Chapter

Biodegradation of Sheep Wool Geotextiles Designed for Erosion Control

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Abstract

Wool geotextiles were formed from the meandrically arranged thick ropes and used as erosion control products. The geotextiles were installed in the experimental sites to protect the endangered slopes and the bank of ditches. Additionally, as a reinforcement of the soil, loose wool fibres were applied. The progress of wool biodegradation on the slope was investigated. Changes in the outer appearance, mechanical parameters, molecular structure and fibre morphology were analysed. Moreover, the nitrogen content in the soil and the effect of compounds released into soil on the grass growth were studied. The measurements revealed that the biodegradation starts at the cleavage of disulphide bonds, followed by disruption of the peptide bonds. Degradation is initiated in the outer cuticle and is followed by the decomposition of the inner cortical cells. During biodegradation, the nitrogen-rich compounds are released. The compounds act as an effective fertiliser which supports the growth of grass and significantly accelerates the greening of the slope.

Keywords: wool, geotextiles, erosion control, biodegradation, enzymes

1. Introduction

Sheep wool belongs to the oldest known natural fibres. The history of wool application coincides with the history of mankind. In many countries wool is highly valued, and manufacturing of wool products has a very long tradition.

For a long time, wool has been used for production of apparel textiles. Fine fibres have been used to manufacture high-quality fabric for luxury clothing. Coarser fibres were used to produce yarns used for knitting the traditional wool products. Coarser wool has been also successfully used for production of blankets, carpets and other interior textiles.

In the recent years, apart from the traditional products available on the market, new wool technical textiles appeared [1, 2]. Among them the most popular are acoustic and thermal materials used in the construction industry for insulation of pitched roofs, walls and ceilings [3–8]. For commercial application, also wool oil sorbents [9, 10], heavy metal-absorbing materials [11, 12] and geotextiles [13] are used.

Wool geotextiles include mats or blankets spread out on the ground and products which are buried in the soil. The mats are used to protect grass seeds in the ground. Due to wool's natural ability to regulate the temperature, mats create the proper microclimate for seed germination and, later, ensure favourable conditions for plant growth. The geotextiles buried in the soil are used in agriculture as plant fertilisers and materials to improve moisture retention [14]. Some products are applied as erosion control materials to protect unstable slopes and embankments [15, 16].

Wool geotextiles do not have a great global significance. The vast majority of geotextiles is produced from synthetic polymers and various biodegradable, natural materials. There are also products manufactured from the cellulosic fibres, mostly jute and coir [17].

In some cases, using wool for production of the geotextiles is reasonable and economically justified. As the product inseparably connected with sheep breeding, wool is available locally. Sometimes, due to low demand from the textile industry, the fibres are not further processed. There are attempts to use wool in agriculture as a nutrient promoting the plant growth [18–21] and organic nitrogen fertiliser [22], or it is mixed with clay to obtain environmentally friendly earthen construction materials [23–25]. However, these attempts are not always effective. Thus production of the wool geotextiles is a reasonable alternative, especially in the case of poor-quality wool treated as waste and a troublesome by-product of sheep breeding.

The geotextiles are exploited in contact with the soil in a humid environment. In such circumstances they are affected by the microorganisms naturally present in the soil. Microorganisms, both fungi and bacteria, secrete the extracellular enzymes which process the wool as a source of carbon, nitrogen and sulphur [26–28]. As a result, the wool is subject to gradual biodegradation. This process leads to the loss of mechanical strength and deterioration of the geotextile properties.

The biodegradation of geotextiles depends on the wool characteristic, product parameters and several environmental factors.

Sheep wool belongs to the group of the proteinaceous fibres which are built from the proteins formed by condensation of L-α-amino acids. A single fibre is composed from approximately 82% of keratinous proteins with high concentration of cystine and 17% of nonkeratinous proteins with a relatively low cystine content. Additionally, the wool contains approximately 1% by mass of non-proteinaceous material, mainly waxy lipids and polysaccharides [29].

A significant portion of the protein chains occur in the form of α-helix and form a compact structure of α-keratin, stabilised with different covalent and noncovalent bonds. The main bonds responsible for keratin stabilisation are disulphide bonds of cystine. The bonds form the intermolecular cross-links between different protein chains as well as intramolecular connections between different parts of the same protein chains. In addition to the disulphide bonds, the keratin structure is stabilised by the isopeptide linkages formed between the amino groups of lysine and carboxyl groups of aspartic or glutamic acid as well as by numerous noncovalent interactions: ionic bonds, hydrogen bonds and hydrophobic interactions.

The biodegradation of keratin is a two-stage process. In the first stage, the major part of the disulphide bonds, which prevent the protein-hydrolysing enzymes from accessing the peptide bonds, is broken. Then, keratin is hydrolysed by extracellular proteases, and the peptide bonds are disrupted. As a result, the soluble peptides which are further hydrolysed to particular amino acids are released. According to Kunert, the biodegradation caused by the fungus includes sulfitolysis and proteolysis [30, 31]. During sulfitolysis the disulphide bonds between polypeptide keratin chains cleave to S-sulfocysteine, and cysteine occurs. The reaction takes place under the alkaline conditions in the presence of inorganic sulphite produced by the fungus [32]. Sulfitolysis entails protein denaturation which facilitates the attack of keratinolytic proteases. As a result of protease activity, the denatured keratin proteins undergo proteolysis during which the peptide bonds are disrupted. Consequently, the simpler proteins, individual amino acids and ammonia, are released. According to Yamamura, in the first stage of degradation caused by the bacterium, the disulphide bonds get reduced by the disulphite reductase-like protein. The denatured keratin formed in the first stage is later decomposed by protease. Finally, the soluble products, peptides and/or amino acids, are released [33].

Wool fibres have complex morphology and consist of the outer layer of cuticle cells surrounding the inner cortex.

The cuticle cells consist of approximately 10% of the fibre weight. The flattened cells form the external layer and the characteristic scales on the fibre surface. The subsequent scales overlap in the longitudinal direction like tiles on a roof, with the edge pointing from the root to the tip of the fibre. The degree of overlap is about one-sixth of the length of the cuticle cells. For fine wool, except places where two cells overlap, the cuticle is normally one cell thick. In coarse fibres, the cuticle is thicker and consists of up to 15 layers of cells. Cuticle cells in fine wool range in thickness from 0.3 to 0.5 μm, while their length and width are about 30 μm and 20 μm, respectively [34].

The cuticle has a higher cystine content than the whole wool and is rich in cystic acid, serine, proline, glycine and valine [35]. The amino acids present in the cuticle belong to non-helix-forming amino acids which do not promote the formation of the α-helical structure. As a result, the cuticle structure is more amorphous than in the rest of the fibre.

The cuticle cells are composed of two distinct major layers: the outer exocuticle and the inner endocuticle. The exocuticle is the layer around 0.3 μm thick and represents approximately 60% of the total cuticle cell. The outer part of the exocuticle consists of a dense layer called the A layer. The exocuticle extends partly around the scale edges and contains the major amount of the cystine occurring in the cuticle. The endocuticle is around 0.2 μm thick and exhibits low cystine content, has a relatively low disulphide cross-link density and is classified as one of the nonkeratinous components of the fibre. The low cystine content makes the endocuticle more susceptible to chemical or enzymatic attack.

Individual cuticle cells are surrounded by a thin membrane called the epicuticle. The epicuticle is approximately 2–7 nm thick and is part of the resistant membrane system which surrounds all cuticle and cortical cells. The surface of the epicuticle is covered by a thin layer of a complex mixture of polar and non-polar lipids with long-chain fatty acids [36, 37]. The lipids are covalently bonded via the ester or thioester linkages and are responsible for the hydrophobic character of the surface of the wool fibres.

The cortical cells comprise the main bulk of almost 90% of the wool fibre. The long and spindle-shaped cortical cells are approximately 100 μm long and 3–6 μm wide. The cells are closely packed and oriented parallel to the fibre axis. The cells are composed of rod-like elements of crystalline proteins called intermediate filaments (microfibrils) embedded in an amorphous matrix. The intermediate filaments have the diameter of 7 nm and are built from the protofibrils formed by coiled coils of two or three α-helices of individual protein molecules. Simultaneously, the intermediate filaments are grouped together into the larger cylindrical units, the so-called macrofibrils with the diameter of about 0.3 μm [38].

The cuticle and the cortical cells are separated by the cell membrane complex (CMC). The CMC forms continuous network and provides adhesion between the particular cells. The membrane accounts for approximately 3.5% of the fibre, and its thickness is around 25 nm. The CMC is built from adhesive material that binds the cuticle and cortical cells together and consists of the central δ layer approximately 15 nm thick sandwiched by the two lipid layers called β-layers, each about 5 nm thick [39].

Due to various composition and cystine content, certain morphological elements exhibit various resistance to enzymes. Each part the biodegradation rate is different.

Based on the investigations on human hair which exhibits similar structure and morphology, various mechanisms for keratinous fibre degradation were proposed.

According to Kunert, degradation is initiated in the intercellular space in the cuticle. Degradation of the cell membrane complex is accompanied by the invasion of enzymes into the endocuticle. After the dissolution of the cell membrane complex, the individual cuticle cells are released and then gradually detached from one another. In the next step, the other parts of cuticle are slowly degraded. In the cortical layer, degradation starts in the intercellular spaces and progresses towards the keratin located between the macrofibrils. As a result, the separation of macrofibrils is observed. The separation is followed by the gradual degradation of macrofibrils, both from the surface and from the centre of the bundle. During the next stage, a gradual separation of individual microfibrils occurs [40, 41].

According to Wilson, degradation occurs in a predictable sequence, dependent on the composition and, hence, relative resistance of the hair structural elements to degradation by microorganisms. Degradation starts with the decomposition of cystine-poor components in both the cuticle and cortical cells. In the cuticle cells, the structural breakdown takes place in accordance to the sequence: cell membrane δ-layer, endocuticle, cell membrane β-layers, exocuticle, epicuticle and A layer. In the cortical cells, decomposition occurs as follows: cell membrane δ-layer, cell membrane α-layers, intermacrofibrillar matrix, microfibrils and intermicrofibrillar matrix [42].

According to Filipello Marchisio, biodegradation caused by fungi takes place in two possible mechanisms. The first mechanism, the so-called surface erosion, involves gradual destruction of the fibre from the external cuticle inwards to the cortical layer. According to this mechanism, the δ-layer of the cell membrane is attacked first. Then, the process continues by invading the hyphae under the scales. The hyphae lift up the cuticle and then secrete enzymes which digest the scales, starting from the cystine-poor endocuticle. In the next stage, the β-layers of cell membrane complex are digested, which is followed by destruction of the remaining cuticle layers. Then, the fungal hyphae attack the outer layers of the cortical cells. In this case, digestion appears to progress more rapidly. The cortex loses its compact structure, and the cells and macrofibrillar bundles of keratin become separated.

The second mechanism, called the radial penetration, involves random attack by variously specialised fungal hyphae which penetrate the fibre perpendicular to its surface. As a result, deep holes with a small diameter axis are formed [43, 44]. DeGaetano revealed that the holes exhibit minimal branching and their openings are placed under the scale edges or directly on the scale surface [45].

As for the product parameters, water absorption capacity is of a great importance for the course of wool biodegradation. For wool nonwovens, due to their porous structure with numerous open pores in the micron and submicron scales, water retention capacity reaches high values. Contrary to the woven and knitted fabrics, the porous structure geometry in the nonwovens is less uniform and is characterised by a greater distribution of pore size. The amount of absorbed water can be several times greater than the weight of the dry product. The water absorbed inside the nonwovens is stored for several days and then is slowly released into the environment. Persistent high humidity promotes the development of microorganisms, what significantly accelerates the biodegradation processes [46].

The most influential environmental factors include geographical location, ultraviolet exposure, temperature and humidity [47, 48]. Solazzo revealed that deterioration of textiles is dependent on the burial conditions, soil composition, pH, temperature, oxygen content and contact with wood coffins and metals [49].

Previous investigations on the biodegradation of wool in the soil focused on archaeological textiles [50, 51]. The literature lacks information on the biodegradation of the contemporary used wool geotextiles.

The chapter presents the results of investigations on the biodegradation of the wool geotextiles designed for erosion control. The geotextiles were installed in some experimental sites, and their biodegradation during 2 years of operation was studied.

2. Materials and methods

2.1 Materials

The locally available wool fibres with the length between 8 and 13 cm and the diameter between 25 and 32 μm sheared from the Polish mountain sheep were applied. Scoured fibres were used to produce a needle-punched nonwoven. The nonwoven was manufactured in industrial conditions by interlocking the wool carded web by means of the one-side needling machine operated from above with the punching density of 70 cm^{-2}. The product was the nonwoven with the thickness of 5.8 mm and the mass of 406 g/m^2.

The nonwoven strips were used for production of thick ropes with the diameter of 12 cm. The ropes were manufactured with the Kemafil machine [52]. The rope cores, made from densely packed wool nonwoven, were wrapped with a sheath made from cotton or thin polypropylene twine with the linear density of 240 tex.

The ropes were arranged in a meander-like pattern. Segments with the width of 2 m and the length adjusted to the length of the slope were prepared. In each segment, the subsequent turns of ropes were connected with five regularly spaced links. The polypropylene three-wire twine from fibrillated fibres with the linear density of 10 g/m was used for linking.

One slope was protected with the ropes made from a mixture of recycled fibres. The ropes installed on the slope were covered with the soil mixed with wool fibres. Mixtures of soil containing 0.25, 0.5 and 1% of wool in relation to dry soil weight were used.

2.2 Methods

During exploitation of the geotextiles, the behaviour of slopes was regularly monitored. The development of vegetation, density of the green cover as well as its colour were visually evaluated. Simultaneously, the external appearance of the ropes and the nonwovens was evaluated organoleptically. Periodically, the samples of geotextiles from randomly selected locations were taken for laboratory tests. Before examinations the samples were dried at room temperature and then mechanically cleaned from plant roots and soil particles. During the examinations the mechanical parameters of the nonwoven were determined. The tensile strength and elongation at break were measured in accordance with the Polish standard PN-EN ISO 10319:2010 [53]. The measurements were carried out along and across the nonwoven by means of the KS50 Hounsfield tensile machine equipped with the wide jaws. The static puncture resistance was determined by the California bearing ratio (CBR) test, in accordance with the Polish standard PN-EN ISO 12236:2006 [54]. The dynamic puncture resistance was measured using the cone drop test, in accordance with the Polish standard PN-EN ISO 13433:2006 [55].

The fibre morphology was studied by means of the scanning electron microscopy (SEM). A scanning electron microscope JEOL JSM 5500 LV was applied. The microscope was operated in the backscattered electron mode. Prior to observations, the fibres were sputtered with gold in JEOL JFC 1200 ionic sputter.

The chemical composition of wool keratin was analysed using the Fourier-transform infrared spectroscopy (FTIR). The FTIR spectrometer Nicolet 6700 equipped with a mirror beam collimator was applied. The measurements were carried out for tablets formed from the chopped fibres blended with powdered sodium chlorine NaCl. The spectra were registered in the range from 400 to 4000 cm^{-1}. During the analysis, the spectra were smoothed with the OMNIC software and normalised against the peak intensity. The band at 1451 cm^{-1} corresponding to CH_2 group was chosen for normalisation.

During the investigations, the nitrogen content in the soil was measured. The content of organic, ammonium (NH^{4+}), nitrite (NO^{2-}), nitrate (NO^{3-}) as well as Kjeldahl and total nitrogen was determined. The measurements were performed according to the Polish standards: PN-ISO 7150-1:2002, PN-73C-04576:2006, PN-82C-04576:1982 and PN-EN 25663:2001 [56–59].

2.3 Installation sites

The wool fibres and wool geotextiles were installed in four experimental sites situated in Bielsko-Biala and surroundings. All sites were located in southern Poland, the temperate climate zone.

In the preliminary research, the samples of ropes made from the wool nonwoven were buried in the experimental site located in the university campus. Then, the geotextiles formed from the meandrically arranged thick ropes were used for the renovation of the bank of the drainage ditch damaged by water surface erosion. In further investigations, the similar wool geotextiles were used for stabilisation of steep slope prone to sliding in the abandoned gravel pit. In both places, the segments of geotextiles were spread on the surface of the slopes and anchored to the slopes with metal "U-shape" pins. Finally, the geotextiles were covered with a layer of topsoil (**Figure 1**).

In recent examinations, geotextiles made from the recycled fibres were applied for protection of a steep slope exposed to intensive rill erosion. The slope was

a b

Figure 1.
Installation of the geotextiles, (a) bank of the drainage ditch in Miedzyrzecze, (b) slope in the abandoned gravel pit in Nieboczowy.

a b

Figure 2.
Installation of the geotextiles in Lipnik, (a) mixing fibres with the soil, (b) the geotextiles covered with a layer of soil mixed with fibres.

Site	Bielsko-Biala (B-B)	Miedzyrzecze (M)	Nieboczowy (N)	Lipnik (L)
Product form	Ropes	Ropes	Ropes	Fibres
Object	Experimental flat plot	Bank of the drainage ditch damaged by erosion	Unstable slope in the abandoned gravel pit	Slope between terraces damaged by erosion
Inclination	Flat	1:1.5	1:1.8	1:1.5
Length	—	6 m	5 m	5.5 m
Installation time	October 2014	May 2015	February 2016	April 2017
Covering soil	Sandy silty clay	Clay of low plasticity	Clay of high plasticity	Clay of low plasticity
pH	7.2	7.1	7.0	7.0
Seeding	Yes	No	No	Yes

Table 1.
Experimental sites and their characteristics

located between flat terraces artificially formed on a gently sloping hill. In this case, the geotextiles were covered with soil reinforced with loose wool fibres (**Figure 2**).

In two locations (Bielsko-Biala and Lipnik), the grass seeds were sown on the installed geotextiles. The seed was a commercial mixture of perennial ryegrass (*Lolium perenne*), commonly used for slope stabilisation.

Basic characteristic of the experimental sites is presented in **Table 1**. More details concerning the site characteristic and installation procedure were presented in the previous publications [60–65].

3. Results

3.1 Slope greening

In site B-B, the samples of ropes were buried in the ground in autumn. In the spring, with the beginning of the vegetation season, the growth of grass was initiated. After a few weeks, the plot was covered with green. In places where wool ropes were buried, the grass was higher and dark green (**Figure 3a**).

In site M, the geotextiles were installed in late spring. In the first year, during the whole vegetation season, rare and miserable self-sown plants appeared on the bank. In the following vegetation season, the ditch bank was covered with high and dense cover consisting of a mixture of grasses and various local herbaceous plants. The plants had an intense dark green colour, much darker compared to the plants grown in other parts of the bank (**Figure 3b**).

In site N, the rope segments were installed at the end of the winter season. In the early spring, first sparse seedlings of local species appeared on the slope. Then, in the following summer weeks, the slope was covered with a dense green cover of grasses and other local herbaceous plants (**Figure 3c**). Next year the slope became green and covered with lush vegetation. The plants reached the high altitude and formed a very dense, uniform cover on the whole surface of the slope. In comparison to the previous year, the vegetation cover was much denser. Apart from the species observed in the previous season, more than 20 other species were identified.

In site L, the geotextiles made from recycled fibres were covered with the soil mixed with wool in the early spring. Shortly after sowing, the quick growth of grass was observed. About 2 months later, the slope was completely greened and

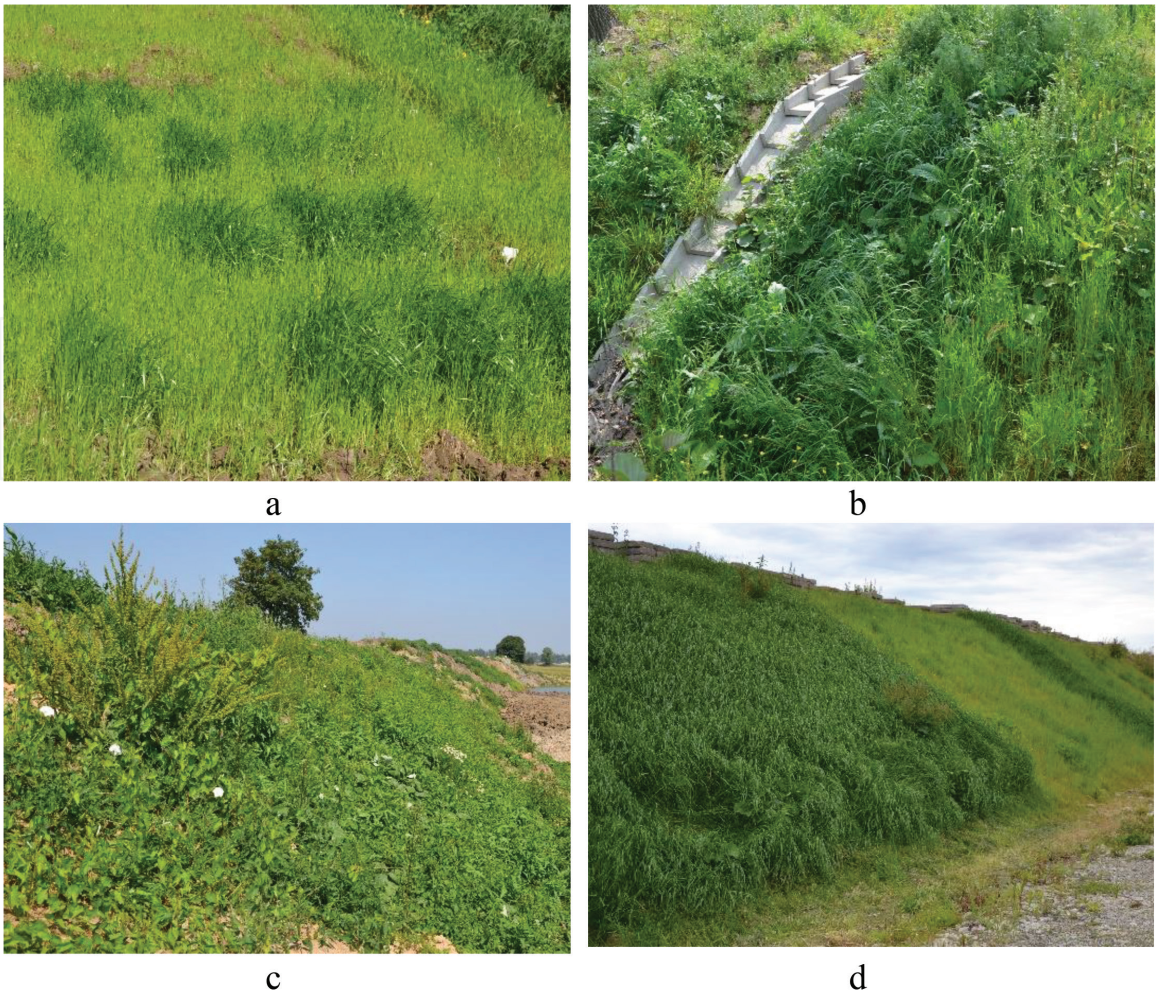


Figure 3.
Influence of wool on slope greening, (a) Bielsko-Biala (6th month), (b) Miedzyrzecze (12th month), (c) Nieboczowy (4th month), (d) Lipnik (3rd month).

	Nitrogen content [mgN/g]					
	Organic	Ammonium NH_4^+	Nitrite NO_2^-	Nitrate NO_3^-	Kjeldahl	Total
1	615	25.2	1.2	0	640	641
2	2481	29.1	1.4	0	2510	2511
3	1396	33.7	1.6	207	1430	1639
4	1338	105.5	2.7	84	1444	1530

1, soil without fibres; 2, soil mixed with wool; 3, soil mixed with wool after 6 months; 4, soil mixed with wool after 12 months

Table 2.
Nitrogen content in the soil mixed with wool used for covering of ropes on the slope in Lipnik

coated with a dense grass cover. The highest and the most dense grass cover with an intense dark green colour appeared in the places protected with the soil mixed with wool (**Figure 3d**).

The ropes were covered with native soil poor in nitrogen compounds. The total nitrogen content in the soil before installation on the slope was low and included mainly nitrogen in an organic form (**Table 2**). Once the wool was added, the nitrogen content in the soil, mainly organic nitrogen, increased by fourfold. After 6 months of using the slope, the organic nitrogen content in the ground decreased by almost a half. At the same time, a slight increase in the content of ammonium nitrogen and a significant increase in nitrate nitrogen were observed. In the second year of exploitation, after 1 year the total nitrogen content in the soil mixed with wool was slightly lower. In this time, the majority of nitrogen occurred in the organic form. The soil also contained a significant amount of ammonium and nitrate form.

3.2 External appearance

In site B-B, after first 12 months of exploitation, the nonwoven did not show external signs of damage. In this time the ropes made from the nonwoven kept their physical permanence. Then, in the following months, the discolorations of wool appeared. The fibres forming the nonwoven became fragile, and the nonwoven could easily be torn in hands.

In site M, the first visible signs of degradation were observed after 1 year of exploitation. Serious damage of the nonwoven was revealed in many places on the bank. Plenty of gnawing holes, discolorations and numerous signs of rotting were visible in the nonwoven. In some places only the rotten remnants of the nonwoven were found. After 18 months the nonwoven completely lost its mechanical integrity.

In site N, there were no visible signs of damage of the nonwoven during the first year. The ropes maintained their shape and mechanical integrity. After 18 months, under the weight of the covering soil, the previously round ropes became flat. Simultaneously, in the nonwoven forming the outer layer of the ropes, small gnawing holes appeared.

In site L, shortly after mixing wool with the soil, the fibres became fragile. Few weeks after introducing into the soil, the destruction of fibres was already strongly advanced. After 6 months only short and broken remnants of the fibres were visible.

3.3 Mechanical parameters

Table 3 presents basic mechanical parameters: tenacity and elongation at break of wool nonwovens before installation and after several months of exploitation in the ground.

For the ropes buried in the site B-B, the tenacity of the nonwoven decreased by 51% after 6 months. After 12 months the reduction of the nonwoven tenacity reached 95%. At the beginning the elongation did not change, and then, after 12 months, it decreased by 58%. For the ropes buried in the ground for a longer time, the nonwoven was easily torn in hands, so it was impossible to measure its strength.

For the geotextiles installed in the site M, during first 6 months, the tenacity decreased by 28%. In the months that followed, the reduction of the nonwoven

Site	Months	Tenacity [kN/m]	Elongation at break [%]
—	0	0.67 ± 0.1	40 ± 3
Bielsko-Biała	6	0.34 ± 0.01	39 ± 3
	12	0.04 ± 0.01	17 ± 3
Miedzyrzecze	6	0.48 ± 0.02	28 ± 2
	12	0.05 ± 0.01	24 ± 2
Nieboczowy	6	0.62 ± 0.01	33 ± 3
	12	0.40 ± 0.01	31 ± 3
	18	0.07 ± 0.01	39 ± 3

Table 3.
Mechanical parameters of the wool nonwoven exploited on slopes

Site	Months	Puncture resistance	
		Static [kN]	Dynamic [mm]
—	0	0.16 ± 0.01	32 ± 0.5
Bielsko-Biała	6	0.02 ± 0.01	30 ± 0.5
	12	—	—
Miedzyrzecze	6	0.04 ± 0.01	38 ± 1
	12	—	—
Nieboczowy	6	0.09 ± 0.01	36 ± 3
	12	0.06 ± 0.01	38 ± 1
	18	0.07 ± 0.01	39 ± 1

Table 4.
Puncture resistance of wool nonwoven after exploitation on the slopes

tenacity was much higher and reached 93% after 1 year of exploitation. The reduction of the nonwoven tenacity was connected with the decrease of the elongation, 30 and 40% after 6 and 12 months, respectively. Similarly to the samples taken in site B-B, the nonwoven exploited for a longer time disintegrated easily in hands, and it was impossible to measure its strength.

For the samples exploited in the site N, the reduction of the nonwoven tenacity was relatively small in the first period and after first 6 months equalled to only 7%. Another 6 months later, it exceeded 35%. During the months that followed, a rapid drop of the nonwoven strength was detected. After 18 months the tenacity reached the minimal value which was 85% lower than the value measured for nonwoven taken after 1 year. The reduction of the nonwoven tenacity was connected with the increase of the elongation at break. The extreme increase of the elongation was observed for the nonwovens exploited in the soil for 18 months.

Table 4 presents the values of static and dynamic puncture resistance measured for the nonwovens before installation and after several months of exploitation in the ground.

Puncture resistance illustrate the resistance of the nonwovens to multidirectional loads. The measurement of static resistance simulates the pressure exerted by roots or stones onto the geotextiles lying on the ground. The test involves pushing a plunger through a flat specimen, while the penetration force is measured. The dynamic resistance measurements imitate dropping sharp stones onto the geotextile surface. The test involves dropping of steel cones from a fixed height while the hole diameter is measured.

The static puncture resistance of the nonwovens in two sites, B-B and M, reduced drastically by 88 and 75% already after 6 months of exploitation. In the same time, the dynamic puncture resistance for the specimen taken in B-B remained at the same level and for the specimen in M—increased by 19%. During further exploitation the nonwoven was weakened, and after 12 months of measuring, the puncture resistance was impossible.

As for the nonwoven exploited in the site N, the reduction of the puncture resistance occurred gradually over time and much less rapidly than in the previous sites. After 6 months, the penetration force—as the measure of the static puncture resistance—dropped by 44%. Then, after 12 months, the force decreased by 63% and remained at the same level even after 18 months of exploitation. Similarly, the dynamic puncture resistance changed during the first 6 months by 13%. After 12 months, the measure of the dynamic puncture resistance changed by 19% and remained at this level until 18 months passed.

3.4 Fibre morphology

On the surface of the raw wool fibres, the characteristic scales with smooth surface and sharp edges were visible. In the samples taken in the site B-B, irregular cracks appeared in many places on the surface of scales already after 1 month of exposure in the soil (**Figure 4a**).

Simultaneously, the erosion of the scale edges began. As the destruction progressed, after 6 months the scales became barely visible. In the next months, the outer cuticle layer was completely destroyed. Then, the particular macrofibrils with the diameter of few microns, parallel to the fibres axis, became visible. After 9 months, the macrofibrils still adhered tightly to one another. Later, after 12 months, the macrofibrils were more separated. After longer period of soil exposition, the microphotographs showed microorganisms digesting the wool structure. The microorganisms possessed relatively big dimensions and adhered locally to the fibre surface (**Figure 4b**).

In the fibre samples extracted in the site M after 6 months, the outer cuticle layer was heavily damaged (**Figure 5a**). In many fibres the scale edges were completely eroded, and their surface was partially removed. On some fibres transverse fractures or longitudinal cracks were visible. As a result of the mechanical damage, the outer cuticle was torn in some fibres. The cracks in the cuticle enabled quick enzymatic penetration, what led to the rapid fibrillization of the fibres. Surface of the fibres taken after 12 months was colonised by numerous fine microorganisms. The microorganisms

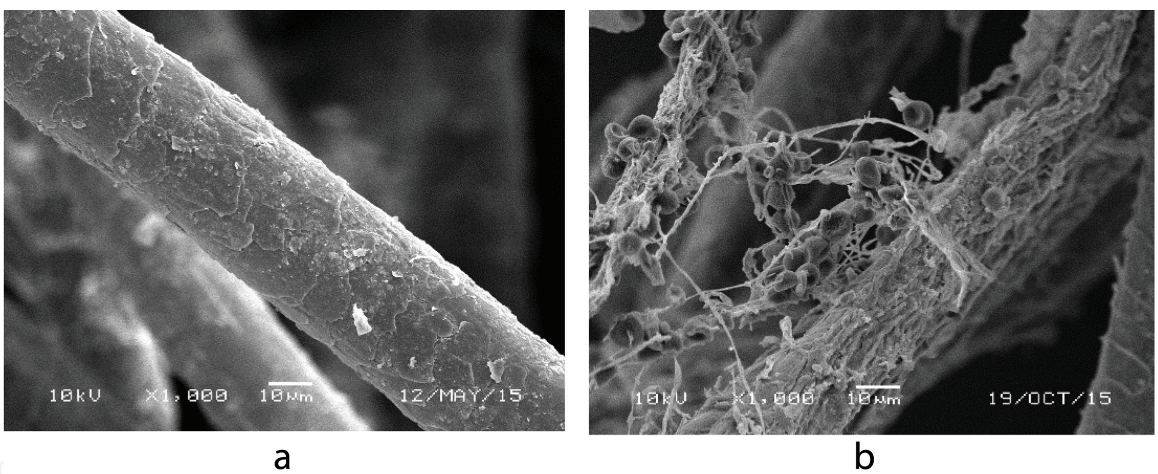


Figure 4.
Morphology of wool taken in Bielsko-Biala after (a) 6 months and (b) 12 months.

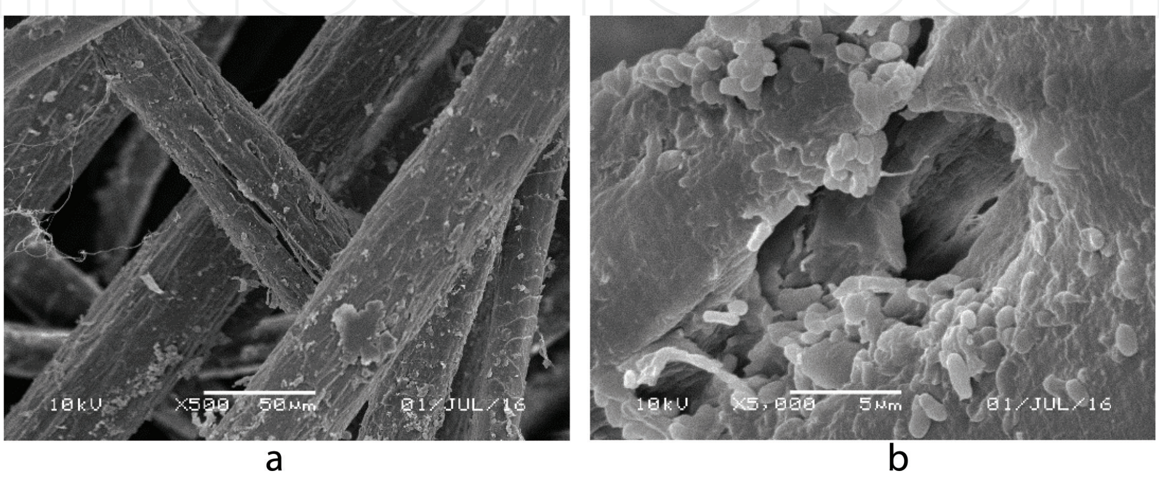


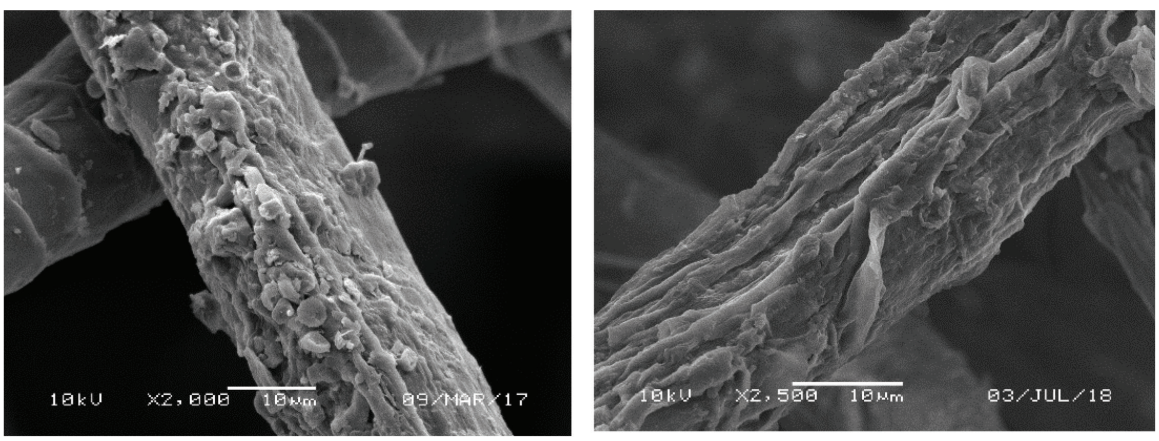
Figure 5.
Morphology of wool taken in Miedzyrzecze after (a) 6 months and (b) 12 months.

formed large colonies which covered almost the whole fibre surface. In fibres extracted after 12 months, the outer cuticle layer was completely destroyed. The scales were no longer visible, and, in many places, the inner fibrillar structure of the core was exposed. The fibres had many deep and widespread gnawed cavities (**Figure 5b**).

Unlike the previous sites, the wool taken from the site N after 6 months still has well visible scales. The significant changes in fibre morphology were observed after 1 year. The scales of all the fibres were barely visible, and the continuous protective thin layer covering the scales was completely destroyed. After 1 year some fibres were colonised with big colonies of microorganisms. The microorganisms formed a thick layer on many fibres, which occupied almost the whole fibre surface (**Figure 6a**).

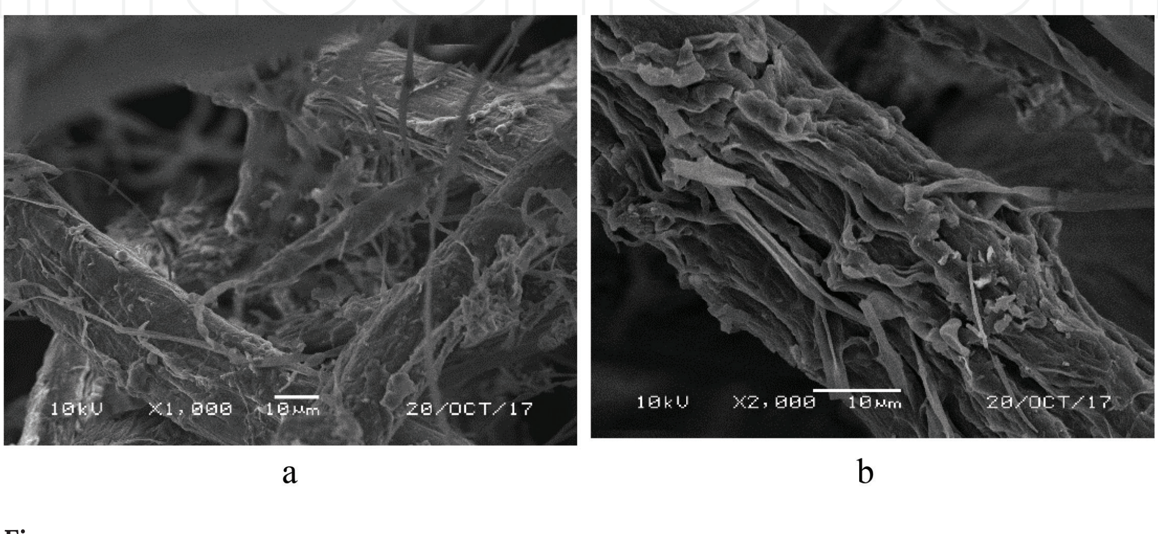
In the fibres inhabited by microorganisms, large cavities penetrating deep inside the fibres were formed. About 18 months after the installation, the scales in almost all the fibres were completely removed, and the inner parts of the fibres were exposed. In many fibres, loosely connected separated fibrils were revealed (**Figure 6b**).

The fibres in the site L showed numerous signs of mechanical and biological damage already after 2 months. Mechanically damaged fibres were cracked, broken or frayed. The scales of many fibres were greatly damaged or even completely destroyed (**Figure 7a**). The deeper layered fragments forming the cortex layer were visible. After 6 months the majority of the fibres showed an advanced stage of fibrillization (**Figure 7b**). Large fragments of many fibres were missing. After 12 months the fibres were totally destroyed, and only fragmentary remnants of fibres could be found.



a b

Figure 6.
Samples of wool geotextiles taken in Nieboczowy after (a) 12 months and (b) 24 months.



a b

Figure 7.
Samples of wool geotextiles taken in Lipnik after (a) 2 months and (b) 6 months.

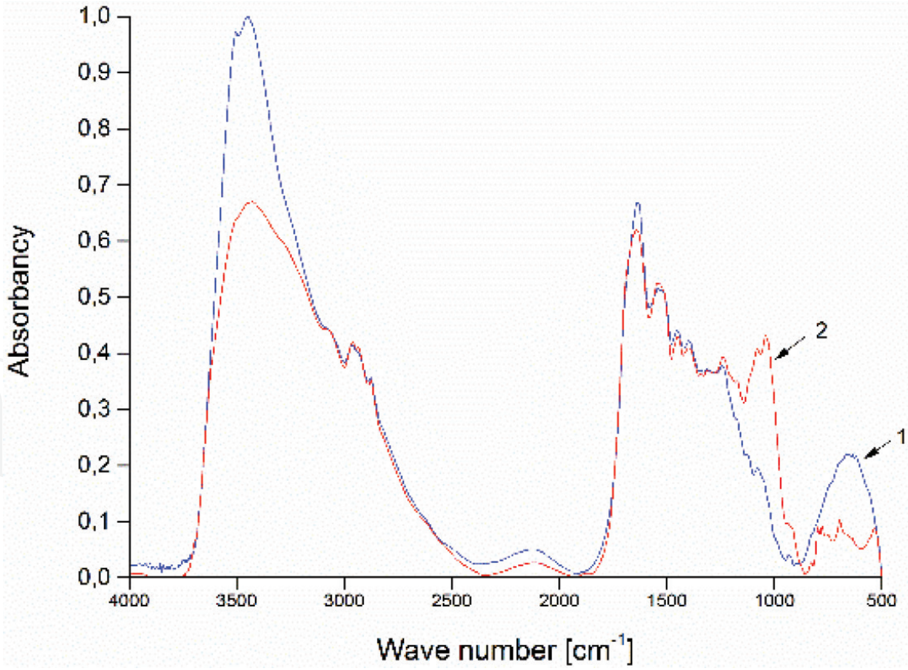


Figure 8.
FTIR spectra of wool used for mixing with soil to protect the slope in Lipnik; (1) raw fibres; (2) after 6 months.

3.5 Chemical structure

The FTIR spectra of all the investigated fibres showed typical bands assigned to the peptide bonds in the amide region. For the raw fibres, before installation of the geotextiles in the soil, strong amide I, II and III bands occurred at 1657 cm^{-1}, 1556 cm^{-1} and 1244 cm^{-1}, respectively. In the sulphoxide region at 1073 cm^{-1}, the band corresponding to S=O bond was observed. For the raw wool, the band possessed low intensity and was poorly visible.

The position and intensity of the amide bands did not change during the first 6 months of exploitation on slopes in three sites: B-B, M and N. The gradual reduction in the amide band intensity was noticed after 12 months. The specimens taken from the site N recorded a lower reduction of the band intensity. Simultaneously, with the decrease of the amide band intensity after 6 and 12 months, the increase of the intensity of the S=O peak was observed.

The fibres mixed with soil in the site L showed no change of the amide band intensity during the first 6 months. At the same time, the intensity of the S=O peak was considerably greater (**Figure 8**).

4. Discussion

Wool biodegradation was caused by the enzymes secreted by the microorganisms in the soil. On the molecular level, the enzymes first attacked the disulphide bonds of cystine. At the beginning, few weeks after installation of the geotextiles in the soil, disruption of the disulphide bonds occurred mostly in outer cuticle cells. Initially, the sharp edges of the scales eroded, and numerous cracks appeared on the hitherto smooth-scale surface. The complete destruction of the cuticle cells was observed in the next stage. The outer appearance of the geotextiles remained virtually unchanged; however, a significant reduction of the mechanical parameters was recorded.

Due to high cystine content, the biodegradation of cuticle runs relatively slowly. The outer cuticle of the geotextiles used in two sites, B-B and M, was destroyed

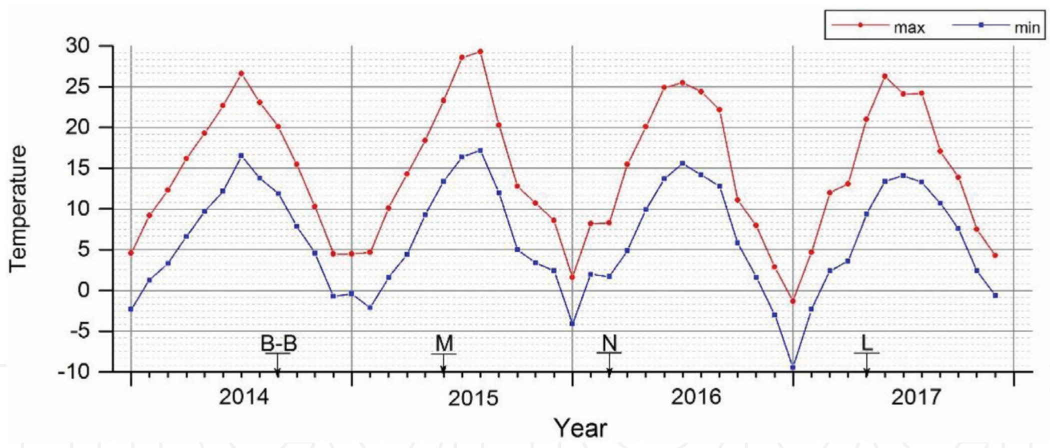


Figure 9.
Minimal and maximal temperature during operation of the slopes.

within 6 months. In B-B this period was in the winter with temperatures between −2 and 5°C (**Figure 9**). In M it was the summer during the vegetation season with temperatures between 10 and 30°C. As for site N, the time of scale destruction was extended to 12 months. This period included the vegetation season with temperatures between 10 and 25°C and winter with temperatures between 0 and −10°C.

Destruction of the cuticle occurred faster in fibres mixed directly with the soil—already 2 months after installation on the slope. In this case, fast destruction resulted from mechanical damage of the fibre scales, which occurred during mixing the fibres with the soil. This rapid degradation was also favoured by weather conditions, positive temperatures and high soil moisture ensured by the heavy rainfall.

During longer operation in the soil, the fibre surface was colonised by microorganisms. The microorganisms adhered to the fibres surface and secreted enzymes which—after disrupting the significant amount of disulphide bonds and denaturing the keratin structure—initiated the breakdown of the peptide bonds. After destroying the cuticle cells, the enzymes penetrated into the deeper layers of the fibres and caused gradual decomposition of the cortical cells. The process started with the breakdown of the amorphous proteins filling the spaces between fibrils. As a result, the fibrillar structure of the cortical cells was revealed. In the first stage, the fibrils adhered to each other. Over time, single fibrils became more separated. Simultaneously, deep and wide cavities appeared in many fibres as the results of enzyme activity.

At this stage, the changes recorded in fibre morphology were connected with geotextile discoloration, changes in the visual appearance and touch and a drastic drop of the mechanical strength.

The biodegradation of cortical cells occurred with a relatively higher velocity. Keratin in the cortical cells possesses lower content of cystine and exhibits smaller resistance to enzymatic attack. As a result, the separation of fibrils and further disintegration of keratin structure occurred relatively quickly—within 3 or 4 months.

Keratin destruction led to the release of the soil nitrogen compounds. Immediately after adding the fibres, the content of organic nitrogen in the soil increased four times. Then, during the exploitation of the slope, the organic nitrogen was transformed into mineral nitrogen forms absorbable by plants. Nitrogen compounds, which drive the growth of plants, considerably accelerated the greening of the slopes. Due to rapid wool biodegradation in site L, the influence of wool on intense grass growth was immediately observed 3 months after installation. In other places the effect was recorded later, in the new vegetation season.

5. Conclusions

The wool geotextiles used for slope and ditch protection remained in humid environment and were exposed to the enzymes secreted by the microorganisms naturally inhabiting the soil. Enzyme activity resulted in the gradual degradation of wool. The process was initiated in the cuticle cells forming the outer layer of the fibres. Due to a relatively high enzymatic resistance of proteins forming the cuticle, the destruction was carried out relatively slowly. It took at least 6 months to destroy the fibres which were not mechanically damaged. Until that time, the geotextiles lost their mechanical properties only to a minimum, maintaining their protective potential.

After a longer time and destruction of the outer cuticle, the enzymes penetrated the inner parts of the fibres. In a relatively short period, the separation of fibrils followed by the total disintegration of the fibre structure was observed. The changes observed in the fibre morphology were connected with a drastic reduction of the nonwoven mechanical strength, what caused the geotextiles losing their protective abilities.

At the advanced stage of the biodegradation, the enzymes catalysed the breakdown of wool keratin into the soluble peptides and certain amino acids. The nitrogen-rich organic compounds released into the soil were gradually transformed into mineral nitrogen forms absorbable by plants and acted as effective fertilisers accelerating the growth of protective vegetation. In this time, the vegetation gradually took over the protective function of the geotextiles, and once they were completely destroyed, the plants ensured the effective protection of the slopes.

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