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The potential application of sheep wool as a component of composites

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SUMMARY

Composite materials, which can have a wide range of properties, can have an important role in protecting the natural environment. Until now, the most popular fibres used in composites have been those obtained by chemical processes. Natural fibres are much less commonly used, but interest in them is growing due to the principles of eco-development, care for the environment, and their important fact that they are biodegradable. Sheep wool, due to its unique physicochemical properties, such as thermal and sound insulation and the ability to absorb and release moisture, can be used as a fibre in biodegradable composites. Biodegradable polymers are becoming increasingly popular as an alternative to plastics, which have a negative impact on the environment. Although the use of biodegradable polymers is limited by their poor mechanical and thermal properties, a filler in the form of sheep wool fibres increases the mechanical properties of the composite and reduces production costs, while maintaining its biodegradability. Mixed wool is treated as a waste product which is difficult to utilize in the textile industry, but innovative applications in agriculture and medicine provide the opportunity to make use of it. As a fibre with unique physicochemical properties, wool can be used as an element of biocomposites in line with the strategies of bioeconomy and sustainable development.

KEY WORDS: sheep wool, materials engineering, composites, polymers

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INTRODUCTION

The ongoing development of civilization and the increasing environmental pollution caused by polymers, which are not degraded naturally, has prompted the introduction of sustainable solutions and the use of biodegradable fibres in materials engineering. Composites, which combine different groups of materials and enable the generation of diverse materials (Fig. 1), can have an important role in protecting the natural environment (Blicharski, 2001). Fibres obtained by chemical processes have been the most popular fibres used in composites, while fibres of natural origin are much less common. Interest in these biodegradable fibres in order to safeguard the natural environment has been increasing (Mao and Russell, 2007; Chandramohan and Marimuthu, 2011; Galán-Marín et al., 2010). Among natural fibres, plant fibres are currently the most commonly used in the design and production of composites (Azwa et al., 2013). Sheep wool, owing to its physicochemical properties, is an animal fibre that can be used in the design of biodegradable composites (Johnson et al., 2003; Cheung et al., 2009). In Poland, sheep wool is an underused material in the textile industry. Breeders of mixed-wool sheep (e.g. Polish Mountain Sheep, Podhale Zackel, Świniarka or Wrzosówka) find it particularly difficult to sell their wool. This type of wool is most often processed into regional or handicraft products. However, this fibre could be put to use in the construction industry, agriculture or medicine, following the development of technologies for creating composites with sheep wool (Allafi et al. 2020, Jóźwiak-Niedźwiecka and Fantilli, 2020). There are literature reports of research on the modification of polymer and cement matrices with wool fibre. In the current economic situation of Polish sheep farming, there is a need for alternative uses of sheep wool. Importantly, entrepreneurs are showing interest in new technological solutions based on natural materials. What is more, natural fibres do not contribute to the degradation of the environment and are easily broken down even in compost bins (Pach and Mayer, 2010). Therefore, this study aims to analyse whether sheep wool can be used in the development of biodegradable composites.

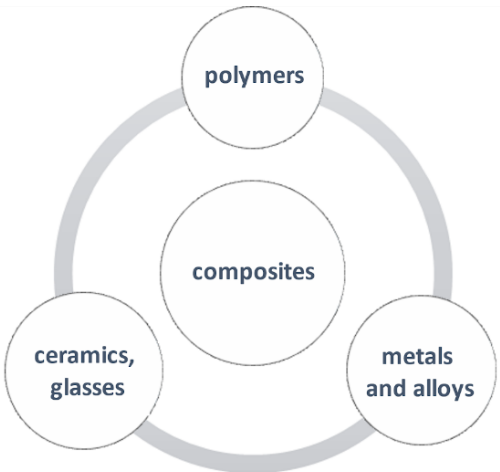

Fig. 1. Groups of materials and their interrelationships (*Blicharski, 2001* – own modification by A. Tadla)

Characteristics of composites

Composites are composed of two phases: the matrix, which is a continuous phase in the material, and the dispersed phase, which is responsible for its properties, including reinforcement. The main purpose of the matrix in the composite material is to transfer external loads to the reinforcement and to protect the reinforcement from external factors (such as UV radiation or humidity). The properties of a composite material depend not only on the properties of each of its phases, but also on their content and distribution in the material, their geometry, and the manner in which the matrix holds the reinforcement (Blicharski, 2001). Composite materials are classified according to origin, purpose, type of matrix, and type of reinforcement. In terms of origin, there are natural composites (e.g. wood) and composites designed and manufactured by humans (Getme and Patel, 2020). With respect to purpose, composites are classified into construction materials and materials with specific physical or chemical properties. The classification according to the type of reinforcement used in the composite is of particular importance in biomaterials engineering. In this case, composites are classified into fibre-reinforced composites (fabrics, mats, etc.), particle-reinforced composites, and dispersion-reinforced composites (Boczkowska et al., 2000). The oldest and most common type of composite is the polymer matrix composite. The following can be used as the matrix: thermoplastic polymers (polyethylene and polypropylene, which soften when heated); thermosetting polymers, which become networked and hard when heat is applied (phenol resins, novolac resins); and chemically cured polymers, which become networked when exposed to chemical substances (polyester resins, epoxy resins) (Konsztowicz, 1986). Composites are most often reinforced by synthetic fibres (glass, carbon, ceramic, aramid, polypropylene or polyethylene fibres) (Fejdyś and Łandwijt, 2010). Out of concern for the natural environment, the design of natural fibre composites is raising interest as a possible alternative to synthetic fibres. Natural fibres include the following:

- plant fibres (cellulose fibres)
- animal fibres (protein fibres)
- naturally occurring mineral fibres (asbestos)

Fibres of plant origin are obtained from seeds or seed pods (e.g. cotton); leaves (e.g. sisal, agave); stems (e.g. jute, banana, bamboo); or fruits (e.g. coconut). Cotton, flax and hemp fibres are of key importance in industry (Chandramohan and Marimuthu, 2011).

The most common sources of animal fibres (protein fibres) for composites are horse hair, dried insect saliva during cocoon construction (e.g. silk), and bird feathers (Chandramohan and Marimuthu, 2011).

Mineral fibres may occur naturally (the only such mineral fibre is asbestos) or may be procured from minerals (Chandramohan and Marimuthu, 2011).

Sheep wool fibres as a component of composites

Sheep wool is a natural material which, due to its physicochemical properties, can be used as a component of composites. This applies in particular to the wool of sheep raised in mountain regions. These breeds have mixed wool composed of three types of fibre: downy, intermediate, and coarse hair (Kawęcka and Kosiek, 2010). Wool fibres are a multicellular material composed of the epidermis, the cortex, and the medulla (Kawęcka and Kosiek, 2010). The epidermis has three layers:

- the outer layer (epicuticle), consisting of α-amino acids with low chemical activity
- the intermediate layer (exocuticle), composed of non-crystalline keratin
- the inner layer (endocuticle), composed of highly crystalline protein

The main component of fibre, which determines its physicochemical properties, is the cortex, which consists of orthocortical and paracortical cells. These cells are made of keratin, with varying cystine content. In the case of orthocortical cells, keratin contains less cystine and is less extensively cross-linked with disulphide bridges than are paracortical cells. Keratin is also an important element of the hair medulla, which is also composed of a layer of large cells filled with air. Important physicochemical traits of sheep wool for the design of a composite matrix are its thickness, strength (tear resistance), and resilience, which allows the fibre to return to its initial state after being stretched. Today, particularly important qualities of wool include its breathability, fire-resistance (ignition temperature over 550°C), and ability to absorb moisture up to 33% of its weight (Ragaišienė et al., 2016; Molik and Potocka, 2019). As a natural fibre, wool has a thermal conductivity of 0.043 W/mK and thermal resistance/insulating power of 0,0065 Km^2W^{-1}, which makes it useful for designing composites used in the building industry or acoustic insulation (Table 1) (Golański, 2011; Gieremek and Cieśla, 2012; Andrzejewska and Topoliński, 2015; Wasilewska et al., 2017; Kim et al., 2015).

Table 1

Density and thermal conductivity of fibres (Andrzejewska and Topoliński, 2015)

Material	Density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]
Polyamide 6 fibre	1140	0,25
PET fibre	1390	0,14
PP fibre	910	0,12
PE fibre	920	0,34
PVC fibre	1360	0,16
Water	1000	0,58
Wool felt	320	0,047
Wool fibres	1300	0,1924
Air	1,29	0,024

Studies of the thermal conductivity and density of various fibres have shown that sheep wool felt has four times higher heat insulation capacity than the best polypropylene fibres and easily adheres to polymers. It is worth noting that felt is three times less dense than the commonly used non-woven polypropylene, so that its actual thermal conductivity is nine times lower (Andrzejewska and Topoliński, 2015; Akcagun et al., 2017; Wasilewska et al., 2017).

Due to the physicochemical characteristics of natural fibres (strength, elongation at break, and elasticity modulus), fibre-reinforced composites are being used on an increasingly wide scale in sectors such as transport (automobiles and aviation) and the military, building, and packaging industries (Chandramohan and Marimuthu, 2011; Pach and Mayer, 2010; Ragaišienė et al., 2016) (Table 2).

Table 2

Comparison of physicochemical properties of natural and glass fibres (Pach and Mayer, 2010, Kim et al. 2015)

Fibres	Strength [MPa]	Elongation at break [%]	Elasticity modulus [MPa]
Cotton	264-654	3,0-7,0	4980-10920
Wool	120-174	25-35	2340-3420
Silk	252-528	20-25	7320-11220
Flax	300-900	2,7-3,2	24000
Jute	342-672	1,7-1,8	43800
Sisal	444-552	2,0-2,5	-
Ramie	348-816	3,6-3,8	53400
Glass fibre	4800	1,8-3,2	86000

A comparison of the properties of natural fibres, including wool, shows that their strength varies widely from 120 MPa for wool to 900 MPa for flax. In comparison to synthetic fibres (e.g. glass fibre, which has a strength of 4800 MPa), these values might seem very low. However, it should be noted that natural fibres, including wool, are 2,5 times lighter than glass fibres, which translates into more favourable specific strength (ratio of absolute strength to material density). This comparison of parameters shows that the specific strength of flax is similar to that of glass fibre. The value of the strength of plant fibres is influenced most by their cellulose content, and especially by the length of the biochemical chain and the phase in which cellulose is present in the fibre. In the case of wool, the high fibre strength value is dependent on the quality of keratin, a protein found in the intermediate and inner layer of the hair (Pach and Mayer, 2010; Kim et al., 2015; Bledzki and Gassan, 1999). Elasticity moduli in natural fibres depend mostly on mechanical strength, whereas larger Young's moduli are observed in fibres with a higher content of crystalline phases.

Biodegradable matrices used in composites

Continuing interest in plastic materials and products, such as packaging, engineering plastics and synthetic fibres, coupled with concern for the natural environment, drives the search for biodegradable composites (Mucha, 2002, Kaczmar and Pach, 2006). It is important to replace non-degradable polymers with biodegradable polymers. Natural polymers are materials obtained from naturally occurring organisms. They can be divided into three groups: polysaccharides (e.g. starch, chitin, and cellulose), polypeptides and proteins (e.g. keratin, elastin, and collagen), and nucleic acids (DNA and RNA) (Azwa et al., 2013; Andrzejewska and Topoliński, 2015; Lewandowska and Sionkowska, 2016). Synthetic polymers, which are obtained in controlled chemical reactions, include polyglycolic acid, polylactic acid and polyaspartic acid (Andrzejewska and Topoliński, 2015). Polylactic acid is an important element of composites. It is a thermoplastic, biodegradable aliphatic polyester which makes up 40% of biodegradable plastics (Andrzejewska and Topoliński, 2015). Its natural monomer, lactic acid, is produced by biological synthesis from starch or by chemical synthesis from renewable feedstocks (acetaldehyde or ethanol), semi-finished products from carbon (acetylene), or petroleum (Lewandowska and Sionkowska, 2016; Latos and Masek, 2017). Polylactic acid is found in two forms: non-transparent crystalline or transparent amorphous (Andrzejewska and Topoliński, 2015). It contains an ester group, which makes it susceptible to the action of microorganisms and hydrolysis. Its degradation involves chain breakage at the ester bond, resulting in monomeric hydroxy acids (Mucha, 2002). Due to physicochemical properties similar to those of plastics commonly used in industry and to its biodegradability, polylactide (PLA) is becoming increasingly popular. It is transparent, rigid (a disadvantage when used for wrap), and easy to mould in technological processes (Mukherjee and Kao, 2011). A major disadvantage, however, is its high density (about 1,25 g/cm^3) and high polarity, which limits its applications (Lewandowska and Sionkowska, 2016). Nevertheless, the good mechanical properties and exceptional barrier properties of PLA make it suitable for producing composites performing specific functions. It should be borne in mind, however, that biodegradable polymers, including PLA, have drawbacks as well. These include fragility and susceptibility to the effects of water, which may trigger the hydrolysis process, thereby shortening the main PLA chain and reducing dynamic strength, i.e. impact resistance (due to the high crystallinity of the polymer itself). These shortcomings (mainly the lack of impact resistance) can be eliminated by adding fibres or natural fillers to PLA matrices, which is a convenient way to improve the overall properties of biodegradable polymers, including PLA (Qin et al., 2011; Mukherjee and Kao, 2011; Pilip et al., 2012; Getme and Patel, 2020). The use of a biodegradable polymer matrix with natural fibre reinforcements makes it possible to obtain biodegradable composites, also known as biocomposites, which have no adverse effect on the environment. They can be used in 3D printing or as a component of surgical sutures, insulation mats or packaging for medical purposes. Sheep wool is a natural fibre that can be used to reinforce PLA. In the available literature, most studies on natural fibres have been performed on plant fibres, which reinforce the composite. The use of wool fibre as a reinforcement in the composite may increase the mechanical properties of biodegradable composites, which are safe for the environment. In Poland, the production of a composite with wool fibre elements will make it possible to exploit wool from sheep, especially breeds in mountain areas.

CONCLUSION

Since the dramatic decline in the sheep population in Poland in the 1990s, sheep wool has been a difficult product to make use of. Sheep farmers in mountain areas find it particularly difficult to sell wool because of its thickness and grade (average hair thickness of 50-70 μm on average) (Kawęcka and Kosiek, 2010). Innovative application of wool as a composite element provides a good opportunity. Composites with only natural phases (wool fibre/ biodegradable matrix) are not subject to the Waste Act and can be decomposed in compost bins. In a landfill, they will eventually be reduced to H_2O and CO_2. Therefore, wool, as a fibre with unique physicochemical properties, can be used as an element of composite materials, in line with the strategies of bioeconomy and sustainable development. A search for alternative solutions making use of mixed wool could support sheep farming.

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