Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Investigation of Mechanical Properties of Textile Waste Composites

Master's Final Degree Project

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Kaunas, 2022

Kaunas University of Technology
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Industrial Engineering and Management (6211EX018)

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Task of the Master's final degree project

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1. **Title of the project**

Investigation of Mechanical Properties of Textile Waste Composites

(In English)

Tekstilės atliekų kompozitų mechaninių savybių tyrimas

(In Lithuanian)

2. **Hypothesis:**

Textile waste is a potentially effective reinforcement material that improves the mechanical properties of the composites.

3. **Aim and tasks of the project**

Aim: To produce composites from textile waste and determine their mechanical properties.

Tasks:

1. To develop composites by using various materials and production methods.
2. To analyse the mechanical properties of the produced composites and compare them.
3. To calculate the cost of the produced composites.
4. To investigate the further development of the composites and their application possibilities.

4. **Initial data of the project**

N/A

5. **Main requirements and conditions**

Hemp fibres; hemp fabrics; tensile test machine Tinius Olsen H10KT; Joos-Laboratory-Press LAP 40; fusing machine Nova-45.

Project author	Gintarė Juodkaitė		2022.02.28
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Summary

Rapidly changing fashion trends and improving standards of living have led to an increase in textile waste. However, the growing environmental concern and the need for sustainable products led to the search for new ways to manage textile waste more efficiently and recycle it into value-added products. One of the possibilities to utilize this waste is to use it in the production of composites. Therefore, the aim of this work was to produce composites from textile waste and determine their mechanical properties. In the theoretical part, the literature on composites with textile materials was reviewed. The most important factors that have an impact on the mechanical properties of these composites were discussed: composite production methods and their parameters, the amount of filler in the composite and the use of different textile materials. The literature on polylactic acid and hemp fibres used in the study was also reviewed. The methodological part described used materials and research methods. In this work, natural fibre reinforced polylactic acid composites were developed. Fibres of two varieties of hemp that are grown in Lithuania, and knitted fabrics made from them, were used as reinforcement for the composites. These composites were produced by hot pressing and fusing methods. Then, the tensile test was performed to evaluate the effect of different composite production methods, different types of hemp fibres and fabrics on the strength of the composites. It was found that USO 31 hemp fibre composite produced by the fusing method has the highest strength. The USO 31 hemp fibre composites were stronger than composites reinforced with Felina 32 fibres. Reinforcing the polylactic acid with a knitted hemp fabric increased its elasticity. In the economic part, the production cost of the composites was calculated to determine whether the production of textile waste composites is more economical than with primary raw materials. The calculation results showed that the production cost of textile waste composites is lower than that of hemp fibre-reinforced composites. It was also found that it is more economical to produce composites by the fusing method than hot pressing. The application possibilities, composting and recycling of these composites, and challenges related to it, were also discussed in the research work.

Juodkaitė, Gintarė. Tekstilės atliekų kompozitų mechaninių savybių tyrimas. Magistro baigiamasis projektas, vadovė doc. Vaida Jonaitienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

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Santrauka

Sparčiai besikeičiančios madų tendencijos ir gyvenimo lygio gerėjimas lėmė tekstilės atliekų kiekio augimą. Tačiau, didėjant visuomenės susirūpinimui dėl klimato kaitos bei poreikiui tvariems gaminiams, ieškoma naujų būdų efektyviau tvarkyti tekstilės atliekas ir jas perdirbti į pridėtinės vertės produktus. Viena iš šių atliekų utilizavimo galimybių yra panaudojimas polimerinių kompozitų gamybai. Todėl šio darbo tikslas – pagaminti kompozitus iš tekstilės atliekų ir nustatyti jų mechanines savybes.

Teorinėje dalyje yra apžvelgiami kompozitų iš tekstilės medžiagų moksliniai tyrimai. Aptariami svarbiausi kriterijai, lemiantys šių kompozitų mechanines savybes: kompozitų gamybos metodai ir jų parametrai, užpildo kiekis kompozite ir skirtingos tekstilės medžiagos. Taip pat apžvelgta literatūra, susijusi su tyrimo metu naudojama polilaktido rūgštimi ir kanapių pluoštu. Metodinėje dalyje aprašytos naudojamos medžiagos ir tyrimo metodai. Tyrimo metu buvo pagaminti polilaktido rūgšties ir augalinių pluoštų kompozitai. Armavimui naudoti dviejų Lietuvoje auginamų kanapių rūšių pluoštai, ir iš jų pagamintos megztinės medžiagos. Kompozitai buvo pagaminti karšto presavimo ir laminavimo metodais. Tempimo bandymo metu buvo įvertinama, kokią įtaką kompozitų stiprumui turi skirtingi kompozitų gamybos metodai ir skirtingų rūšių kanapių pluoštai, bei medžiagos. Tyrimo metu nustatyta, jog laminavimo metodu pagamintas USO 31 kanapės pluošto kompozitas yra stipriausias. USO 31 kanapių pluoštu sustiprinti kompozitai buvo stipresni nei Felina 32 pluoštu armuoti kompozitai. Polilaktido rūgšties sustiprinimas megztine medžiaga taip pat turėjo teigiamos įtakos bandinių tamprumui. Ekonominėje dalyje yra apskaičiuojama kompozitų gamybos kaina, siekiant išsiaiškinti, ar tekstilės atliekų kompozitų gamyba yra ekonomiškesnė nei kompozitų su pirminėmis žaliavomis. Skaičiavimo rezultatai parodė, kad tekstilės atliekų kompozitų gamybos kaina yra žemesnė nei kanapės pluoštais armuotų kompozitų. Taip pat išsiaiškinta, kad ekonomiškiau kompozitus yra gaminti laminavimo metodu nei karštu presavimu. Tiriamajame darbe aptartos ir šių kompozitų panaudojimo, kompostavimo, perdirbimo galimybės ir su jomis susiję iššūkiai.

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Abbreviations:

FFAC – compression moulded Felina 32 fabric reinforced polylactic acid composite;

FFC – compression moulded Felina 32 fibre reinforced polylactic acid composite;

FFF – fused Felina 32 fibre reinforced polylactic acid composite;

ICT – Information and communications technology;

PE – polyethylene;

PET – polyethylene terephthalate;

PLA – polylactic acid;

PP – polypropylene;

Pc – piece;

PS – polystyrene;

Psc – pieces;

UFAC – compression moulded USO 31 fabric reinforced polylactic acid composite;

UFC – compression moulded USO 31 fibre reinforced polylactic acid composite;

UFF – fused USO 31 fibre reinforced polylactic acid composite;

wt – weight.

Introduction

Worldwide textile consumption has increased more than two times over the last two decades [1]. Lithuania consumed 19611 tonnes of textile in 2018 [2]. Even though this number is smaller compared with some other European countries, consumption is increasing rapidly – from 2017 to 2018 it increased by 37% [2]. Increased demand for textiles led to the creation of new jobs and the growth of the economy, but also the increased amount of pre-consumer and post-consumer waste. Pre-consumer waste includes all materials and by-products generated during the production of the product. Post-consumer waste is clothing, footwear, bedding, carpets, soft toys, curtains, and other discarded textile products. According to the 2021 data, textile waste in Lithuania accounts for approximately 8% of total municipal waste [3]. The growing focus on sustainability and stricter rules on waste disposal and the use of landfills have made traditional waste disposal less acceptable. Therefore, in 2020, the European Commission adopted a circular economy action plan to transition from a linear to a circular economy and to ensure that products are more sustainable and last longer. This plan targeted several industries, including the textile industry and demanded to reduce the amount of generated waste by managing it more efficiently. That includes sorting, recycling and reusing textile waste. One of the possible ways to recycle textile waste into new products is to use it in the production of composites.

Composites are composed of one or more reinforcing materials and a matrix that holds reinforcing materials together. Compared with raw materials, composites can provide compliance with environmental regulations, lower energy use, low weight and high performance at a low cost. Textile reinforced composites can be designed to replace plastic and metal materials that are used in automotive, aerospace, marine and other sectors. Different types of textile materials can be used as reinforcements for composites: fibres, yarns, knit fabrics, non-woven fabrics and woven fabrics. These materials can also be synthetic, natural, or a mixture of both.

Hemp fibres are one of the most used natural plant-based textile fibres in the production of composites. These fibres are biodegradable, have low density, high stiffness, high strength and good heat resistance [4]. The mechanical properties of hemp fibres can even be comparable with glass fibres, which are commonly used synthetic fibres in composites [4]. Moreover, the green composites can be produced using hemp fibres with biodegradable matrix materials. Polylactic acid (PLA) is a biodegradable polymer produced from lactic acid through the fermentation of plant starch. It has the highest strength among all biodegradable polymers and, in terms of its mechanical properties, can be compared to polyethylene terephthalate (PET) and polypropylene (PP) [4,5].

The use of different types of textiles, matrix materials and production methods result in different mechanical properties of the composites. Therefore, it is essential to investigate textile waste and its comparability with polymeric matrices to find more applications for composites with textile waste. This work is focused on the development of composites reinforced with different types of hemp and the investigation of their mechanical properties.

The aim of this work is to produce composites from textile waste and determine their mechanical properties.
Tasks:
1. To develop composites by using various materials and production methods.
2. To analyse the mechanical properties of the produced composites and compare them.

3. To calculate the cost of the produced composites.
4. To investigate the further development of the composites and their application possibilities.

1. Analytical part

1.1. Relevance and novelty of the research through literature analysis

Textiles are an important part of everyday life: they are used for clothes, packing, furniture, cars, sports gear, building insulation and more. The population growth and the increasing wealth of the general population resulted in increased production and consumption of textiles [6,7]. In 2020, more than 108 million metric tonnes of textile fibres were generated globally (Fig. 1.). Over 45 years, the production of textile fibres increased 4.5 times, and it is also forecasted that it will reach 156 million metric tons by 2030 [1].

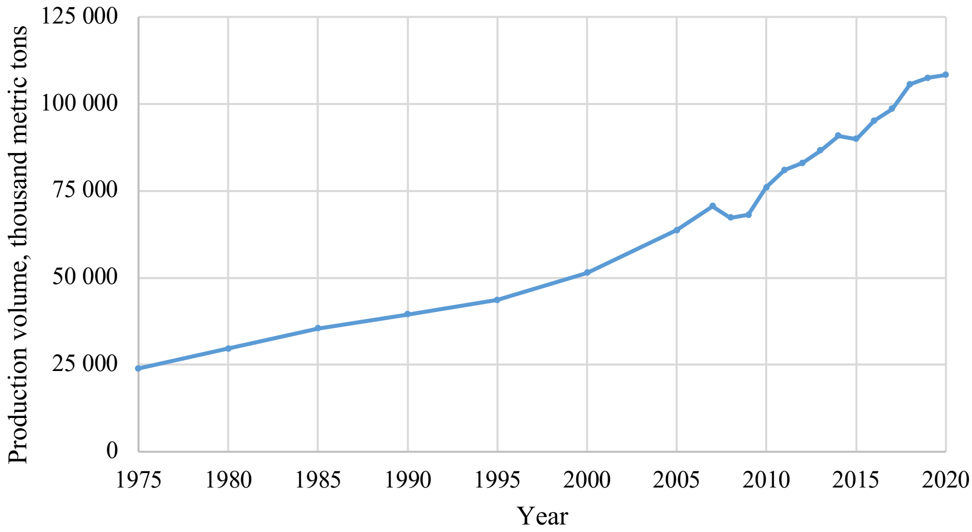

Fig. 1. Global textile fibre production volume 1975-2020 [1]

With the increased demand for textiles, the amount of waste increased as well. It was estimated that the textile industry in Europe generates 16 million tonnes of textile waste annually [8]. According to 2019 data, only 13% of all textile waste is collected for recycling globally and the rest ends in landfills or is incinerated [9]. The latest statistics showed that more than 90% of that disposed textile waste has the potential to be recycled and reused [9]. Therefore, textile waste should be managed in a more sustainable way.

Textile fibres are classified into two main categories: natural fibres and synthetic fibres. Natural fibres are derived from plants, animals and minerals. Examples of plant-based natural fibres are bamboo, hemp, cotton and flax. The animal-based fibres are wool, cashmere, alpaca and silk [10]. The mineral-based fibre example is asbestos [10]. Synthetic fibres can be inorganic and organic. Inorganic fibres are glass, metal, ceramic and carbon. Organic fibres can be classified into two more categories: natural polymers, such as modal, viscose, lyocell and synthetic polymers – acrylic, elastane, polyamide, polyethene and polyester [10]. Polyester is the most produced synthetic fibre, which accounts for more than 50% of all textile production, and cotton fibres are the second most-produced fibres, accounting for 24.4% (Fig. 2.).

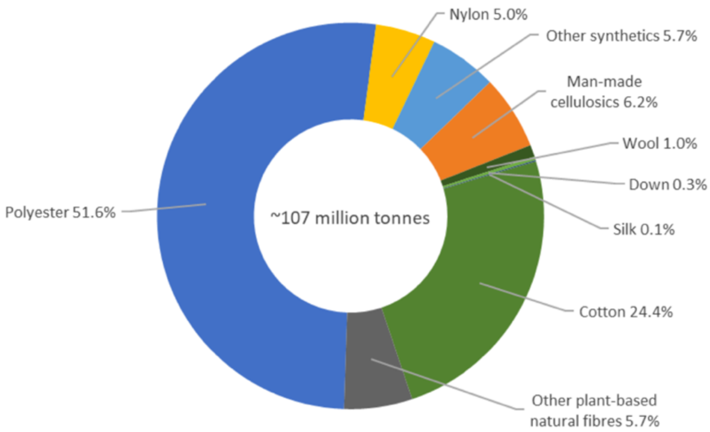

Fig. 2. Global fibre production in 2018 [10]

The most common problems associated with synthetic fibres are water and land pollution, health risks, ethical issues and use of non-renewable resources. The textile sector is the third-largest plastic waste contributor, generating 14% of all plastic waste [10]. Moreover, the production and use of synthetic textiles generate greenhouse gas emissions and create water pollution by releasing microplastics into the environment. According to 2017 statistics, synthetic textiles account for 35% of all microplastics in the oceans and are the main source of microplastics in water [11]. It was announced that a single polyester garment could release more than 1900 fibres during each wash [9]. Polyester is also classified as non-biodegradable material which can take up to 200 years to decompose [12]. However, natural textile fibres also have a negative impact on the environment. The cultivation of natural fibres requires a large amount of water, agrochemicals and land. The average water consumption for 1 kg of fibres is shown in Table 1.

Table 1. Average water consumption and carbon dioxide emission [13,14,15]

No.	Fibre	Water, litres for 1 kg	Carbon dioxide emission, kg of CO_2 per metric ton of fibre
1	Cotton	9800	4.3
2	Hemp	2700	4.5
3	Viscose	3000	9.0
4	Acrylic	210	5.0

The table above shows the amount of water used for cotton and hemp and synthetic fibres: viscose and acryl. It can be seen that cotton fibres need approximately 3 times more water than viscose fibres and hemp fibres need 13 times more water than acrylic fibres. However, the production of natural fibres releases slightly less carbon dioxide when compared with synthetic fibres. To mitigate these environmental impacts of textile production, recycling and reusing both synthetic and natural textile fibres is important.

Increased concerns and awareness of environmental issues have led to the implementation of new strategies to reduce the negative human-caused impact on the environment. In 2020 the European Commission adopted the circular economy action plan, which aims to address global challenges, such as biodiversity loss, land and water pollution, climate change and waste [16]. The plan targets 7 high-impact sectors:

1. Electronics and ICT;
2. Batteries and vehicles
3. Food and water;
4. Construction and buildings;
5. Plastics;
6. Packing;
7. Textiles [16].

The essential actions for the textile sector are to ensure textile waste sorting, recycling, and reusing [15]. The circular economy strategy should replace the linear model of the textile industry, which is based on the "take-make-waste" approach. In a linear model, the raw materials are collected, made into products, and thrown away after use. The circular economy strategy closes that cycle (Fig. 3.). In this model, the post-production textile waste and post-consumer waste are collected to recycle and use as raw materials or components. Post-production waste is industrial waste, which includes processing scraps, trimmings and print trials. Post-consumer waste includes garments, furniture, packing and household items.

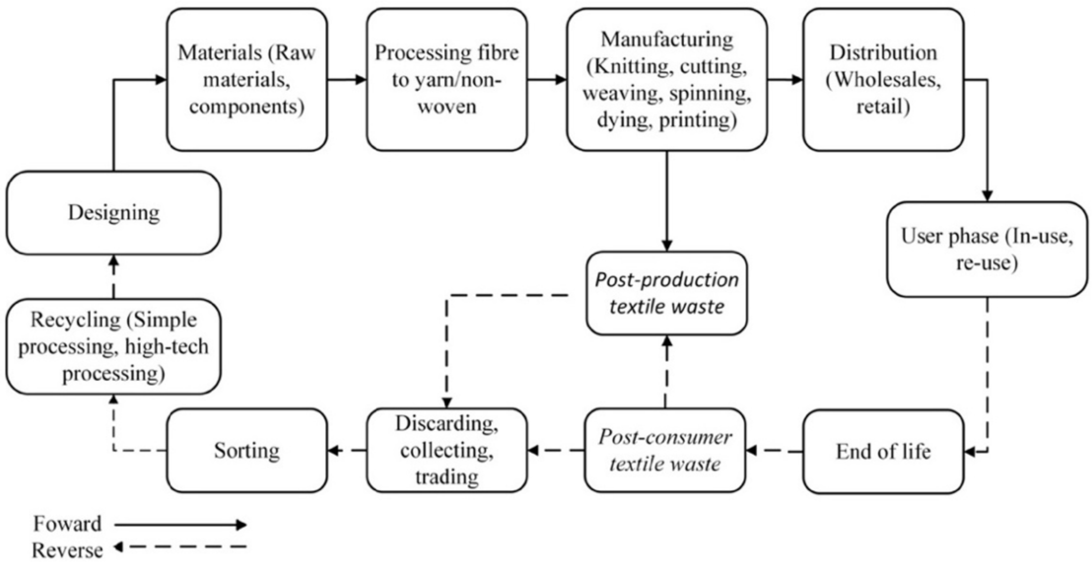

Fig. 3. Circular economy model for the textile industry [17]

Although textile reuse of textile is more environmentally friendly than recycling, it is less common because of the unusable and damaged garments that are not economically feasible to repair. Textile recycling is a relatively simple process. There are 2 main methods used for textile recycling: mechanical and chemical [18]. In the mechanical recycling process, the textile waste is cut, shredded and pulled into the fibres and after transformed into new yarns or fabrics [18]. All types of fibres can be used in this process. However, the mechanical recycling process is not recommended for natural fibres since shredding harms natural fibres and can result in low-quality products [18]. In chemical recycling the textile is broken down into monomers, oligomers or chemicals, this process is suitable for plant and petroleum-based fibres [18]. This recycling process is less eco-friendly since hazardous chemicals are used. The recycling process can also consist of both methods to achieve a high-quality product.

The development of composites with textile waste is one of the possible ways to reuse textile waste and create a valuable product by minimising the impact on the environment. A composite is a combination of two or more materials. It has a matrix, which is usually made of polymer, metal or ceramic and filler – usually flakes or fibres. The textile waste can be used as a filler material for the composites. Textile waste reinforced composites can offer several advantages when compared with raw materials. They are environmentally friendly, can be biodegradable and have low cost. The production of such composites requires less energy and water and produces less carbon dioxide. Researchers have proven that composites with textile waste can be successfully used in the construction industry, car manufacturing, furniture and textile industries [6,8]. Products that can be made from textile-reinforced composites include thermal insulation, sound insulation, lightweight concrete bricks, filter products, shoe insoles, rags and blankets and mattress covers [6]. However, to increase the recyclability of textile waste and reduce the environmental impact of the textile industry, more studies on textile reinforced composites are needed. It is essential to analyse the mechanical properties of composites and their behaviour to find new potential applications in different industries and improve their properties. Therefore, this research is focused on textile reinforced composites and their mechanical properties.

1.2. Literature review

High strength and low weight are desirable properties of materials, and scientists are constantly working to achieve them in composites. However, the mechanical properties of the textile waste reinforced composites strongly depend on the type and quality of fibres, selected production process, process parameters and content of the fibres. Therefore, many studies have been conducted to analyse various combinations of composites reinforced with textile waste and their mechanical properties.

1.2.1. Textile materials

Textile materials can be classified into 3 main categories: fibres, which can be natural and synthetic, yarns, which can be spun yarns and filament yarns, and fabrics. Fabric textile can be woven, knitted and non-woven (Fig. 4.).

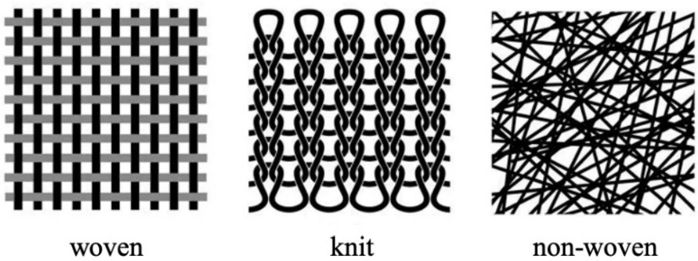

Fig. 4. Main types of fabric [18]

Woven fabrics usually consist of two sets of yarns that are arranged vertically by each other [19]. The woven fabric reinforced composites have better mechanical properties than non-woven fabric composites because the fibres are more arranged [20]. These composites have high strength, stiffness and good energy absorption [21].

Knitted fabrics consist of yarns woven into loops. There are two knitting methods: warp knitting and weft knitting [19]. The knitted fabrics became popular composite reinforcement since they are light, elastic and less expensive than woven fabrics [21]. The composites reinforced with knitted fabric have a low thermal expansion and high corrosion resistance, they are also easy to recycle [21]. Scientists compared knitted fabric with several other reinforcements: short fibres, continuous fibre mats, woven fabrics, and unidirectional laminates [22]. It was concluded that knitted fabrics have higher stiffness and strength than short fibres and continuous fibre mats [22]. The interlaminar fracture toughness of knitted fabrics was found to be higher than woven fabrics and unidirectional laminates [22].

Non-woven fabric is made of continuous or chopped fibres that are sewed or bonded together [19]. Bonding can be chemical or thermal. Then non-woven fabrics can be developed from recycled fibres and are cheaper than other types of fabric. However, non-woven fabrics are not resistant to water and lose their strength when wet [21]. The strength of the non-woven fabric composites also strongly depends on the content of fibres and fabric direction [21].

Kamble, Z. and Behera, B. K. (2021) analysed the difference between non-woven and web cotton fibre composite mechanical properties. The researchers used the shredded cotton waste as the reinforcement, Lapox ARL 125 epoxy resin as the matrix and the curing agent Lapox AH 365 [8]. The first composite was composed of cotton shoddy web and epoxy. Cotton shoddy web weight in composite was 35.86%, and epoxy weight was 64.14% [8]. The second epoxy composite had needle-punched cotton fibre web – non-woven fabric. The weight of materials in the composite was the same as in the previous one [8]. The composites were produced using a compression moulding machine. All composites were compressed for 60 minutes at a temperature of 120 °C [8]. Table 2 shows the mechanical properties of the produced composites and raw materials.

Table 2. Properties of raw materials and composites [8]

No.	Material	Density, g/cm^3	Tensile strength, MPa	Elongation, %	Elastic modulus, GPa
1	Epoxy resin	1.15	59.90	4.90	2.50
2	Cotton fibres	-	167.00	5.00	4.49
3	Cotton shoddy web/epoxy	1.28	80.54	5.52	2.94
4	Cotton shoddy non-woven/epoxy	1.27	76.80	5.44	3.28

As it can be seen, produced composites had a slightly higher density when compared with pure epoxy resin. The density of cotton shoddy web composite was 11.3% higher, and the density of cotton shoddy non-woven composite was 10.43% higher. Reinforcing the epoxy resin composite with cotton shoddy web led to increased tensile strength by 34.46%. The cotton shoddy non-woven/epoxy composite had 28.30% higher tensile strength than epoxy resin. The cotton reinforcement also resulted in higher elongation and elastic modulus of the epoxy resin composite. This research showed that the cotton shoddy web and cotton shoddy non-woven composites did not have a significant difference in terms of their density and mechanical properties.

1.2.2. The fibre content in composites

The content of the fibres in the composite has a significant influence on the tensile properties of the produced composites. It is important to find an optimal content of fibres, which would result in the highest tensile strength of the composite.

Several researchers studied fibre content's influence on the tensile strength of the composites. In the analysed research the researchers prepared four cotton reinforced polypropylene (PP) composites and four polyester-reinforced polypropylene composites with different weight ratios of the materials (Table 3). The used cotton was obtained as textile waste and shredded for composite production. Cotton and polyester fibres were carded, needle punched to develop non-woven fabrics and then compression moulded with PP [23]. Cotton/PP composites were compressed at 185 °C for 20 minutes, and polyester/PP composites were pressed at 190 °C for 20 minutes [23].

Table 3. Mechanical properties of the composites and polypropylene matrix [23]

No.	Material (weight, %)	Tensile strength, MPa	Elongation, %	Elastic modulus, GPa
1	Polypropylene fibres	103.23	34.08	3.47
2	Cotton (20%)/PP	83.55	31.67	3.80
3	Cotton (30%)/PP	80.18	31.77	4.15
4	Cotton (40%)/PP	68.66	24.06	4.72
5	Cotton (50%)/PP	55.88	22.16	5.54
6	Polyester (20%)/PP	31.89	34.08	3.47
7	Polyester (30%)/PP	36.59	25.58	2.12
8	Polyester (40%)/PP	49.77	17.21	2.51
9	Polyester (50%)/PP	61.52	22.38	2.75

The cotton/PP composites had higher tensile strength, elongation and elastic modulus values than the polyester/PP composites. The higher content of polyester fibres in the composites also led to increased tensile strength values. However, the higher volume of cotton in composite resulted in decreased tensile strength. Pure PP has a higher tensile strength when compared with produced composites. According to the authors, this was the result of the voids in the matrix and the adhesion problems between the fibres and the matrix [23].

Another research was conducted on the fibre content in the composites and its influence on the tensile strength. The research authors used needle-punched non-woven polyester fabric (400 g/m^3 and 600 g/m^3) and LY 556 epoxy [24]. The composites were produced using the hand lay-up technique [24]. Table 4 shows the properties of the textile reinforced composites.

Table 4. Density and tensile strength of composites [24]

No.	Material	Density, g/cm^3	Tensile strength, MPa
1	400 g/m^3 Polyester (20%)/epoxy	1.01	35.00
2	400 g/m^3 Polyester (30%)/epoxy	1.02	27.00
3	400 g/m^3 Polyester (40%)/epoxy	1.09	25.00
4	600 g/m^3 Polyester (20%)/epoxy	1.05	29.00
5	600 g/m^3 Polyester (40%)/epoxy	1.07	24.00
6	600 g/m^3 Polyester (60%)/epoxy	1.08	32.00

In this research, the density of the composites increased with the higher content of fibres. The tensile strength of the composites with 400 g/m^3 fabric decreased as the content of fibres increased. However, the tensile strength of the composites with 600 g/m^3 fabric was the highest with 60% of fibres.

These studies have shown irregular trends in the correlation between fibre content and tensile properties. As it was seen from the analysed results, this can be because of defects in the composites. Other reasons can be fibre degradation, incompatibility between the matrix and fibres, and incorrect manufacturing process for the chosen composite materials.

1.2.3. Production methods of the composites

The manufacturing process is selected depending on the desired cost, size, shape and strength of the composite. Other important factors that also have to be considered are composite materials, cycle time and the end-use application of the composite. The main production methods used to manufacture the composites are compression moulding, hand lay-up, extrusion moulding, injection moulding, vacuum infusion, resin transfer moulding and spray lay-up. In this subsection, several studies that analysed the different production methods and their parameter influence on the mechanical properties of composites will be reviewed.

Temmink, R., Baghaei, B. and Skrifvars, M. (2018) analysed the properties of denim waste reinforced composites, which were produced by different manufacturing techniques [25]. The research authors used post-consumer denim jeans with 100% cotton as reinforcement. Different types of matrix materials and hardeners were used: polyester resin and its hardener, acrylated epoxidized soybean oil resin with tert-Butyl peroxybenzonate and styrene, and SuperSAP ONE epoxy with its hardener [25]. The composites were developed by resin transfer moulding, compression moulding, hand lay-up and vacuum infusion methods. 10 composites were produced and all of them had 4 layers of textile [25].

Compression moulding is a commonly used manufacturing method for polymer composites. In compression moulding, the mould cavity is preheated to the required temperature. The composite is placed in the heated cavity of the mould and the press is closed at a programmed speed, and pressure. The composite is pressed for a predetermined amount of time. After the pressure is released and the part is removed. The advantages of this manufacturing method are the smooth surface of the produced parts, low cost, fast set-up time and even pressure distribution on the composite [26]. The disadvantages of this production method include slow process time and limitations in composite shapes.

Hand lay-up is an inexpensive composite manufacturing technique. In this technique, the anti-adhesive agent is applied to the mould surface to avoid sticking. After the coat of the anti-adhesive agent cures, the fibres are placed in the mould. The resin matrix is poured on the reinforcement material and spread with a brush or roller. Layers of fibres and resin are built until the desired thickness is achieved. The roller is used for each layer to remove entrapped air. The advantages of the hand lay-up process include low tooling cost and a wide range of materials that can be used [26]. However, this method consumes more time when compared with other methods, the quality of the composites depends on the skills of the worker.

Resin transfer moulding is widely used for the medium-volume production of large complex parts. In this process, the fibres are laid in the cavity of a mould. Then the mould is closed, and resin is injected into a mould cavity under pressure. The composites produced with resin transfer moulding usually have high quality, tight dimensional tolerance, low void content and good mechanical properties [26]. However, the drawbacks associated with this process are high tooling cost and size limitations by the mould cavity.

The vacuum infusion process uses vacuum pressure to inject a resin into a laminate. In this process, fibres are placed into a mould, and the vacuum is applied. Then the resin is fed into the mould cavity via tubing. This process is used for large parts. It also provides even resin distribution and good mechanical properties of the produced composites.

Table 5 presents the mechanical properties and density of the composites produced by the described production methods.

Table 5. Mechanical properties, density and manufacturing methods of composites [25]

No.	Material	Manufacturing method	Density, g/cm^3	Tensile strength, MPa	Elastic modulus, GPa
1	Cotton (38%)/polyester	Resin transfer moulding	1.20	23.00	4.30
2	Cotton (40%)/ SuperSAP ONE epoxy	Resin transfer moulding	1.18	34.00	5.30
3	Cotton (39%)/ SuperSAP ONE epoxy	Vacuum infusion	1.22	48.00	7.90
4	Cotton (40%)/ SuperSAP ONE epoxy	Hand lay-up	1.25	56.00	7.80
5	Cotton (43%)/acrylated epoxidized soybean oil resin	Vacuum infusion	1.15	15.00	0.90
6	Cotton (41%)/acrylated epoxidized soybean oil resin + 15 wt% styrene	Vacuum infusion	1.18	25.00	1.80
7	Cotton (41%)/acrylated epoxidized soybean oil resin + 30 wt% styrene	Vacuum infusion	1.20	24.00	3.30
8	Cotton (45%)/acrylated epoxidized soybean oil resin	Compression moulding	1.22	26.00	7.00
9	Cotton (55%)/acrylated epoxidized soybean oil resin + 15 wt% styrene	Compression moulding	1.26	36.00	4.10
10	Cotton (60%)/acrylated epoxidized soybean oil resin + 30 wt% styrene	Compression moulding	1.25	18.00	1.00

The hand lay-up produced composite had the highest tensile strength (56 MPa) of all the composites. It also had 1.2 times higher tensile strength than the composite produced with the same materials by vacuum infusion and 1.6 times higher strength than the one produced with resin transfer moulding. The vacuum infusion produced composite with cotton (43%)/acrylated epoxidized soybean oil resin had the lowest tensile strength (15 MPa) and elastic modulus (0.9 MPa). The composites produced by compression moulding also had higher tensile properties than the ones produced by the vacuum infusion method.

Zhang, X. (2016) analysed the influence of production process parameters on composite mechanical properties. The researcher produced hemp woven fabric reinforced polypropylene composites that were compression moulded under different pressure (0.3-0.7 MPa) [27]. The researcher also analysed the influence of compression moulding temperature [27]. Therefore, the composites were compressed at different temperatures (160-200 °C) [27]. The tensile test results of these composites are presented in Table 6 and Table 7.

Table 6. Mechanical properties of composites produced under different manufacturing pressures [27]

No.	Material	Pressure, MPa	Tensile strength, MPa	Elongation, %	Elastic modulus, GPa
1	Hemp woven (19.4%)/PP	0.30	39.30	5.10	1.80
2	Hemp woven (20.0%)/PP	0.40	40.30	4.90	1.82
3	Hemp woven (20.1%)/PP	0.50	39.40	5.20	1.78
4	Hemp woven (20.0%)/PP	0.60	41.70	5.00	1.90
5	Hemp woven (20.9%)/PP	0.70	39.50	4.20	1.95

The research showed that the optimal pressure to achieve the highest tensile strength is 0.6 MPa. However, the results do not have a monotonic trend and the composites produced under 0.3 MPa, 0.5 MPa and 0.7 MPa have just slightly different tensile strength values. The elastic modulus slowly increases as more pressure is applied, with the exception of the sample at 0.5 MPa pressure, where the decrease occurs. The elongation is highest when 0.5 MPa pressure is applied and lowest at 0.7 MPa. It can be concluded that compression moulding pressure does not have a significant effect on hemp fibre reinforced composite mechanical properties.

Table 7. Mechanical properties of composites produced at different temperatures [27]

No.	Material	Temperature, °C	Tensile strength, MPa	Elongation, %	Elastic modulus, GPa
1	Hemp woven/PP	160	43.30	5.90	1.70
2	Hemp woven/PP	170	42.00	5.80	1.70
3	Hemp woven/PP	180	39.00	4.80	1.75
4	Hemp woven/PP	190	41.00	5.00	1.88
5	Hemp woven/PP	200	35.00	4.90	1.60

The results of the tensile test showed that the strength of the composites decreased when the compression temperature increased. Strength may be reduced due to decreased matrix-microfibril bonding that occurs with moisture loss. The elongation of the composites showed a similar trend as the tensile strength. The elastic modulus slowly increased as the temperature increased, except at 200 °C, where the decrease occurred. Several other authors also reported a decrease in the mechanical properties of natural fibres at temperatures above 170 °C [28]. These trends were attributed to the changes in structural properties of cellulose and hemicellulose at high temperatures.

1.2.4. Effect of specimen direction on tensile properties

Several researchers performed tensile tests of specimens in two directions – 0° and 90° based on non-woven production direction and compared the obtained results (Fig. 5.).

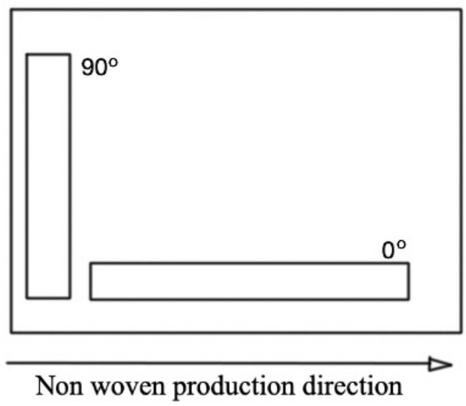

Fig. 5. Specimens and their tensile testing direction [29]

In the analysed research the first composite was made with 100% cotton fibres, the second one – with 60% cotton and 40% polyester fibres, and the third one with 90% polyester and 10% of mixed fibres [29]. Sicomin SR 800 epoxy was used as a matrix together with hardener Sicomin SD 7203 [29]. The composites were produced using the vacuum infusion method [29]. The vacuum infusion process was performed at room temperature using 1 bar pressure, and the composites were left for 24 hours for curing [29]. Table 8 shows the obtained properties of the composites.

Table 8. Properties of the composites and epoxy resin [29]

No.	**Material**	**Density, g/cm^3**	**Tensile strength, MPa**	**Specific tensile strength, MPa/ g·cm^3**	**Elongation, %**	**Elastic modulus, GPa**
1	Epoxy resin	1.18	39.00	33.00	1.50	2.90
2	Cotton (21%)/epoxy	0.92	38.18 (0°) 31.74 (90°)	41.50 (0°) 34.50 (90°)	1.75 (0°) 2.40 (90°)	3.45 (0°) 3.04 (90°)
3	Cotton-polyester (23%)/epoxy	0.93	38.13 (0°) 32.55 (90°)	41.00 (0°) 35.00 (90°)	1.50 (0°) 2.50 (90°)	2.70 (0°) 2.33 (90°)
4	Polyester (25%)/epoxy	0.95	36.10 (0°) 31.35 (90°)	38.00 (0°) 33.00 (90°)	2.10 (0°) 2.50 (90°)	2.66 (0°) 2.33 (90°)

The results of the tensile test showed that the density of composites is lower than the density of epoxy resin. The strength of the composites also decreased. However, the researchers calculated a specific tensile strength that was higher or very similar to the epoxy resin (33 MPa/ g·cm^3). The elongation was higher when specimens were stretched at a 90° direction because the textile fibres are parallel to the tensile force direction. The tensile strength was slightly higher at 0° direction.

The analysed studies showed that needle punching of the textile web does not have a significant effect on the tensile properties. A substantial improvement in elongation was observed when the specimens were tested at a 90° direction for tensile strength. The optimal fibre content in composites that provides the highest tensile properties is dependent on the type of materials used. The composites produced with hand lay-up, vacuum infusion and compression moulding show the highest tensile strength values.

1.3. Composite materials

1.3.1. Hemp fibres

Hemp fibres are plant-based natural fibres that are widely cultivated all over the world and used in the production of composites. The cultivation of industrial hemp in Lithuania was legalised only in 2014. During that time, the area of hemp expanded from 1062.89 hectares in 2014 to 4780.12 hectares in 2021 [30,31]. Industrial hemp (Cannabis sativa L.) has a low concentration of tetrahydrocannabinol (THC) and is grown for industrial uses. The fibres are extracted from bast of hemp plant and contains approximately 70-74% cellulose, 3.5-5.7% lignin, 15-20% hemicellulose, 0.8% pectin, 1.2-6.2% wax and 0.8% ash [32]. The high content of cellulose results in high fibre strength and stiffness. Hemp fibres and their composites are currently used to produce paper, the interior of cars, sports equipment, door panels, thermal insulation, acoustic insulation, clothes and bags [33]. The main reasons that led to the popularity of the hemp fibre reinforced composites are high tensile strength, low density, biodegradability, high stiffness, low cost and high availability of fibres [33].

Hemp fibres are one of the strongest natural fibres and can be a biodegradable alternative to synthetic fibres in the production of composites. They also have a lower density than most synthetic fibres and are suitable for lightweight applications. The density and mechanical properties of the hemp fibres are presented in Table 9.

Table 9. Properties of hemp fibres [24,32]

Density, g/cm^3	Tensile strength, MPa	Elongation at break, %	Modulus of elasticity, GPa	Thermal degradation, °C
1.4	550-1110	2-4	30-70	150

1.3.2. Polylactic acid matrix

The matrix is used in composites to hold the fibres together and transfer the loads [34]. It also provides the shape to the composite, texture, colour and durability. When the matrix is stressed, it evenly transmits the external load to the fibres and is used to prevent the propagation of cracks and damage [34]. The polymer matrices are commonly used in the production of composites as they are lightweight and can be processed at low temperatures [34]. Polymers can be classified based on:

- Molecular forces: thermoplastic polymers – these polymers soften through heating and hardens upon cooling. The changes are reversible since there is no chemical bonding and can be repeated many times; thermoset polymers – harden on the application of heat. Curing is an irreversible chemical reaction where the cross-links are made between macromolecular chains; elastomers – cross-linked, amorphous polymers, that are highly elastic and can return to the original shape after being stretched [34].
- Solid-state: amorphous polymers – the molecules are arranged randomly. These polymers have high elasticity and low density; crystalline polymers – have ordered molecule structures, high density, and are strong and rigid [35].
- Origin: natural – derived from animals and plants; semi-synthetic – obtained by making chemical modifications in natural polymers; synthetic – artificially synthesized in the laboratory [35].
- Line structure: linear polymers – the monomers are joined together in a straight line [35]. Linear polymers have high density and high melting points; branch chain polymers –

monomers are arranged in a straight chain with different length branched chains. They have low density and low melting points; cross-linked polymers – monomers are arranged in the form of a three-dimensional network (Fig. 6.).

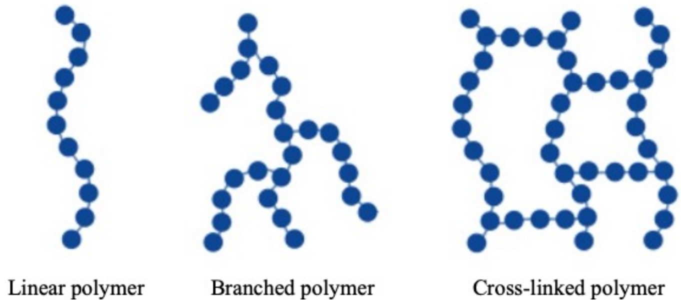

Fig. 6. Structure of polymers: linear, branched and cross-linked polymers [37]

– Mode of polymerization: addition polymers – formed by the repeated addition of monomer molecules, small particles are not eliminated; condensation polymers – formed by the combination of monomers, with the elimination of small molecules [35].

The polymer matrices can also be fully biodegradable, partially biodegradable and non-biodegradable. The use of biodegradable polymers as matrices for composites is gaining more attention since bio-based polymers can be used in order to produce green or partly eco-friendly composites (Fig. 7.).

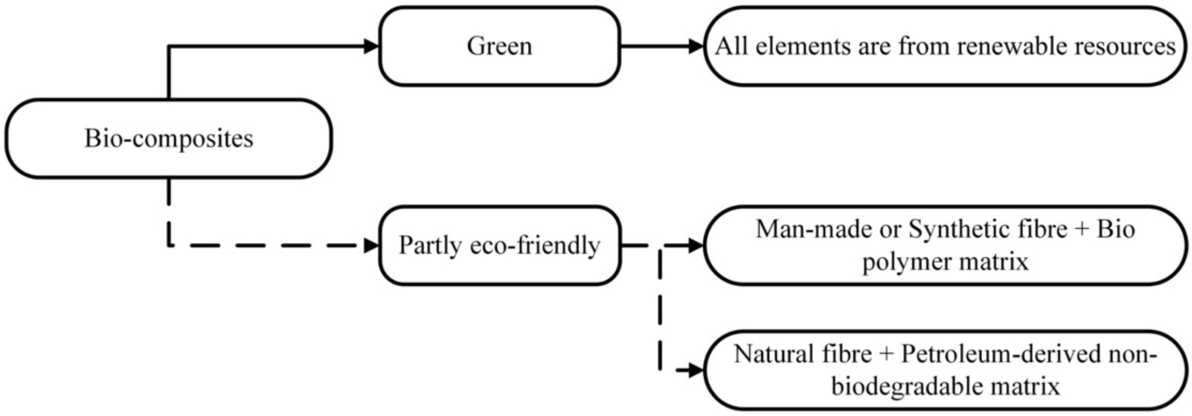

Fig. 7. Bio-composite classification [38]

Polylactic acid (PLA) is a thermoplastic polymer produced from renewable resources, which is biodegradable under controlled composting conditions [39]. It is obtained from lactic acid through fermentation of plant starch, for example, corn, potatoes, sugar beets or sugarcane. Compared with other widely used thermoplastics – polypropylene (PP), polyethylene (PE) and polystyrene (PS), PLA has high tensile strength and elastic modulus [39]. Moreover, the production of PLA consumes approximately 25-55% less fossil energy when compared with petroleum-based polymers [39]. It also can be manufactured by traditional manufacturing methods. Another advantage of PLA is its low melting temperature which is safe for natural fibres since they can degrade at a temperature above 200 °C [24]. The disadvantages of PLA are brittleness and low ductility [39]. The properties of PLA are presented in Table 10. Polylactic acid is commonly used for textile, biomedical, automotive, packing and agriculture applications [40].

Table 10. Properties of the polylactic acid (PLA) polymer [25,41]

Density, g/cm^3	Tensile strength, MPa	Elongation at break, %	Elastic modulus, GPa	Melting point, °C	Water absorption, %
1.28	40.10	2.50-6.00	2.27	156	0.06-2.00

Adding the fibres can improve the properties of the PLA composite, including low impact strength and brittleness. Shakoor, A., Muhammad, R., Thomas, N. L. and Silberschmidt, V. V. (2013) analysed the mechanical properties of hemp fibres reinforced PLA composites. The authors used PLA granules and dry retted hemp [42]. The PLA was melted and blended with fibres in the mixer at 170 °C for 10 minutes [42]. The mixing speed was 60 rpm [42]. After, the composites were compression moulded at the temperature of 180 °C for 3 minutes at 10-12 tons of pressure [42]. The properties of the produced composites are presented in Table 11.

Table 11. Properties of hemp/PLA composites [42]

No.	Material	Tensile strength, MPa	Elongation, %	Elastic modulus, GPa
1	PLA	43.0	4.1	4.1
2	Hemp (10%)/PLA	24.0	2.0	4.8
3	Hemp (20%)/PLA	30.0	2.0	6.9
4	Hemp (30%)/PLA	38.0	1.0	9.3

The table shows that hemp fibres can improve PLA elastic modulus by more than 2 times. The tensile strength decreased after adding the fibres, but the slowly increased with a higher volume of hemp fibres. The hemp fibres are brittle material, as well as PLA, therefore the elongation decreases as more fibres are added.

The analysis of scientific research on hemp fibres and polylactic acid polymer showed that hemp fibres are suitable reinforcement material for PLA composites. The combination of hemp fibres and PLA results in a green composite, which can be used to replace non-biodegradable polymers. Reinforcing the PLA composite with hemp fibres increases the elastic modulus. The tensile strength can also be increased, but it strongly depends on the content of fibres, their quality and fibre-matrix adhesion.

2. Materials and methods

2.1. Materials used

For the production of the composites, the polylactic acid sheets were used as a matrix. The thickness of the polylactic acid sheets was approximately 0.8 mm. PLA Ingeo 6201D (Nature Works LLC, USA) was received as resin granules and produced into sheets (Fig. 8.).

Fig. 8. PLA resin granules

The properties of the PLA polymer used in this work are shown in Table 12.

Table 12. Properties of PLA

Polymer grade	Density, g/cm^3	Tensile strength, MPa	Elongation at break, %	Elastic modulus, GPa	Melting point, °C
6201D	1.24	24.1	3.1	0.78	160-170

6 composites were developed: 2 with hemp fabric and PLA sheets and 4 with hemp fibres, and PLA. Two types of knitted hemp fabric were used as reinforcement for the composites – USO 31 and Felina 32 (Fig. 9.).

Fig. 9. Knitted hemp fabrics – USO 31 – left; Felina 32 – right

Two varieties of hemp fibres were used: USO 31 and Felina 32 (Fig. 10.). These fibres were manually straightened with a comb to lay them in one direction and to remove tangles, short fibres and impurities.

Fig. 10. Hemp fibres: USO 31– left; Felina 32 – right

USO 31 is monoecious hemp that was developed in 1987 in Ukraine. It has good seed yields, high oil content, high quality and fibre content. Therefore, USO 31 is used for the production of fibres, seed and biomass [43]. It is EU certified and is widely cultivated in Europe because of its adaptability [43]. Felina 32 is a monoecious type of hemp that originated in France and now is cultivated across Europe [44]. It was developed to produce seeds and fibres and is used for many applications, including insulation, construction, bedding, food and cosmetics [44]. The characteristics of these hemp plants are shown in Table 13.

Table 13. Characteristics of the USO 31 and Felina 32 hemp [45,46,47]

Variety	Vegetative cycle, days	Height, m	Fibre content in the stem, %	Tensile strength, MPa	Elongation at break, %	Elastic Modulus, GPa
USO 31	100-120	2-2.5	30-35	647-830	4.3-4.4	-
Felina 32	130-140	2.5-3.5	30-35	699	3.3	31.2

According to the literature, the USO 31 hemp fibres can have higher tensile strength when compared with Felina 32 fibres. The USO 31 fibres are also more ductile, their elongation at break is 30-33% higher than Felina 32.

The received USO 31 fibres were long and thick and had pale yellow colour. The length of these fibres was approximately 15-25 cm. Felina 32 fibres were short and thin, of similar yellow colour, and approximately 7-15 cm long.

Both fabrics were weft-knitted. The USO 31 fabric yarns were thinner when compared with Felina 32 fabric. Felina 32 fabric was grey, and the USO 31 was yellow. Commonly, the colour of hemp fibres varies from yellow to dark grey, these changes are related to hemp growth and different retting duration [48]. The grey colour appears because of the development of microorganisms on the surface of the plant stem [48].

2.2. Production of sheets and composites

The sheets and 4 composites were produced using Joos-Laboratory-Press LAP 40 (Gottfried Joos Maschinenfabrik GmbH & Co., Germany) (Fig. 11.). The LAP 40 press has a pressing surface of 500 × 500 mm and can be heated up to 250 °C. The maximum force that can be applied is 400 kN.

Fig. 11. Joos LAP 40 press (Gottfried Joos Maschinenfabrik GmbH & Co., Germany)

The LAP 40 press was heated up to 180 °C for the production of PLA sheets. The granules were placed in between two sheets of heat resistant paper. Then materials were transferred to the press and pressed at 180 kN for 2 minutes until the granules melted and formed a sheet. The process was repeated to obtain 8 PLA sheets.

For the composite production, the press was heated up to 180 °C. The USO 31 hemp fibres were placed in between PLA sheets. Then the USO 31/PLA composite was covered with heat resistant paper sheets and transferred to the heated LAP 40 press. 127 kN pressure was applied to the composite, and it was pressed for 2 minutes. The process was repeated with Felina 32/PLA composite and with hemp fabric/PLA composites. The Fig. 12. shows the produced hemp fabric/PLA composites.

Fig. 12. Produced knitted hemp fabric/PLA composites, Felina 32 fabric/PLA – left, USO 31 fabric/PLA – right

One USO 31 fibre/PLA composite and one Felina 32 fibre/PLA composite were produced in the Lithuanian textile institute with the fusing machine Nova-45 (Reliant Machinery, Ltd., United Kingdom) (Fig. 13.). Nova-45 has two pressure rolls, that were heated to 190 °C. The fibres were pressed in between two polymer sheets and the composite was covered with heat resistant paper. Then composite was transferred through the machine and fused with the heat and 48.3 kPa pressure for 25 seconds. The heat resistant paper was removed after the composite cooled down. The process was repeated with Felina 32 fibre/PLA composite.

Fig. 13. Nova-45 (Reliant Machinery, Ltd., United Kingdom) fusing machine

The mass of the produced composites and reinforcement weight are listed in Table 14.

Table 14. Composition of the produced composites

No.	Materials	Manufacturing method	Abbreviation	Reinforcement mass, g	Matrix mass, g	Reinforcement wt., %
1	USO 31 fabric/PLA	Compression	UFAC	29.38	64	32
2	Felina 32 fabric/PLA	Compression	FFAC	40.12	64	39
3	USO 31 fibre/PLA	Compression	UFC	12.12	64	16
4	Felina 32 fibre/PLA	Compression	FFC	12.12	64	16
5	USO 31fibre/PLA	Fusing	UFF	9.60	43	18
6	Felina 32 fibre/PLA	Fusing	FFF	9.30	33	22

2.3. Preparation of specimens and testing

For the tensile test, 5 specimens of each composite were cut with a guillotine. The size of the specimen is shown in Figure 14. The specimens of hemp fibre reinforced composites were cut so that the fibres would be oriented along the specimen.

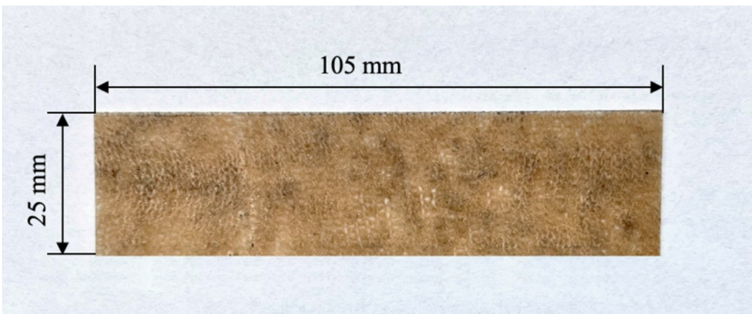

Fig. 14. Specimen size

The thickness of the specimens was measured to calculate the initial cross-sectional area. The measured thickness of the composite specimens is: UFAC – 1.0 mm, FFAC – 1.1 mm, UFC – 0.9 mm, FFC – 0.8 mm, UFF – 1.8 mm and FFF – 2.0 mm.

The test was performed at room temperature - 20 ºC (±2 ºC). The specimens were tested at Kaunas University of Technology using Tinius Olsen H10KT universal testing machine (Tinius Olsen, Ltd., United Kingdom) (Fig. 15.). Tinius Olsen machine has a frame capacity of 10kN and is designed for testing the tension, compression, flexure, and peel. The selected parameters for the tensile test were: 50 mm distance between upper and bottom grips and 5000 N stretching strength sensor. The speed of the upper grip was kept at 25 mm/min. Each specimen is placed in between the grips and pressed firmly. Then the upper grip moves at the selected speed, and the specimens are stretched until they break.

Fig. 15. Tinius Olsen H10KT (Tinius Olsen, Ltd., United Kingdom) universal testing machine

The testing machine is operated with a "QMat Professional" software. After the test, the tensile results in this software are presented in a graph. During the tensile test, the graph of the force (F) and change in length (ΔL) relationship was drawn. The software automatically calculates maximum elongation and force at break, their mean and standard deviation. When the test results were obtained, stress at break of the specimens was calculated using formula (1):

$$\sigma = \frac{F}{A}; \quad (1)$$

Where σ – stress, MPa; F – force, N; A – cross-sectional area, mm^2.

The initial cross-sectional area of the specimens was calculated using formula (2):

$$A = h \times b; \quad (2)$$

Where A – cross-sectional area, mm^2; h – height, mm, b – width, mm.

The elongation was calculated using the following formula (3):

$$\varepsilon = \frac{\Delta L}{L_0} (\times\ 100\%); \tag{3}$$

Whereε – elongation, %; ΔL – change in length, mm; L_0 – initial length, mm.

The elastic modulus was calculated using formula (4):

$$E = \frac{\sigma}{\varepsilon \times 1000}; \tag{4}$$

Where E – elastic modulus, GPa; σ – stress, MPa; ε – elongation.

2.4. Statistical data analysis

To evaluate the reliability of results and identify the trends, arithmetic mean, and standard deviation were calculated.

Arithmetic mean, also called the average, is calculated by summing all the variables and dividing them by their number. It was calculated using the formula (5):

$$\bar{x} = \sum \frac{x_i}{n} \tag{5}$$

Where $\bar{x}$ – arithmetic mean; x_i – individual variables in the data set; n – number of variables in the data set.

Standard deviation measures the dispersion of a dataset relative to its arithmetic mean. The high standard deviation indicates that data is spread out, while the low indicates that data is close to the mean. The formula (6) was used to calculate it:

$$S = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}} \tag{6}$$

Where S –standard deviation; n – number of variables in the data set; x_i – individual variables in the data set; $\bar{x}$ – arithmetic mean of the x_i.

3. Results and discussion

3.1. Tensile test results

5 specimens from each composite were tested. After the tensile test was performed, one specimen with the values closest to the calculated mean of all composite specimens was selected and compared with other specimens selected correspondingly. This comparison was made to have a visual representation of the force-extension curves of the composites. The composite specimens were compared based on:

- The variety of hemp fabric – the Felina 32 fabric-reinforced and USO 31 fabric reinforced composite specimens were compared with each other.
- The variety of fibres – Felina 32 and USO 31 fibre reinforced composite specimens were compared with each other.
- Production method – compression moulded fibre reinforced composite specimens were compared with fused fibre reinforced composite specimens.

The FFAC and UFAC specimens had similar tensile behaviour (Fig. 16.). The force-extension curves were changing from linear elastic to elastoplastic deformations. As seen in the graph, both specimens had high extension – the selected FFAC and UFAC specimens extended 4.3 mm and 2.3 mm, respectively. The test results also showed that the FFAC specimen can withstand a 2 times higher force than the UFAC specimen before fracture. The elongation of the FFAC specimen was also 2 times higher.

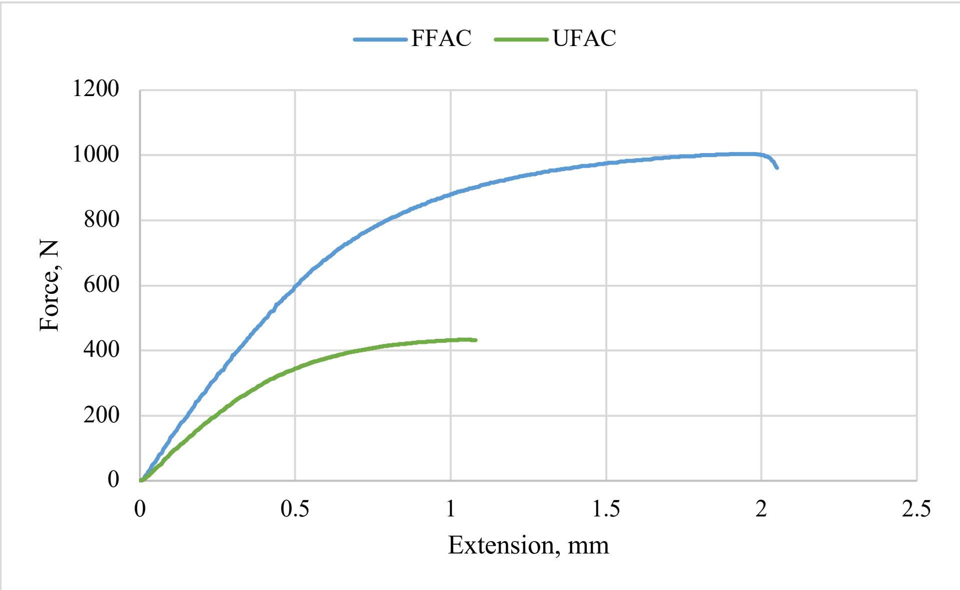

Fig. 16. Relation between force and extension of FFAC and UFAC specimens

When comparing tensile results of UFC and FFC specimens, it can be seen that the extension of both composite specimens is relatively proportional to the applied force (Fig. 17.). The specimens of these composites were stiff and did not extend as much as FFAC and UFAC specimens. These results may be related to the fact that fibres have higher stiffness than knitted fabric. FFC specimen could withstand 3% less force than UFC before breaking. UFC specimen elongation was 10% higher than the FFC specimen.

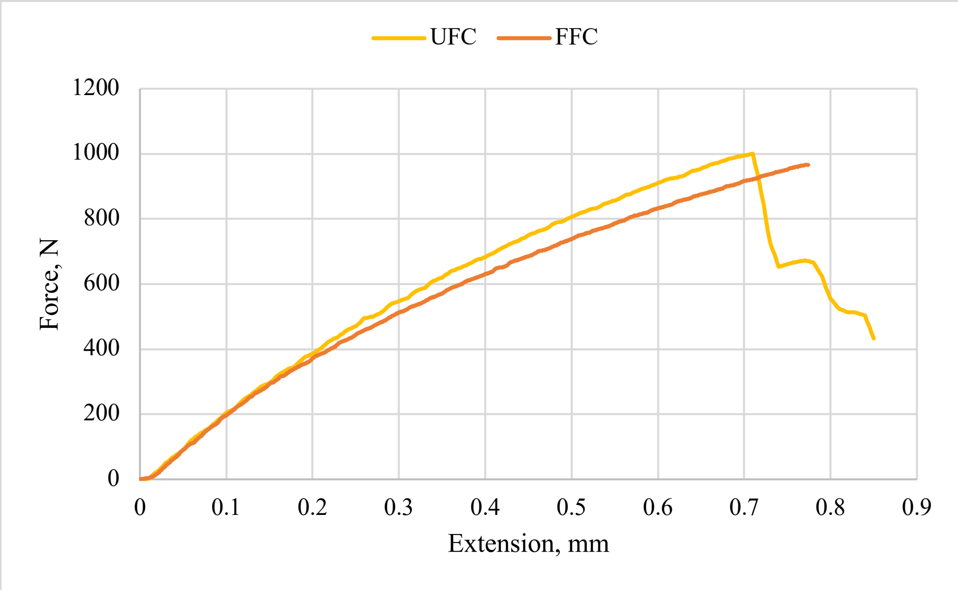

Fig. 17. Relation between force and extension of UFC and FFC specimens

From the force-extension graph of UFF and FFF can be seen that the specimens had similar tensile behaviour to the compression moulded hemp fibre composite specimens (Fig. 18.). The specimens were relatively rigid, and their deformations were small. The UFF specimen extended 3.7 mm and the FFF specimen extended 4.5 mm. The UFF specimen was stronger than FFF – UFF specimen withstood 20% higher force before breaking. However, the FFF specimen elongation was 24% higher.

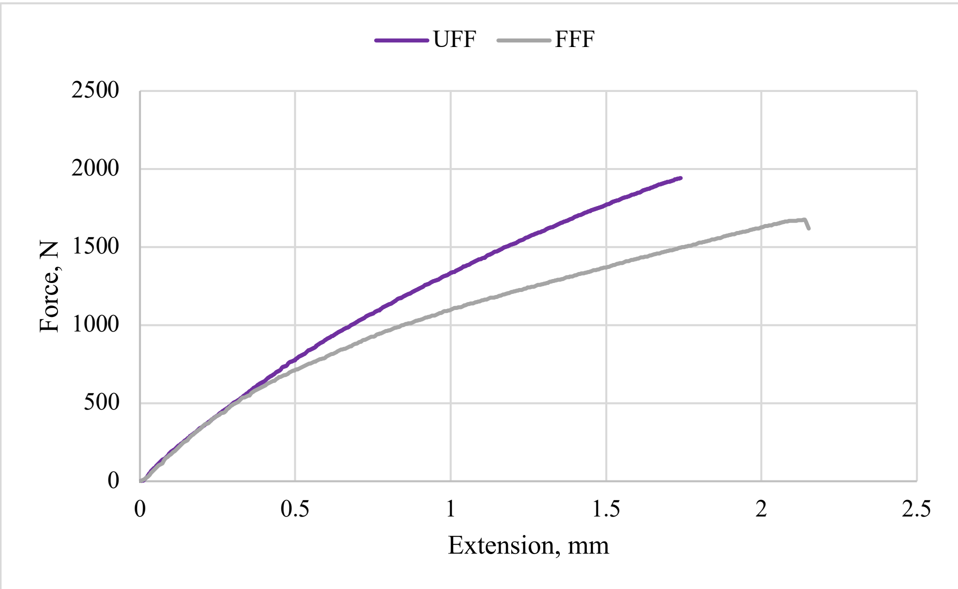

Fig. 18. Relation between force and extension of UFF and FFF specimens

The specimen UFF was extending proportionally to the applied force and broke right after reaching its maximum force, while the UFC had several fractures before its final failure (Fig. 19.). The UFF specimen was also more resistant to pulling, its force at break was 1.9 times higher, and its elongation was 2.5 times higher than the UFC specimen.

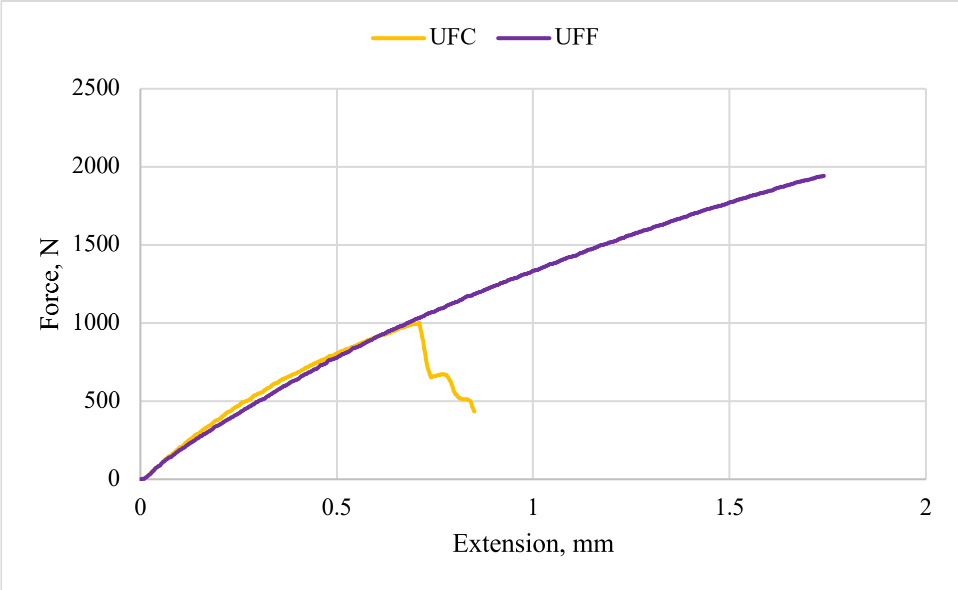

Fig. 19. Relation between force and extension of UFC and UFF specimens

Both specimens have an analogous force-extension curve shape (Fig. 20.). The specimen produced by the fusing machine can withstand 1620 N force before breaking, while the FFC specimen breaks at 966 N. The FFF also elongated by 4.49% and extended 4.7 mm, while FFC elongated only by 1.90% and extended 2 mm.

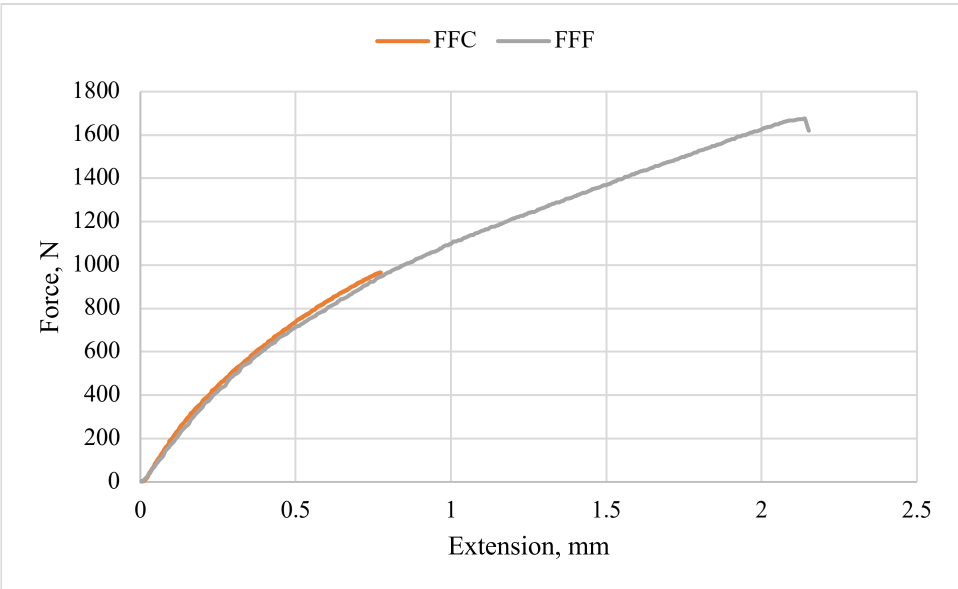

Fig. 20. Relation between force and extension of FFC and FFF specimens

The tensile test results of these specimens, the mean values of the specimen groups and the standard deviation are presented in Table 15.

Table 15. The test results of the selected composite specimens

No.	Composite	Elongation, %	Elongation at break, %	Max force, N	Force at the break, N	Stress at break, MPa	Elastic modulus, GPa
1	UFAC	2.16 ± 0.26	2.07 ± 0.14	433.50 ± 44.69	431.50 ± 37.38	17.26 ± 1.50	0.86 ± 0.12
	Mean	2.43 ± 0.26	2.21 ± 0.14	428.96 ± 44.69	422.12 ± 37.38	16.88 ± 1.50	0.71 ± 0.12
2	FFAC	4.10 ± 0.74	3.80 ± 0.60	1004.00 ± 30.19	1004.00 ± 30.99	36.51 ± 0.13	0.89 ± 0.17
	Mean	3.97 ± 0.74	3.72 ± 0.60	1002.60 ± 30.19	998.60 ± 30.99	36.31 ± 0.13	0.94 ± 0.17
3	UFC	1.70 ± 0.29	1.42 ± 0.32	1000.00 ± 98.82	1000.00 ± 98.82	44.44 ± 4.39	2.61 ± 0.23
	Mean	1.73 ± 0.29	1.68 ± 0.32	1016.20 ± 98.82	1016.20 ± 98.82	45.16 ± 4.39	2.63 ± 0.23
4	FFC	1.55 ±1.29	1.54 ± 0.64	966.00 ± 448.60	966.00 ± 448.48	48.30 ± 22.42	3.11 ± 0.68
	Mean	1.90 ± 1.29	1.60 ± 0.64	819.00 ± 448.60	818.80 ± 448.48	40.94 ± 22.42	2.29 ± 0.68
5	UFF	3.48 ± 1.19	3.48 ± 1.17	1942.00 ± 436.20	1942.00 ± 436.60	43.16 ± 9.70	1.24 ± 0.18
	Mean	4.42 ± 1.19	4.40 ± 1.17	2063.00 ± 436.20	2062.00 ± 436.60	45.83 ± 9.70	1.06 ± 0.18
6	FFF	4.30 ± 1.67	4.27 ± 1.04	1676.00 ± 678.96	1620.00 ± 655.12	32.40 ± 13.10	0.75 ± 0.29
	Mean	6.49 ± 1.67	4.49 ± 1.05	1462.00 ± 678.96	1012.00 ± 655.12	28.72 ± 13.10	0.49 ± 0.29

The calculated standard deviation was relatively high for FFC, UFF and FFF specimens. It showed that the measured values were far from the mean values (Fig. 21.). These results might have been influenced by the production parameters – the fibres were straightened manually, and the composites contained fibres of different lengths, so the fibre volume in the composite could vary. Therefore, it would be recommended to repeat the tensile test for these composites, to obtain more accurate results.

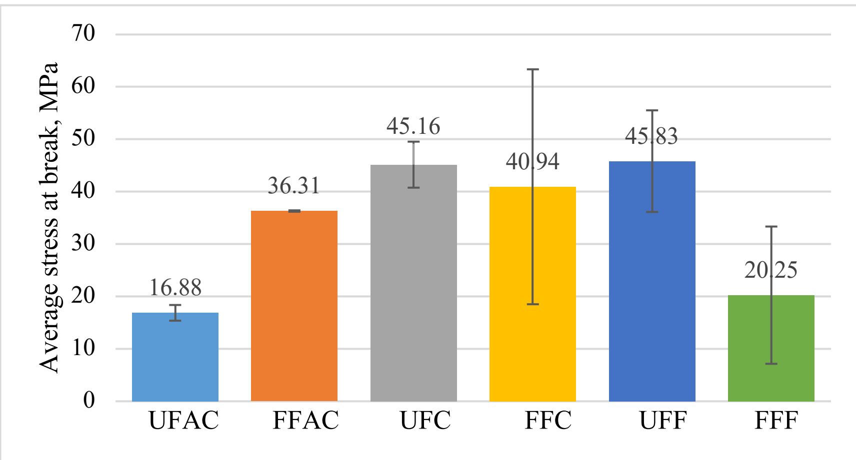

Fig. 21. The average stress at break and standard deviation of the composite specimens

When comparing the strength of the composites and the pure PLA material (24.1 MPa), reinforcement with USO 31 hemp fabric (UFAC) resulted in 43% lower strength and 40% lower elongation at break, although the stiffness of the composite increased – the elastic modulus was 10% higher. Theoretically, the reinforcement with knitted fabric should increase the strength and elastic modulus. However, it can be seen that the experimental results can be different. The strength of the composite can be influenced by the quality of the fabric, yarn structure, knitting parameters and other factors. The average strength of FFF was also 19% lower than PLA, and the elastic modulus was 59% lower, but the ductility of the composite increased – its elongation at break was 45% higher than pure PLA. The compression moulded composites with hemp fibre had 84.5% (UFC) and 63% (FFC) lower elongation at break than PLA material, but their strength and stiffness increased. A substantial improvement in strength was observed when PLA was reinforced with USO 31 fibres and produced by compression moulding, as well as fused.

As was expected, the strength of the USO 31 fibre reinforced composites was higher than Felina 32 fibre composites since the USO 31 fibres have higher tensile strength (647-830 MPa) than Felina 32 (699 MPa). However, the USO 31 knitted fabric reinforced composite showed the opposite tendency. The maximum stress that FFAC can withstand was 36.31 MPa, and the stress at the break of UFAC was 2.2 times lower – 16.88 MPa. The elastic modulus of the FFAC was 32% higher than UFAC. The average elongation before the break of the FFAC was 1.7 times higher. These results can be due to the higher linear density of the yarns that were used for the Felina 32 fabric.

The knitted fabric reinforced composites had higher ductility than compression moulded composites, but their strength and elastic modulus were lower. As was mentioned, the composite with Felina 32 fabric had higher mechanical properties, which could be obtained because of the higher density yarns. Therefore, to increase the strength of these composites, the second layer of the knitted fabric could be used.

The fused composite specimens could withstand high force before breaking, but their stress at break was relatively low. These results were affected by the larger cross-sectional area of the specimens. The fused composites had higher elongation at break, but lower elastic modulus compared to the compression moulded hemp fibre composites. However, no trends were observed, when comparing the stress at break of the compression moulded composites with the fused composites. These results might have been influenced by the production parameters – the fibres were straightened manually, and the composites contained fibres of different lengths, so the fibre volume in the composite could vary. Therefore, it can be concluded that to produce high strength composites both methods can be used.

4. Economical part

4.1. Cost calculation of the composites

The production cost of the hemp fabric/PLA and hemp fibre/PLA composites will be calculated. The results will be analysed to determine whether the production of textile waste composites is cost-effective.

Total production costs include indirect and direct costs. Indirect costs are related to maintaining and running a company and are not attributed to a specific product. Therefore, the indirect costs will not be included in the calculation. Direct production costs are the costs that can be directly attributed to the produced product. These costs include direct material costs, manufacturing costs and special one-off expenses. Direct material costs refer to raw materials used for each composite production cycle. Manufacturing costs refer to direct machine costs, direct labour costs and energy costs. Special one-off expenses include costs of machinery and other manufacturing equipment required for a certain part of the product only, for example, a mould. The production of these composites did not have special one-off expenses. The production cost will be calculated using the following formula:

$$C_{Total} = C_D + C_M + C_S \tag{7}$$

Where C_{Total} – total production cost; C_D – direct material costs; C_M – manufacturing costs; C_S – special one-off expenses.

In this calculation, direct materials are hemp fibres, hemp fabric, polylactic acid resin granules and heat resistant paper. The hemp fabrics are collected as textile waste; therefore, their price is 0 Eur. Direct costs of the composite materials are shown in Table 16.

Table 16. Direct material costs

No.	Composite	Material	Amount	Material price	Total price, Eur
1	UFC and FFC	Hemp fibres [49]	12.12 g	8.83 Eur/kg	0.11
		PLA resin granules [50]	64 g	2.82 Eur/kg	0.18
		Heat resistant paper [51]	6 psc	0.12 Eur/pc	0.72
2	UFF	Hemp fibres	9.60 g	8.83 Eur/kg	0.08
		PLA resin granules	43 g	2.82 Eur/kg	0.12
		Heat resistant paper	6 psc	0.12 Eur/pc	0.72
3	FFF	Hemp fibres	9.30 g	8.83 Eur/kg	0.08
		PLA resin granules	33	2.82 Eur/kg	0.09
		Heat resistant paper	6 psc	0.12 Eur/pc	0.72
4	UFAC	USO 31 hemp fabric	29.38 g	0.00	0.00
		PLA resin granules	64 g	2.82 Eur/kg	0.18
		Heat resistant paper	6 psc	0.12 Eur/pc	0.72
5	FFAC	Felina 32 hemp fabric	40.12 g	0.00	0.00
		PLA resin granules	64 g	2.82 Eur/kg	0.18
		Heat resistant paper	6 psc	0.12 Eur/pc	0.72

The total cost of raw materials for UFC and FFC is 1.01 Eur. The cost of materials for UFF is 0.92 Eur, and 0.89 Eur for FFF. The cost of materials for UFAC and FFAC is 0.90 Eur.

To calculate the cost of energy, the time of the production cycle needs to be estimated. To produce one composite with a compression moulding machine 3 pressing cycles are required. One cycle lasts 2 min. The press also has to be pre-heated, which takes approximately 5 minutes. Therefore, the total processing time for the compression moulded composites is 11 minutes.

- Time of press use – 11 min. = 0.18 h.
- Energy cost rate – 0.167 Eur/kWh [52]
- Press power – 26.9 kW

The cost of consumed energy is calculated using formula (8):

$$C_E = E_R \times P \times t \quad (8)$$

Where C_E – cost of consumed energy, Eur; E_R – energy cost rate, Eur/kWh; P – power, kW; t – time of use, h.

$C_E = 0.167 \times 26.9 \times 0.18 = 0.81$ Eur

It takes 25 seconds to produce a composite with a fusing machine and 5 minutes to pre-heat the machine. The PLA sheets were produced with the press. Therefore, the cost of their production will be added to the calculation.

- Time of fusing machine use – 5.42 min. = 0.09 h.
- Time of press use – 9 min. = 0.15 h.
- Fusing machine power – 3.2 kW

$C_E = (0.167 \times 3.2 \times 0.09) + (0.167 \times 26.9 \times 0.15) = 0.05 + 0.67 = 0.72$ Eur

To calculate the labour cost, the total composite production time has to be calculated. As mentioned before, the processing time for compression moulded composites is 11 minutes. However, first, the fibres need to be manually straightened with a brush. Then composite materials need to be prepared and assembled, it takes 5 more minutes.

- Total fibre reinforced composite production time – 46 minutes = 0.76 h.
- The average monthly salary of a production technologist in Lithuania is 1244 Eur = 7.18 Eur/hour [53].

Therefore, the labour cost can be calculated using the following formula (9):

$$C_L = R_L \times t_i \quad (9)$$

Where C_L – labour cost, Eur; R_L – labour cost rate, Eur/hour; t_i – total production time, h.

$C_L = 7.18 \times 0.76 = 5.46$ Eur

As calculated previously, it takes 5.42 minutes to produce hemp fibre composites with a fusing machine. The preparation time for these composites is identical to compression moulded fibre composites – 35 minutes. Therefore, the total production time is 0.67 hours. The total labour cost was calculated using formula (9).

$C_L = 7.18 \times 0.67 = 4.81$ Eur

The fabric-reinforced composite process time is 11 minutes. The preparation time is 5 minutes – the fabrics need to be cut and laid between PLA sheets and heat resistant paper. The total production time is 0.26 hours. The total labour cost was calculated as:

$C_L = 7.18 \times 0.26 = 1.87$ Eur

The total production cost of all composites was calculated according to formula (7) and is presented in Table 17.

Table 17. Total production cost of the produced composites

Composite	**Total production cost, Eur**
UFC and FFC	7.28
UFF	6.45
FFF	6.42
UFAC and FFAC	3.58

The calculations showed that producing composites with a fusing machine is less expensive than with a press since its cost of energy is lower. The total production cost of UFF and FFF was relatively low. However, these composites contained lower amounts of materials than the rest of the composites. If UFF and FFF would have the same quantity of fibres and PLA as UFC and FFC, their total production cost would be 6.54 Eur. To further reduce these costs, the PLA sheets could be manufactured by the fusing machine. The production cost of textile waste reinforce composites is 3.70 Eur lower than compression moulded composites with fibres. It can be concluded that the use of textile waste in composites is cost-effective. However, it has to be considered that the quality of these composites strongly depends on the textile waste quality. Therefore, to produce high-quality composites, the use of primary raw materials is recommended. However, the production cost of these composites would be higher since the production of fabric has more stages: fibre preparation, spinning them into yarns and then kitting them into the fabric.

4.2. Further development of the composites

4.2.1. Applications

The produced composites are lightweight and biodegradable but stiff and in the shape of sheets, which limits the possible applications. They could be used as an eco-friendly alternative to layer pads, which are often produced from polypropylene or cardboard. These layer pads are used to divide layers of stacked products: cans, bottles and containers in the beverage, food, and glass industries (Fig. 22.).

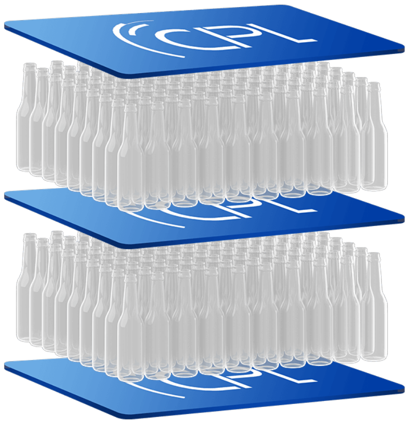

Fig. 22. Polypropylene layer pads [54]

The main requirements for these products are reusability and recyclability. They have to be lightweight but strong, durable and non-toxic [54]. Polylactic acid is commonly used in medical and food industries since it is non-toxic and does not produce fumes if melted. However, this plastic is not resistant to heat and chemicals. The glass transition temperature of PLA is 50-62 °C, and in temperatures above it, the PLA can lose strength and deform [55]. Therefore, this product should not be exposed to the sun for a long time and should be used mostly indoors.

The hemp reinforced composites could be used as partitions, which are usually made of polypropylene, polymethyl methacrylate, or cardboard (Fig. 23.). These partitions have many applications: they are used to divide office desks, inside of the packing boxes, and drawers. Compared to the cardboard partitions, the composite ones would have higher strength, no paper dust and higher bending stiffness. They can also be a biodegradable alternative to the polypropylene and polymethyl methacrylate partitions.

Fig. 23. Partitions [56]

4.2.2. Biodegradation and composting

Polylactic acid (PLA) is a biodegradable polymer that can be degraded under certain environmental conditions. According to the American Society for Testing and Materials standard D-548894d biodegradable material can decompose into carbon dioxide (CO_2), water (H_2O), methane (CH_4), inorganic compounds or biomass [57].

The PLA polymer can degrade in several environments: composts, soils, and aquatic environments. However, the degradation in the soil is more complex and slower when compared with composting since it needs optimal environmental conditions. According to several researchers, the degradation in soil takes approximately one year, while it takes only 60-100 days in compost [58]. Similar to degradation in soil, the PLA degradation in the aquatic environment requires more time. The fastest degradation of PLA in these conditions was 90% degradation within 120 days at 60 °C [58]. The most efficient degradation of PLA occurs in two steps: the first step is PLA reaction with water (hydrolysis) at high temperatures, followed by microbial degradation. The microorganisms mineralize PLA particles and generate CO_2 under aerobic composting conditions (in the absence of oxygen) and CH_4 under anaerobic composting conditions (without oxygen). However, the anaerobic degradation of PLA is slower. In a study that compared these degradation conditions, was reported that PLA degraded only by 10% in 210 days under aerobic composting conditions, while in anaerobic conditions, PLA degraded by 60% in 100 days at the same 37 °C temperature [59]. The degradation of PLA also depends on these factors:

- Humidity – the degradation is faster in a higher moisture environment since it increases the hydrolytic degradation. Ideally, the relative humidity for PLA degradation should be 60% or higher.
- Oxygen – aerobic PLA degradation requires the presence of oxygen, while anaerobic does not.
- pH – it was reported that the degradability of PLA is fast in basic (pH 13.0) conditions and slightly slower in acidic (pH 1.0) conditions [58]. The degradation is relatively slow in neutral, moderately basic and acidic conditions [58].
- Temperature – PLA degradation increases when the temperature is higher than its glass transition temperature, which is 50-62 °C [54]. Biodegradation of PLA at 50-60 °C under compositing conditions takes 180 days [60]. Temperatures higher than 65 °C are not recommended as they cause the death of microorganisms [61].
- Type and distribution of microorganisms – several researchers reported that microorganisms that degrade PLA are not widely distributed in the environment. Therefore, PLA has a lower chance to degrade in natural soil than other biodegradable polymers, such as polycaprolactone (PCL) or polybutylene succinate (PBS) [58]. Currently, scientists are working to find and investigate new potential microorganisms that could degrade PLA.
- The characteristics of PLA polymer – degree of crystallinity and molecular weight. Higher crystallinity of the polymer results in a lower degradation rate [22].

Natural fibres are more biodegradable than PLA polymer since they are hydrophilic. Several studies concluded that reinforcing polylactic acid with fibres increases the biodegradation rate. Fibres in a composite allow humidity and microorganisms to reach the inside of the composite [62]. The figure below illustrates the degradation process of fibre reinforced composite.

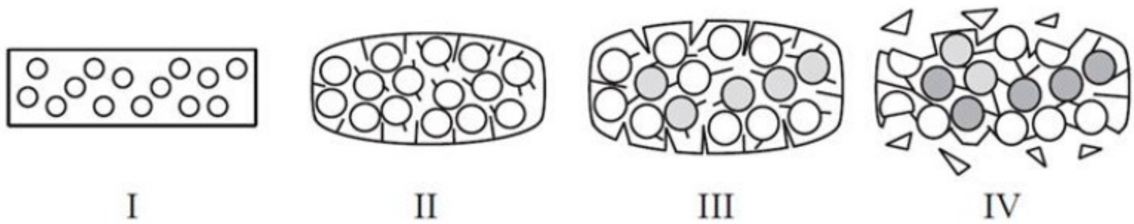

Fig. 24. Stages of degradation of natural fibre reinforced composite [62]

The fibres absorb humidity and start swelling (I). Then the cracks in the matrix appear (II) the number of them increases as the microorganisms attack the fibres, and the hydrolytic degradation of the matrix begins (III) [61]. Then the composite becomes brittle and breaks (IV) [62].

The PLA composites should be discarded in industrial composting facilities or composted at home. Discharge of these composites together with municipal waste should be avoided since the conditions for degradation of PLA polymer are not suitable.

4.2.3. Recycling

As mentioned previously, the composite with hemp fibres and polylactic acid can be classified as a green composite, produced from renewable sources and biodegradable under controlled environmental conditions. However, PLA composites can also be recycled. Figure 25 illustrates all possible ways to discharge plastics after their service and sequence based on energy consumption and desirability. The desirability of the disposal ways is based on the ability to protect the environment, human health, and resources. Recycling is more desirable than composting since it allows to reduce the cost of materials for new products and helps to save energy and resources [63,64].

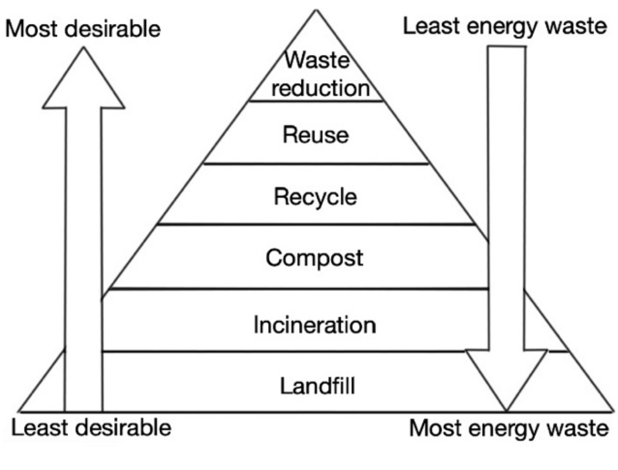

Fig. 25. Pyramid of plastic disposal [22]

Polylactic acid and its composites can be recycled by three methods: mechanical recycling, chemical recycling, and thermal processing:

- In mechanical recycling, the composite is cut and ground. The fibres are separated by sieving. Mechanical recycling has several advantages: it is easy, allows the control of technological parameters and is relatively inexpensive [63]. However, it requires high amounts of energy, and the recycled materials are low quality [64].

- In chemical recycling, the matrix and fibres are separated by dissolving the matrix [63]. The disadvantage of this process is that it is not environmentally friendly since chemical waste is generated during recycling.
- In thermal processing, the resin is decomposed, and the fibres are separated under high temperatures. After that, the fibres are regenerated, and secondary fuel or thermal energy is produced through gasification, pyrolysis, or incineration [63]. However, the quality of fibres is reduced during this process.

As it can be seen, all the processes for composite recycling have limitations and still need to be improved to make recycling more efficient. However, the higher demand for composite materials can put more attention on their recycling and the development of improved separation technologies.

Conclusions

1. In this work, six composites reinforced with different materials and produced by different methods were developed. Four composites were produced by compression moulding and reinforced with hemp fibres and knitted hemp fabric waste. Obtained hemp fibres were from two hemp plants: USO 31 and Felina 32, the fabrics were also produced from these varieties of hemp. The other two composites were produced with a fusing machine and were reinforced with the same varieties of hemp fibres. Polylactic acid was used as a matrix material for all six composites.
2. To determine the mechanical properties of the produced composites the tensile test was performed. It was determined that the USO 31 fibre reinforced composite produced by the fusing method had the highest strength, its stress at break was calculated as 45.83 MPa. Both fused composites had higher elongation at break, but lower elastic modulus compared to the compression moulded hemp fibre composites. The elongation at break of UFC was 1.68%, the FFC elongated by 1.60% before breaking, while UFF and FFF elongated by 3.48% and 4.49% before breaking. The elastic modulus of the UFC was 2.63 GPa, for FFC it was calculated as 2.29 GPa. The elastic modulus of UFF and FFF was calculated as 1.06 GPa and 0.49 GPa, respectively. It was observed that USO 31 fibre reinforced composites were stronger than Felina 32 fibre reinforced composites, the UFC could withstand 45.16 MPa, the UFF – 45.83 MPa before breaking, while the FFC and FFF could withstand 40.94 MPa and 28.72 MPa, respectively. The Felina 32 knitted fabric reinforced composite showed the opposite tendency in terms of strength. The maximum stress that FFAC can withstand was 36.31 MPa, and the stress at the break of UFAC was 2.2 times lower – 16.88 MPa.
3. The total production cost of the fabric-reinforced composites was the lowest: UFAC and FFAC cost was 3.58 Eur. The cost of the fused composites was lower than of the compression moulded fibre composites: UFF cost was 6.45 Eur, and the cost of the FFF was 6.42 Eur when the cost of the UFC and FFC was calculated as 7.28 Eur.
4. Produced composites are a suitable environmentally friendly alternative to polypropylene layer pads, that are used to divide layers of stacked products. These composites can also be used as partitions to divide office furniture, packing boxes and drawers. After the service, the composites can be decomposed or recycled. Recycling is preferable since it produces less energy waste and helps to save resources.

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