Settings		Basis weight [g/m^2]	Stretch [%]	Tenacity [cN/tex]	Basis weight [g/m^2]	Stretch [%]	Tenacity [cN/tex]
S1	$\bar{x}$	802	27,3	0,055	808	37,1	0,046
	Minimum	759	24,0	0,050	743	29,5	0,031
	Maximum	895	33,0	0,061	881	46,5	0,057
	s	55	3,5	0,005	49	6,7	0,010
	$\hat{c}_v$	6,8	12,8	9,2	6,1	18,0	22,6
S2	$\bar{x}$	886	15,8	0,021	876	21,7	0,018
	Minimum	835	5,0	0,007	803	15,0	0,011
	Maximum	932	28,0	0,035	940	37,5	0,023
	s	35	10,1	0,012	56	9,5	0,005
	$\hat{c}_v$	4,0	64,0	57,6	6,4	43,7	26,4
S3	$\bar{x}$	930	16,6	0,030	849	24,2	0,023
	Minimum	869	14,0	0,020	740	16,5	0,015
	Maximum	978	19,5	0,040	921	28,5	0,031
	s	44	2,4	0,008	71	4,6	0,008
	$\hat{c}_v$	4,8	14,5	25,7	8,4	19,0	33,8
S4	$\bar{x}$	785	7,8	0,010	768	18,0	0,014
	Minimum	682	3,0	0,005	718	5,0	0,006
	Maximum	909	13,5	0,014	823	28,0	0,021
	s	82	4,5	0,004	47	8,5	0,006
	$\hat{c}_v$	10,5	57,4	36,9	6,2	47,0	40,6
S5	$\bar{x}$	873	23,3	0,035	815	29,5	0,036
	Minimum	830	19,0	0,026	745	19,5	0,027
	Maximum	925	29,0	0,039	875	43,5	0,051
	s	35	4,4	0,005	57	9,3	0,010
	$\hat{c}_v$	4,0	18,7	15,3	6,9	31,4	27,8
S6	$\bar{x}$	816	22,8	0,025	751	26,3	0,020
	Minimum	749	11,0	0,017	622	21,0	0,016
	Maximum	856	30,5	0,033	912	34,5	0,027
	s	47	7,8	0,006	111	7,0	0,005
	$\hat{c}_v$	5,7	34,1	24,5	14,8	26,8	22,7
S7	$\bar{x}$	704	23,6	0,022	696	25,8	0,022
	Minimum	651	18,5	0,017	672	12,5	0,013
	Maximum	787	34,5	0,026	715	38,5	0,033
	s	56	6,4	0,004	20	10,6	0,007
	$\hat{c}_v$	7,9	27,3	16,5	2,9	41,2	34,0
S8	$\bar{x}$	877	22,1	0,032	907	19,2	0,019
	Minimum	783	16,0	0,017	744	15,0	0,013
	Maximum	946	32,0	0,045	1008	22,0	0,033
	s	63	6,3	0,012	122	2,8	0,008
	$\hat{c}_v$	7,2	28,5	38,2	13,5	14,8	44,5
S9	$\bar{x}$	982	18,1	0,031	923	29,0	0,033
	Minimum	859	12,0	0,019	834	21,0	0,017
	Maximum	1034	27,5	0,042	1036	37,0	0,046
	s	74	7,4	0,010	83	6,3	0,010
	$\hat{c}_v$	7,5	40,7	33,5	9,0	21,8	31,9

The highest average value of tenacity of hemp nonwovens in the MD (0,55 cN/tex) was achieved by setting no. 1, and the second highest average value of tenacity (0,035 cN/tex) was achieved by setting no. 5. Whilst S1 samples had below-average basis weight (802 g/m^2), S5 samples had above-average basis weight (873 g/m^2). The lowest tenacity was achieved by nonwovens made by setting no. 4. In the cross directions the results and relations are similar; only the coefficients of variation are higher than those in the machine direction.

Table 13 Basis weight, stretch and tenacity of flax nonwovens for different machine settings – adjusting the frequency of rotation

		MD			CD		
Settings		Basis weight [g/m2]	Stretch [%]	Tenacity [cN/tex]	Basis weight [g/m2]	Stretch [%]	Tenacity [cN/tex]
S1A	$\bar{x}$	671	60,8	0,229	551	55,9	0,071
	Minimum	588	52,5	0,126	537	43,5	0,041
	Maximum	804	75,0	0,316	568	63,5	0,094
	s	112	8,4	0,081	13	7,8	0,020
	$\hat{c}_v$	16,7	13,9	35,3	2,4	14,0	28,4
S1B	$\bar{x}$	644	57,8	0,297	586	64,9	0,124
	Minimum	592	49,0	0,195	497	47,0	0,059
	Maximum	766	65,0	0,382	695	76,0	0,181
	s	71	6,4	0,078	81	11,7	0,047
	$\hat{c}_v$	11,0	11,1	26,1	13,8	18,1	37,6
S1C	$\bar{x}$	664	60,1	0,225	733	65,0	0,147
	Minimum	616	54,5	0,175	652	47,5	0,085
	Maximum	734	75,0	0,249	773	72,5	0,185
	s	47	8,5	0,030	49	10,3	0,043
	$\hat{c}_v$	7,1	14,1	13,1	6,7	15,9	29,2
S1D	$\bar{x}$	776	61,3	0,245	702	80,7	0,134
	Minimum	676	54,5	0,174	614	71,0	0,108
	Maximum	825	68,0	0,313	772	92,0	0,154
	s	62	6,3	0,054	62	7,6	0,019
	$\hat{c}_v$	8,0	10,3	22,2	8,8	9,5	14,4
S5A	$\bar{x}$	611	62,1	0,237	538	76,8	0,131
	Minimum	570	51,5	0,166	485	66,5	0,086
	Maximum	658	73,0	0,354	625	89,5	0,191
	s	38	7,9	0,070	61	9,5	0,038
	$\hat{c}_v$	6,2	12,8	29,3	11,3	12,3	29,0
S5B	$\bar{x}$	662	58,0	0,251	696	72,3	0,177
	Minimum	592	55,0	0,207	671	61,5	0,098
	Maximum	726	61,0	0,334	720	81,5	0,267
	s	53	2,5	0,053	20	8,5	0,063
	$\hat{c}_v$	8,1	4,3	21,3	2,8	11,8	35,7
S5E	$\bar{x}$	653	53,5	0,169	652	66,3	0,137
	Minimum	631	40,5	0,098	639	53,5	0,104
	Maximum	694	76,0	0,277	667	77,0	0,163
	s	25	13,5	0,071	11	10,0	0,022
	$\hat{c}_v$	3,9	25,3	42,1	1,7	15,1	15,9

When adjusting the frequency of rotation, the highest average values of tenacity of flax nonwovens in the MD were achieved by setting B (the upper two rows of spikes were rotating at a frequency level of 80 Hz and the lower two rows were rotating at a frequency level of 40 Hz). The nonwovens produced by these setting achieved great tenacity despite the fact that their basis weight was below-average. This cannot be applied to CD because the basis weight of nonwovens with high tenacity was above-average.

Table 14 Basis weight, stretch and tenacity of hemp nonwovens for different machine settings – adjusting the frequency of rotation

		MD			CD		
Settings		Basis weight [g/m2]	Stretch [%]	Tenacity [cN/tex]	Basis weight [g/m2]	Stretch [%]	Tenacity [cN/tex]
S1A	$\bar{x}$	911	20,3	0,037	999	31,6	0,053
	Minimum	835	11,5	0,012	948	20,0	0,029
	Maximum	1067	33,0	0,069	1046	40,0	0,069
	s	95	9,6	0,022	44	9,4	0,019
	$\widehat{c_v}$	10,5	47,2	58,2	4,4	29,9	35,3
S1B	$\bar{x}$	1028	21,8	0,046	1009	27,5	0,047
	Minimum	942	12,5	0,028	905	23,0	0,040
	Maximum	1046	29,0	0,058	1107	31,5	0,054
	s	66	6,3	0,012	72	3,2	0,006
	$\widehat{c_v}$	6,4	28,9	26,6	7,1	11,6	12,0
S1C	$\bar{x}$	867	23,1	0,035	802	30,1	0,027
	Minimum	802	18,5	0,028	778	16,5	0,017
	Maximum	1121	32,5	0,039	822	38,5	0,032
	s	46	5,7	0,004	17	8,3	0,006
	$\widehat{c_v}$	5,3	24,8	12,4	2,1	27,6	22,4
S1D	$\bar{x}$	1010	26,0	0,035	945	31,8	0,056
	Minimum	895	11,0	0,017	804	20,5	0,032
	Maximum	1107	39,5	0,061	1059	41,5	0,095
	s	74	11,4	0,017	107	7,7	0,031
	$\widehat{c_v}$	7,4	44,0	47,6	11,3	24,2	55,4
S5A	$\bar{x}$	977	25,0	0,032	1025	31,8	0,036
	Minimum	939	19,0	0,019	986	25,5	0,026
	Maximum	904	27,5	0,042	1072	40,5	0,043
	s	27	3,6	0,011	38	5,5	0,007
	$\widehat{c_v}$	2,8	14,3	32,8	3,7	17,2	18,7
S5B	$\bar{x}$	970	21,1	0,023	1021	25,8	0,024
	Minimum	892	15,0	0,018	958	23,5	0,020
	Maximum	822	25,0	0,028	1169	29,5	0,028
	s	78	4,0	0,005	85	2,5	0,004
	$\widehat{c_v}$	8,0	18,8	19,6	8,4	9,8	15,3
S5C	$\bar{x}$	1239	24,6	0,041	1077	26,4	0,032
	Minimum	1195	15,0	0,024	1005	18,5	0,018
	Maximum	1094	29,5	0,050	1170	39,0	0,052
	s	40	5,6	0,011	68	7,8	0,014
	$\widehat{c_v}$	3,2	22,6	25,7	6,3	29,7	45,4
S5D	$\bar{x}$	1106	23,5	0,031	1098	29,7	0,034
	Minimum	999	20,5	0,023	984	26,0	0,028
	Maximum	1059	29,5	0,040	1209	36,5	0,040
	s	90	3,7	0,007	102	4,1	0,004
	$\widehat{c_v}$	8,2	15,7	23,2	9,3	13,7	12,5
S5E	$\bar{x}$	848	25,8	0,026	894	24,9	0,023
	Minimum	765	20,0	0,016	767	13,5	0,013
	Maximum	1009	34,0	0,035	988	32,5	0,046
	s	82	5,5	0,008	81	7,5	0,014
	$\widehat{c_v}$	9,7	21,3	30,5	9,1	30,3	58,5
S5F	$\bar{x}$	936	28,1	0,056	920	21,7	0,025
	Minimum	892	19,0	0,043	830	15,0	0,018
	Maximum	1072	37,5	0,074	1009	33,5	0,035
	s	33	6,7	0,013	70	7,0	0,007
	$\widehat{c_v}$	3,5	24,0	23,4	7,6	32,3	28,4

The highest average value of tenacity (0,046 cN/tex) of hemp nonwovens in the MD when adjusting the frequency of rotation was achieved by setting 1B. This setting also achieved a good performance in the cross direction. Whilst nonwovens made by S5F had the second highest average tenacity in the MD, in the CD the average value of tenacity was the worst.

The lower four figures show that nonwovens made by settings number S1 (all spike rollers rotate in the production direction) and S5 (spike roller n. 4B rotates in the opposite direction) have a higher tenacity than fabrics made by other settings. Most of these relations are statistically significant (see Supplements 19 – 26). Visual observations of web quality also correspond with this tensile testing.

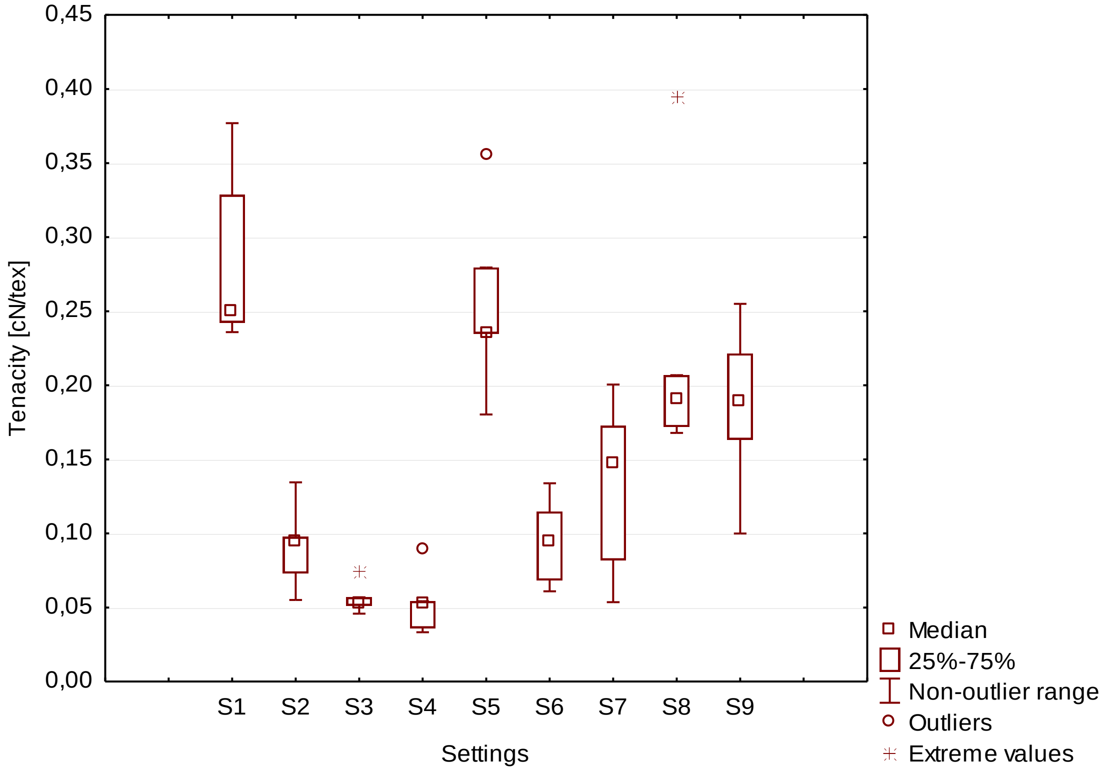

Figure 34 Comparison of tenacity of flax nonwovens in the MD – adjusting the direction of rotation

Here we see the different sizes of the 25%-75% ranges achieved in the MD and the CD by particular machine settings. For example, the size of the 25%-75% range of S3 in the MD and the CD differ strongly, which may be caused by dissimilar intensity of occurrence and the extent of web errors across and along the fibre web, or across and along the specimen.

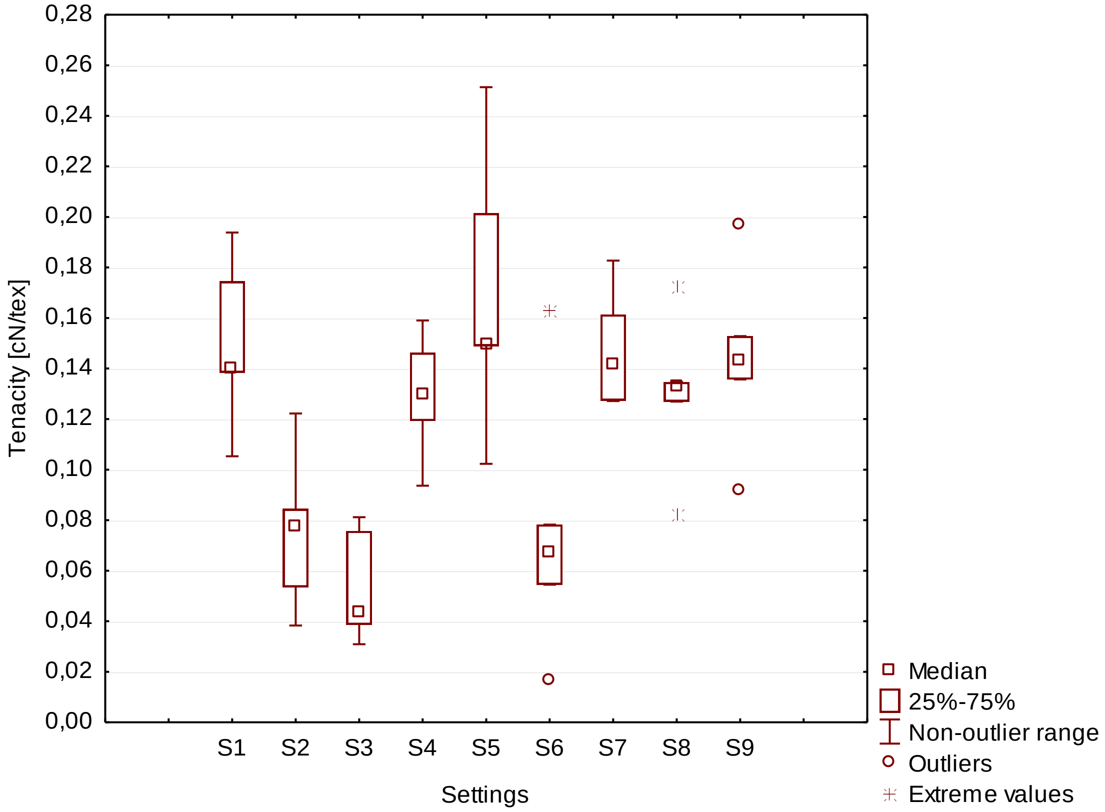

Figure 35 Comparison of tenacity of flax nonwovens in the CD – adjusting the direction of rotation

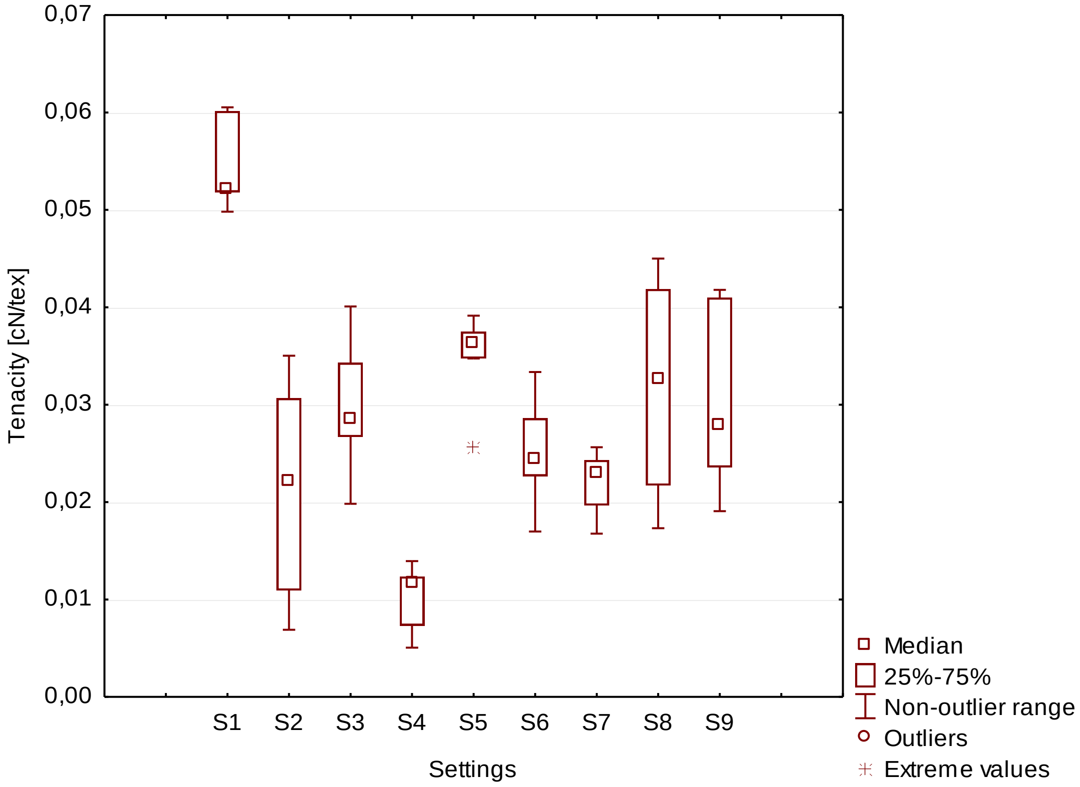

Figure 36 Comparison of tenacity of hemp nonwovens in the MD – adjusting the direction of rotation

Similarly to flax nonwovens, the size of the 25%-75% value range of hemp nonwovens produced by S3 and S9 differ strongly in the MD and the CD. Whilst the 25%-75% range of S3 is smaller in the MD than in the CD, the 25%-75% range of nonwovens made by S9 is smaller in the CD. However, hemp nonwoven samples produced by both S3 and S9 had the 25%-75% value ranges of tenacity larger than nonwoven samples from flax.

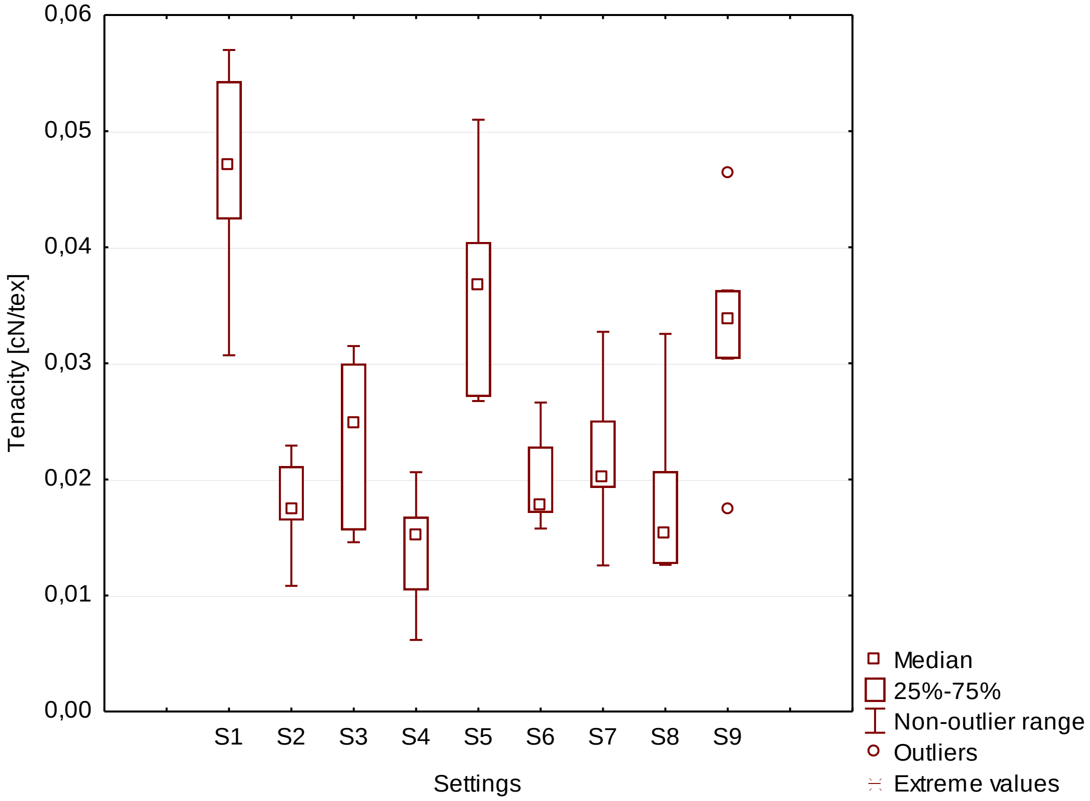

Figure 37 Comparison of tenacity of hemp nonwovens in the CD – adjusting the direction of rotation

The box plots graphically depict the value range of measured values. We can see that values of tenacity (or stretch) of nonwoven samples produced by a certain setting had very low variance, and some had very high variance. This is partially caused by a low number of samples in each group; however, the number of samples is defined by international standards. Furthermore, some of the settings tended to produce nonwovens with variable properties along the fibre web (waviness, low dense areas, fissures) and the high variation of basis weight is also caused by manual feeding.

The following four figures depict influences between frequency of rotation of spike rollers and tenacity of nonwovens. As mentioned above, the frequency of rotation of spike rollers affects fibre trajectories and creation of a web. However, no influence was observed between the frequency of rotation of spike rollers and fibre mat tenacity or stretch. The graphical representation shows that setting 1A provided nonwoven samples (especially from hemp) with a variance of measured values (both tenacity and stretch) higher than the other settings and setting 1C with slightly lower variance.

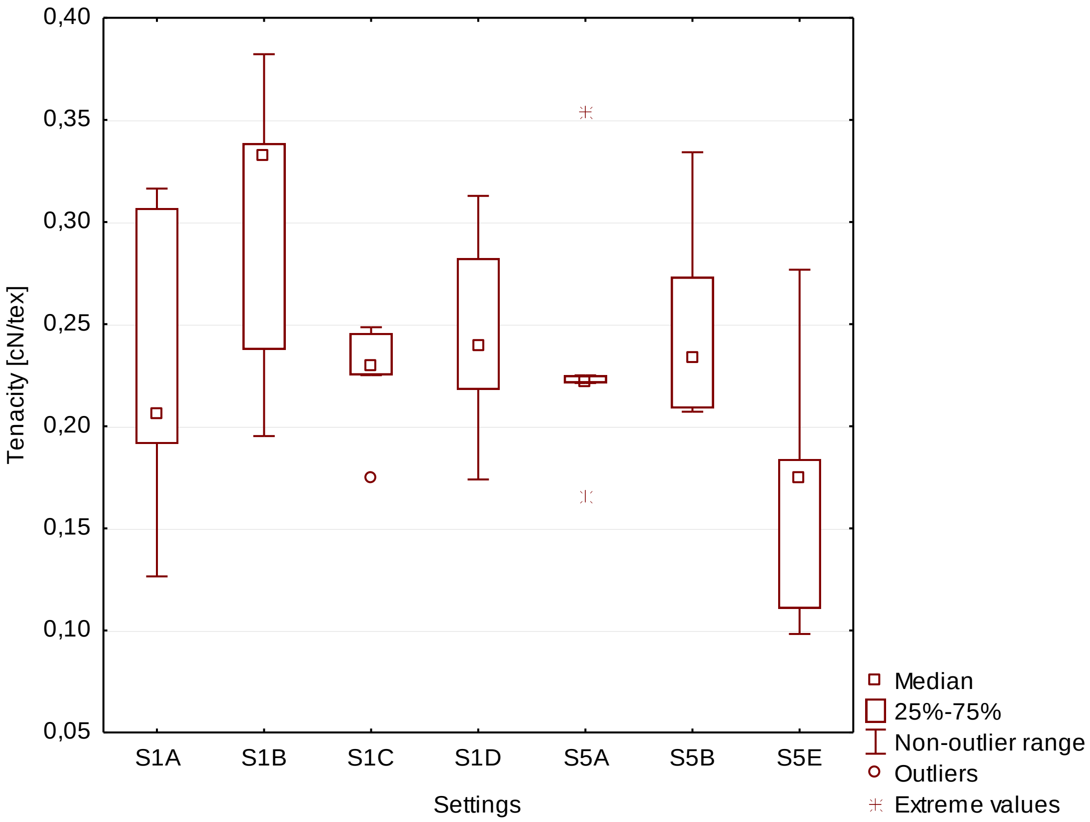

Figure 38 Comparison of tenacity of flax nonwovens in the MD – adjusting the frequency of rotation

Setting 5A provided flax nonwoven samples with a very small 25%-75% value range of tenacity both in the MD and the CD. However, in both cases there are two extreme values. As mentioned in the methodology, the extreme values should not be discarded from the results. If these extreme values are included in the results, the nonwovens produced by setting 5A also show high variation of tenacity.

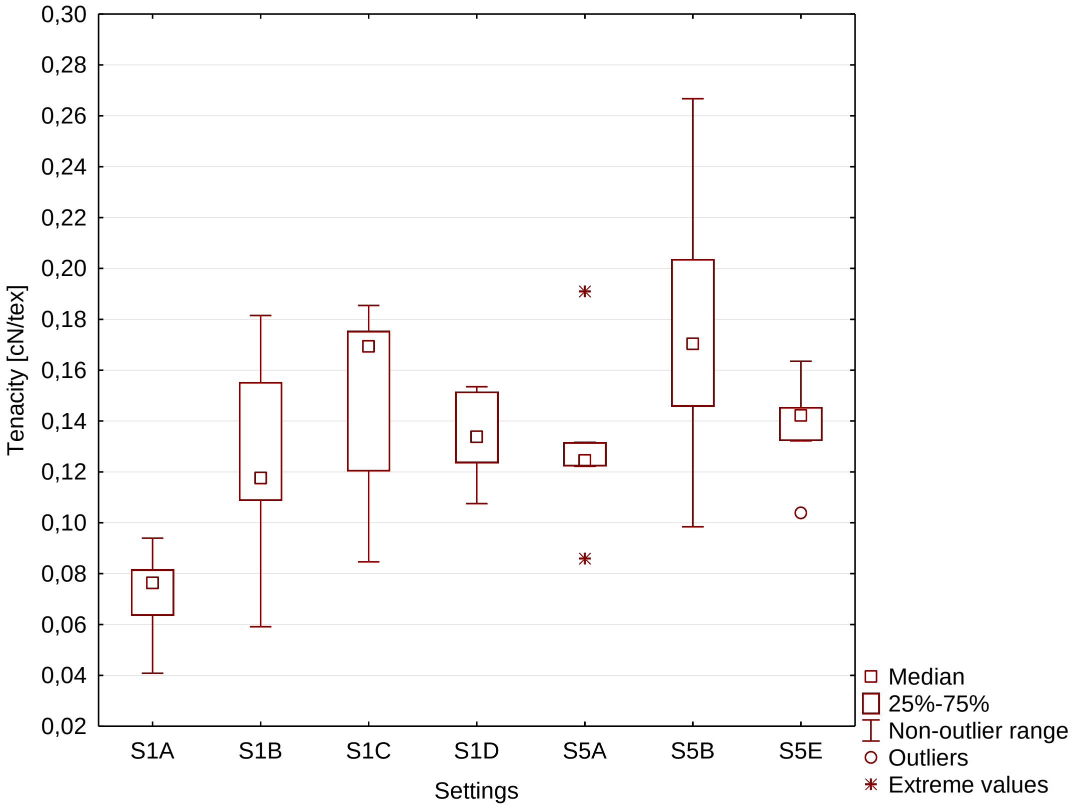

Figure 39 Comparison of tenacity of flax nonwovens in the CD – adjusting the frequency of rotation

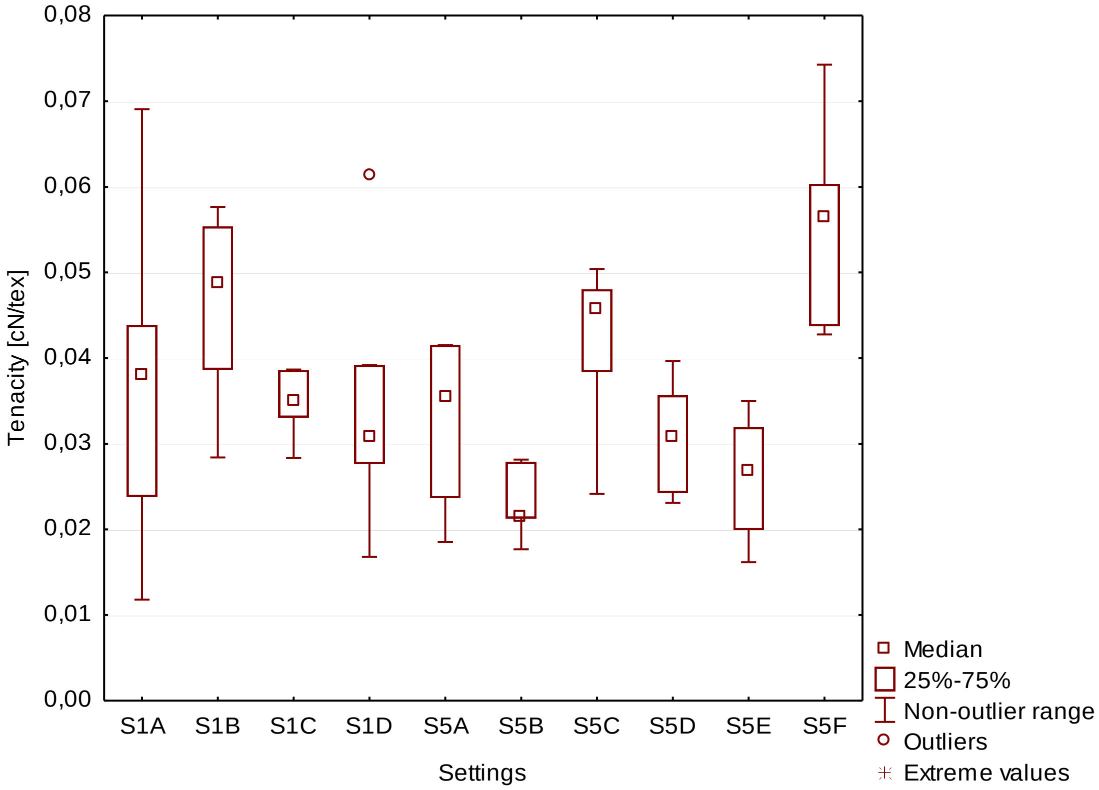

Figure 40 Comparison of tenacity of hemp nonwovens in the MD – adjusting the frequency of rotation

The following box plot graphically depicts the tenacity of hemp nonwovens in the CD. The graph shows that one half of the machine settings produced nonwovens from hemp with very low scattering of tenacity in the CD. On the other hand, settings 1D and 1A produced nonwovens with very high scattering of tenacity in the CD.

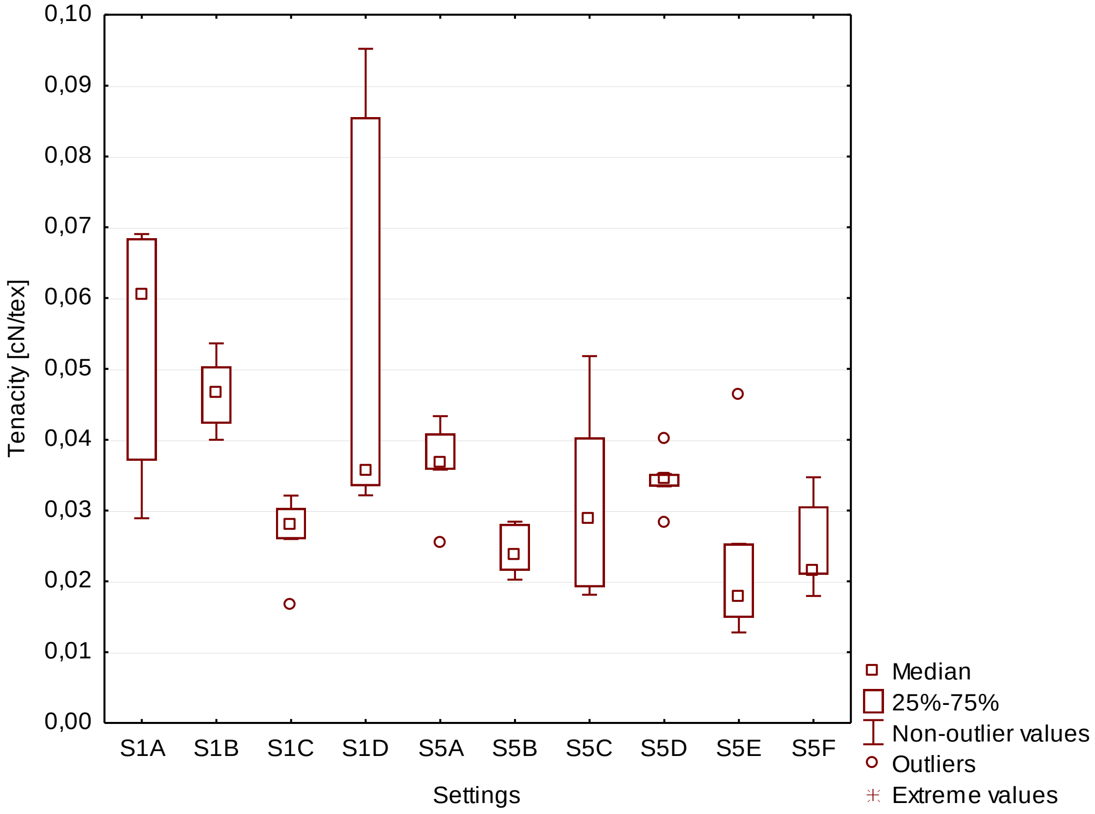

Figure 41 Comparison of tenacity of hemp nonwovens in the CD – adjusting the frequency of rotation

Generally, flax nonwovens have greater tenacity and stretch than hemp nonwovens. Figs. 41 and 42 plot stress-strain curves of nonwoven samples that were observed during tensile testing. Fig. 41 depicts stress-strain curves of flax nonwovens; it can be seen that the first part of each curve up to ca. 25% of elongation has a concave shape. At the inflection point, the curve changes to being convex. This phase is characterized by an increase in stiffness. The five upper curves in the figure are loading curves of specimens in the machine direction, the lower five of specimens in the cross direction. In the machine direction, the stress-strain curve of flax nonwoven has a greater slope than in the cross direction.

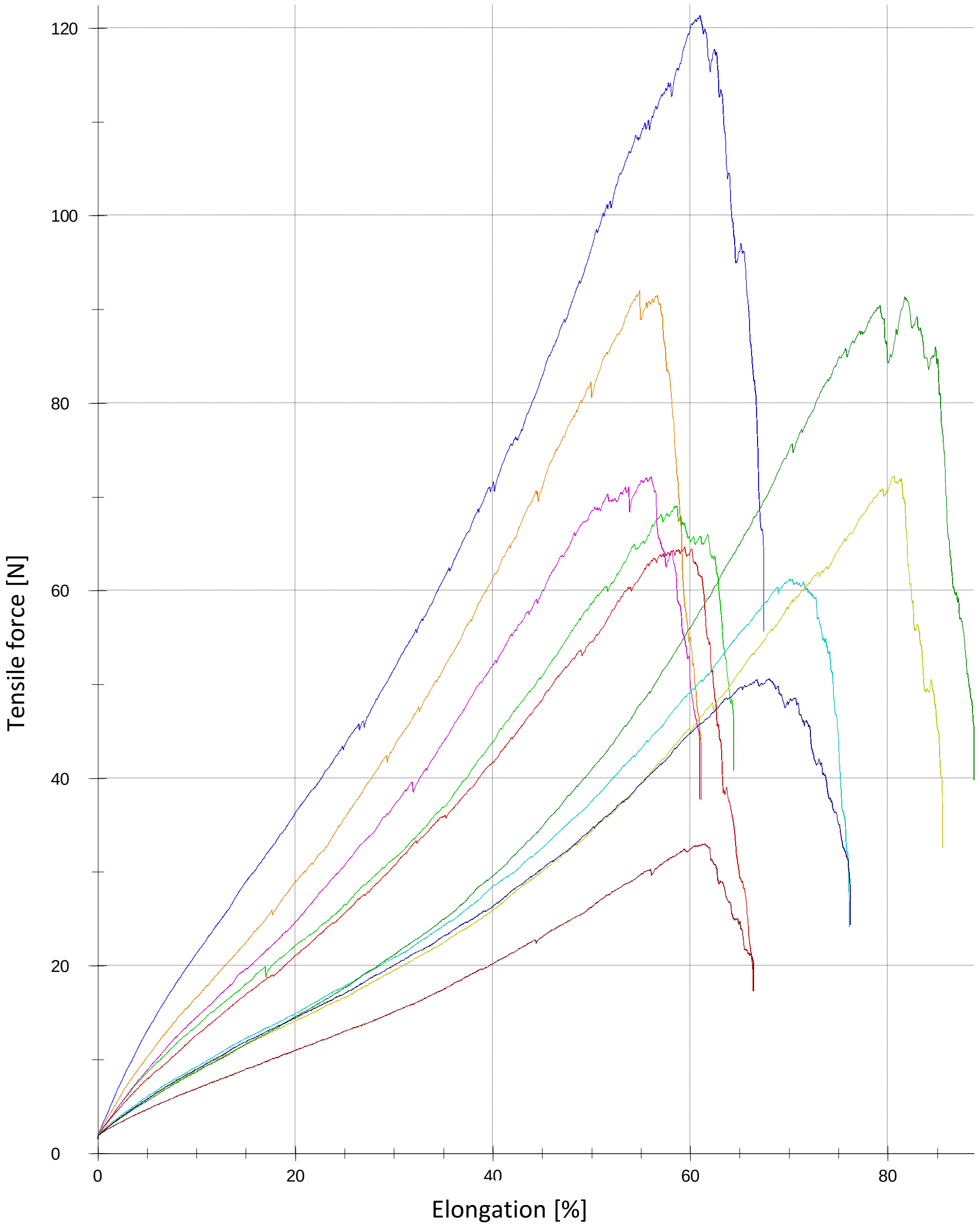

Figure 42 Influence between elongation and tensile force of flax nonwoven, setting S5B

The loading curves of hemp nonwovens do not have the same phenomena as the loading curves of flax nonwovens. All of the curves are only concave, and there is also no difference between slope of curves of specimens in the machine direction or in the cross direction.

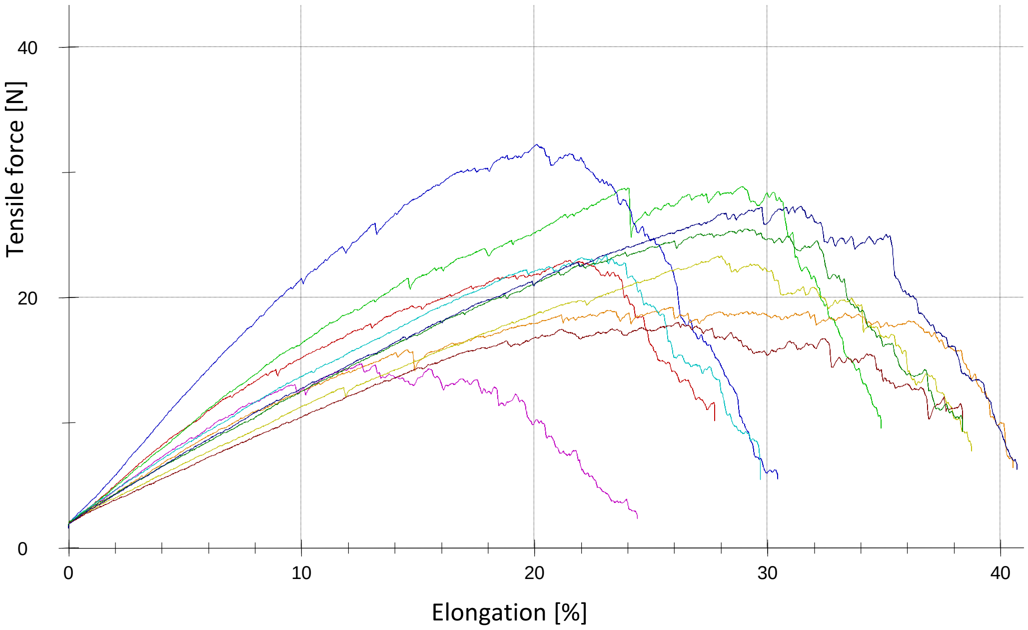

Figure 43 Influence between elongation and tensile force of flax nonwoven, setting S1B

3.3.4 Organization of devices

During the experimental part of the work, some changes in the organization of devices in the laboratory were suggested and carried out. These changes were carried out in order to obtain lower variability of nonwoven properties, higher labour productivity and lower dustiness during nonwoven fabrication.

Former organization

The forming wire in the air-laying machine is not long enough to produce a long nonwoven - some other conveyor has to follow this forming wire. In the former organization, a stationary wooden-slat conveyor had been used for this purpose. The conveyor had not been connected to a needle-punching machine and a laid web would have to be manually transported in front of the input part of the needle-punching machine. The laid web would have to be shifted on a board, moved in front of the needle-punching machine and slid down. This process would be carried out manually and many errors and disturbances of the web would be caused because of this. The following points show the main disadvantages of the former organization.

1) The stationary wooden-slat conveyor is self-made, unfortunately imprecisely. The length of the slats is not constant, and if two successive slats have a very different length the tooth gets jammed with a leading roller. This mishap also

stops the forming wire; however, air-laying can continue and it causes a passage with higher area weight of the web.

2) Using a higher speed the stationary conveyor gets under strong vibrations.
3) By shifting the web from the conveyor to the board the conveyor moves with constant speed; however, the board is moved manually. This shifting can change the area weight of the entire web and generate low and high-density areas in the web.
4) By sliding down the web from the board into the input of the needle-punching machine, the conveyor of the needle-punching machine moves at a constant speed; however, the sliding down of the web is performed manually. This sliding down of the web can change the area weight of the entire web and generate low and high-density areas in the web.

New organization

In the new organization, the stationary conveyor is replaced with a mobile belt-conveyor. This mobile conveyor is equipped with its own electric motor and frequency converter. This equipment clears the way for constant shifting of the web from the forming wire on the mobile conveyor, and subsequently from the mobile conveyor on the conveyor of the needle-punching machine. The required frequency of the electric motor can be always set. For better manipulation, the needle-punching machine was positioned parallel to the air-laying machine so that only small movement with the mobile conveyor is required. The placement of the mobile conveyor in the device organization eliminates all four of the aforementioned disadvantages of the stationary conveyor. However, this conveyor also has one disadvantage - the frequency converter does not enable high-speed running.

The spike air-laying technology is one of the most dust-producing technologies of web formation. Usage of nature fibres increases dustiness even more. There are three main openings in the machine which enable dust to fly out of the machine: the output for laid web, perforated roof of the machine housing (serves as drainage of air that is produced by a transport fan) and the air cleaner. Inputs of a draught fan (Fig. 43) were placed over all of these passages. Despite these installations, a lot of dust is produced during web forming and respirators must be used.

Figure 44 Installed inputs of a draught fan

3.4 Discussion

3.4.1 Fibre deposition dynamics and fibre-web quality

Coincidently with Carsten Andersen, it was observed that the upper two rows of spike rollers reduce fibre clusters and the bottom two rows determine the fibre trajectory in the lower part of the forming box and the fibre alignment on the forming belt. The observation of the function of the fibre-catcher (belt screen) was same as C. Andersen supposed. However, our observations show that the role of the fibre-catcher is not as essential as C. Andersen expected. The air-laying machine was able to produce a web with acceptable quality without the fibre-catcher.

In order to better understand the air-laying process, functions of the particular machine elements were analysed further and the results are presented in chapter 3.3.1. The influences of the particular machine elements on the air-laying process were described, and several combinations of machine settings were found that are suitable for fabricating an even and consistent web without fissures, or a web with high density. Setting number 5 can be used to fabricate a web with high density due to the fact that the last bottom opposite rotating spike blows fibres onto the back part of the forming wire, which causes the fibres in the forming web to be comprised and the web is denser. A setting of the machine that can be used when high productivity of the machine is required was also found, i.e. setting number 7. In this case the fibres from the inlet are directly sucked into the space under the first two rows of spikes instead of circulating in the upper part of the forming box. The usage of several machine settings is also dependent on the types of fibres.

Before needle-punching, some of the properties of webs were verbally evaluated: the surface waviness along and across the production direction, low-dense areas in the surface and the size and frequency of fissures. These properties could not be measured exactly because of the fibrous structure of the webs. Due to this phenomenon, the boundaries of the fissures and surfaces were not unequivocally determined, but the boundaries were often more than 2 centimetres broad. The webs were categorized into the quality scale on the basis of a verbal evaluation.

The observation of the fibre process time in the machine shows that the frequency of rotation of spike rollers has no influence on the fibre process time. Fast-rotating spike rollers in the two upper rows throw fibre clusters into the upper part of the forming box with great energy and the fibres rotate in this part, whereas slower rotating spike rollers do not throw fibre clusters with such high energy and the fibres can continue on to the next part of the machine more quickly. From this view it is suitable to use lower frequencies, because at lower frequencies of rotation the slats of the belt screen are less stressed, and fibres are also less shredded by spikes.

3.4.2 Fibre-mat quality

Tenacity is widely used to characterize the tensile properties of fabrics in the textile industry. This characteristic expresses breaking load applied on a specimen related to its basis weight. Basis weight does not influence the tenacity of nonwoven fabrics directly; however, there is an indirect influence. Regrettably, the indirect influence has not been quantified so far. The tenacity first increases with the increase of the basis weight up to an optimum level (different for different fabrics) and then decreases. The increase is caused by higher interlocking of fibres, and thereafter the tenacity is reduced with increased web weight due to non-interlocking of fibres (Midha and Mukhopadyay, 2005; Roy and Ray, 2009; Sengupta *et al.*, 2008). Despite this indirect influence, tenacity was used to compare fabrics with different basis weight. Therefore, a low variance of basis weight of the fabrics is required. Due to the manual feeding of fibres into the suction pipe and manual manipulation of webs, a coefficient of variation of basis weight equal to 12% was achieved. The high level of this coefficient of variation developed an even higher level of the coefficient of variation, or the standard deviation of the tenacity.

Elongation at a maximum load, called stretch, is the second observed tensile property. This property is an important characteristic of nonwovens used as reinforcement in composites, especially in formed composites. The basis weight of nonwoven fabric also influences its stretch. An increase in fabric weight reduces the fabric stretch due to restrictions of fibre movement in a highly interlocked structure, which is caused by an increase in weight. The contact between the horizontal and vertical structure increases and the structure is more rigid and less extensible. As the fabric weight increases further, needling action becomes more severe, causing breakage of the fibre and resulting in a reduction in inter-fibre friction. As a result the fibres separate more easily due to a relative lack of resistance to straining, and stretch decreases continuously (Midha and Mukhopadyay, 2005; Roy and Ray, 2009). This direct effect of basis weight on stretch cannot be eliminated as in the case of tenacity, and this can be the reason why any influence between the fabric stretch and the machine adjustments was not observed. High variation of basis weight makes results in terms of stretch incomparable and unsuitable for further statistical analysis.

Factors which influence the properties of needle-punched fabric are given in Table 15.

Table 15 Factors influencing properties of needle-punched fabric, Midha and Mukhopadyay 2005

Raw material variables	Fibre type Fibre length, fineness, cross-section, crimp, contour Mechanical properties of fibres
Web characteristics	Orientation of fibre in the web Web weight and uniformity Presence of scrim
Needle-punching machine design parameters	Needle density on the board Arranged pattern of needles in the needle board Type of needles Single or double-sided needling Pre-needling
Needle-punching machine variables	Needle-punch density Needle penetration Entry and exit speeds

There are many combinations of these factors, and this is the reason why it is not possible to compare numerical results with other research. There is also no research concerned with nonwovens formed by spike air-laying technology. However, it is possible to compare trends of influences between tenacity, stretch and basis weight. The 3D graph in Fig. 44 plots the influence between tenacity, stretch and basis weight of hemp nonwovens in MD. The tenacity increases with the increase to the basis weight up to 820 g·m^{-2} and then decreases, and an increase in fabric weight reduces the fabric stretch. Midha and Mukhopadyay, 2005; Roy and Ray, 2009; Sengupta *et al.*, 2008 observed this behaviour as well. For jute needle-punched nonwoven fabric, the optimum level of basis weight is 700 g·m^{-2} and the achieved tenacity is 0.35 cN·tex^{-1} (Sengupta *et al.*, 2008).

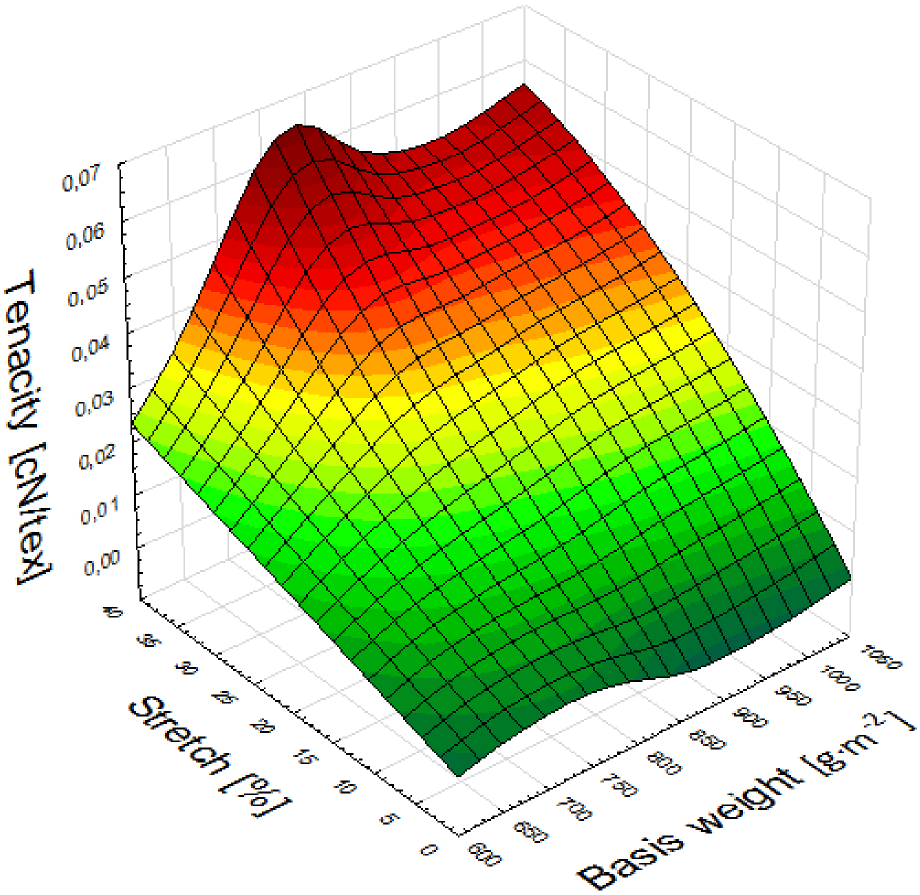

Figure 45 Influence between tenacity, stretch and basis weight of hemp nonwoven in MD

The harvesting time of plants, or fibre ripeness, fundamentally affects the mechanical properties of their fibres. Both flax and hemp plants can be grown for fibres or for seeds (Pickering, 2008; Struik *et al.,* 2000). Unfortunately, the harvesting time of fibre harvest differs from harvesting time of seed harvest. Generally, seeds are not fully ripe during the fibre harvesting time, and adversely, fibres are overripe and do not have the best mechanical properties during the seed harvesting time (Baltina *et al.*, 2011; Mediavilla *et al.*, 1998). The results of these harvesting periods are that hemp and flax plants can be grown either for fibres or for seeds. Whilst the fax fibres used in this research come from fibre flax plant, the hemp fibres originate from a seed hemp plant. It can be stated that the hemp fibres used in this research are harvesting rests. This origin of the hemp fibres is one of the reasons why the tensile properties of fabricated hemp nonwovens are lower than the tensile properties of flax nonwovens. Furthermore, hemp fibres have on average a lower tensile strength than flax fibres (see Table 2). However, the tensile strength of single fibres was not measured in this research. Another reason for the lower tenacity of hemp fabric is that hemp fibres were treated in the opening roller three times, whilst flax fibres only once. This triple treatment causes shortening of fibres. Fibre length plays a very important role in the tensile properties of needle-punched fabric. A longer and finer fibre in the web leads to greater fabric tensile properties. A small increase in length causes a marked increase in stiffness and strength due to the reduced slippage of fibres. (Midha and Mukhopadyay, 2005). Despite the triple treatment of hemp fibres in the opening roller, they still contained more shive fraction than the flax fibres. This shive fraction also decreases the tensile properties of nonwovens.

When we compare the results from the evaluation of fibre-web quality and from the evaluation of fibre-mat quality, we find that small errors and fissures in the fibre web (low-dense areas in the surface layer, fissures in the surface layer or rare fissures with a depth max. of one half of web high) do not significantly deteriorate the tensile properties of needle-punched fabric. The fibre web is compressed during the needle-punching process from ca. 12 cm to ca. 1 cm (depending on basis weight) by the action of barbed needles. These needles are able to mechanically entangle the fibre mat so extensively that the missing entanglement of fibres in the fibre web (because of some small fissure) is fully substituted. Needle-punching improves the compactness or packing of the fibre assembly and causes structural changes in the fibre web (Sengupta *et al.*, 2008). It is assumed that every error in the fibre web influences the mechanical properties of a needle-punched nonwoven; however, our results are distorted due to the high coefficient of variation of the basis weight.

It is often stated that air-laying technology produces webs with more balanced structure and random orientation of fibres (Fang *et al.*, 2000; Midha and Mukhopadyay, 2005; Russell, 2007). It can be deduced from the results that spike air-laying technology does not produce random-laid webs. Firstly, it was obvious during visual observation of the fibre webs that there is a predominant orientation of fibres in the web, and secondly, it can be calculated from the results that the MD:CD tenacity ratio is not 1:1. On average, the tenacity ratio is lower than 2 and hemp nonwovens have this ratio slightly lower than those from flax. The lower tenacity ratio of hemp fabric may be caused by shorter hemp fibres.

The frequency of rotation of spike rollers affects fibre trajectories and creation of a web; however, no influence was observed between the frequency of rotation of spike rollers and fibre mat tenacity or stretch. There are some significant influences between the frequencies of rotation of spike rollers and tenacity. However, these are isolated cases and it is assumed that these cases are influenced by variable fabric basis weight, or by the presence of a fissure in the specimen; for example, the tenacity of hemp fabric fabricated by setting 1D in the CD is significantly higher than the tenacity of hemp fabric made using settings 1C, 5B, 5D and 5E, but the influence is not the same in the case of the MD or linen fabric.

For needle-punched fabric, the slippage of fibres is a dominating factor in the deformation of fabric, influencing its tensile behaviour. The effect of the fibre type on the properties of needle-punched fabric shows that some fabrics exhibit stick-slip behaviour in extension and others deform smoothly. For example rayon, acrylic, jute, jute/polypropylene and jute/viscose fabrics show stick-slip oscillations, whereas cotton and wool give smooth curves with no noticeable oscillations. The behaviour during extension can be related to the frictional properties of its constituent fibres (Midha and Mukhopadyay, 2005). The stress-strain curves in Fig. 41 and 42 plot the behaviour of flax or hemp needle-punched fabric during tensile testing. There is no evident phase with an increase in stiffness in the stress-strain curves of hemp fabric. This may be caused by greater slippage of hemp fibres than those from flax. The observation of cracking during loading corresponds to this theory. Whilst cracking of linen fabric was observed during the convex shape, before the peak, cracking of hemp fabric was observed after the maximum load. Slippage can be further influenced by the length of fibres, whereas long flax fibres can be more entangled, hemp fibres are shorter and less entangled. For longer fibres, there is also greater difference between the slope of stress-strain curves in the MD and the CD.

3.4.3 Variability

Unlike synthetic fibres, natural fibres have greater variability in their mechanical properties due to the conditions experienced in the field, and also due to the potential damage arising from the production processes and measurement conditions. The factors that affect the mechanical properties of natural fibres are summarised in Table 16. There are several different stages in the production processes of flax/hemp fibres, and in each stage several factors can influence the quality of fibres (Yan *et al*. 2014). The variability of fibre properties can be seen in the value ranges reported in Table 2.

Table 16 Factors affecting mechanical properties of natural fibres, Yan *et al.* 2014

Plant growth	Specimens of plant, crop cultivation, crop geographical origin, fibre location in plant, local climate (e.g. rainfall, temperature)
Harvesting stage	Fibre ripeness, which effects: cell wall thickness, fibre coarseness, adhesion between the fibre and surrounding structure, the size and shape of lumen, porosity, microfibril angle
Fibre extraction stage	Decortication process, type of retting method, separating conditions
Supply stage	Transportation conditions, storage conditions, age of fibres
Measurement conditions	Tensile speed, initial gauge length, moisture, temperature, different cross-section of fibres at different points
Surface treatment	Chemical treatment, upgrading treatment, water treatment, drying treatment

In this project, fibres from one bale (for both hemp and flax) were used to minimize the influencing factors that arise from fibre variability. Unfortunately, there are other area of possible origin of variability. Manual feeding of fibres into the suction pipe was as uniform as possible; however, the air-laying technology is very sensitive to any kind of unevenness in the fibre supply. Even the smallest unevenness in fibre supply creates uneven fibre alignment or variability in basis weight of a fibre web, which consequently causes the properties of the end product to vary (Fang *et al.*, 2000). The air-laying technology is more demanding on the even fibre supply than the carding technology (Russell, 2007). The high variance of fabric basis weight caused even higher variance of the tensile properties, and therefore the conclusions cannot be as clear. In order to reduce the variance of the fabric basis weight, a mobile belt-conveyor was implemented for nonwoven production. Using this mobile conveyor eliminates manual manipulation with fibre webs, thereby reducing the variance of basis weight. However, the manual feeding of fibres into the suction pipe has the greatest negative influence on variance of basis weight.

Another place where variability of properties of nonwovens could arise is the needle-punching process. Sometimes a barbed needle hits a foreign particle (rest of stem) and breaks. The area where one needle is missing is susceptible to extension. If there is an area with broken needles in a part of the needle head, the nonwoven is not bonded uniformly and has variable mechanical properties. It is therefore important to remove the shive fraction from the fibres before air-laying, and to change the needles if they break. Fig. 45 depicts a specimen after tensile testing. This specimen has ruptured at a very low load due to an error in its structure. The error might be caused by low basis weight or by low entangled fibres due to missing needles.

Figure 46 Specimen broken at low load

As discussed above, there are many effects that can cause variability of properties of nonwovens. In this study, the variability of properties was observed on four levels: variability between fibres, between fibre mats, within a fibre mat and within a specimen. These may be the reason why the conclusions cannot be as clear.

4 Conclusion

This diploma thesis was focused on air-laying nonwoven fabrication and evaluation of natural-fibre nonwoven properties. Firstly, a literary search dealing with natural fibres and nonwoven fabrication was obtained. Secondly, extensive investigations of natural-fibre nonwoven optimization were designed. SPIKE® air-laying technology from the Formfiber Denmark ApS Company was used. The web-formation processes and the properties of the fibre-webs were evaluated. After needle-punching, the properties of the reinforced fibre-mats were evaluated. The investigations have clearly revealed that the settings of the air-laying machine affect web-formation process and nonwoven properties. The following conclusions can be drawn and the following settings of the air-laying machine can be recommended:

- The upper two rows of spike rollers reduce fibre clusters and the bottom two rows predominantly determine the fibre trajectory in the lower part of the forming box and the fibre alignment on the forming belt.

- The more the fibres are compressed by the pressure roller, the more they expand behind the roller. In order to prevent the creation of fissures in the fibre-web, it is appropriate to use settings which throw fibres onto the back part of the forming wire. These are settings where the lowest row of spike rollers rotates in the production direction.

- A machine setting was ascertained that can be used when high productivity of the machine is needed – setting no. 7. The upper two rows of spikes rotate opposite to the production direction. This adjustment causes the fibres from the inlet to be sucked directly into the space under the first two rows of spikes, and only a small amount of the fibres circulate in the upper part of the forming box.

- Setting 5 should fabricate high-density webs. The last bottom opposite rotating spike (4B) blows fibres onto the back part of the forming wire, which causes the fibres in the forming web to be comprised and the web is denser. Webs with high density can also be produced using settings where the lower two rows of spikes rotate at a high frequency level (80 Hz).

- The observation of the fibre process time in the machine revealed that the frequency of rotation of spike rollers has no influence on the fibre process time. From this view, it is suitable to use lower frequencies, because at lower frequencies of rotation the slats of the belt screen are less stressed, and the fibres are also less shredded by the spikes.

- Nonwovens with great tensile properties can be fabricated by using settings nos. 1 (all of the spike rollers rotate in the production direction) and 5 (the last, lower 4B spike rotates in the opposite direction).

We had to contend with fluctuation of fabrics basis weight during the course of all of the experiments. The variance of the fabrics basis weight comes mainly from manual feeding of fibres into the suction pipe because the air-laying technology is very sensitive to any kind of unevenness in the fibre supply. Due to the high coefficient of variation of the basis weight, some of the data (stretch) is unsuitable for drawing conclusions. Some measures were implemented to the nonwoven production in order to reduce the variation of the fabric basis weight.

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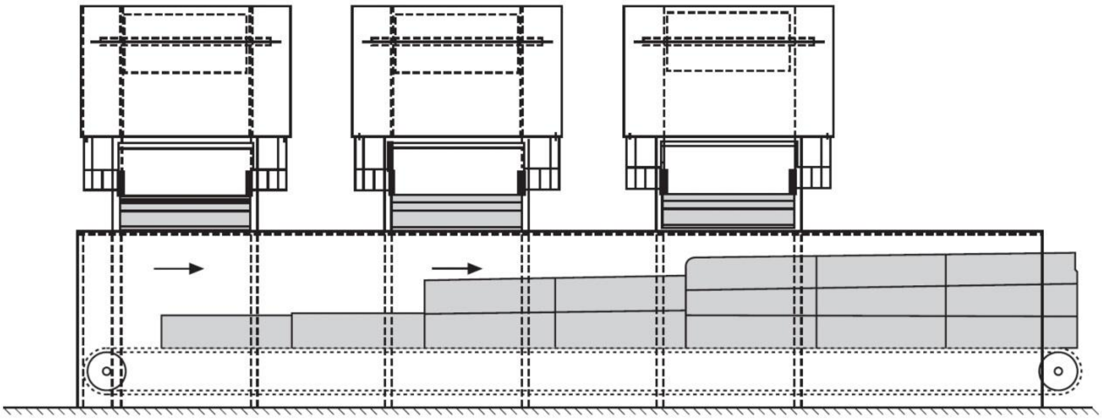
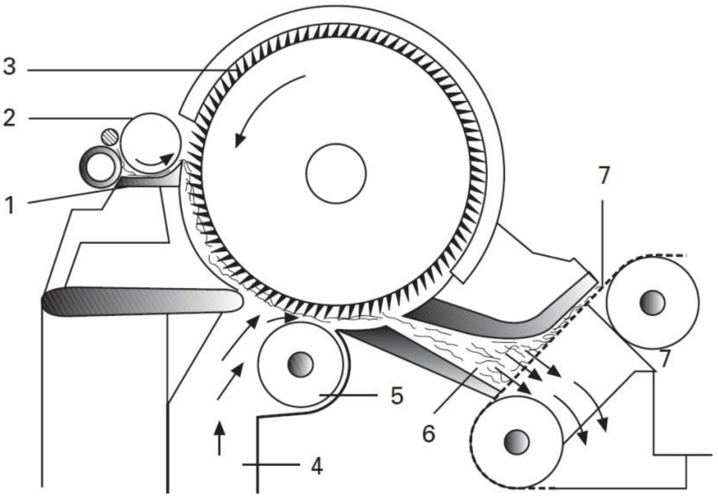
6 Supplement

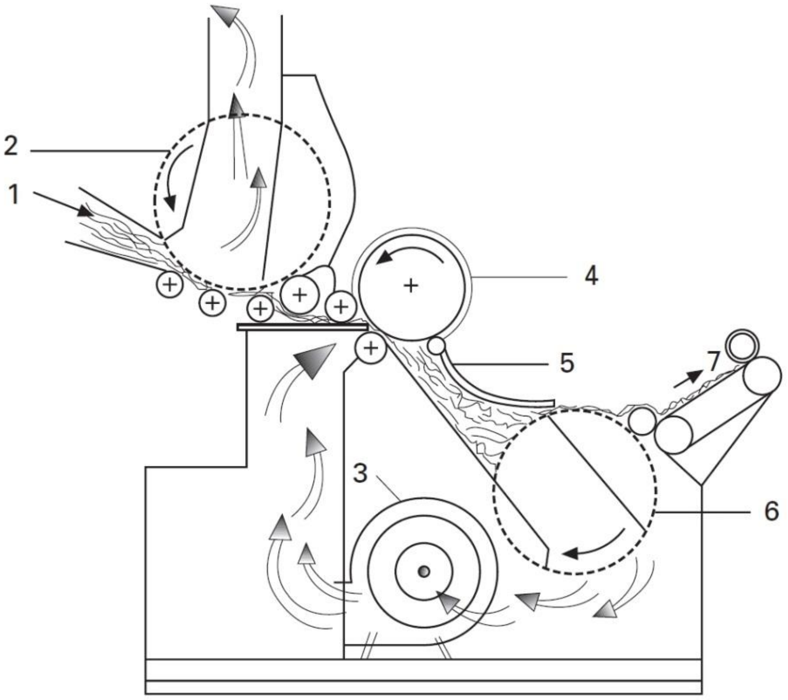
List of supplements



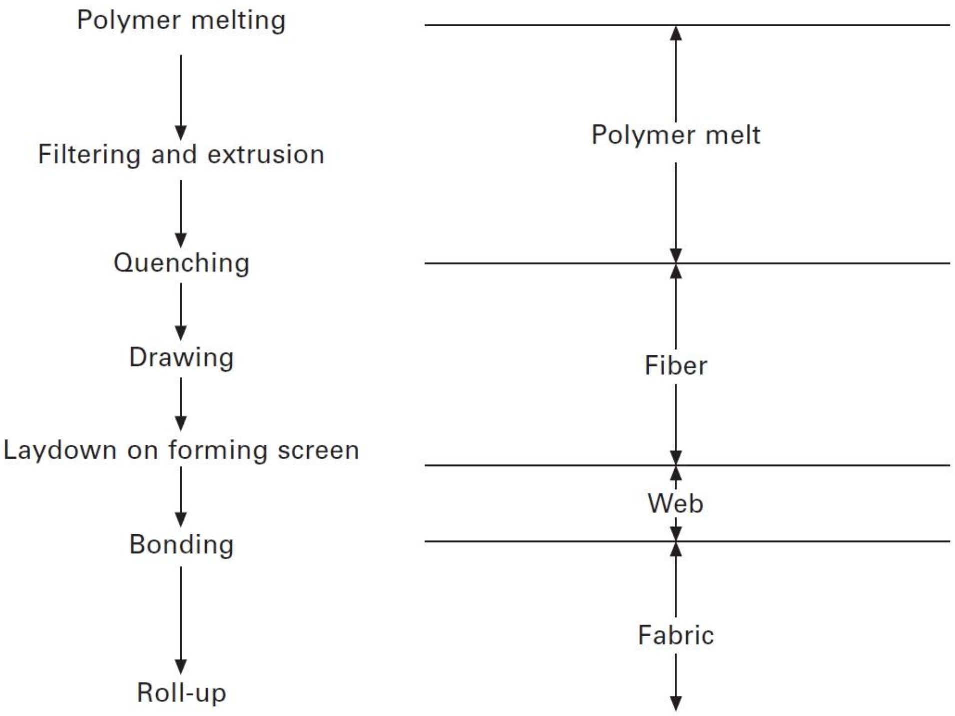
Supplement 1 Multi-hopper system, Russell 2007



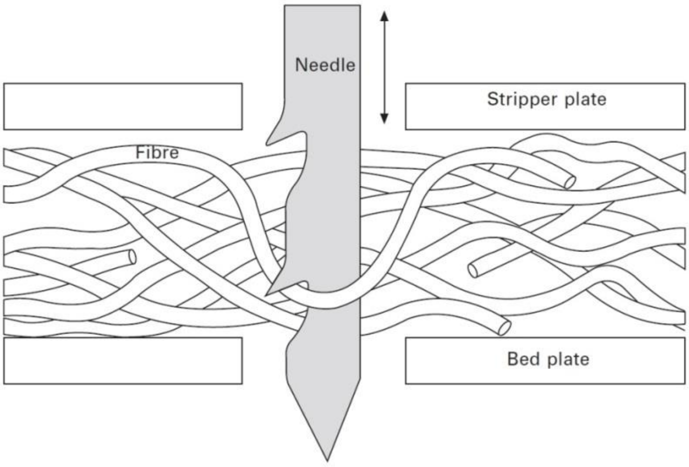
Supplement 2 Rando-webber air-laying – model A, Russell 2007
1 – feed plate, 2 – feed roller, 3 – saw toothed licker-in, 4 – airflow duct, 5 – saber tube, 6 – fibre transfer chamber, 7 – landing belt



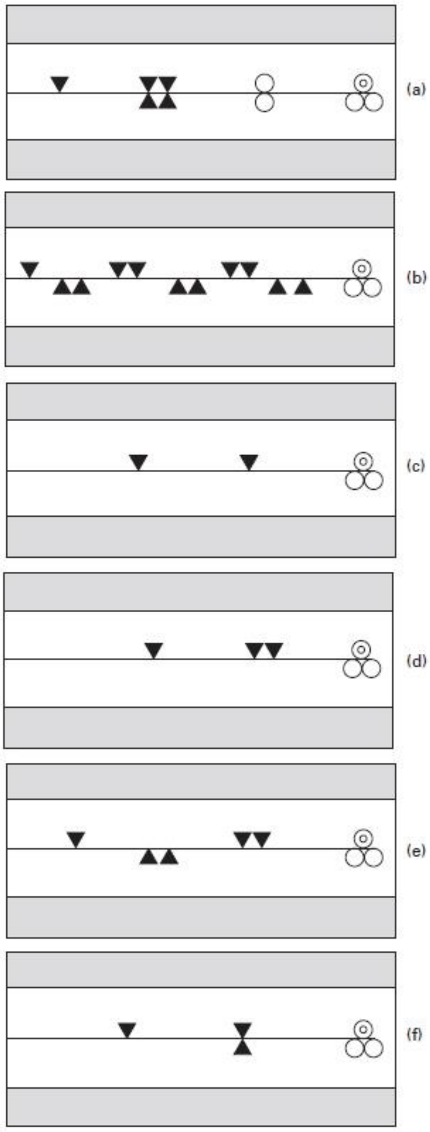
Supplement 3 Rando-webber air-laying – model B, Russell 2007
1 – fibrous web input, 2 – condenser, 3 – air blower, 4 – licker-in, 5 – fibre transport chamber, 6 – cylindrical condenser, 7 – air-laid web out



Supplement 4 Stages of the spunbond process, Russell 2007

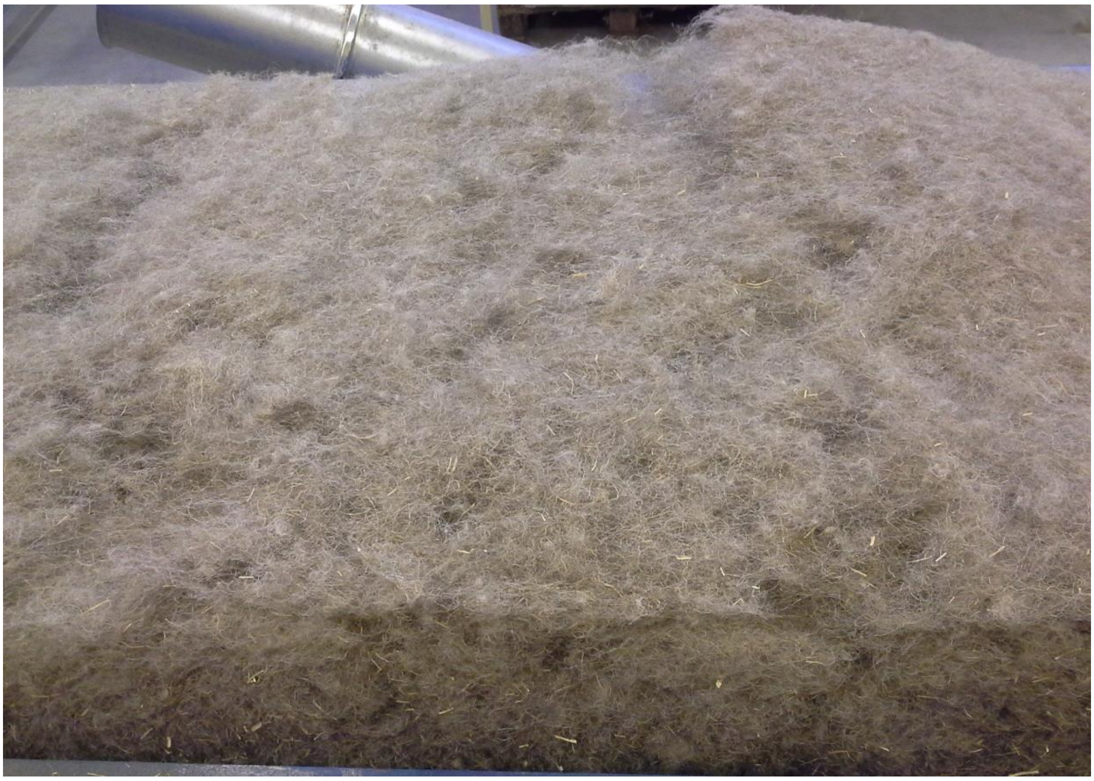


Supplement 5 Action of barbed needle, Russell 2007



Supplement 6 Common sequences of needle-punching machines, Russell 2007

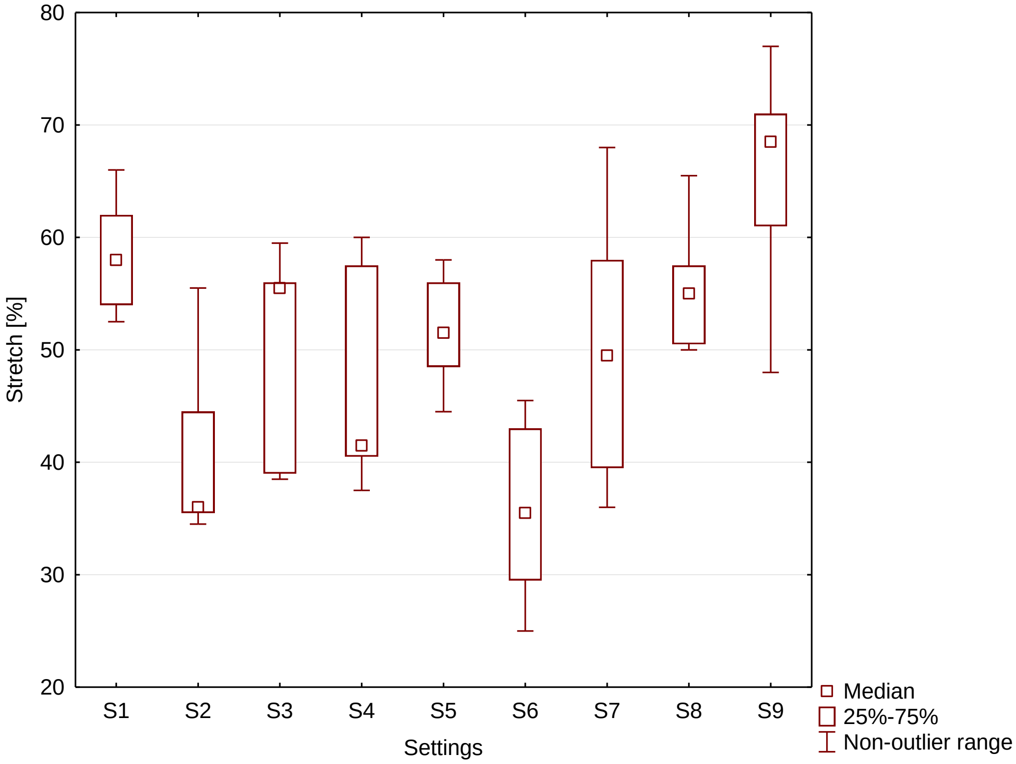
Supplement 7 Hemp web, quality level 1



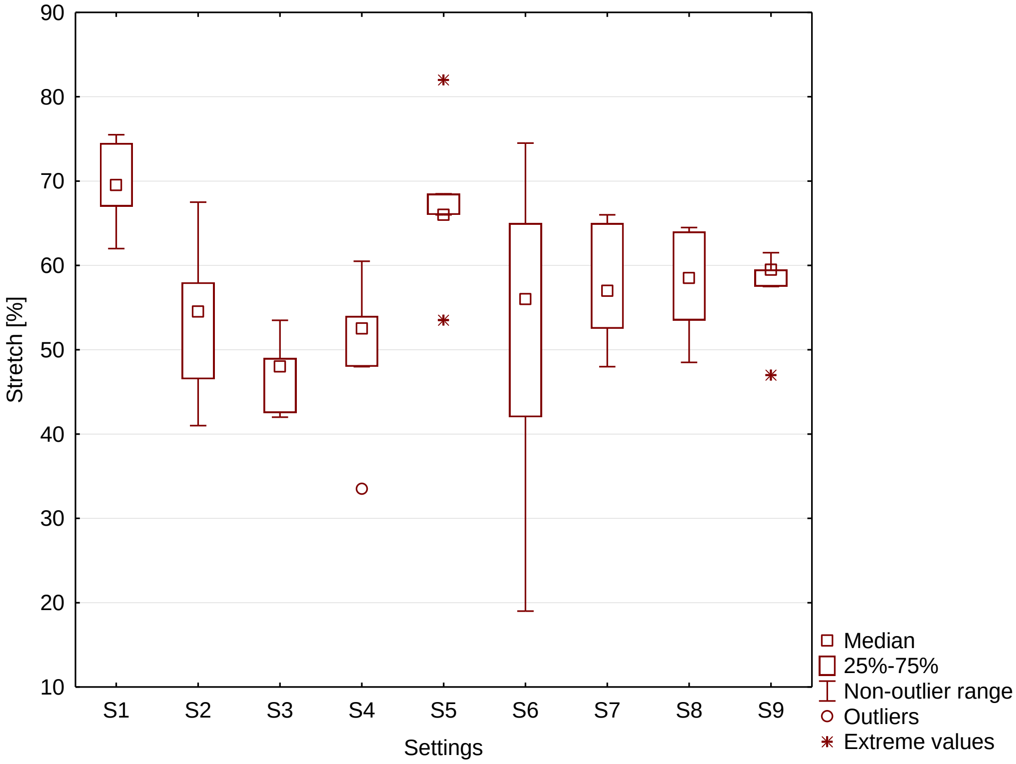
Supplement 8 Flax web, quality level 2

Supplement 9 Flax web, quality level 3

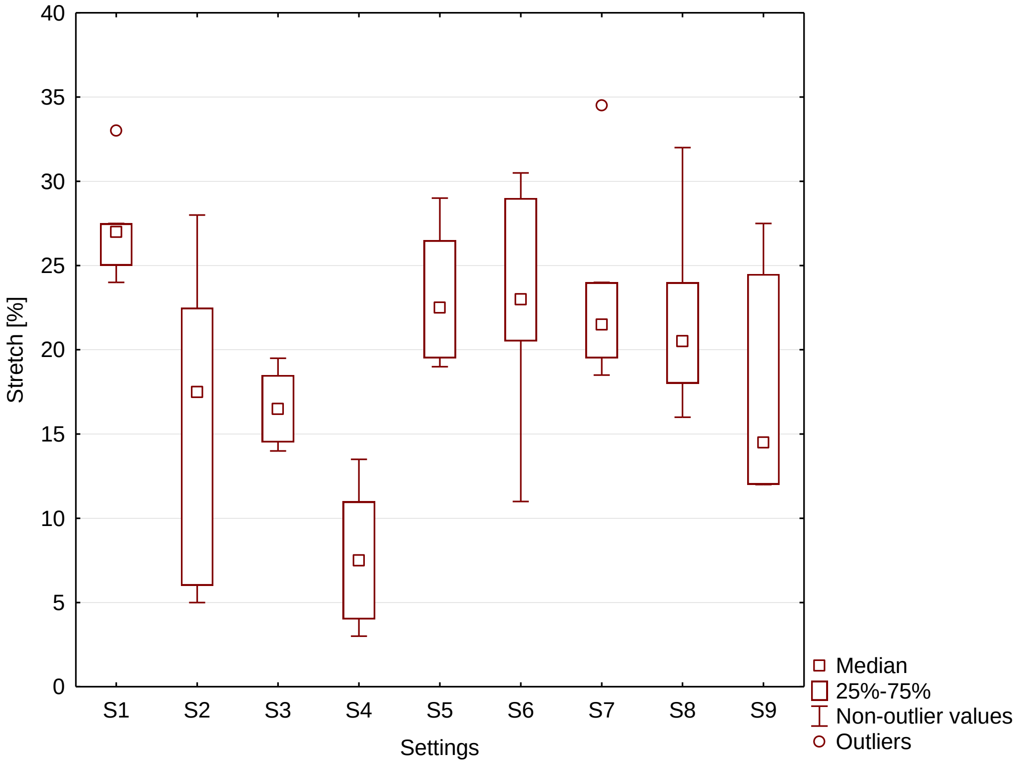
Supplement 10 Flax web, quality level 4



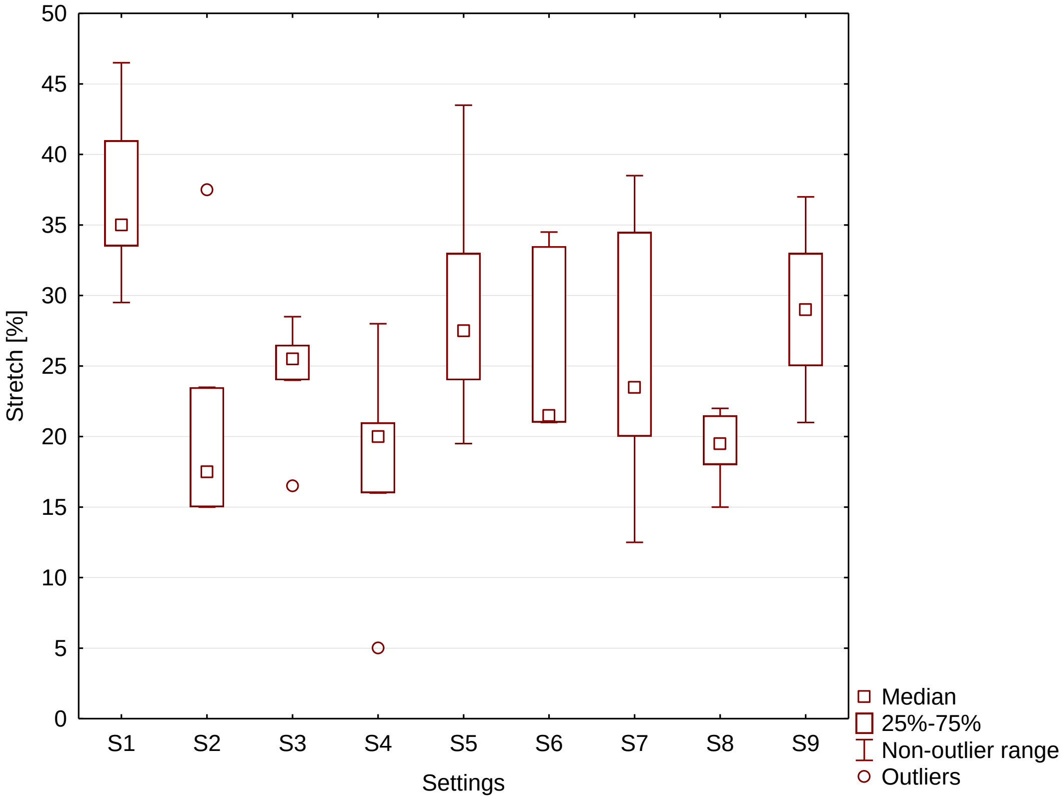
Supplement 11 **Comparison of stretch of flax nonwovens in the MD – adjusting the direction of rotation**



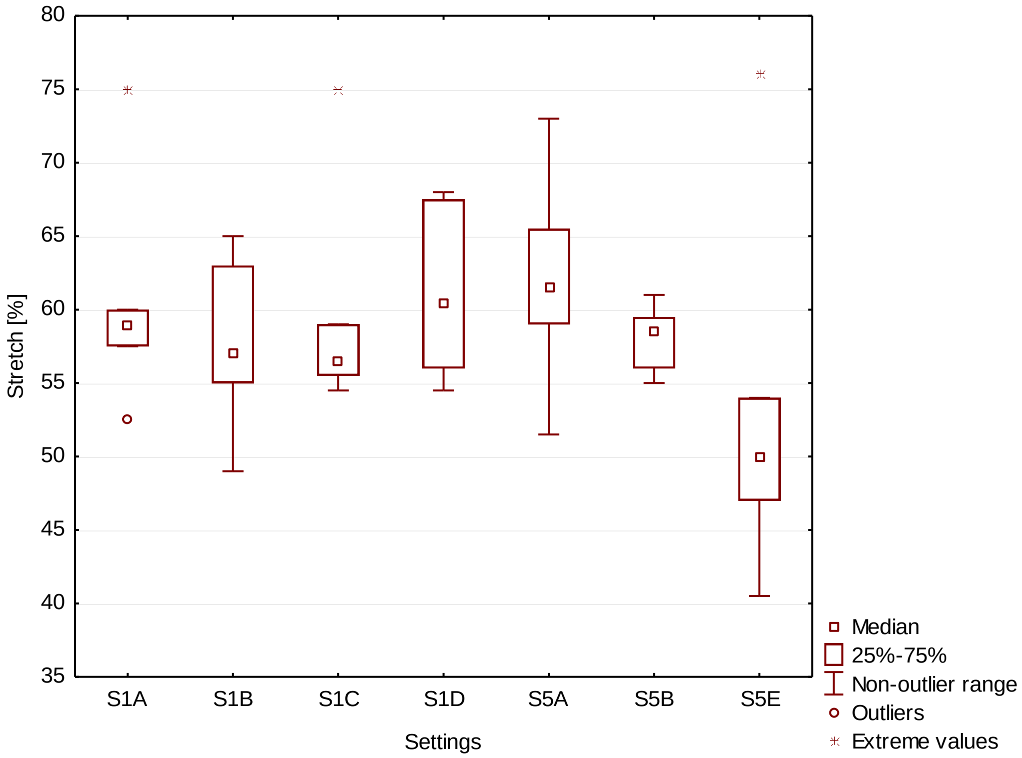
Supplement 12 **Comparison of stretch of flax nonwovens in the CD – adjusting the direction of rotation**



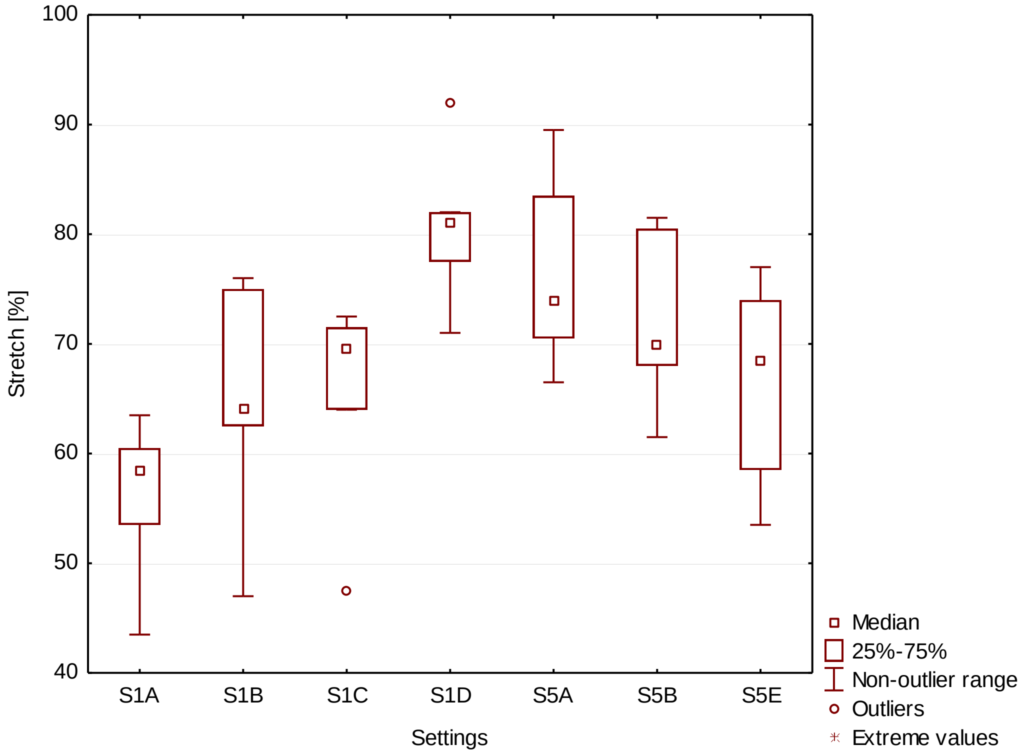
Supplement 13 Comparison of stretch of hemp nonwovens in the MD – adjusting the direction of rotation



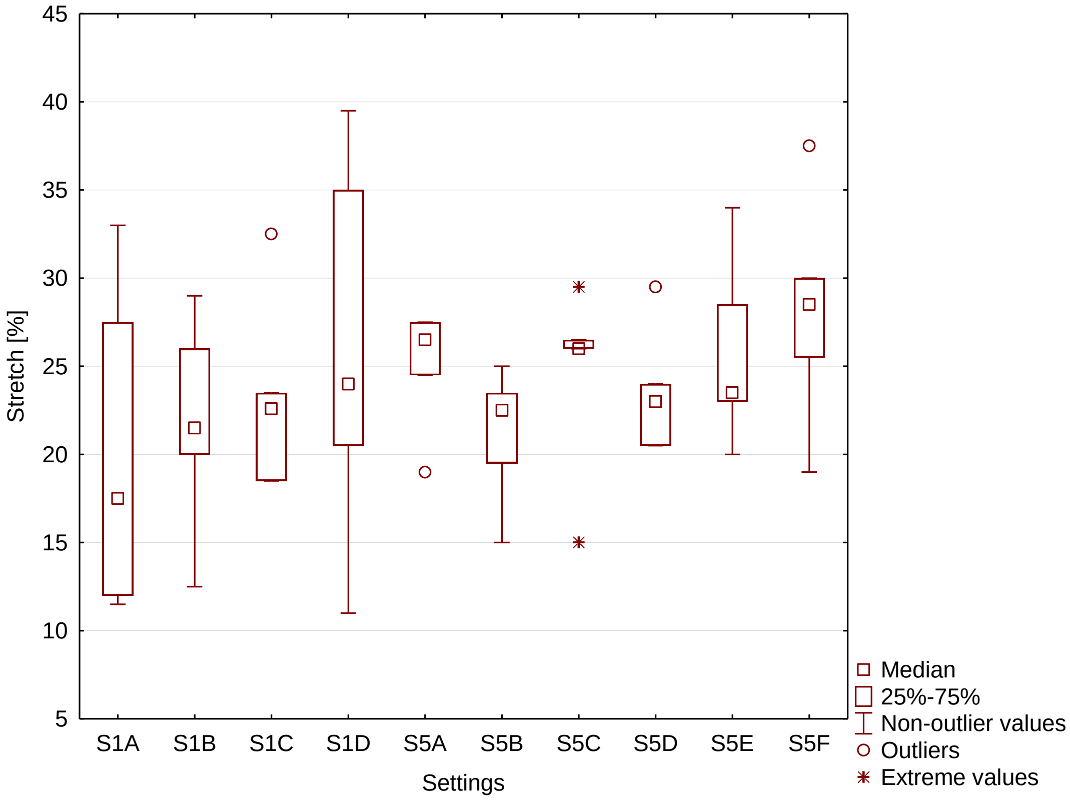
Supplement 14 Comparison of stretch of hemp nonwovens in the CD – adjusting the direction of rotation



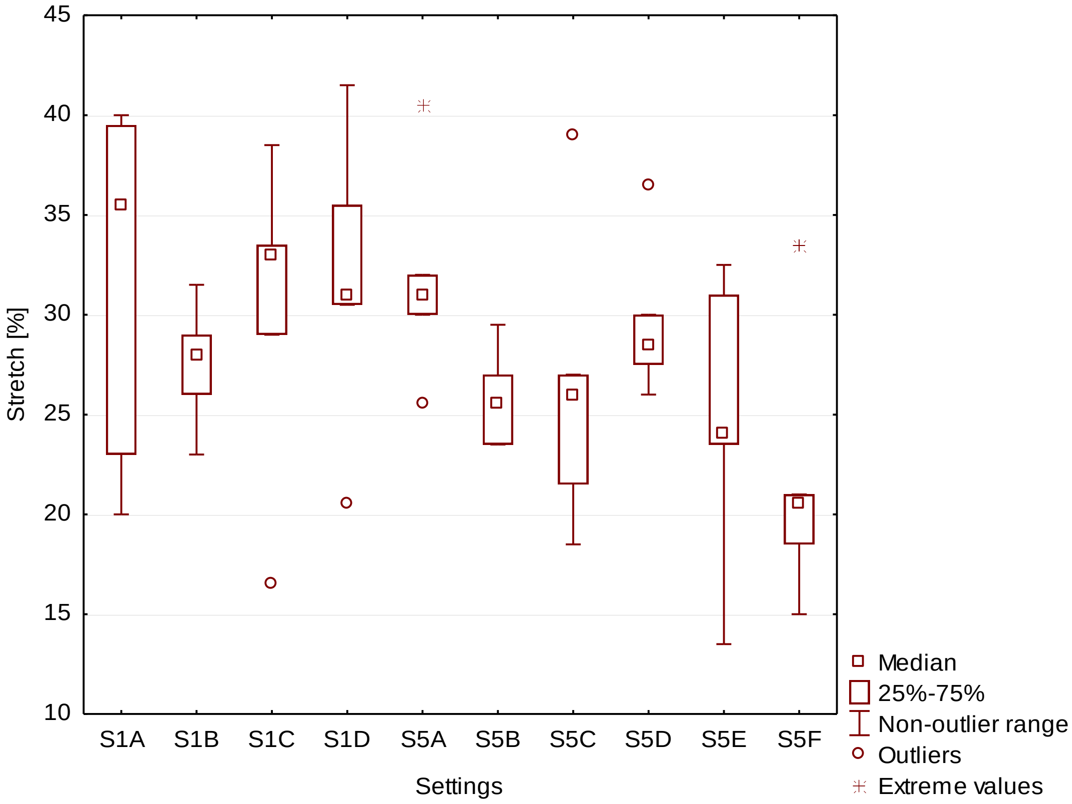
Supplement 15 **Comparison of stretch of flax nonwovens in the MD – adjusting the frequency of rotation**



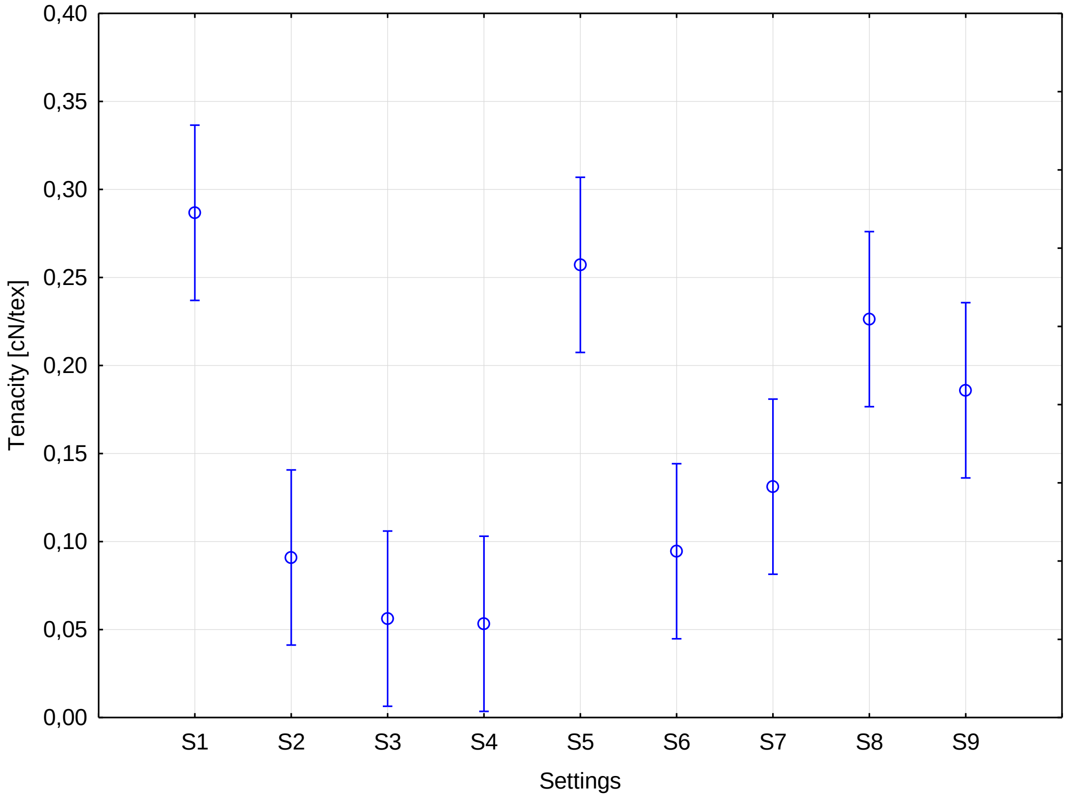
Supplement 16 **Comparison of stretch of flax nonwovens in the CD – adjusting the frequency of rotation**



Supplement 17 Comparison of stretch of hemp nonwovens in the MD – adjusting the frequency of rotation



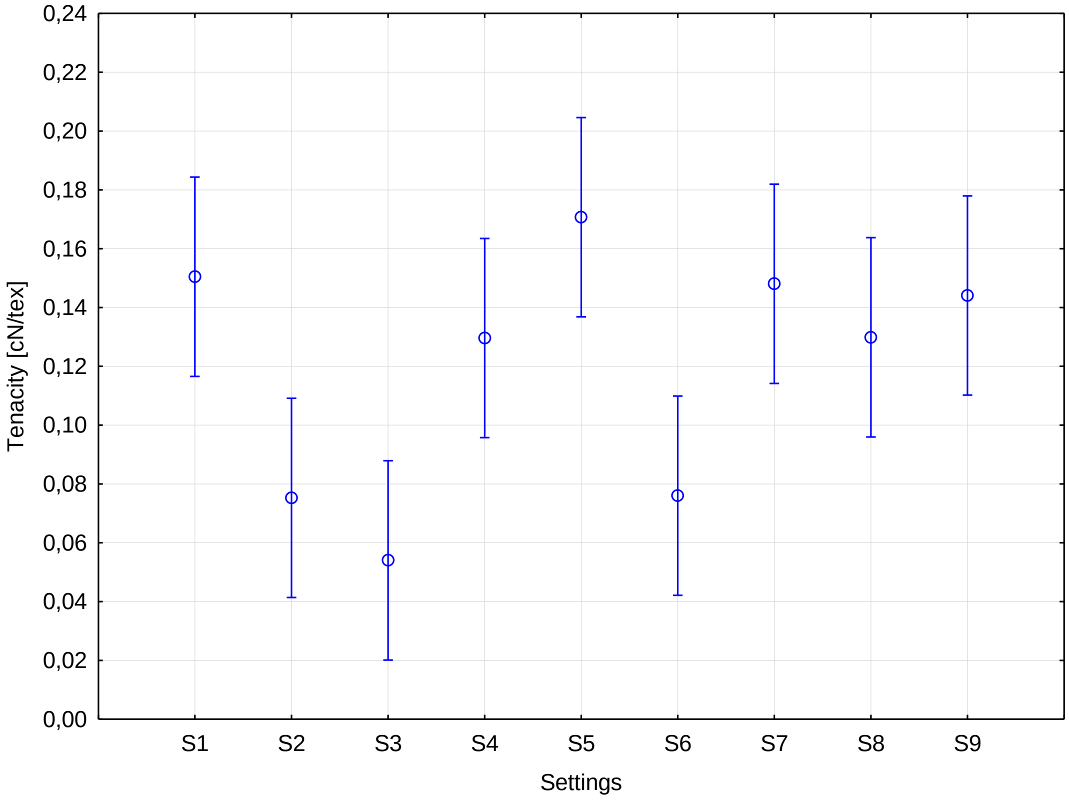
Supplement 18 Comparison of stretch of hemp nonwovens in the CD – adjusting the frequency of rotation



Supplement 19 ANOVA – tenacity of flax nonwovens in the MD – adjusting the direction of rotation

Settings	S1	S2	S3	S4	S5	S6	S7	S8	S9
S1		0,000193	0,000141	0,000141	0,994179	0,000215	0,002199	0,717848	0,120999
S2	0,000193		0,983438	0,972925	0,000958	1,000000	0,959819	0,010712	0,170603
S3	0,000141	0,983438		1,000000	0,000172	0,969972	0,451056	0,000720	0,016535
S4	0,000141	0,972925	1,000000		0,000164	0,954124	0,400436	0,000589	0,013266
S5	0,994179	0,000958	0,000172	0,000164		0,001270	0,021790	0,992241	0,518185
S6	0,000215	1,000000	0,969972	0,954124	0,001270		0,976774	0,014086	0,207947
S7	0,002199	0,959819	0,451056	0,400436	0,021790	0,976774		0,169050	0,810116
S8	0,717848	0,010712	0,000720	0,000589	0,992241	0,014086	0,169050		0,958885
S9	0,120999	0,170603	0,016535	0,013266	0,518185	0,207947	0,810116	0,958885	

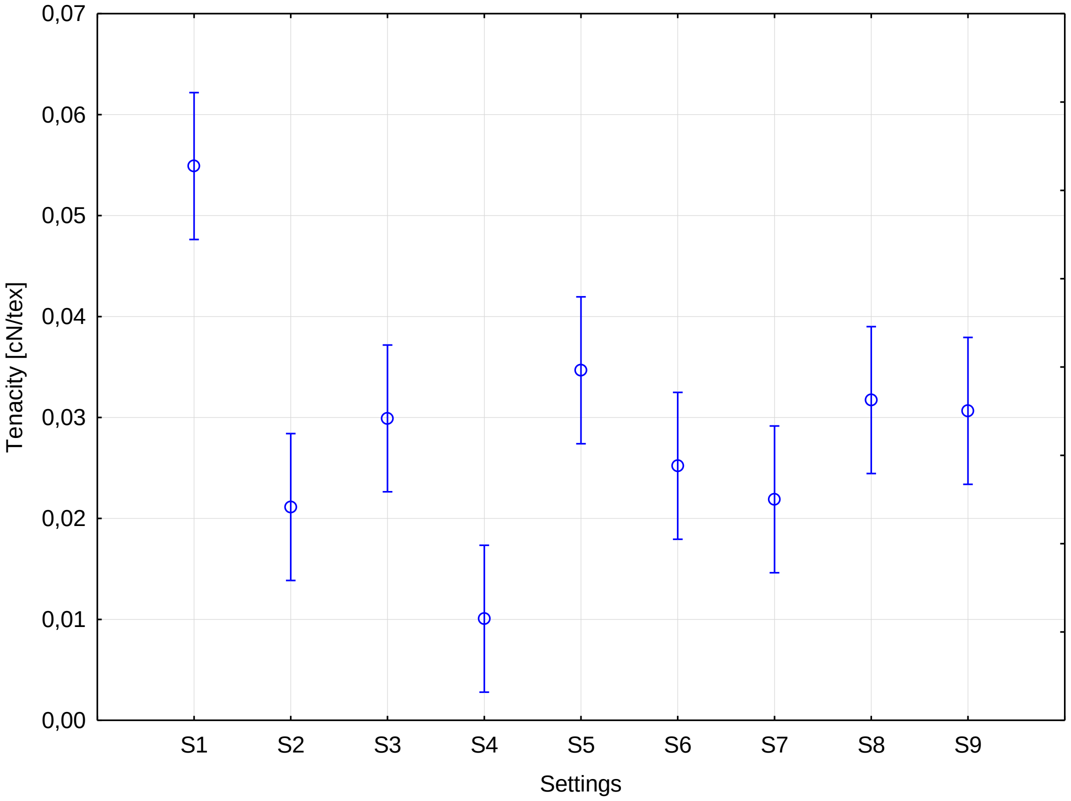
Supplement 20 P-values of Tukey test – tenacity of flax nonwovens in the MD – adjusting the direction of rotation



Supplement 21 ANOVA – tenacity of flax nonwovens in the CD – adjusting the direction of rotation

Settings	S1	S2	S3	S4	S5	S6	S7	S8	S9
S1		0,065432	0,006584	0,992676	0,993957	0,070498	1,000000	0,993203	0,999999
S2	0,065432		0,991663	0,367764	0,007393	1,000000	0,082484	0,362209	0,119207
S3	0,006584	0,991663		0,062820	0,000660	0,989495	0,008685	0,061387	0,013621
S4	0,992676	0,367764	0,062820		0,719644	0,386216	0,996808	1,000000	0,999451
S5	0,993957	0,007393	0,000660	0,719644		0,008075	0,987410	0,725603	0,966081
S6	0,070498	1,000000	0,989495	0,386216	0,008075		0,088670	0,380520	0,127611
S7	1,000000	0,082484	0,008685	0,996808	0,987410	0,088670		0,997084	1,000000
S8	0,993203	0,362209	0,061387	1,000000	0,725603	0,380520	0,997084		0,999512
S9	0,999999	0,119207	0,013621	0,999451	0,966081	0,127611	1,000000	0,999512	

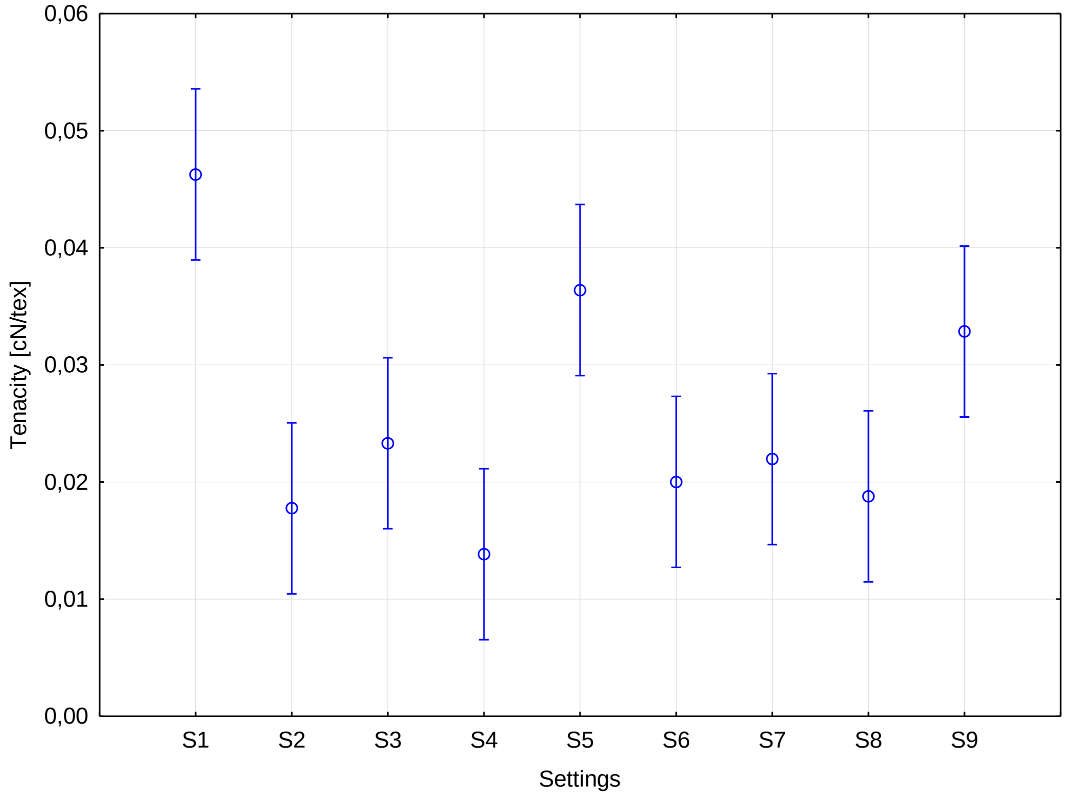
Supplement 22 P-values of Tukey test – tenacity of flax nonwovens in the CD – adjusting the direction of rotation



Supplement 23 ANOVA – tenacity of hemp nonwovens in the MD – adjusting the direction of rotation

Settings	S1	S2	S3	S4	S5	S6	S7	S8	S9
S1		0,000141	0,000677	0,000140	0,008487	0,000166	0,000142	0,001740	0,000984
S2	0,000141		0,723361	0,439124	0,194027	0,996020	1,000000	0,494731	0,631325
S3	0,000677	0,723361		0,010436	0,988917	0,989853	0,807947	0,999990	1,000000
S4	0,000140	0,439124	0,010436		0,000823	0,101962	0,351618	0,003928	0,007008
S5	0,008487	0,194027	0,988917	0,000823		0,639864	0,255859	0,999625	0,996454
S6	0,000166	0,996020	0,989853	0,101962	0,639864		0,999097	0,929187	0,974484
S7	0,000142	1,000000	0,807947	0,351618	0,255859	0,999097		0,591631	0,725233
S8	0,001740	0,494731	0,999990	0,003928	0,999625	0,929187	0,591631		1,000000
S9	0,000984	0,631325	1,000000	0,007008	0,996454	0,974484	0,725233	1,000000	

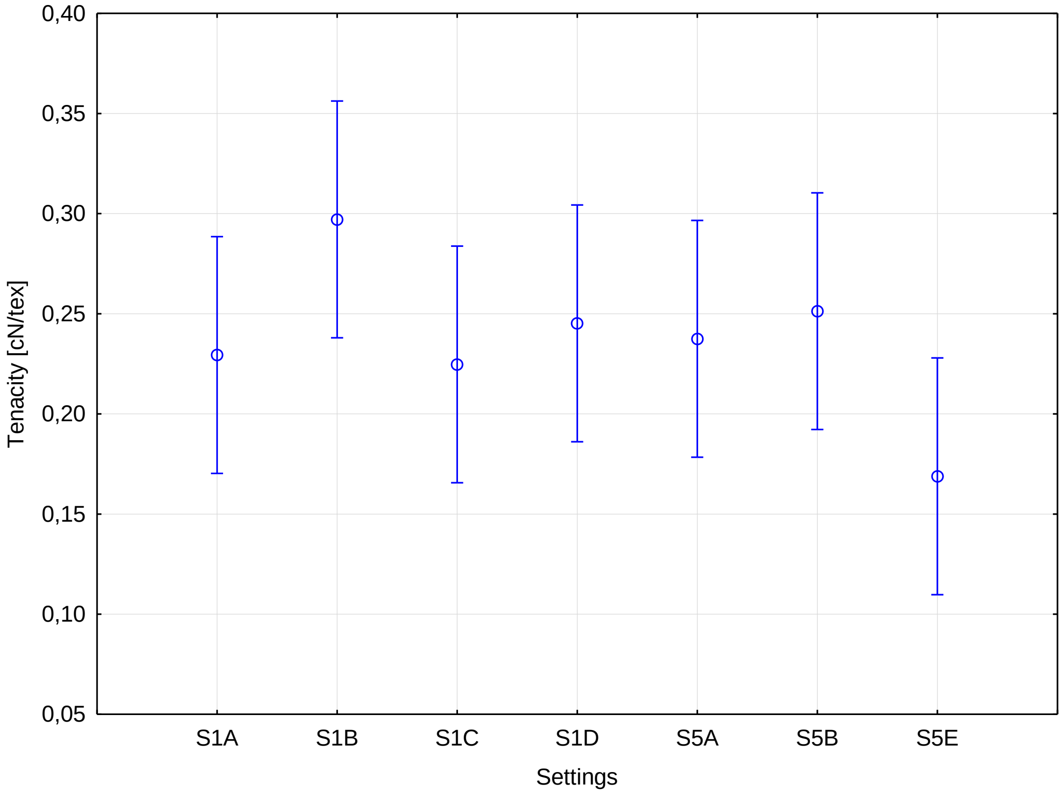
Supplement 24 P-values of Tukey test – tenacity of hemp nonwovens in the MD – adjusting the direction of rotation



Supplement 25 ANOVA – tenacity of hemp nonwovens in the CD – adjusting the direction of rotation

Settings	S1	S2	S3	S4	S5	S6	S7	S8	S9
S1		0,000202	0,002058	0,000144	0,592545	0,000406	0,001002	0,000260	0,207796
S2	0,000202		0,971789	0,997135	0,020211	0,999950	0,995274	1,000000	0,106636
S3	0,002058	0,971789		0,643539	0,234846	0,999164	0,999999	0,992191	0,635396
S4	0,000144	0,997135	0,643539		0,002549	0,948536	0,801602	0,986401	0,016760
S5	0,592545	0,020211	0,234846	0,002549		0,060435	0,140241	0,033692	0,998582
S6	0,000406	0,999950	0,999164	0,948536	0,060435		0,999984	1,000000	0,255882
S7	0,001002	0,995274	0,999999	0,801602	0,140241	0,999984		0,999364	0,464380
S8	0,000260	1,000000	0,992191	0,986401	0,033692	1,000000	0,999364		0,162186
S9	0,207796	0,106636	0,635396	0,016760	0,998582	0,255882	0,464380	0,162186	

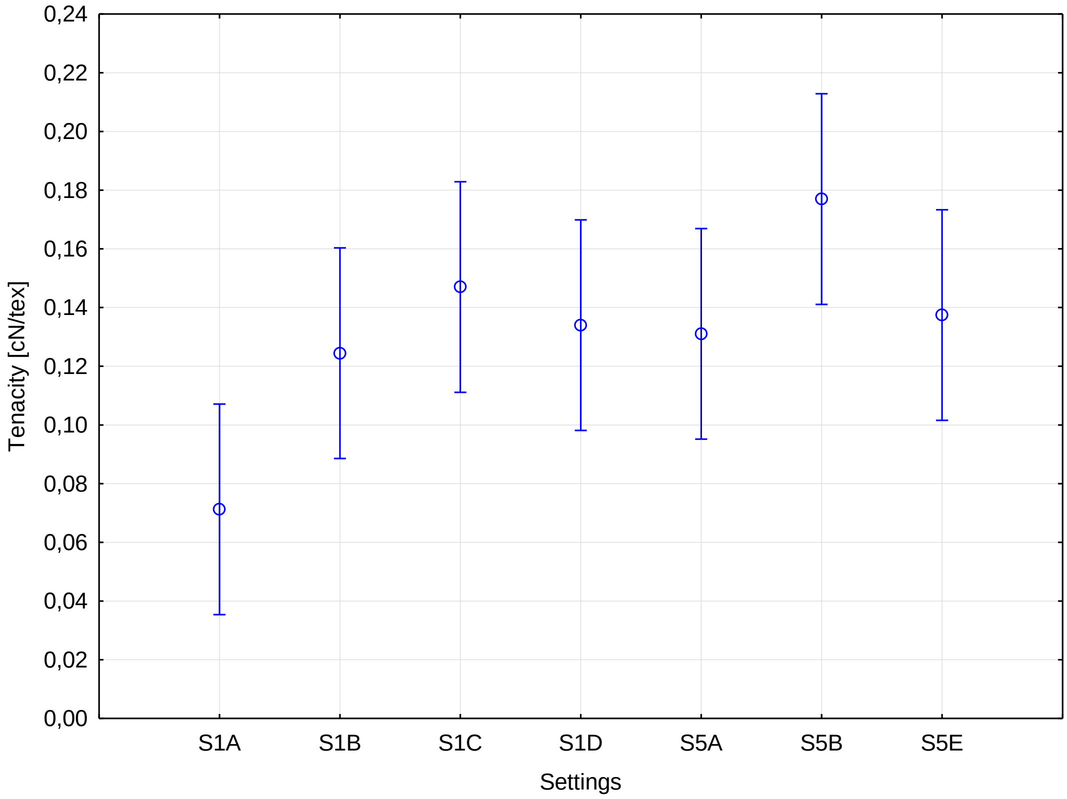
Supplement 26 P-values of Tukey test – tenacity of hemp nonwovens in the CD – adjusting the direction of rotation



Supplement 27 ANOVA – tenacity of flax nonwovens in the MD – adjusting the frequency of rotation

Settings	S1A	S1B	S1C	S1D	S5A	S5B	S5E
S1A		0,647166	1,000000	0,999701	0,999994	0,998034	0,752066
S1B	0,647166		0,575383	0,859023	0,764708	0,916049	0,053556
S1C	1,000000	0,575383		0,998660	0,999913	0,994230	0,813423
S1D	0,999701	0,859023	0,998660		0,999996	0,999999	0,514862
S5A	0,999994	0,764708	0,999913	0,999996		0,999863	0,633110
S5B	0,998034	0,916049	0,994230	0,999999	0,999863		0,424931
S5E	0,752066	0,053556	0,813423	0,514862	0,633110	0,424931	

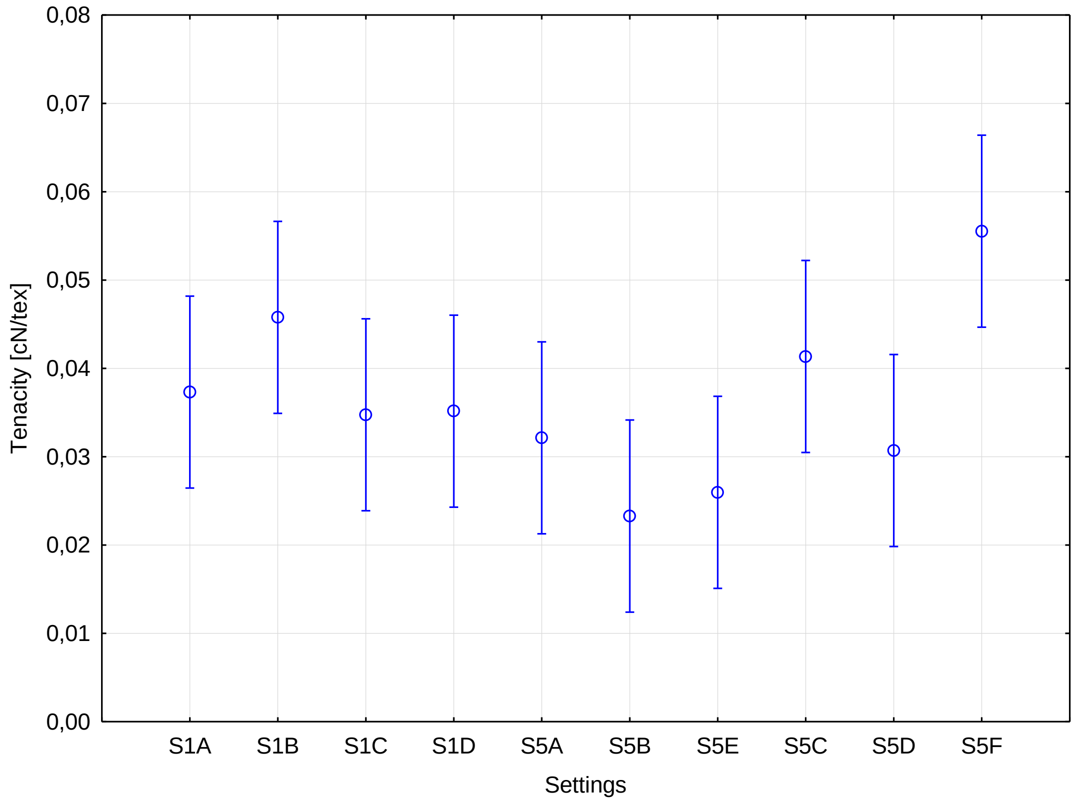
Supplement 28 P-values of Tukey test – tenacity of flax nonwovens in the MD – adjusting the frequency of rotation



Supplement 29 ANOVA – tenacity of flax nonwovens in the CD – adjusting the frequency of rotation

Settings	S1A	S1B	S1C	S1D	S5A	S5B	S5E
S1A		0,354543	0,064445	0,186270	0,230516	0,003526	0,143156
S1B	0,354543		0,967752	0,999711	0,999967	0,368935	0,998277
S1C	0,064445	0,967752		0,998262	0,994574	0,884705	0,999708
S1D	0,186270	0,999711	0,998262		1,000000	0,599763	0,999999
S5A	0,230516	0,999967	0,994574	1,000000		0,525231	0,999972
S5B	0,003526	0,368935	0,884705	0,599763	0,525231		0,686157
S5E	0,143156	0,998277	0,999708	0,999999	0,999972	0,686157	

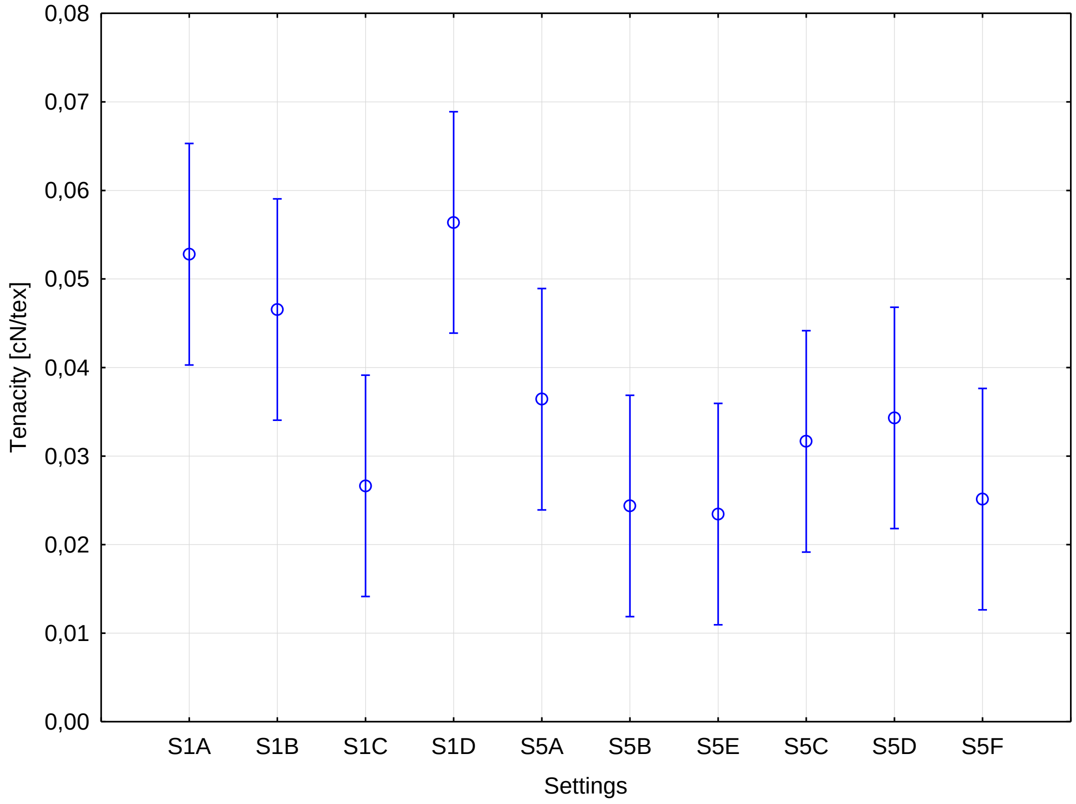
Supplement 30 P-values of Tukey test – tenacity of flax nonwovens in the CD – adjusting the frequency of rotation



Supplement 31 ANOVA – tenacity of hemp nonwovens in the MD – adjusting the frequency of rotation

Settings	S1A	S1B	S1C	S1D	S5A	S5B	S5E	S5C	S5D	S5F
S1A		0,980486	0,999999	1,000000	0,999510	0,703340	0,887443	0,999937	0,996654	0,355691
S1B	0,980486		0,903036	0,921488	0,734695	0,123065	0,248872	0,999864	0,616155	0,952062
S1C	0,999999	0,903036		1,000000	0,999998	0,881101	0,975182	0,996665	0,999937	0,195592
S1D	1,000000	0,921488	1,000000		0,999995	0,857639	0,966593	0,997988	0,999857	0,217296
S5A	0,999510	0,734695	0,999998	0,999995		0,973782	0,998043	0,966078	1,000000	0,094843
S5B	0,703340	0,123065	0,881101	0,857639	0,973782		0,999998	0,366317	0,992077	0,004580
S5E	0,887443	0,248872	0,975182	0,966593	0,998043	0,999998		0,589155	0,999762	0,012292
S5C	0,999937	0,999864	0,996665	0,997988	0,966078	0,366317	0,589155		0,920386	0,691633
S5D	0,996654	0,616155	0,999937	0,999857	1,000000	0,992077	0,999762	0,920386		0,061412
S5F	0,355691	0,952062	0,195592	0,217296	0,094843	0,004580	0,012292	0,691633	0,061412	

Supplement 32 P-values of Tukey test – tenacity of hemp nonwovens in the MD – adjusting the frequency of rotation



Supplement 33 ANOVA – tenacity of hemp nonwovens in the CD – adjusting the frequency of rotation

Settings	S1A	S1B	S1C	S1D	S5A	S5B	S5E	S5C	S5D	S5F
S1A		0,999290	0,114812	0,999993	0,687169	0,063512	0,049235	0,344075	0,529553	0,077936
S1B	0,999290		0,425615	0,979080	0,974716	0,281474	0,232836	0,787909	0,920345	0,326220
S1C	0,114812	0,425615		0,043931	0,979778	1,000000	0,999997	0,999878	0,996405	1,000000
S1D	0,999993	0,979080	0,043931		0,422096	0,022594	0,017080	0,162267	0,287251	0,028361
S5A	0,687169	0,974716	0,979778	0,422096		0,926925	0,890824	0,999923	1,000000	0,950048
S5B	0,063512	0,281474	1,000000	0,022594	0,926925		1,000000	0,997572	0,977604	1,000000
S5E	0,049235	0,232836	0,999997	0,017080	0,890824	1,000000		0,994038	0,960591	1,000000
S5C	0,344075	0,787909	0,999878	0,162267	0,999923	0,997572	0,994038		1,000000	0,998989
S5D	0,529553	0,920345	0,996405	0,287251	1,000000	0,977604	0,960591	1,000000		0,986909
S5F	0,077936	0,326220	1,000000	0,028361	0,950048	1,000000	1,000000	0,998989	0,986909	

Supplement 34 P-values of Tukey test – tenacity of hemp nonwovens in the CD – adjusting the frequency of rotation