Part II

Biomimetic applications in textiles

6

Biomimetic principles in clothing technology

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Abstract: Some key problems facing the clothing sector are explored in terms of the possibilities emerging from the principles of biomimetics. An overview is presented of the clothing sector including design process and product requirements and a brief description of biomimetic design and development methods is given. Opportunities, key issues and future trends for biomimetic innovation in the clothing industry are explored. Biomimetics can help improve the ecological footprint of the sector while inspiring innovative design through clever use of materials and structures.. The framework for biomimetic innovation is focused on the functional aspect of clothing and not on the aesthetic.

Key words: biomimetics, clothing design, clothing technology.

6.1 Introduction

Bionics, biomimesis, biomimicry, biognosis and *biomimetics* are all synonyms used in various parts of the world to describe developments inspired by the functional aspects of biological structures. However, the notion of biomimetics is often confused with *biomorphic* which refers to the visual abstraction of organic or biological forms. This was a term used to describe the work of surrealist artists in the 1930s such as Barbara Hepworth and Joan Miró. Biomimetic developments have no intentional or direct impact on the aesthetic aspects of design (Hollington, 2007); instead developments are informed by biological structures that aim to transfer functional properties of biological 'mechanisms' into the man-made world.

Biology has always been a rich source of visual and aesthetic inspiration for the design of clothing, common to every culture and era. There are countless examples of motifs such as flowers, insects and various animals, incorporated into the design of textiles either through structural patterning, print or embroidery; London designer Mathew Williamson uses floral motifs extensively in elaborate designs. Patterns inspired by plants and animals are equally as common, replication of animal markings such as the 'leopard print' has become a trademark for Italian fashion house Dolce and Gabanna.

The natural environment has provided essential raw materials for the construction of clothing for thousands of years. The incorporation of animal skins into clothing ensured human survival in conditions of extreme cold. Inuit hunters for example, were able to transfer the protective functionalities of natural skins into their clothing systems, by using combinations of seal and bird skins they create highly insulating and water resistant clothing (Ammitzboll *et al.*, 1991). Plants and animals were also the sole source of fibres (cotton, flax, silk, wool, etc.) used for the construction of textiles until the dawn of the man-made fibre industry in the early twentieth century.

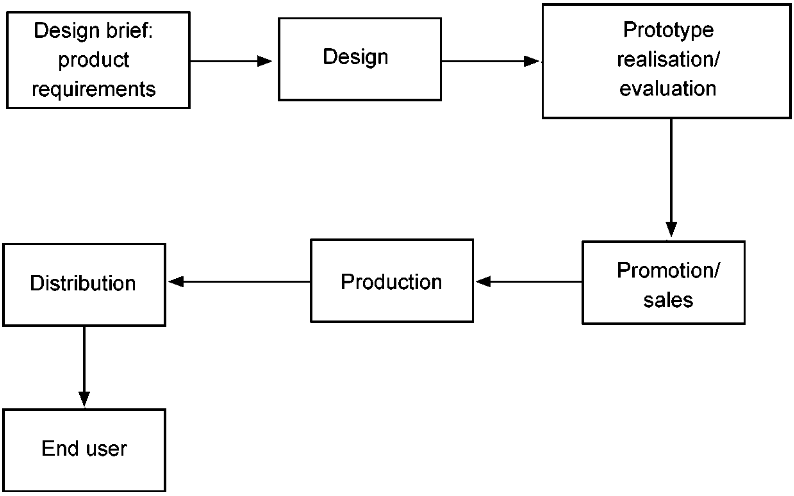
Innovations inspired by a biological mechanism have rarely found application in the clothing sector. In fact, the first development linked to biomimetics was the invention of Velcro in 1950. The hooks by which burrs attach themselves to animal fur inspired this dry adhesive tape. Today, the product has many applications in industry with a strong presence in the clothing sector.

The last decade though, has seen a gradual migration of biomimetic technologies into clothing mainly through functional and performance textiles. These developments have both introduced novel functionalities to clothing, such as performance enhancement offered by Speedo's FastSkin swim suits, as well as alternative methods for incorporating additional functionality to textile systems. The Lotus Effect, for example, adds stain resistant properties to textiles that are more environmentally sound than conventional coatings and finishes (Slater, 2003).

With only a few commercially available examples, biomimetic innovation in the clothing sector is undoubtedly in its infancy. To date, there have been no publications dedicated to the investigation of the possibilities biological paradigms could offer the clothing industry from a functional perspective. In this chapter, the aim is to commence such an exploration by pairing some key problems facing the clothing sector with suggestions emerging from the principles of biomimetics. An overview of the clothing sector including design process and product requirements will be followed by a brief explanation of the principles of biomimetic design and development methods. Finally, opportunities, key issues and future trends for biomimetic innovation in the clothing industry are explored.

6.2 The technology of clothing

The relationship between the clothing industry and biomimetics requires an outline of each field before the links between the two can be identified. This section will focus on the clothing industry and will provide a brief overview of the processes involved in production of clothing from design to point of sale. In addition, the generic requirements of clothing functionality from the perspective of product performance are also described and will include clothing designed for casual use and protective apparel. This section highlights key events and concepts necessary for the purpose of this chapter; it is by no means exhaustive.



6.1 Apparel production process (source: V. Kapsali).

6.2.1 Overview of clothing design and production

The clothing sector produces a wide variety of products whose end use can range from aviation and space travel to fast fashion items that are designed to have value for a limited period of time. Various models specific to each sector have been developed to illustrate the production stages. Figure 6.1 is a simplified model highlighting the core procedure from the design table to point of sale. The field is so large that for the purposes of this study, the map illustrated in Fig. 6.1 deliberately omits the production of components, textiles, packaging and other products associated with making, storing, transporting and distribution of garments. The focus is placed on the sequence of events that occur as a result of clothing design decisions; assuming that the components, textiles, etc. chosen by the design team are based on information such as the composition, performance and history of the particular item.

The planning stage is essential to the overall product development process because it is at this point that the design brief is identified. The definition of the brief is influenced by factors such as past sales, trend predictions, customer requirements, consumer profile and functional requirements. The fashion sector places emphasis on current trends, culture and aesthetic values (Black *et al.*, 2005). Clothing whose purpose is to protect the wearer commands an advanced level of performance and technical expertise; in this case, the functional requirements compiled are essential to the design brief. This initial step in the product development process is crucial as the expectations of the product are defined; the design brief will govern the majority of decisions made during the design process.

The next stage is to realise the design brief and interpret it into a collection of garments, this may involve a single designer or an entire team. High levels of creative processes are required to interpret the brief into product ranges; this often involves a dynamic flux of idea generation and decision making. Other factors such as cost, ergonomic considerations and aesthetics inform decisions. Designers are specialised individuals who are able to decide on the optimal combinations of form and shape with components of the garment range to suit the brief requirements as well as to visualise and communicate every aspect of their ideas to production and sampling teams.

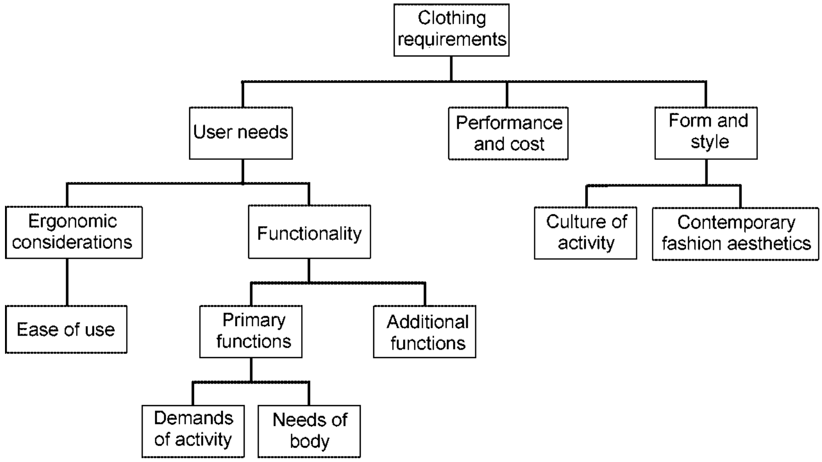
Following the design process, teams of pattern cutters, cutters and sample machinist, produce samples of the designs. This step occurs in close collaboration with the designers to ensure that the interpretation of each garment is true to the original design. The sample garments are then subjected to various tests that determine their performance and the compatibility of their components. The level of assessment varies with end use and sophistication of functional requirements; protective clothing is subjected to more stringent tests than that of 'disposable' or 'fast fashion'. This is usually the point at which the involvement of the design team ends and the work on the next project or range commences.

The time allocated for the completion of a cycle from design table to consumer varies according to the market sector; high-street chains can produce new ranges every six weeks whereas couture fashion houses produced a range twice a year. The promotion and sales period is also unique to each clothing sector. New lines are often displayed at trade exhibitions, catwalk shows such as the biannual Fashion Week that occurs in key international fashion centres such as New York, Paris, London and Milan.

The nature of buying and selling in apparel varies greatly; the client can order products from an in-house sales team or visit a sales agent that can represent a variety of product lines from different companies. Many large chains have buyers working with the design team to select the items that will be produced for retail. Again, production lead times vary greatly depending on the nature of the business.

6.2.2 Clothing system requirements

The clothing industry caters for a wide range of end users from disposable fashion to high-tech protective clothing. In order to achieve this variety, each sector uses specialist technology developed and adapted to suit each particular product specification. At one end of the spectrum, rapid response systems have been developed to produce clothing to cater for fast fashion consumers used by retailers such as Zara. At the other, garments can be engineered specifically to meet the needs of an individual such as couture garments or made to measure tailored suits. Black *et al.* (2005) developed a generic map (Fig. 6.2) to reflect the core requirements of a system of clothing common to each sector. This section will offer a brief description of a clothing system and highlight the key requirements common to conventional clothing.



6.2 Clothing requirements (source: Black *et al.*, 2005).

A system of clothing is a very complex structure that creates a *portable environment* (Watkins, 1995) encapsulating the wearer. The role of this environment is to provide the necessary physiological and psychological conditions for an individual to operate and engage within the surrounding physical and social environment. The system can be made up of one or many layers of clothing and constitutes both the fibrous material and the air that extends from the surface of the skin to the outer face of the external garments. The micro-climate created within the system is dynamic and influenced both by external factors (external climate, activity of the wearer) and internal factors (fibre properties, textile structure, design of garment). Depending on the end use of the clothing system, emphasis on the design may be placed to cater either for psychological functions (fashion) or for physiological (performance or protective garments), however all clothing must satisfy some basic requirements.

Successful design is heavily dependent on the satisfaction of such core requirements (Fig. 6.2). The form and style of each item within a clothing system must suit the culture of the activity and meet basic contemporary design aesthetics. Although this may appear more important to the fashion sector, Black *et al.* (2005) identified several cases where individuals working in hazardous environments rejected their protective clothing because they were deemed unsuitable in terms of look and design. Evidently, the aesthetic qualities of clothing are a requirement important to all sectors and end uses necessary to satisfy the basic psychological functionality of clothing.

A clothing product needs to balance performance with cost; a successful design convinces the consumer that its price is suitable to the performance of the garment. Clothing must also satisfy basic ergonomic considerations to avoid inhibiting general life activities and functions. It is vital that a clothing system is easy to use (adding and removing garments) and does not restrict movement. Any additional functionality is determined by the design brief and the expectations of the product's end use.

The primary functions of a clothing system ensure the physiological needs of the wearer are met and the properties of the system are compatible with the demands of the activity and environment. Fire fighters require their clothing to protect them from flames yet prevent them from overheating in the extreme conditions of a burning environment and the energy produced during activity. Cold water diving suits need to sustain the core temperature of the wearer to prevent hypothermia. Urban dwellers in cities such as London or New York require insulating coats and jackets that protect them from short periods of extreme cold experienced during the winter months. These items of clothing also need to be light and durable and easily removed when they are within an enclosed public transport system, place of work or residence.

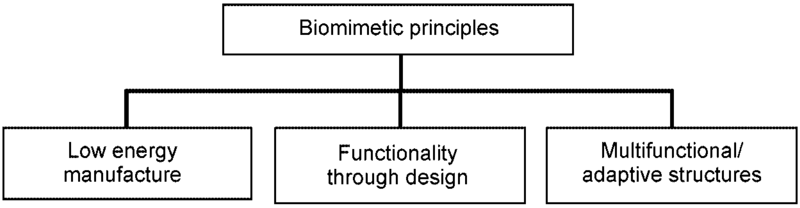
Additional functional requirements represent possible future demands from clothing enabled by new and emerging technologies. The advancing fields of *bio, nano-, electro-* textiles are introducing new properties to apparel that could supplement the functionality of conventional clothing to meet changing needs of the consumer's lifestyle. Remote connectivity, for instance, enabled by innovations in wearable electronics offers clothing that can take on additional roles currently performed by devices such as mobile phones, PDAs and satellite tracking devices. This sector of the clothing industry is very new and the first innovations that have begun to appear on the mass market have been mainly pioneered by the sportswear and performance sectors.

6.3 Overview of biomimetic design and development

The overview of the clothing industry and product requirements described in Section 6.2 provides one half of the story in the possible relationship between biology and the design of clothing. This section will highlight the key principles of biomimetic design and the methods used to develop ideas into new technology thus providing the missing component necessary to embark on the exploration of the links between clothing and inspiration from biology.

6.3.1 The principles of biomimetic design

Our knowledge of evolution depicts the natural environment as a testing ground for design development in nature. Selective pressures are exerted onto the organisms of an ecosystem, for example, through limited reserve of nutrients vital to sustain life. In order to survive, plants and animals evolve mechanisms and structures that enable them to make optimal use of minimal resources (Beukers and



6.3 Biomimetic principles (source: V. Kapsali).

Hinte, 1998; Vincent *et al.*, 2006), thus successful 'design' survives and bad 'design' disappears.

Originally, the conceptual link between energy or resource in nature and cost in the engineering world established a bridge between the two fields. Optimal use of minimal resources was interpreted as an opportunity to develop clever yet cheap materials and structures (Beukers and Hinte, 1998). This notion of energy = money evolved to encompass the greater cost to the environment and the consumption of natural resources in the construction of man-made products (Benyus, 1997). Biomimetic scientists believe nature is a rich source of clever and sustainable design whose basic principles are illustrated in Fig. 6.3.

Functionality through design

The functional properties of biological materials are engineered through design and distribution of their basic building blocks (Benyus, 1997; Beukers and Hinte, 1998). Conventional engineering relies on the properties of the materials to deliver desired function such as stiffness, strength or elasticity to structures. Usually, whenever a new property is required, a new material is synthesised; as a result there are over 300 man-made polymers currently available. There are only two polymers in the natural world – protein and polysaccharide, whose structural variations offer a range of properties that surpass those of their man-made counterparts (Vincent *et al.*, 2006). Insect cuticle, for instance is made from chitin and protein and can demonstrate a host of mechanical properties, it can be stiff or flexible, opaque or translucent, depending on variations in the assembly of the polymer (Vincent, 1982).

Conditions of manufacture

The production of conventional man-made materials and structures generally requires great amounts of energy, high temperatures, high pressures and toxic chemicals. The man-made fibre industry is a prime example of 'high-energy', 'high-waste' production processes. Natural materials, however, are manufactured in 'low-energy' conditions employing normal temperatures and pressures no different from those necessary for life. There is no need for esoteric chemicals; usually water is adequate for the creation and growth of structures (Benyus, 1997).

Multifunctional/adaptive structures

The multifunctional profile of biological materials ensures their efficient and clever use of available resources. Structural design features are a key tool for introducing additional properties in a material. The texture of a surface for instance can evolve to provide water resistant properties to a plant or animal. Functional surfaces often occur on the upper surface of a leaf, where they protect the plant from contamination; the lotus is a plant well known for this property. Several species of insects employ functional surface textures that render their wings hydrophobic. Also, the shell of the dung beetle owes its anti-adhesion and anti-wear properties to its surface texture (Nagaraja and Yao, 2007).

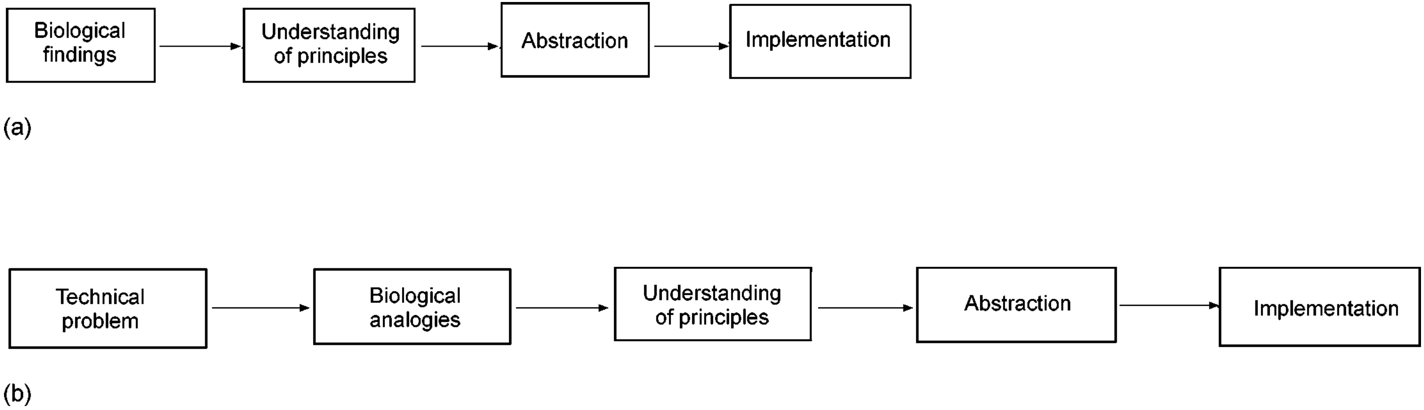
In the man-made world, multifunctional materials are often created using composite technology – the property of one material is added to another to create a material with two or more properties – this is often the case in textile technology. The commercialisation of breathable, wind and water resistant membranes such as *Goretex* and *Sympatex* brands has lead to the introduction of many 'composite textiles' to the clothing sector. Layers of fabric and membrane are laminated together to create multifunctional systems, whose properties amount to the sum of the individual properties of each component, for example Belgian-based Concordia Textiles produce a composite range branded *Omniclima* which is made of three layers (a hydrophilic polyurethane film, a foam and a textile) to create systems that are breathable, water and wind resistant. Also Italian mills, Eurojersey and Lanifico Bengali create textiles using combinations of fleece and adaptive membranes as part of their *Sensitive* range.

Adaptive

There is a fundamental difference between the nature of materials in biology and those of the man-made world. Biological materials are created by the organism whereas their man-made counterparts are fabricated by external efforts (Hollington, 2007). The structure of biological materials is defined partly by DNA and partly by the environment – 'Nature and Nurture'. The survival of plants and animals depends on the ability of their structures to adapt to the changing demands of the environment; some key properties are self-assembly, reproduction, self-repair and redistribution of vital resources (Beukers and Hinte, 1998). The design brief for man-made structures, however, is predetermined and aimed to satisfy a specific set of requirements that remain unaltered during the useful life of a product.

6.3.2 Development models of biomimetic technology

Biomimetic technology is a relatively new interdisciplinary field with a short history; as a result there is currently no standard methodological approach to the interpretation of ideas. There is, however, increasing debate in the area with key



6.4 Biomimetic development model: (a) bottom up (b) top down (source: Gester, 2007).

institutions around the world developing potential models. A popular model is one adopted by the Biomimetic Guild, which illustrates a linear progression of ideas from biology to engineering (Gester, 2007). According to this method biomimetic developments can follow one of two directions: bottom up (Fig. 6.4a) or top down (Fig. 6.4b).

The bottom-up approach (Fig. 6.4a) denotes a development or innovation that has been instigated by a single biologist or a team. The biologist(s) identifies an interesting mechanism in nature that they believe would potentially have a beneficial application in industry. An understanding of the operational aspects of the mechanism is then generated in terms of functional morphology, biomechanics and anatomy. The principles are abstracted into a model that is then taken up by a team of engineers who identify methods of interpreting it into a man-made product. The Lotus Effect for instance is believed to be a bottom-up innovation originally embraced by the paint industry to create self-cleaning paint (Gester, 2007).

The top-down process (Fig. 6.4b) is initiated by industry need or a gap identified in the market. This need or gap is defined in terms of a technical problem for which analogies are sought in biology. Once suitable paradigms are identified a process similar to the bottom-up approach is followed, where a team of biologists study the mechanism(s), identify how they work and pass on the information to engineers, who interpret the ideas into solutions to the technical problem.

The model succeeds in creating a simple illustration that is reflective of the technology transfer process among biomimetic teams today. However, the model is limited by the fact that both bottom-up and top-down directions rely on a serendipitous and non-systematic approach to problem solving (Vincent and Mann, 2002). An alternative model, currently under development at the University of Bath's Centre for Biomimetic and Natural Technologies, has adopted the TRIZ (Russian acronym for Theory of Inventive Problem Solving) framework, a verified methodology used by engineers for decades that offers a systematic approach to the definition and solution of problems. Researchers at Bath University are working on adaptations to the tool, which in its traditional form is based on a database of design solutions derived from thousands of engineering patents, to include design solutions from biology (Vincent *et al.*, 2006).

6.4 Biomimetic principles and the clothing industry

The concept of biologically inspired innovation is not entirely novel to the textile and clothing industry. There have been two key occasions where attempts to imitate the properties of natural materials have led to great milestones in the history of textile technology. The properties of the silk fibre had been the object of man's obsession for centuries. Efforts to synthesise a material that imitates the strength, fineness and lustre of silk, date as far back as 3000 BC in China; it was not, however, till the early twentieth century that these efforts were successful and the first man-made fibre was mass produced: rayon imitated the lustre of silk but lacked its strength (Cook, 1984). A few decades later, the mass production of nylon caused an unprecedented revolution in the clothing and textile industry as it provided a more successful alternative to silk that was both fine and incredibly strong (Handley, 1999).

The second wave occurred in the 1970s when garments made from synthetic fibres began to fall from favour and demand for clothing made from natural materials increased. The advantages of products made from the 'new' materials such as ultra-fine cheap stockings and quick drying, no-need-to iron clothing were overpowered by the unforeseen drawbacks of the technology. Consumers increasingly complained about discomfort sensations the garments caused during wear (Kemp, 1971) such as clamminess, static and cling. The overpowering negative sensations were attributed to the hydrophobic nature of the fibres (Slater, 1977) and as a result, great efforts were made to identify ways in which synthetic fibres and textiles could imitate the comfort properties of natural fibres.

6.4.1 Biomimetic technology in clothing today

Stain-repellent textiles

The Lotus Effect™ was inspired by the protective mechanism used by the lotus leaf to prevent its surface from contamination and is, by far, the most popular biomimetic technology to have permeated the clothing sector. The technology was developed by German botanists Barthlott and Neinhuis, who discovered that the plant's self-cleaning properties were due to the surface morphology of the leaf (Barthlott and Neinhuis, 1997). This innovation was originally adopted by the paint industry to produce self-cleaning paint and later found additional application in the clothing sector in the form of stain- and soil-resistant finishes for garments.

Structural colour

Morphotex™ by Teijin Fibre Corporation is another biomimetic innovation that has recently appeared at key textile trade fairs such as Premiere Vision. Teijin researchers noticed that colour in plants and animals can be achieved using two different mechanisms, pigment and structural coloration. Pigment is the conventional method used to introduce colour to textiles and clothing but this is one of the most toxic processes in the clothing industry (Slater, 2003). Structural colour is created by the interference of reflected light caused by the morphology of the biological surface (Rossbach *et al.*, 2003). Based on the design of the wing of the South American Morpho butterfly, researchers at Teijin created a fibre made of 61 alternating nylon and polyester layers capable of producing basic colours such as blue, green and red without the use of pigments.

Performance enhancement

The drag reduction properties of shark skin were originally studied and applied to the design of aircraft skins (Vincent *et al.*, 2006); it was the competitive swimming sector though that truly adopted this technology and applied it to the design of a textile. Several swimwear companies have produced ranges using 'shark skin' fabric; the most popular is Speedo's Fastskin™ range. A single-layer clothing system employs a textile designed to imitate the functionality of shark skin to help improve the speed of competitive swimmers. Speedo claims their current version Fastskin FSII can reduce up to 4% of the passive drag during a race. However, there is no scientific evidence to support these claims and the sport's governing body FINA concluded that it was not performance enhancing. Athletes, though, claim to feel better and faster when they are wearing the swimsuit and at a disadvantage when they are not (Harding, 2004).

Adaptive ventilation

Concentration of moisture within a clothing system is a key factor in physiological comfort; conventional clothing relies on manual or behavioural methods to replenish saturated air in the microclimate of a garment. Dawson *et al.* (1997) developed a prototype textile system, based on the opening and closing mechanism of a pinecone, able to increase its permeability to air in response to an increase in microclimate relative humidity. A similar concept was recently implemented into a clothing system by Nike under the trade name Macro React[1], the technology was incorporated into a tennis dress worn by Maria Sharapova at the 2006 US Open. The garment featured a fish scale pattern on the back panel that opened as the athlete perspired to increase local ventilation and maintain the wearer's comfort.

6.4.2 Nature as a model for sustainability in the clothing sector

Increasing consumer awareness of the environmental and social cost attached to clothing has placed pressure on the industry to seek alternative methods of production as well as take on responsibility for the post-consumer stage of its products. The introduction of certification, standards and new legislation coupled with various initiatives have begun to map out new routes for improvement or indeed reform of various aspects of the industry; there is, for instance, a growing market for organic textile products. In the context of the clothing sector, organic certification ensures that the fibres (mainly cotton) have been grown without the use of toxic pesticides. Textiles made from biodegradable polymers have recently been made available to clothing manufacturers as an alternative to synthetic fibres. These are only a couple of many examples in which the industry is trying to reduce

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[1] United States Patent Application 20050208860

its impact on the environment. This section will look more closely at some of the key stages of a garment's life cycle and identify opportunities where biological paradigms may provide some good ideas.

Aspects of the clothing sector have been scrutinised by various scholars and campaigners. Slater (2003) completed a comprehensive review of the environmental impact of current production and processing methods used in the textile industry. Groups such as 'Let's Clean Up Fashion'[2] and 'War on Want'[3] have exposed the social implications of cheap clothing. A study conducted by the Institute for Manufacturing at the University of Cambridge (Allwood *et al.*, 2006) combined the individual processes involved in the production of textile products and developed a model for estimating the 'energy profile' of a particular product at each stage of its life cycle.

The energy profile of a product is measured in the quantity of mega joules (MJ) consumed by the item at the five stages of its life cycle (material, production, transportation, use and disposal). The report compared the energy profile of a cotton t-shirt with that of a viscose blouse. The findings revealed that the cotton t-shirt consumed most energy during use, mainly from washing (65 MJ) whereas the viscose blouse required most resource for the manufacture of the fibre (33 MJ). The report highlights that the energy profile of garments varies greatly depending on what they are made from and how they are used. This model will be used as a framework to identify biological paradigms that may help reduce the energy profile of garments.

Pre-consumer

Often, the most costly processes have occurred before the garment reaches the consumer. The energy required for the manufacture of the textiles and components is the main contributing factor to the energy profile of an item of clothing followed by garment assembly and transportation of goods. The textile industry uses 'high-energy' processes for the manufacture of textiles and produces a great deal of waste. Both natural and man-made fibres rely on extreme temperatures, pressure and toxic chemicals for their production and processing. The cultivation of natural fibres such as cotton requires insecticides and fertilisers which pollute the soil and water. In the case of linen, although the separation of leaf and stem fibres is less energy consuming, hand retting in ditches has been replaced with high temperatures, and chemicals which speed up the process (Slater, 2003).

Recently, low energy alternatives from biotechnology have begun to replace some of these wasteful processes with enzymes. The conventional method used for the cleaning and preparation of fibre surfaces for dying, for example, requires high temperatures and toxic chemicals; the use of enzymes enables these tasks to be done at mild temperatures and without the use of any hazardous chemicals.

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[2] www.cleanupfashion.co.uk

[3] www.waronwant.org

Enzymes are also replacing traditional finishing techniques such as stone and sand washing which also require great amounts of resources.

Biological materials are formed using low energy processes and require no harmful chemicals. The idea of growing garments or textiles using a biological paradigm such as skin or plants is immersed in an aura of science fiction; however, Suzanne Lee[4] currently a research fellow at Central St Martins School of Design has been collaborating with a biologist to grow garments. The project titled BioCouture uses low energy conditions to grow bacterial cellulose which is made into garments. Although the work is at a very early and experimental stage, it indicates possibilities for alternative methods of producing textiles and indeed garments.

Biological materials rely on design and assembly on a molecular scale for functionality as opposed to the nature of the raw material in the man-made world. One example is the use of microfibril orientation of cellulose in the cell walls of plant fibres. Highly orientated microfibrils produce stiff fibres that are resistant to moisture sorption, less ordered configurations are used to produce fibres that absorb larger amounts of water and swell, combinations of these two types of material are used widely in nature to power hygroscopic shape change such as the opening and closing mechanism of the pinecone (Dawson *et al.*, 1997), whereas the potential remains relatively unexplored in the textile industry.

Hygroscopic swelling of fibres is generally considered a disadvantage in the textile sector. However, this mechanism has been used to increase the water-resistant properties of a clothing system in rainy conditions. Using a tightly woven cotton fabric in the external layer of garment, during rain, the cotton fibres swell across their width as they absorb water reducing the gaps between the yarns. In turn, this improves the water-resistant properties of the garment by delaying the penetration of water from rain into the clothing system. The orientation of molecules in man-made fibres is currently managed during the later stages of spinning where the fibre is stretched; this aligns the polymer chains increasing the fibre's strength. It is possible that biological paradigms may suggest new ways of introducing properties to textiles using adaptations to these techniques and enabling the transformation of the swelling mechanism in fibres from a disadvantage to an advantage.

The use and production of surface coloration in natural materials can offer ideas for alternative methods to the highly toxic processes used for printing and dyeing (Slater, 2003). Pigment has been used to colour fibres and cloth for thousands of years, although efforts have been underway to develop non-hazardous synthetic dyes; Morphotex, has successfully transferred the structural coloration mechanism found in the Morpho butterfly into fibre technology. This invention delivers a unique method of alternative coloration that could potentially reduce the energy consumption and pollution generated during textile dyeing.

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[4] www.biocouture.co.uk

Consumer use

The study conducted by Allwood *et al.* (2006) revealed that the care and maintenance of a garment during its useful life can also increase its energy profile. The data from the profile of the cotton t-shirt revealed that frequent washing cycles necessary to keep the item clean consumed more resources than the 'high-energy' processes involved in its manufacture. If an item of clothing required less washing and ironing the energy used for its maintenance would significantly decrease. The coating of fibres or textiles with compounds made from silicone or organofluorochemicals is one method currently used by the industry to protect garments from soiling and staining, but these substances are highly toxic (Slater, 2003). An environmentally sound alternative is the Lotus Effect. Enabled by plasma technology, the treatment offers a low-energy, low-pollution alternative.

The energy profile of a garment would also be significantly reduced if the useful life of the garment was extended. In today's throwaway society, consumers are more likely to replace an item of clothing once it is damaged, than repair it. Biological materials and structures are able to self-repair or self-heal, most man-made materials do not have this ability; instead they require additional resources for their maintenance and repair. A self-healing membrane[5] has been developed based on the structure of the vine *Aristolochia machrophylla* (Knott and Schampel, 2007). Although this technology is not yet suitable for introduction into textiles or fibres, it is possible that it could be implemented in the future.

Post-consumer

In 2004, the United Kingdom produced 1.5 million tonnes of textile waste. As the demand for polyester and polyamide fibres increases (Slater, 2003; Allwood *et al.*, 2006) the proportion of waste that is non-biodegradable will grow. Although natural and regenerated man-made polymers readily decompose, they do not demonstrate the properties that make synthetics so essential to the industry. Synthetic fibres are inherently hydrophobic and thermoplastic and demonstrate high tensile strength, unlike natural and regenerated fibres that are absorbent but not as strong. It would be ideal if fibres could be engineered to behave like synthetics but decompose like cotton or wool.

Polyester and polyamide fibres are conventionally synthesised from non-renewable sources. Efforts to find alternative raw materials have delivered polylactic acid (PLA) fibres synthesised from corn starch. The first PLA fibre was introduced by Kanebo Inc. under the trade name Lactron™ and, in 2003, Cargill Dow LLC (now Nature Works LLC) launched Ingeo™. PLA demonstrates many similar properties to poly(ethyleneterephthalate) (PET), which is the most common form of polyester used in the clothing industry (Farrington *et al.*, 2005). More recently, EI du Pont de Nemours and Company has launched Apexa® fibre which is also

[5] Patent no WO2007009280

made from a biodegradable polymer. Alternative methods to reduce the vast amount of energy necessary for the production of synthetic fibres are being explored by use of biotechnology. Genetically modified micro-organisms are used to synthesise polyhydroxyalkanoates (PHAs), but they are not yet commercially available (Lee, 2006).

The post-consumer processing of clothing waste is further complicated by the fibre blends and multi-component composition of garments. The industry can recycle textile fibres and reintroduce them into clothing products, Italian textile mill Figli di Michelangelo Calamai s.r.l. for instance, has incorporated fine single jersey textiles made from recycled cotton fibres into their collection since the Autumn/Winter 2007–08 season. But quality fibres can only be reclaimed from 100% compositions. Recycled fibres of mixed and unknown origin create fabrics that are bulkier and of low aesthetic value. It is now possible to create completely biodegradable garments by using polymers such as Du Pont's Apexa® that can also be made into buttons, zips, tape, etc. Biological methods such as surface morphology or fibre orientation may offer efficient alternatives to yarn blending and composite textile systems for multifunctional garments.

6.4.3 Future requirements of clothing

> 'The suit is my shape, extended, but its mind isn't mine; it's independent.'
> (Banks, 1993)

The functional profile of clothing is undergoing reform driven by advances in textile technology from the military and space industries. The permeation of new functional and smart technologies into other textile sectors is gradually finding a path into mass production clothing. As these new technologies offer non-conventional roles to garments, the boundaries between clothing and body are shifting. In the medical sector, textiles used for drug delivery are integrated into the body; telemedicine uses items of clothing to monitor a patient's bodily functions remotely. It is very likely that aspects of such applications will diffuse into mainstream products.

Science fiction literature offers a glimpse into the possible future of clothing functionality: some envisage garments that fulfil all the conventional requirements yet maintain an individual existence, able to change appearance, self-repair and alter their composition. Although it is not possible to accurately predict consumer demands of future clothing, they will undoubtedly be influenced by factors such as changes in lifestyle, available technology, social and political issues and changes to the environment.

Tao (2001) uses the living cell as a metaphor for future textile functionalities and forecasts behaviours such as self-repair and adaptation. We can expect clothing of the future to host an array of new properties that may interact or integrate with the body, self maintain, reproduce and self assemble to accommodate changes in our activity and environment. Materials and structures in nature already demonstrate these functions and can indicate ways of transferring the technology into clothing. Biomimetics can operate as a platform to accommodate these future requirements and provide a new perspective in the design and assembly of clothing systems.

6.5 Key issues

As industry is increasingly interested in turning to biology for ideas and solutions to key design problems, it is apparent that there is a cultural gap between biology and industry that prevents the flow of information from one specialist area to another. The language or terminology used to describe mechanisms in industry is very different to that of biology for obvious reasons. It is, therefore, very difficult for an individual in the clothing industry, for example, to describe or even imagine a problem in biological terms; accordingly biologists rarely know anything about the language used in garment design and construction.

There are few innovations that have recently found application in the clothing sector offering novel functionalities to garments. Adaptations to aspects of textile technology such as structure, finish and fibre formation have been used as a platform to introduce biomimetic developments to clothing systems. Although the application of technology from other industries is a cost effective way to introduce biomimetics to the clothing sector; persistent immigration threatens to develop 'novelty' products with functionalities that are not relevant to clothing consumers.

Biomimetic researchers can speculate on potential applications for their developments but they lack the specialist market knowledge to identify successful opportunities, so that technology push is not met by consumer pull. It is usually the biologists who identify potential mechanisms for study that they believe would have useful applications in industry. In the case of clothing and textiles, biomimetic teams have very limited knowledge of the sector and consequently their ability to identify opportunities for biomimetic innovation is limited. It is crucial that clothing designers and manufacturers work closely with biomimetic teams to identify successful projects.

6.6 Future trends

The role of clothing systems is changing, fuelled by advances in material science and textile technology, the functional profile of garments is evolving while the boundaries between wearer and clothing are blurring. Shape memory alloys have been used to alter the shape of a garment in response to heat or electrical currents. Microcapsules filled with various substances such as essential oils and synthetic wax have been successfully incorporated into foams and fibres for use in clothing. Washable electronic circuitry has been introduced into garments through textiles that enable the system to perform a range of new functionalities. Predictions suggest that future garments will imitate the behaviour of living organisms able to adapt, self heal and reproduce.

The urgent need for the clothing and textile sector to minimise its impact on the environment has driven the industry to seek alternative methods for the most hazardous aspects of their operations. Consumers are also increasingly aware of the impact their patterns of consumption have on the health of the planet and will therefore actively seek products with low-energy profiles. Biomimetics offers numerous paradigms that could help reduce the damage the production of textiles and clothing causes the environment during their lifespan.

As technology becomes more invisible, new functionality will become more conventional and everyday products of the future will interact with users to ensure their health, comfort and enhanced lifestyle. The role of the clothing designer is evolving into that of an engineer, not only creating three-dimensional structures of cloth but of a portable environment. Biomimetic principles can help steer the use and development of new technology in clothing design toward an exiting yet sustainable future.

6.7 Conclusions

In-depth knowledge of biological structures coupled with advances in micro- and nano-technologies have enabled the systematic study and transfer of useful mechanisms from biology into the man-made world. The application of biomimetic principles to engineering in general, promises sustainable, innovative functional design that makes optimal use of available resources.

In the context of the clothing industry, biomimetics can help improve the ecological footprint of the sector while inspiring innovative design through clever use of materials and structures. The framework for biomimetic innovation is focused on the functional aspect of clothing and not on the aesthetic; designers of the future will be required to take into consideration the additional functional properties that the consumers will require from their clothing.

The main obstacles that prevent the transfer of technology from biology to industry are the conceptual and cultural barriers enforced by language. Much work needs to be done in terms of building links with industry that will enable the flow of ideas, problems and solutions and thus consolidate the link between consumer pull and technology push.

Biomimetics does not always offer the most practical solution as biology does not always share a common agenda with industry; time for instance is not an important factor in nature, but it is crucial in the man-made world. The development of suitable technology can entail a long and costly process, often small adjustments to existing technology is the most effective path. Biological models may not always be the most appropriate solutions, but it is wise to explore the possibilities (Ball, 1999).

6.8 Sources of further information and advice

Centre for Biomimetic and Natural Technologies at Bath University, http://www.bath.ac.uk/mech-eng/Biomimetics/
Biomimetics at Reading University, http://www.rdg.ac.uk/Biomim/
Online resource from the US-based Biomimicry Institute, http://www.biomimicry.net/indexbiomimicryexp.htm
German Biomimetic network, http://www.biokon.net/index.shtml
Biomaterials Network, http://www.biomat.net/
Centre for Sustainable Design, http://www.cfsd.org.uk/
Sustainable Composites Network, http://www.bc.bangor.ac.uk/suscomp/index.htm
Sustainable Design Network, http://www.sustainabledesignnet.org.uk/
The Biomimetics network for industrial sustainability, http://www.extra.rdg.ac.uk/eng/BIONIS/

6.9 Acknowledgements

Special thanks to Professor Julian Vincent (Department of Biomimetic and Natural Technologies, University of Bath), Professor Sandy Black (London College of Fashion), Barbara Toll and Jane Rickard.

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7

Self-cleaning textiles using the Lotus Effect

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Abstract: The self-cleaning property of the lotus plant, named the 'Lotus Effect', is based on the specific properties of micro- and nanostructured ultrahydrophobic surfaces, which are always completely cleaned by rainfall: the contact area of water and dirt particles is largely minimized by the double structured surface. Methods to test superhydrophobicity and self-cleaning, which differentiate between conventional soil-repellent finished textile samples and textiles that are finished with products that impose nano-dimensional structures on the fibre surface, are described. The effect of the nanostructure on the 'Lotus Effect' is investigated and applications, including architectural textiles, and future trends are outlined.

Key words: self-cleaning textiles, Lotus Effect, nanostructure, superhydrophobicity.

7.1 Introduction: basics of self-cleaning textiles

In many applications, the use of textiles is limited due to their soiling and wetting behaviour. To overcome this limitation, textiles are improved with a variety of finishes of different product classes. Recently, products have been invented that make use of the Lotus Effect and implement self-cleaning properties to a textile surface. The successful realization of this effect leads to a significant reduction in the cleaning requirement of such surfaces.

To achieve self-cleaning properties nature uses an efficient method, which has been perfectly realized on the leaves of the lotus plant.[1] Besides this species, self-cleaning properties can be found on a variety of other biological surfaces, such as cabbage, reed and nasturtium. The main function of nanostructured superhydrophobic surfaces in nature is probably the protection against pathogenic organic contamination like bacteria or spores. These are regularly removed from the leaves by rainfall.

Although discovered already in the 1970s, Barthlott and his team in the 1990s identified the reason for the self-cleaning properties and named it the 'Lotus Effect'. It is based on the specific properties of micro- and nanostructured superhydrophobic surfaces, which are always completely cleaned by rainfall: the contact area of water and dirt particles is largely minimized by the double structured surface. This in combination with hydrophobic chemistry results in extremely high contact angles that let water drops roll off at the slightest inclination, in so doing, taking up all adherent particles and removing them, leaving behind a clean and dry surface.

On many of these surfaces even high-viscous liquids (e.g. honey) drip off. The Lotus Effect is based on a minimization of the contact area of hydrophobic surfaces by an overlapping double structure approximately 100 nm to approximately 100 μm in size.

Because of this active principle, the Lotus Effect differs from the 'soil-repelling' and 'soil-release' function. As the Lotus Effect depends only on physicochemical characteristics it is independent of the living system and can be transferred into technical systems. The first commercial products with the Lotus Effect were wall painting and roof tiles. The term 'Lotus Effect' is a registered trademark for many applications.

7.2 Learning from the Lotus Effect: superhydrophobicity and self-cleaning

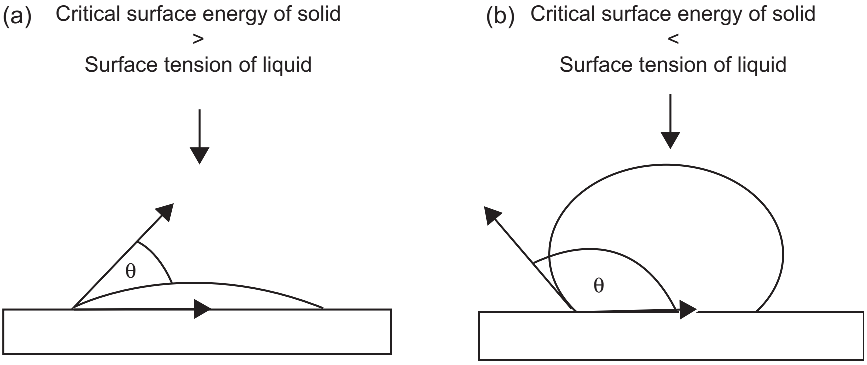
7.2.1 Basis for superhydrophobicity

The wettability of a surface with water and air as the surrounding medium depends on the interfacial tensions on the border of the three phases. The relation of the tensions determines the contact angle (the angle between the surface and the tangent at the water drop lying on it). If the critical surface energy of the solid is higher than the surface tension of the liquid, the liquid drop wets the solid surface well, because the wetting leads to a condition of lower energy (Fig. 7.1a). If, however, the critical surface energy of the solid is lower than the surface tension of the liquid (Fig. 7.1b), the drop assumes a spherical shape, because the spreading of the liquid would lead to a bigger area with high surface energy, thus to a condition of higher energy. A high contact angle results.

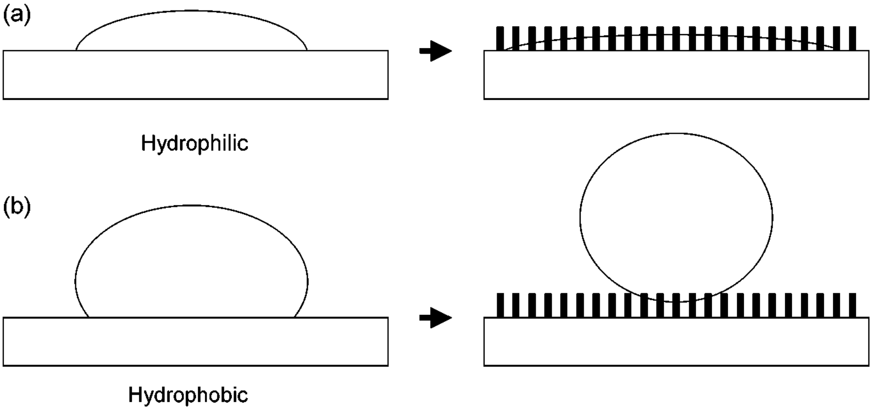
Thus, a strongly hydrophobic surface must have a very low surface energy. The maximum attainable contact angle of smooth low-energy surfaces is approximately 120°, if the surface is composed of closely packed CF_3 groups. In this instance the critical surface energy amounts to approximately 6, 7 mN m^{-1} at 20 °C.[2]

When considering rough surfaces the following two cases (Fig. 7.2) have to be distinguished. If the surface is hydrophilic (Fig. 7.2a), roughening improves the wettability with water; the water becomes sucked into the capillaries. Roughening of a hydrophobic surface (Fig. 7.2b) further reduces the wettability with water and leads to superhydrophobicity with contact angles higher than 140°.

Surfaces with an overlapping of structure elements of approximately 100 nm to approximately 10 μm in size such as those found for example on lotus leaves, but also on other leaf surfaces, thus lead to water contact angles of over 160°.[1] On such



7.1 Correlation between wetting behaviour, critical surface energy and surface tension.



7.2 Correlation between surface roughness and wettability.

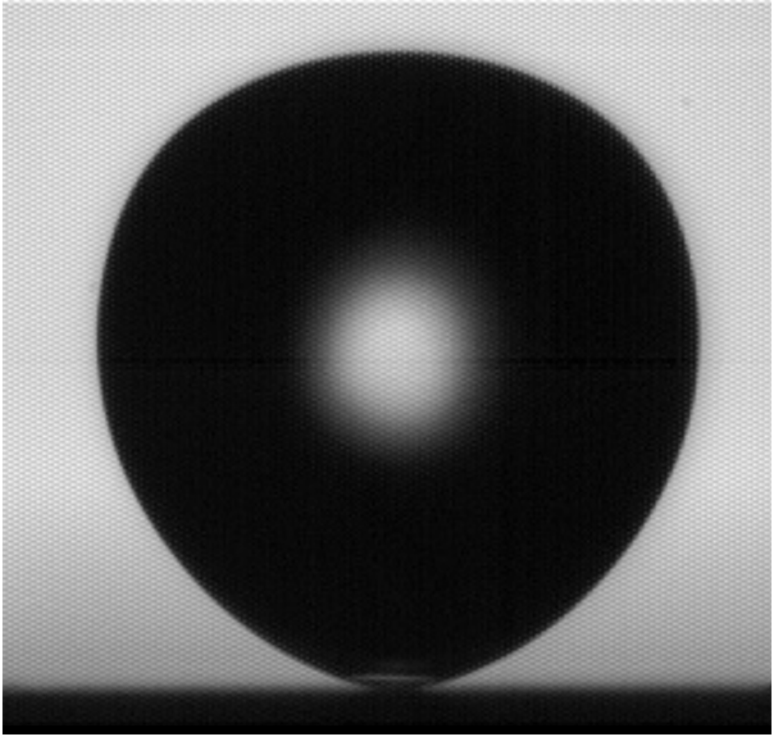
superhydrophobic surfaces, the water drop lies only on the peaks and air is trapped in the microstructures. Thus, the contact area between the solid and the water drop is minimized and the interfacial tension to air is increased. The water drop gains only very little adsorption energy to compensate for the energy which would be necessary for further wetting. This forces the water drop to adopt a spherical shape (Fig. 7.3).

Attempts have been made to describe the wetting of rough surfaces mathematically in terms of the resulting contact angles, e.g. by Wenzel[3] or Cassie and Baxter,[4] whose work is summarized in reference to. On an ideal micro- and nano rough hydrophobic textile surface, wetting with water droplets seems to be absolutely impossible (Fig. 7.4).

7.2.2 Self-cleaning function

In the technological implementation, various methods have been used to avoid the adhesion of dirt and to improve the release of dirt.

7.3 Water drop on superhydrophobic textile surface.



7.4 Rebounding droplet from a superhydrophobic surface.

Smooth surfaces without specific hydrophilicity or hydrophobicity

Extremely smooth surfaces show a reduced soiling behaviour because particles have only low mechanical hold and can be removed by air or liquids. However, the adhesion of residues from drying of liquids or filming cannot be prevented. To remove them, detergents (surfactants) and mechanical support are necessary. Therefore, the self-cleaning effect of smooth hydrophilic surfaces is low. With extremely smooth surfaces low soiling is sufficient to impair the aesthetic impression crucially, long before the function is limited (e.g. paints and panes).

Smooth hydrophilic surfaces

Hydrophilic coatings force aqueous drops to spread out to very thin surface films. Therefore, residues from drying up are deposited relatively evenly with little interference on the surface. Moreover, the extremely good wettability facilitates the cleaning effect of aqueous solutions. An improvement of the self-cleaning ability can be achieved by the introduction of photo-catalytic effects, as for example with the use of titanium dioxide. Organic dirt components can thereby be decomposed to low-molecular-weight products such as CO_2 and H_2O.

Smooth hydrophobic surfaces

If hydrophobic coatings are applied to smooth surfaces, the soiling behaviour can be reduced and the self-cleaning effect increased. Aqueous solutions drip off, so that the formation of residues by drying is decreased. In the textile sector, the water and oil repellency treatment of fibres with fluorine-based chemistry for the decrease of soiling of clothing and technical textiles is well examined and has reached technical maturity.

Rough hydrophobic surfaces (Lotus Effect surfaces)

If overlapping structures in dimensions of some micrometres and superposed structures of 50 to some hundred nanometres are applied to surfaces, and the chemistry of the surface is hydrophobic, soiling behaviour can be dramatically reduced and a real self-cleaning effect can be achieved. The effective surface contact area for dirt particles is extremely minimized by the surface structure and thus the adhesion is very low. Simply with drops of water rolling over the surface dirt particles are removed. Also, oily soiling can be washed off such surfaces by agitated water. When a drop of water rolls over such a surface, dirt particles lying on it are removed by adhesion to the surface of the drop.

Because of the roughness of the surface and the consequential low contact area, the adhesion energy of the particle to the solid surface is very low. Consequently, dirt particles from a superhydrophobic surface are completely removed, in contrast to a smooth hydrophobic surface where the energy is higher allowing only for the relocation of particles. For a smooth surface, the adhesion energy between particle and solid surface is relatively higher than between particle and water drop.

On rough surfaces, like textiles, the kinetic energy of a drop that falls onto it results in another positive effect for the dirt removal: particles lying in cavities of the rough solid surface are not reached by a drop that simply rolls over it. As a result of the impact when falling on the surface the drop deforms, so that it penetrates into the cavities and reaches the particles lying there.

7.3 Measuring techniques for the characteristic Lotus Effect properties

Methods to test superhydrophobicity and self-cleaning were developed to sensitively differentiate between conventional soil-repellent finished textile samples that have a smooth fibre surface on the one hand and textiles that are finished with products that impose nano-dimensional structures on the fibre surface on the other hand.

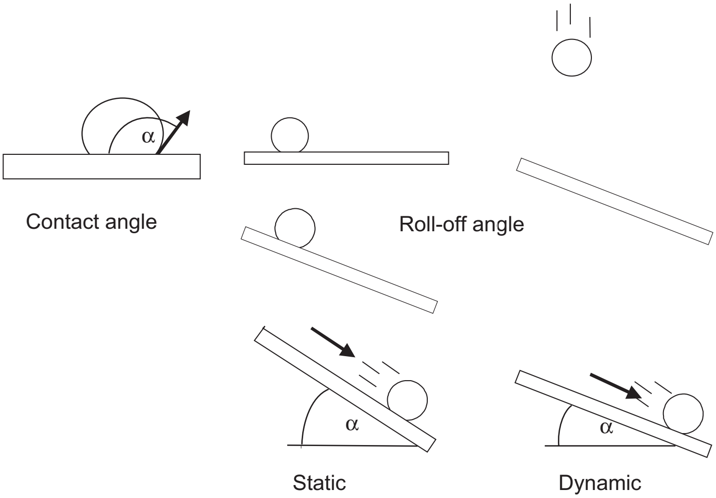
7.3.1 Water repellence test

The rate of superhydrophobicity is measured by determining the dynamic roll-off angle. In contrast to that, the static or dynamic contact angle which is used for the characterization of smooth surfaces like foils is applicable for textiles only in special cases. When dealing with micro-rough surfaces, especially where distant fibres dominate the surface structures, the contact angles can not be measured satisfactorily with optical testing methods. The dynamic roll-off angle represents the boundary value at which a liquid drop of defined volume that is placed on the inclined sample surface from a defined height rolls off the sample (Fig. 7.5). Correlations of roll-off angle and contact angles are given by Furmidge.[3]

For the test an instrument for measuring the contact angle, equipped with a tilting table and evaluation software, is used. The dynamic roll-off angle has turned out to be an important criterion, because it is readily measurable on textiles and allows a better differentiation of the samples than the static contact angle. Moreover with this method, the dynamic impact of the drop is included which brings the test closer to application.

7.3.2 Determination of the self-cleaning ability of textiles

To measure the self-cleaning ability quantitatively, a reproducible and standardized method exists at the Institute of Textile Technology and Process Engineering (ITV) Denkendorf. Self-cleaning efficiency is measured with testing methods using dirt that is known from other textile-testing standards and consists of



7.5 Wettability tests for the determination of Lotus Effect properties.

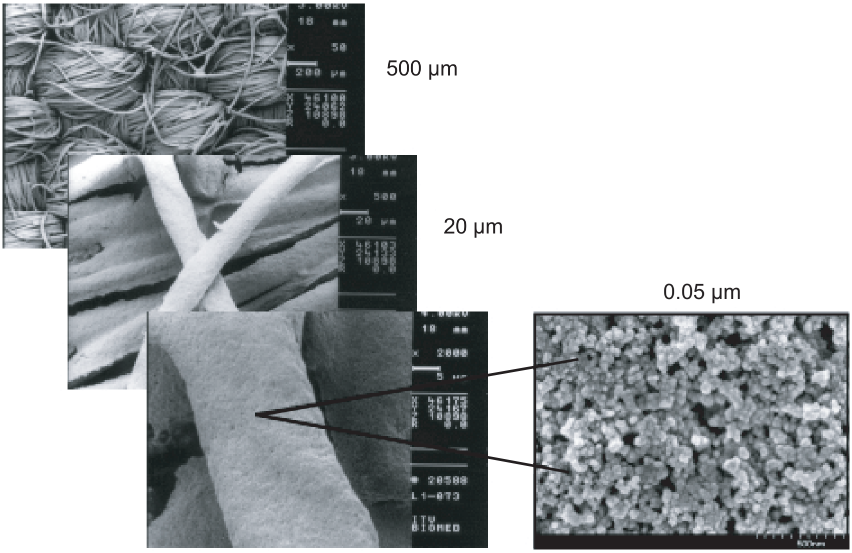
mixtures of different components or of a single component such as carbon black. Dirt mixtures that are used for testing include components like silica, mineral oil, olive oil and carbon black. In the applied test method the dirt is mechanically rubbed into the surface of the textiles to simulate the impact. After contamination the sample is sprayed with water.

Evaluation of remaining contamination is either done qualitatively by a standardized rating method using the grey scale according to the standard DIN EN 20105 A02/A03 or with quantitative methods in which the residual contaminants are detected and quantified using a microscope with image processing and subsequent particle detection software.

7.4 Technical transfer

One of the specific features of textiles in this context is that they readily bring along rough structures with at least two topological structure elements represented by the filament or fibre arrangement within the yarn structure and the yarn arrangement within the fabric structure (Fig. 7.6).

Subsequent approaches to implement the self-cleaning effect on textile-based surfaces include the optimization of fabric and yarn construction structures as well as modifying the fibre surface to low surface energies. Textile surface-finishing chemicals that meet the above mentioned requirements can for example consist of polymer-based dispersions with nano-particle additives. Other products are organic–inorganic hybrid materials based on sol–gel chemistry, some also having nano-filler additives. For successful transfer to modern textile production lines the finishing systems should be water-based. Processes for appling the chemicals



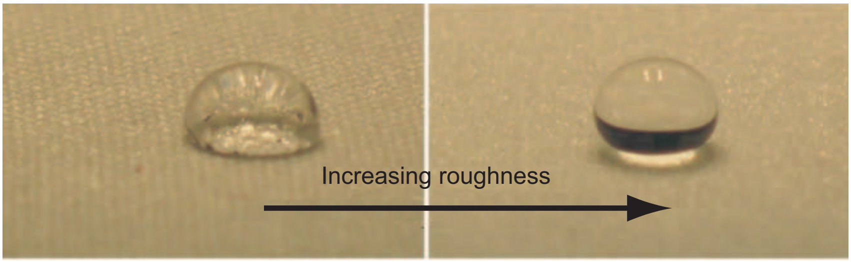
7.6 Three structure levels of textiles with Lotus Effect: fabric construction; yarn construction; fibre surface structure.

consist of standard textile finishing processes such as padding, face padding or spraying. Another attempt that is being investigated at ITV Denkendorf is to modify the fibre surface with fibre coatings at the yarn stage.[7] This process is especially interesting if finishing processes after fabric construction are limited or for sewing thread. However, dyeing processes, such as yarn dyeing or spin dyeing, have to be applied before the yarn finishing.

Textile construction also plays a crucial role in the effect of self-cleaning. In two ITV studies that were financially supported by the German Federal Ministry of Research and Technology, the influence of textile structure on superhydrophobicity and self-cleaning was investigated.

In a first study to analyze the general feasibility of the development of extremely self-cleaning textiles, the influence of construction parameters on woven fabrics made of filament yarn was investigated.[8] Particularly low wettability was measured for woven fabrics with an open yarn structure. These fabrics have distinct microstructured surfaces and show superhydrophobicity. High filament fineness supports hydrophobicity compared to yarns with thicker filaments if the yarn is constructed with low compactness so that the filaments lie side-by-side with adequate distance. Aspect rates between 1 and 2, based on distance and height differences of adjacent filaments, turn out to be especially favourable for high water repellence.

In the study to analyze the influence of structure and arrangement of staple fibres and filaments in fabrics of different types of constructions such as knitted goods, nonwovens, warp knit fabrics and woven fabrics, textile parameters, such as fibre material, yarn spinning method, filament and fibre construction, and surface



7.7 Surface wettability depends strongly on the surface roughness.

modification by mechanical and chemical methods, were varied.[9] The investigations show significant influence of hairiness of the surfaces of the samples on the water repellence. Widely spaced fibres, which are particularly present in samples made of ring-spun yarn prevent the applied small water droplets of approximately 2 mm in diameter from rolling off and therefore result in poor repellence compared to equivalent samples made of open-end yarn and Vortex-yarn. In contrast to that, the self-cleaning behaviour is not affected by widely spaced fibres and therefore the spinning method has no markable effect on it. With increased density of distant fibres the water repellence increases as contact area decreases. This can be demonstrated on flock-coated textiles (Fig. 7.7). With very dense flock fibres the water drop sits only on the fibre endings. The same effect is observed in the opposite way with singeing or calendering which results in smoother surfaces. On the other hand, for such surfaces that have less undercutting structures, the accessibility of soil particles and therefore self-cleaning ability is enhanced.

7.4.1 Influence of nanostructure

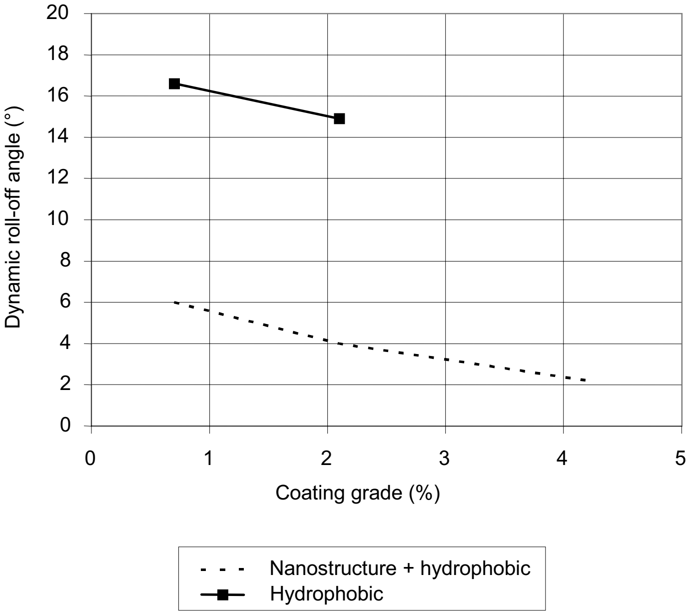
The implementation of nano-dimensional structures on the fibre surfaces enhances superhydrophobicity and the self-cleaning effect. This is shown in Fig. 7.8 and Fig. 7.9.

In this method, soot particles were deposited on the sample surface by means of a particle disperser. Then individual water drops of defined size were dropped onto the surface from a defined height. The number of particles on the treated spot were determined after each drop.

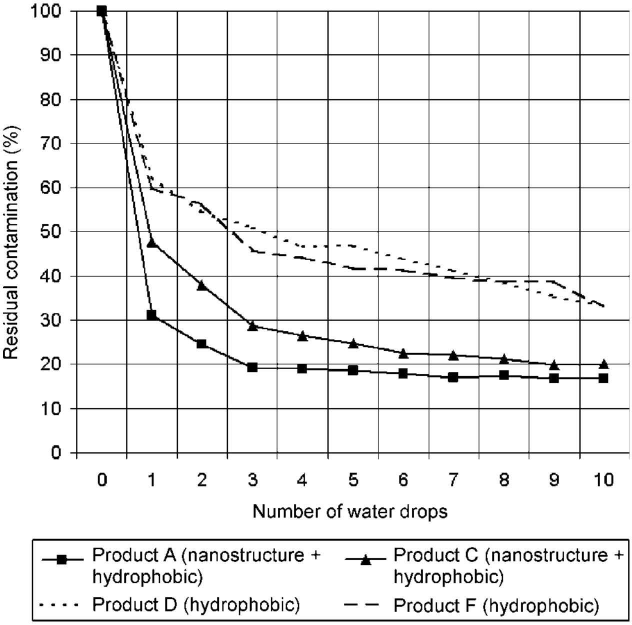
The normally smooth synthetic fibre surface can be finished with special coatings to form nanostructures that further decrease the surface contact area. Other methods to form nanostructures on the fibre are ablation processes, such as etching, embossing or the use of nano-dimensional fibres.

7.5 Applications

The implementation of self-cleaning properties on technical surfaces by using the



7.8 Dynamic roll-off angle; multifilament fabric with hydrophobic respectively superhydrophobic nanostructured finishing.



7.9 Residual contamination with soot particles after impact of water drops; multifilament fabric with hydrophobic and superhydrophobic nanostructured finishing.

Lotus Effect includes a wide potential for the development of new materials or new products and applications for known materials. For the growing market of technical textiles, a further increase in production volume, sales and application fields can be expected by a successful transfer of the Lotus Effect to textile materials. Structure-based soil- and water-repellent properties include an efficient use of materials and are therefore in agreement with the principles of sustainable development. The product lifetime is expanded and the effort required for cleaning is decreased by the self-cleaning effect.

The greatest gain lies in applications that cannot be cleaned or not without a great deal of effort, and that come into contact with rain from time to time. This includes textiles in architectural applications for weather protection, decorative or other technical functions. In many cases, the loss of aesthetic impression or other optical functions by dust, rust or the growth of algae necessitates early replacement of materials long before the loss of other technical or static/mechanical functions.

There is a variety of applications for fibre-based surfaces with self-cleaning characteristics. These include outdoor applications, such as textile roofs for airports and sports stadiums, sunscreen textiles, outdoor clothing, and indoor applications for materials that come into contact with water or water-based solutions, for example shower curtains.

Although the main requirement of the effect is the impact of rain, textiles in applications which are not exposed to the weather can be cleaned in a simple way by the impact of spraying water systems, without surfactants, and without other mechanical influences.

Whilst products for architectural uses, such as awnings with the Lotus Effect have reached market state, other applications are still in development. These are mainly textiles that are not subject to rubbing, which can destroy the surface structures that are essential for the Lotus Effect, or applications where frequent contact with water is not possible. This also applies to textiles that have to be washed frequently for hygienic reasons, for example T-shirts, shirts or bed linen.

Interesting applications in the apparel area include sport functions and safety wear. Besides the ability of self-cleaning against particle contamination in these applications, the extreme water repellence behaviour typical for Lotus Effect surfaces is the main point of interest. Examples are cycling, jogging or ski-wear.

Ongoing research and development tasks include the modification of fibres, examination and development of textile formation, surface treatment, and coatings with new nanostructured chemicals, application methods and durability tests. The durability of this superhydrophobic surface has to be measured under the conditions of product usage. Awning fabric, tested in climate-exposure test cabinets with high UV penetration for 1000 h and intermediate application-dependent mechanical load in the form of grinding exhibited better self-cleaning behaviour than awning fabric prepared with conventional finishing systems.[10]

7.10 Quality mark for self-cleaning textiles.

7.6 Future trends

To prove that textile products have a superhydrophobic and self-cleaning effect, ITV issues the Quality Mark ‘selfcleaning – inspired by nature’ to products that have passed the foregoing testing methods (Fig. 7.10).

Additionally, in the testing procedure for this seal of approval, the filament surface of the fibre is examined with a scanning electron microscope to analyze the surface structures, underlining the prerequisite of nano-scaled structures for the self-cleaning effect.

Recent research and development work in the field of nano-scaled surfaces on textiles at ITV Denkendorf focuses strongly on the optimization of the mechanical abrasion resistance of such surfaces. The ability for recovery of impaired surfaces, which is given for plants by growth, plays an important role in the further development of long-lasting self-cleaning technical surfaces.

7.7 Sources of further information and advice

Informative websites:
www.lotus-effect.de
www.selfcleaning.eu
www.nanopartikel.info

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8

Analysing the thermal properties of animal furs for the production of artificial furs

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Abstract: With the continuing development and increasing production of man-made fibres, artificial furs have become a common commercial product, but they still do not act as a subtitute for animal furs in the market. This may be partly because many customers are convinced, that not only the appearance, but also the comfort properties of animal furs are better. Evidence is presented that shows that at least the thermal comfort properties of artificial furs, developed with application of biomimetic principles, can be better then those of animal furs. The thermal conductivity, thermal resistance and warm–cool feeling characteristics of 15 artificial poly(acrylonitrile)/polymer (PAN/PES) furs and 16 animal furs, differing mostly in fabric structure, were experimentally determined and the effect of hair length and diameter analysed. The warm feeling of animal furs generally decreased with the ratio of hair diameter to hair length. As expected, thermal resistance of all the furs increased linearly with their thickness. In addition, the water-vapour permeability of both kinds of fur was determined and compared. Artificial furs mostly exhibited warmer contact feeling than animal furs and offered better thermal insulation than the same thickness of animal fur. They were more permeable to water vapour than the animal furs, exhibiting a water-vapour permeability similar to that of regular cotton shirts, probably due to the open structure of the basic knitted fabric.

Key words: artificial fur, animal fur, thermal properties, biomimetics, comfort fibre.

8.1 Introduction

Properties of textile fabrics and garments include both purely mechanical properties and thermophysical (mainly heat and moisture transfer) properties. The complex effects of these properties and their interaction characterise the comfort properties of fabrics. Properties that involve the influence of fabric moisture content on selected mechanical properties, along with the effect of deformation and the skin contact force on the user's perception of garment comfort while wearing the garment, are called 'sensorial properties'. With regard to the fabric hand or handle, this is perceived by touch (tactile) and involves mechanical properties such as drape and thermal properties mentioned above that characterise the 'warm–cool feeling' of fabrics. Kawabata emphasised the importance of the latter fabric parameter.[1] Whereas the tactile properties of fabrics have been extensively studied, the 'warm–cool feeling' characteristics of fabrics and furs have been studied to a lesser extent.

Warm–cool feeling refers to our response or feeling when the skin momentarily touches a textile fabric, leather, or any material used in clothing, furniture or carpets; this is especially important if the article is in a damp condition. Since this feeling strongly affects the choices made by people when buying clothing, the objective assessment of this feeling has become very important in the last decade or so.

The main objective of this chapter is to review the thermophysiological and thermal-contact properties of 15 artificial and 16 natural furs. No similar study is to be found in the literature, despite the importance of the so-called 'biomimetic approach' for the future development of new fabrics and synthetic furs with improved comfort properties.

8.2 Brief survey of the manufacture of artificial furs

Truly artificial furs became commercially important following the availability of chemical fibres such as polyamide and poly(acrylonitrile) (PAN). Modern artificial furs exhibit several advantages over animal furs and today represent an important textile product, which in some cases cannot be substituted by animal furs.

Artificial furs can be manufactured by various procedures, such as weaving, tufting, gluing and knitting. The latest technology was developed in the USA a hundred years ago and appears to be still the most productive and economical. All the artificial furs used in the following research were knitted. This technology utilises the classical circular knitting machine, linked to a small carding machine. After drawing, the carded sliver is inserted onto knitting needles and interlaced in the knitted fabric. The resulting fur is then dimensionally fixed, mostly by coating the fabric backing or by thermal shrinking (up to 40%). The latter treatment can be achieved with steam or with dry heat, provided that the fabric contains at least 50% of shrinkable fibres. This procedure also enables the longitudinal shrinkage of certain fibrous components in the fibre cluster, in order to produce an undercoat layer in which the hairs are much shorter than the outer hairs (pile). The undercoat fibres are always much finer then the outer hairs, and as many as five different fibres are used (which are already present in the sliver), differing in composition, fineness and length, in order to provide special thermal-contact and thermophysiological properties. Thus, a very natural appearance and good thermal comfort properties can be achieved in artificial furs.

Some thermal finishing processes, such as simple or pattern thermal ironing, and unidirectional or vortex hot-air surface treatment, also facilitate the achievement of similarity with animal furs. The furs can also be naturally printed or dyed in piece.

8.2.1 Applications of artificial furs

Furs to be used for outer applications require a beautiful appearance, simulating animal fur. In this case, the hairs are longer, less textured and have greater density. Furs used as interlining are more functional, with shorter, more curled hair, and higher water-vapour permeability. Furs are also used in upholstery, shoe production, toys, the automotive industry and in medicine (for alleviating pressure sores). In this last area, the use of animal furs proved complicated or impossible.[2]

8.2.2 Advantages of artificial over animal furs

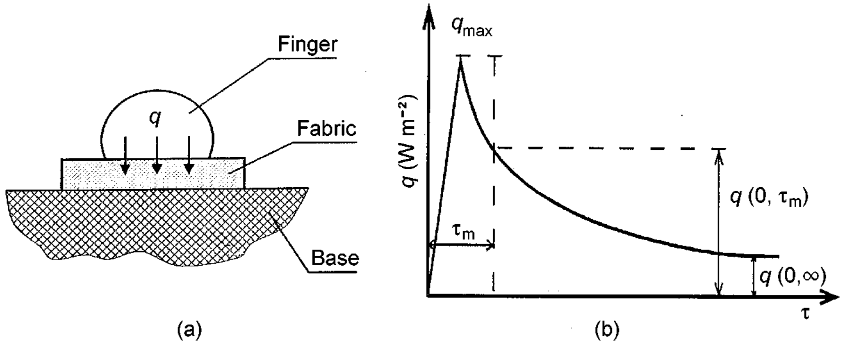
The following advantages are found for artificial compared with animal fur:

- lower price,
- lower square mass (up to 50%),
- greater durability and abrasion resistance in most cases,
- very high resistance to biological damage,
- easy dry cleaning and easy manufacture,
- higher water-vapour permeability,
- availability of any level of thermal insulation,
- has the effect of saving the lives of millions of animals (75% of animal furs are currently produced using captured animals – about 30 000 000 per year. These animals suffer from fear, cannibalism, lower immunity and killing their own young).

8.3 Experimental study

8.3.1 Device for testing thermal properties of furs

The commercial computer-controlled Alambeta device was used in this study for the fast measurement of transient and steady-state thermophysical properties (thermal-insulation and thermal-contact properties). This device works semi-automatically and calculates the statistical parameters of the measurements. The instrument also incorporates auto-diagnostics which check the precision of the measurements and avoids any faulty operation of the instrument. The whole measurement procedure involves the measurement of thermal conductivity λ ($W\ m^{-1}\ K^{-1}$), thermal insulation level characterised by thermal resistance R ($m^2\ K\ W^{-1}$) – see equation 8.3, peak level of contact heat flow q_{max} ($W\ m^{-2}$) and sample thickness h (m). Evaluation of the results takes less than 3–5 min. The so-called 'thermal absorptivity' b ($W\ s^{1/2}\ m^{-2}\ K^{-1}$) was also introduced as the objective measure of the warm–cool feeling of fabrics.[3]



8.1 Heat flow during thermal contact of a fabric with a skin (a) and its time course (b).

8.3.2 Importance of thermal contact (warm–cool) feeling of textile fabrics

Warm–cool feeling means the feeling we get when the human skin touches any object for a short period of time, in our case textile or other fabric used in clothing, furniture or carpets. As can be seen on Fig. 8.1, when warm skin is placed on cooler fabric the heat flow between the skin and the fabric immediately increases and then slowly decreases. The peak level of this heat flow (see below) characterises this thermal contact feeling. It was found that this parameter characterises well the transient thermal feeling when we put on undergarments, shirts, gloves or other textile products. Since this feeling strongly affects people's choice when buying clothes, the objective assessment of this feeling has become very important in recent years.

Instruments for evaluation of warm–cool feeling of textile fabrics

The first device that was able to evaluate the warm–cool feeling of fabrics objectively, was developed by Yoneda and Kawabata in 1983.[1] They introduced the maximum level of the contact heat flux q (W m^{-2}) as a measure of this transient thermal characteristic, and they have published the first objectively determined values describing the thermal-contact properties of textile fabrics. Their instrument, called Thermo-Labo, was commercialised. It consists of several blocks, which are manually operated. The q_{max} parameter then depends on the composition and surface structure of the fabric, but also on the temperature gradient between the tested fabric and the pre-heated block of the Thermo-Labo instrument.

In 1986, another device for the objective evaluation of the warm–cool feeling of fabrics, but based on a different concept, was completed at the Technical University in Liberec[3] and later commercialised by the Sensora company.[4] The previously mentioned thermal absorptivity b (W s^{½} m^{-2} K^{-1}) was introduced as the objective measure of warm–cool feeling of fabrics.[3] The meaning of this parameter (formerly used in the civil engineering and ergonomics) is explained in next paragraph.

Thermal absorptivity in characterisation of the warm–cool feeling of fabrics

Provided that the time τ of thermal contact between human skin and a fabric is short, textile fabric is idealised to a semi-infinite body of thermal capacity ρc (J m^{-3}) and initial temperature t_2. Transient temperature field between human skin and a fabric is then given by the solution of a specific partial differential equation[3] and can be used for the calculation of the initial level of heat flow q passing between the skin (characterised by a constant temperature t_1) and textile fabric according to the next equation (the details of solution for the boundary condition of 1st order are given in reference 5):

$$q_{\mathrm{dyn}} = b(t_1 - t_2)/(\pi\tau)^{½} \qquad [8.1]$$

Thus derived, thermal absorptivity b (W s^{½} m^{-2} K^{-1}) then follows from the relationship:

$$b = (\lambda\rho c)^{½} \qquad [8.2]$$

As can be seen, the level of thermal absorptivity depends neither on the temperature gradient between the fabric and skin, nor on the measurement time, but only on the contact pressure, which corresponds to the real situation. The pressure is adjustable.

The validity of thermal absorptivity as a new warm–cool feeling parameter for fabrics was confirmed by several tests where the results of relative subjective feeling of 100 people were compared with the values of thermal absorptivity found by means of the Alambeta instrument.[6] Within various research projects the thermal-insulation and thermal-contact properties of all common textile products were experimentally investigated. It was found that practical values of thermal absorptivity of dry fabrics range from 20 to 1000 (see Table 8.1). Higher values represent cooler feeling. The results show that the thermal-contact feeling of the fabrics is strongly affected by their structure and composition. It was found[7] that fibres and fibre polymers of higher moisture regain, also provide a cooler feeling. Therefore, the warmest feelings can be achieved from fabrics made from polyvinyl chloride (PVC), polypropylene (PP), PAN, whereas viscose, flax, cotton and both PAD 6 and PAD 66 fibres show the coolest feeling. Which feeling is better, depends on customer requirements: for hot summer garments, a cooler (cotton) feeling is demanded, whereas in the north of Europe warmer clothing, based on polyester (PES)/wool is preferred. As the thermal absorptivity is mainly a superficial property, its level can be changed by any superficial or finishing treatment, such as raising, brushing and coating. The instrument is so sensitive that it can reliably distinguish the warm–cool feeling of identical fabrics made of ring spun

Table 8.1 Effect of fabric structure, composition and treatment on thermal absorptivity

Thermal absorptivity, *b* ($\mathrm{W\,s^{1/2}\,m^{-2}\,K^{-1}}$)	
20–40	Micro-fibre or fine PES fibre non-woven insulation webs
30–50	Low density raised PES knits, needled and thermally bonded PES light webs
40–90	Light knits from synthetic fibres (PAN) or textured filaments, raised tufted carpets
70–120	Light or rib cotton ring spun (RS) knits, raised wool/PES fabrics, brushed micro-fibre weaves
100–150	Light cotton or viscose (VS) knits, rib cotton woven fabrics
130–180	Light finished cotton knits, raised light wool woven fabrics
150–200	Plain wool or PES/wool fabrics with rough surface
180–250	Permanent press treated cotton/VS rough weaves, dense micro-fibre knits
250–350	Dry cotton shirt fabrics with resin treatment, heavy smooth wool woven fabrics
300–400	Dry VS, Lyocell, silk weaves, smooth dry resin-free heavy cotton weaves (denims)
330–500	Close to skin surface of wetted (0.5 ml of water) cotton/PP (or speciality PES) knits
450–650	Heavy cotton weaves (denims) or wetted knits from speciality PES fibres (Coolmax)
600–750	Rib knits from cotton or PES/cotton, micro-fibres knits, if superficially wetted
>750	Other woven and knitted fabrics in wet state
1600	Liquid water (evaporation effect not considered)

yarns and open end (OE) yarns. It can be also used for optimising the level of enzymic treatment. Figure 8.1 shows the heat flow with time.

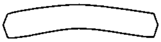
An important aspect of the warm–cool feeling evaluation is the change in feeling when the textile product gets wet. Because the time of the warm–cool feeling evaluation of samples in the Alambeta device is very short, less than 3 min, the evaluation of wet samples is reliable (the sample does not turn dry during the measurement). Because the thermal conductivity and thermal capacity of water is much higher than those of dry textile structures, the negative feeling of coolness of garments moistened by sweat can exceed 1000. A new field of application of this instrument is the indirect determination of the so-called 'moisture absorptivity'.[7]

Structure and properties of artificial furs

Under pressure, the fabric density increases, the orientation of the fibres changes, the thickness of furs h, and degree of porosity are reduced. Thermal resistance R becomes lower, in spite of a certain decrease of thermal conductivity (in most cases due to lower porosity) because of the relationship:

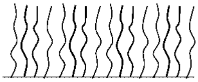
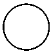
$$R = h/\lambda \qquad [8.3]$$

Table 8.2 Structure and composition of the artificial fur Afrodita

Fur structure (similar to wool 32 mm and Ambra 60 mm hair length)		Hair length	28–51 mm
		Hair fineness	Various fibres with fineness ranging from 3.3 to 22 dtex
Typical hair cross section		Average equivalent hair parameter	35.2 μm
Undercoat		Hair material composition	2% polyacryl, 98% modacryl
Hairs (pile)		Total density of knitted fabric	684 520 loops m^{-2}
		Square mass	450 g m^{-2}

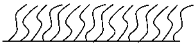
Note: all the hairs are mixed in the sliver.

Table 8.3 Structure and composition of the artificial fur Daniel

Fur structure (similar to Katka with 12 mm hair length)		Hair length	20 mm
		Hair fineness	From 3.4 to 17 dtex
Typical hair cross section		Average equivalent hair parameter	26.6 μm
Polyacryl		Fur composition	15% polyacryl, 85% polyester
Polyester		Total density of knitted fabric	652 400 loops m^{-2}
		Square mass	830 g m^{-2}

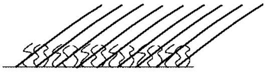
Note: backing fixed by resin.

Table 8.4 Structure and composition of the artificial fur Norsko

Fur structure (similar to Bakara 8 mm, Javor 6 mm, Brigita 8 mm hair length)	Hair length	10 mm
	Hair fineness	3.4 dtex
Typical hair cross section	Density of knitted fabric	767 496 loops m^{-2}
	Square mass	370g m^{-2}

Note: hair material composition is 100% polyacryl.

Table 8.5 Structure and composition of the artificial fur Otmar

Fur structure (similar to Upal 32 mm hair length) 	Hair length Hair fineness	35 mm 4.4–22 dtex
Typical hair cross section	Equivalent hair diameter	46.6 μm
Undercoat 	Hair material composition	40% modacryl shrinkable, 60% modacryl heat set
Outer hairs 	Density of knitted fabric Square mass	651 408 loops m^{-2} 530 g m^{-2}

Note: different length of hairs by shrinking.

Table 8.6 Structure and composition of the artificial fur Teran

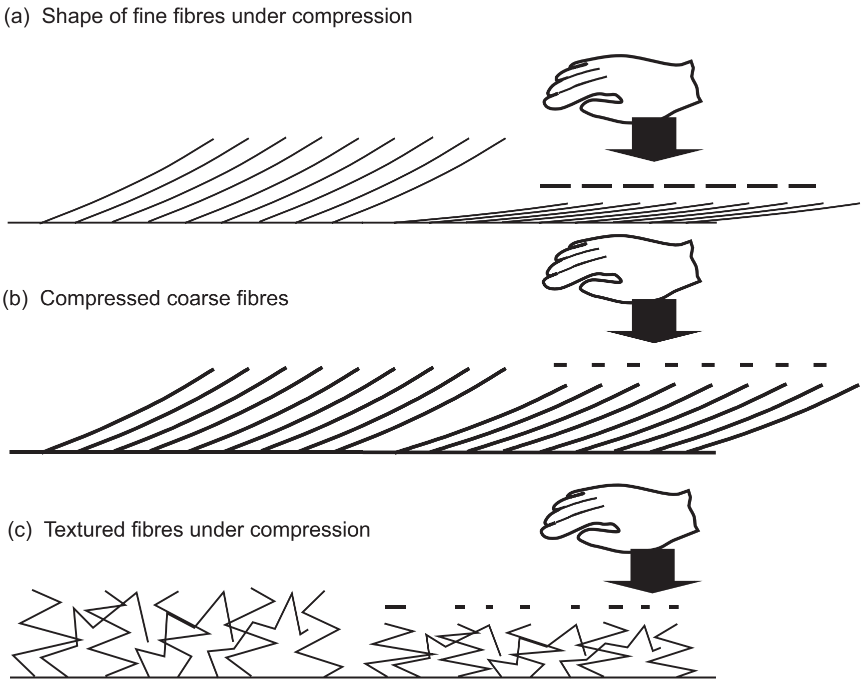
Fur structure 	Hair length Hair fineness	10 mm 3.4 dtex
Typical hair cross section 	Equivalent hair diameter Hair material composition Density of knitted fabric Square mass	9.7 μm 100% polyacryl 715 284 loops m^{-2} 340 g m^{-2}

Note: thermal finishing by tamblering.

To maintain high thermal resistance, the fur hairs should exhibit a certain resistance to compression. Since this resistance increases to the 4th power of the hair diameter, even coarse fibres are sometimes used as components of the fur hair. Fine fibres and micro-fibres reduce the heat flow passage, owing to higher absorption of infrared radiation and lower heat conduction along the fibres.[8] That is why the undercoat layer of artificial furs often simulates the structure of animal furs and is made up of very fine fibres – see Tables 8.2–8.6, which show the structure and composition of furs studied, which were manufactured by the Czech BONEKA Company.

Figure 8.2 shows the effect of fur compression on the contact area. Fine fibres can easily be compressed, resulting in a large contact area. More heat is then conducted away from the hand and the contact feeling is cooler. Thus, fine fibres in a free state provide better thermal insulation than coarse fibres, but when compressed (in the case where is no system to prevent their compression), their thermal resistance decreases rapidly.

In contrast, when compressing coarse or textured fibres (hairs), the increase of the contact area is much smaller. This leads to a warmer feeling (this is discussed in more detail in the following sections).



8.2 The effect of contact force on fibre deformation for (a) untextured fine fibres, (b) untextured coarse fibres and (c) textured fibres.

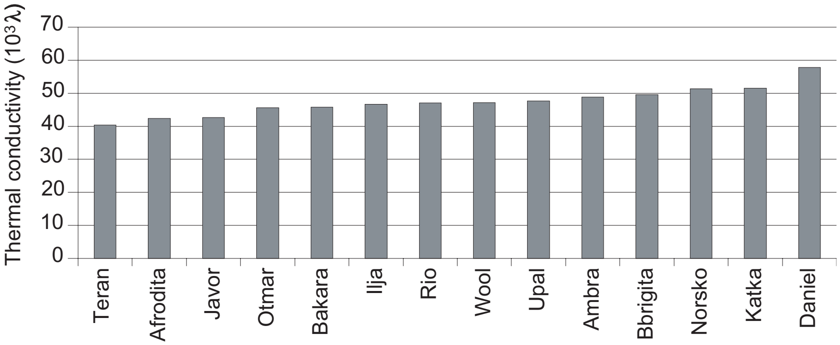
8.3.3 Results of thermal conductivity measurements

The thermal conductivity of various artificial furs is displayed in Fig. 8.3. Correlating these values with the structure of the furs, we can conclude that the lowest (best) levels are achieved where the fine hairs are perpendicular to the heat flow direction (see Teran fur). Moreover, the hairs should create many closed pores. In contrast, when the heat flow passes along the hair (as in the case of Daniel fur), then the thermal conductivity is higher (worse).

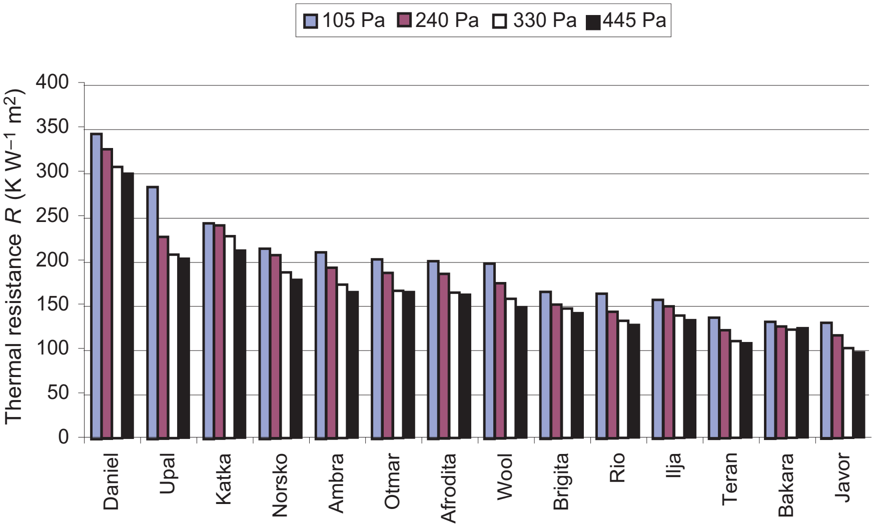
As can be seen in Fig. 8.4, comparing the thermal conductivity of artificial and animal furs, most artificial furs exhibit higher (worse) levels of this property. This characteristic has been explained by Vorlova.[9]

8.3.4 Thermal resistance of furs

As stated in the previous section, thermal resistance R is calculated by the ratio of thickness h and thermal conductivity λ. This thickness depends on the contact pressure. The effect of the contact pressure of the measuring head on the thermal



8.3 Thermal conductivity of artificial furs.



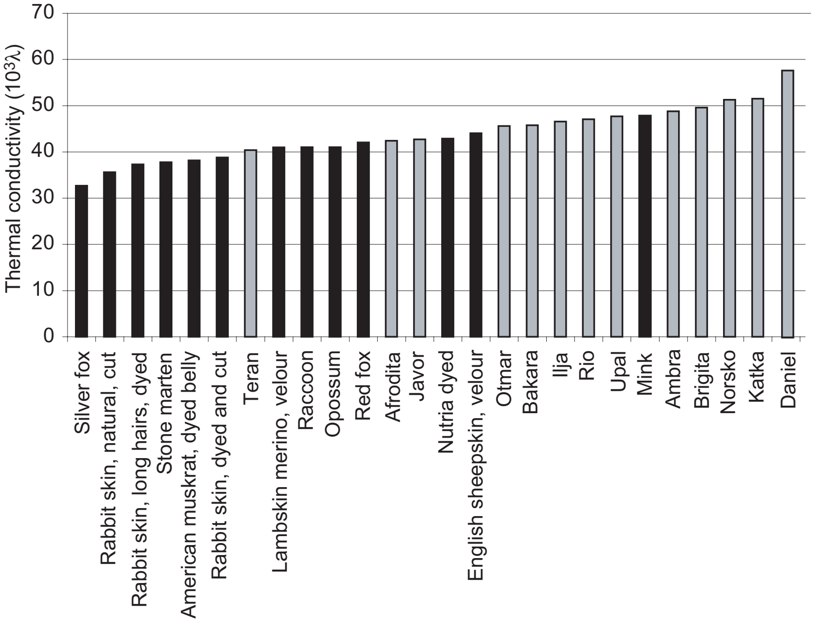
8.4 The effect of contact pressure on thermal resistance of artificial furs.

resistance of artificial furs is shown in Fig. 8.5. Data collected at four different pressures allow the thermal resistance at zero pressure to be easily extrapolated. It is clear that the technology of artificial furs enables furs to be designed with very good resistance to compression.

Comparison of the thermal resistance of artificial and animal furs, shown in Fig. 8.6, demonstrates that the thermal resistance of artificial furs is generally higher than that of animal furs, and that it can be as high as required, despite higher levels of thermal conductivity.

8.3.5 Effect of hair parameters on thermal contact area

Artificial and animal furs can be idealised on a system of cylindrical beams,



8.5 Thermal conductivity (W m^{-1} K^{-1} of artificial (shaded bars) and animal (black bars) furs.

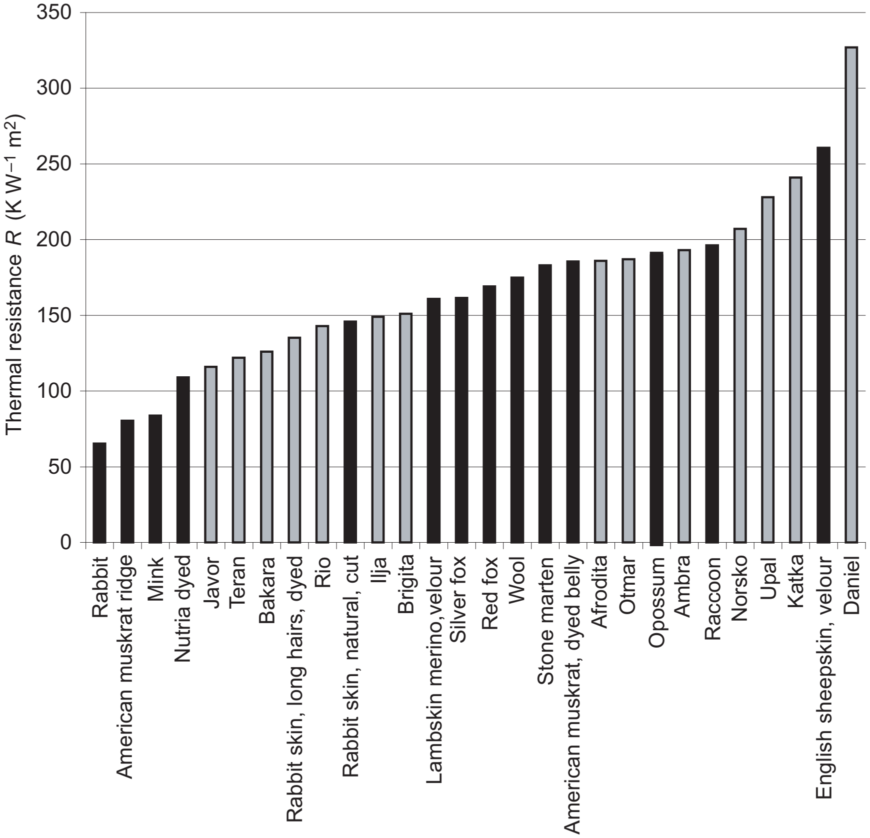
anchored in the skin at a certain angle. Moreover, these beams are curved and their ends are frequently located almost parallel with the skin. When touching the skin, the contact force F acting more or less perpendicularly on the hair end, causes bending deformation y, which is the level of the fur compression towards the skin surface. The deformation y depends on the hair length l and hair diameter d, according to the generally recognised relationship, in which E indicates Young's modulus and J is the moment of inertia:

$$y_{\max} = y_B = \frac{Fl^3}{3EJ} = \frac{64Fl^3}{3E\pi d^4} = Cl^3/d^4 \qquad [8.4]$$

From this relationship, it follows that the hair deformation (and also the fur compressibility) are proportional to the ratio l^3/d^4. It can be concluded that (under pressure) long and fine hairs will create a larger contact area, which results in a cooler contact feeling than in the case of short and coarse hairs.

Professional furriers differentiate the hand-feel of various furs by means of the fineness coefficient, given by the ratio d/l. As follows from the previous simple analysis, the application of such an empirical coefficient is quite well justified. Given this observation, the thermal absorptivity and conductivity of the furs analysed in this study will also be correlated with this empirical coefficient.

Table 8.7 shows that, as expected, the thermal resistance of furs increases with thickness. But this thermal resistance, calculated by the relation $R = h/\lambda$, also



8.6 Comparison of thermal resistance of artificial (shaded bars) and animal (black bars) furs.

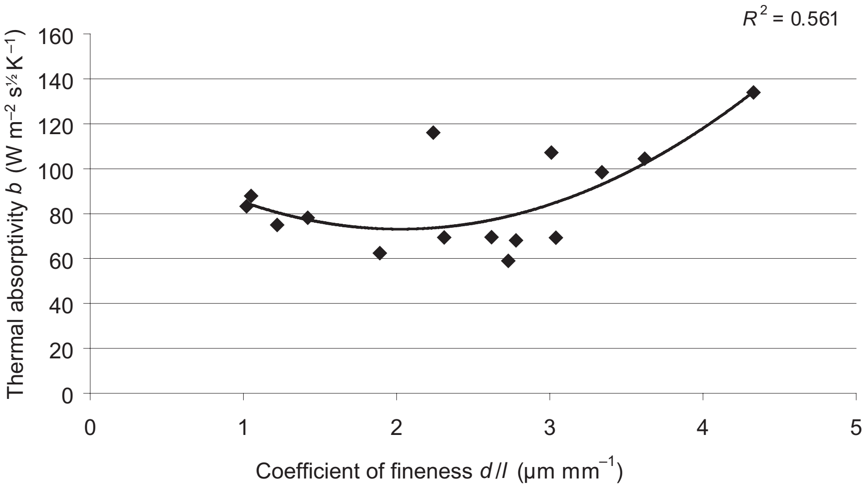
depends on thermal conductivity λ. When comparing the values of λ of the various furs mentioned in Table 8.6 we find that the λ of silver fox fur is incredibly low. This 'natural miracle' results from the special structure of the fur of this animal, which lives in a severe arctic climate. The hairs are hollow (confirmed by microscopic technique at TU Liberec[8]), but the cavity is separated into individual cells in order to prevent even very low heat transfer by natural convection. Deeper analysis of this fur is recommended for the future biomimetic development of artificial furs.

The study (Fig. 8.7) of the effect of hair parameters on the thermal absorptivity of furs demonstrates that the warmest feeling is achieved when the ratio *d/l* is 2–2.5. This result can be applied in the design of synthetic furs with the warmest contact feeling.

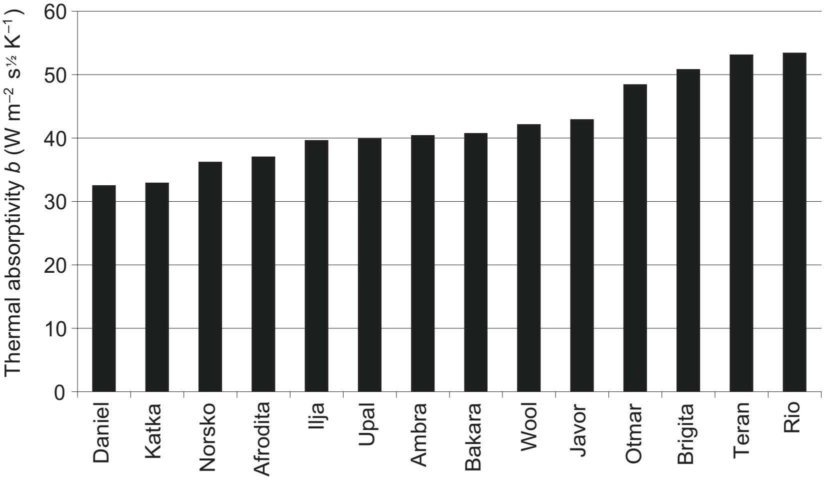
As indicated in Fig. 8.8, the thermal absorptivity of artificial furs varies according to the structure of the fur and fineness of the outer fibres (hairs). In this case, the effect of fibre fineness acts conversely to that of thermal conductivity

Table 8.7 Effect of hair geometry on the thermal properties of animal furs

	Average value (CV in %)				
Type of fur	Length l (mm)	Diameter d (μm)	Hair fineness coefficient d/l (μm mm^{-1})	Thermal conductivity λ (mW m^{-1} K^{-1})	Thermal absorptivity b (W s$^{1/2}$ m^{-2} K^{-1})
Silver fox	91.6	77.77	0.85	32.76(2.14)	49.55(14.11)
Red fox	70	71.44	1.02	42.06(2.78)	83.25(10.56)
Chinchilla	31	32.53	1.05	39.02(2.00)	87.83(4.09)
Opossum (North American)	90	109.49	1.22	41.04(4.17)	74.93(7.03)
Raccoon	66	93.70	1.42	41.03(1.36)	78.18(3.12)
Rabbit skin, long hairs, dyed	45.8	86.38	1.89	37.31(3.48)	62.46(8.87)
American muskrat, ridge	34	76.16	2.24	42.25(2.34)	116.10(7.04)
American muskrat, dyed belly	32	73.92	2.31	38.14(1.63)	69.38(4.09)
Stone marten	33	86.57	2.62	37.78(3.23)	69.56(12.58)
Lambskin merino, velour	12.1	33.06	2.73	40.96(1.81)	59.01(2.46)
English sheepskin, velour	15	41.64	2.78	44.06(1.36)	68.12(3.78)
American muskrat, belly	26	78.14	3.01	39.00(1.63)	107.20(4.09)
Rabbit skin, natural, cut	20.6	62.72	3.04	35.33(1.40)	69.28(4.32)
Rabbit skin, dyed and cut	16	53.38	3.34	38.79(1.03)	98.42(7.85)
Nutria dyed	42	152.21	3.62	42.88(2.15)	104.45(12.2)
Mink	19	82.27	4.33	47.87(1.19)	133.90(2.79)



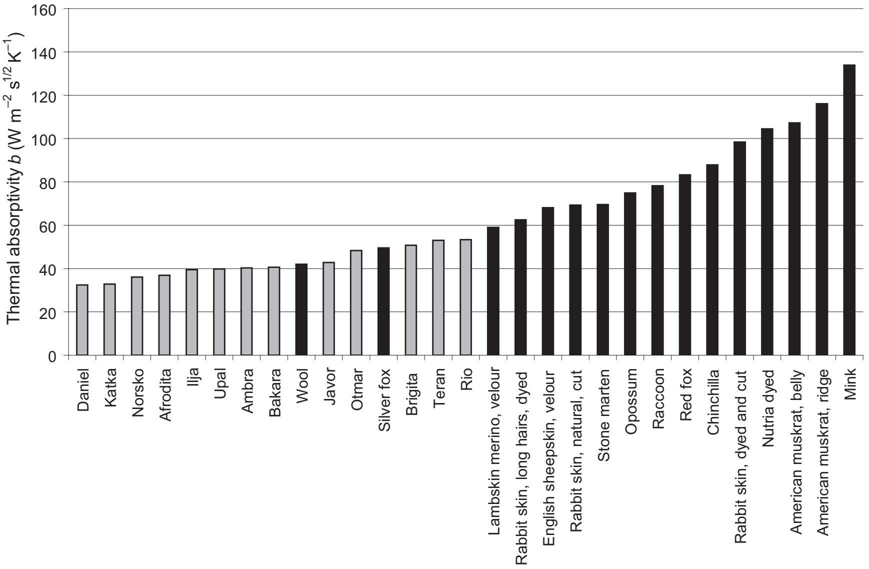
8.7 The effect of hair geometry on thermal absorptivity of animal furs.



8.8 Thermal absorptivity (warm–cool feeling) of artificial furs.

requirements: hairs oriented along the heat flow direction offer a lower contact area and therefore exhibit a better (warmer) feeling than furs with hairs located perpendicularly to the heat flow direction. Fortunately, versatile artificial fur technology enables nearly any level of the warm–cool feeling to be achieved.

The levels of thermal absorptivity (warm–cool feeling) of artificial and animal furs are compared in Fig. 8.9, which demonstrates that artificial furs generally exhibit a much warmer feeling than animal furs.



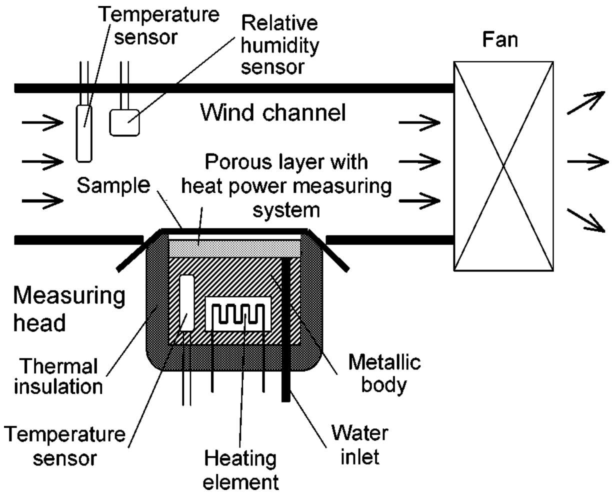
8.9 Comparison of thermal absorptivity of artificial (shaded bars) and animal (black bars) furs.

8.4 Water-vapour permeability of furs

Water-vapour permeability of fabrics represents, along with fabric thermal resistance, the most important characteristic of clothing comfort. That is why increased attention has been paid to this parameter in recent decades. Testing of this parameter by means of any common testing instrument is time consuming and requires special samples of large dimensions cut from pieces of fabrics. Unfortunately, animal samples used in this study were of small dimensions. That is why the only instrument which enabled the testing on furs was the non-destructive fast working Permetest skin model.

Results of measurement can be expressed in units defined in the ISO Standard 11092, but also in the form of the relative water-vapour permeability P, which was used in this study. The principle of this instrument is shown in Fig. 8.10. Here, the slightly curved porous surface is moistened (either continuously or on demand) and exposed in a wind channel to a parallel air flow. A tested sample is located on a semipermeable layer covering the metallic wetted area of diameter about 80 mm and characterised by high thermal conductivity. The amount of evaporation heat of liquid water taken away from the active porous surface is measured by a special integrated system. Thus, a very low time constant was achieved for the whole system, resulting in a short measurement time (full signal is registered within several minutes).

At the beginning of the measurement, the heat flow value q_0 without a sample is



8.10 Measuring facility.

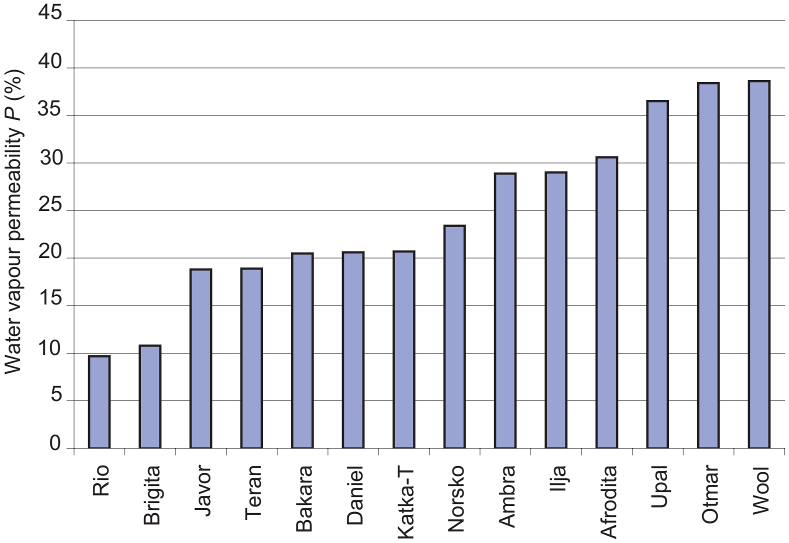
8.11 Permetest instrument.

recorded. In the next step, the measuring head is covered by the tested sample and the heat flow level q_1 is recorded. The instrument is shown in Fig. 8.11.

Relative water-vapour permeability P of the textile sample is calculated from the formula:[10]

$$P[\%] = 100\, q_0/q_1 \qquad [8.5]$$

A value of 100% permeability here represents the level of evaporation from a free water mirror, whereas the permeability relating to this reference level includes the permeability of the fabric itself, permeability of the 1.5 mm air gap and permeability of the boundary layer at walking velocity of 3.6 km h^{-1}. Given that the typical relative water-vapour permeability of new denim jeans is about 20%, then the



8.12 Relative water vapour permeability of artificial furs.

permeability of furs is generally high (Fig. 8.12). The lower the density of the basic knitted fabric, the higher the permeability. Compared with these artificial furs, the permeability of animal furs is quite low – 5% on average. Some furs, such as buffalo, are almost impermeable. Nevertheless, the thermophysiological properties of these furs are still very high because of their special advantages: extremely high moisture absorption, resulting in additional warmth for the wearer in cold, wet weather and cooling for the wearer on hot, dry days. Artificial furs lack this characteristic of water and water-vapour management.

Some results presented in this chaper have already been presented by Hes.[11] In this chapter, some imperfections have been corrected and additional information has been included.

8.5 Conclusions

Experimental results presented in this paper demonstrate that artificial furs generally exhibit higher thermal resistance, warmer contact feeling and higher water vapour permeability than animal furs. Their lower weight, lower price and easier maintenance present further advantages over animal furs. Nevertheless, the improved appearance and high price of animal furs have transformed them into status symbols like luxury cars. Despite this, the enormous potential of artificial fur technology and the use of new comfort fibres should open up new markets for the latest generation of artificial furs, at least in technical areas of use, such as sports, the food industry, military applications and other areas where protection against the cold is required.

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9

The role of plant stems in providing biomimetic solutions for innovative textiles in composites

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Abstract: The significance of inspiration from nature for technical textiles and fibrous composite materials is demonstrated by examples of technical solutions that either parallel biology or are inspired by biological models. Two different types of biomimetic approach are briefly presented and discussed for the 'technical plant stem', a biomimetic product inspired by a variety of structural and functional properties found in different plants. The most important botanical role models are the stems of the giant reed (*Arundo donax*, Poaceae) and of the Dutch rush (*Equisetum hyemale*, Equisetaceae). After analysis of the structural and mechanical properties of these plants, the physical principles were deduced and abstracted and finally transferred to technical applications. Modern computer-controlled methods for producing technical textiles and for structuring the embedding matrix of compound materials render unique possibilities for transferring the complex structures found in plants into technical applications. This process is detailed for the 'technical plant stem,' a biomimetic, lightweight, fibrous composite material based on technical textiles with optimized mechanical properties and a gradient structure.

Key words: *Arundo donax*, biomimetic textiles, *Equisetum hyemale*, 'technical plant stem', smart composites.

9.1 Introduction

Modern biomimetics is a systematic approach taken by collaborating researchers from different scientific backgrounds in developing new ideas as a result of looking at an abundance of biological role models. Most helpful and catalytic for this kind of collaboration has been the development of new measuring methods and instruments, which are able to unearth natural principles or regularities hitherto unknown. The biomimetic process is very transdisciplinary, encompassing approximately seven different fields of bionic research (according to the German Federal Bionics Competence Network BIOKON): (1) architecture and design; (2) lightweight construction and materials; (3) surfaces and interfaces; (4)

fluid dynamics, swimming, and flying; (5) biomechatronics and robotics; (6) communication and sensors; and (7) optimization. The boundaries between individual fields, however, are often somewhat blurred, and the transition between subdivisions is gradual (Speck and Harder, 2006; Speck *et al.*, 2006a).

For lightweight construction and materials, very often fiber-reinforced plastics (composites) are first choice. In many instances textiles from high performance fibers are used, because they are easier to handle, need less work and are less expensive in the process of fabrication of a composite part than Prepreg materials.

Thus, in the field of composites and in many other applications of technical textiles, textiles are no longer just simply a means of producing clothing, seat covering, or carpets. So-called 'smart' textiles with high functionality conquer the market. New fiber developments are stronger, chemical- and fire-resistant, electrically conductive, or adjustably biodegradable. Using high-tech fibers, textiles nowadays are used for environmental pollution control or lifesaving implants (Milwich and Mueller, 2005). Snowboarding jackets can play MP3s and have incorporated GPS transmitters (Stollbrock, 2005). Incorporated sensors in carpets, called 'thinking' or 'smart' carpets, give emergency light, detect the heat of a fire, call a nurse if a patient falls and remains on the ground, and detect footsteps of an intruder (Lauterbach, 2005).

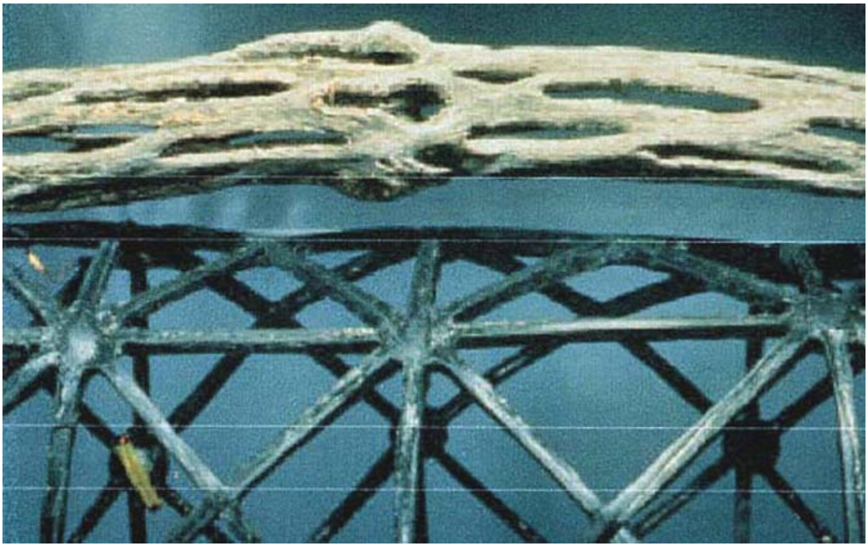
A common research topic for all these examples is the integration of 'smart' functionalities that preferably should be integrated into the fiber or the textile as deep as possible. That means that any 'smart' functionality should not be a rigid, sharp-angled form, which stands out from the textile or fibers as a foreign body, but should be as smooth as the textile surrounding it. Thus, the smart function itself should be made of the special fibers or textiles. In so doing, we come full circle back to nature's soft, flexible, and adaptive structures. A good example for the deep integration of a smart function is the Baby Body Clothing, developed by ITV Denkendorf (Linti and Horter, 2005). Without any hard edges or planes, it records body functions of the baby and calls for help if breathing or heart beats are unsteady (Fig. 9.1).

In the background of these examples, nature's own 'smart functions' are a broad source for textile solutions and textile applications. Biologists in Freiburg, Dresden, and Bonn, with their expert insights into special plant and animal functionalities, cooperate with ITV Denkendorf in various biomimetic projects striving for textile solutions (Stegmaier *et al.*, 2004; Harder, 2006).

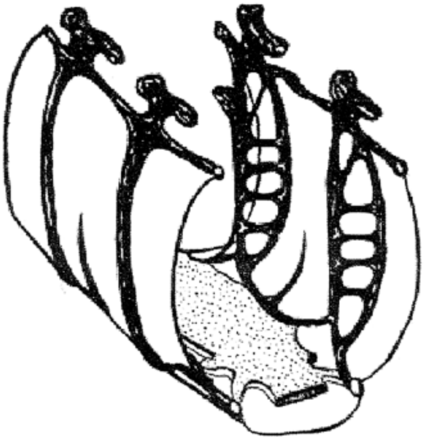
With the use of strong, specially developed fibers such as glass, carbon, or aramid and their embedment in polymer or ceramic matrices, very strong and lightweight composite materials and structures can be processed. An advantage of using flexible fiber material is that they can be laid exactly in the direction of the strain lines of a designed structure. Fiber composites can be found in airplanes, space shuttles, or in racing cars. American architect Peter Testa has proposed building a skyscraper of thick strands of helically and circumferentially wound carbon fiber composites arranged similarly to a mesh, with the spaces in between the strands filled with glass plates.

9.1 ITV Denkendorf Baby Body recording body functions.

Fiber composites can thus be regarded as functional technical textiles and are a classic example for biomimetic translation of nature's wisdom into technology. Many principles of composites have their counterpart in nature. Bones, plant stems, and wood have highly optimized the use of fibers in the exact directions of effective loads (Mattheck, 1990, 1996, 1998; Vogel, 1998) and are emulated by various textile methods. The optimized microscopic fiber arrangement in biological materials, finds its extension in an optimal macroscopic arrangement of struts for load-carrying structures. Figure 9.2 shows the macroscopic wood arrangement of the stem of a cactus, which found its biomimetic counterpart in the Rotex robotic arm, made manually by DLR Germany, with 0°- and 90°-fiber bundles (tensile/compression/bending forces) and 45 °-fiber bundles (torsional loads). Figure 9.3 shows the thorax of a dragonfly, in which the ribs themselves are weight-optimized structures and are macroscopically arranged as weight-saving spacer structures connected by a thin layer of outer skin.



9.2 Robotic arm modeled after cactus wood (courtesy of DLR Stuttgart, Germany).



9.3 Illustration of an exoskeleton (thorax) of a dragonfly (courtesy of Prof. Nachtigall, Saarbruecken University, Germany).

A successful transfer from biological composites into technical applications dates back to the early 1980s and was accomplished by the group of R. Gordon, C. R. Chaplin, and G. Jeronimidis at Reading University. They patented a bio-inspired composite structural panel with high strength and toughness (Chaplin *et* *al.*, 1983) based on (ultra-)structural features in wood (Gordon and Jeronimidis, 1980; Jeronimidis, 1980, 1991). The orientation of the fibers in this biomimetic composite is based on angles found in micro-fibrils of wood tracheids.

9.2 Composites under development: 'smart composites'

Today, composites are used widely and are undergoing development. Research goes into reducing production costs, developing more sophisticated methods for constructing ultimate lightweight structures, or creating higher functionality, the functionality preferably deeply integrated into the textile or the fiber. Examples for such functionalities are: (1) passive, form-optimizing adaptive wings for maximum energy yield of airplane wings or wind turbine blades (Breitbach and Sinapius, 2004), (2) integrated (fibrous) glass sensors for damage control in bridges and airplanes, and (3) active damping of disturbing or harmful vibration with piezo-ceramic fibers (Monner, 2005).

9.4 Extremely lightweight carbon fiber/reinforced plastics robot-arm, produced by tailored fiber placement (courtesy of Kuka GmbH, Germany).

9.5 Example of a tailored fiber placement preform.

Ultimate lightweight composite structures are manufactured with so-called 'gradient textile techniques'. As in nature, every single fiber strand is exactly laid within the structure in the direction necessary to neutralize outer forces so that no unnecessary fibers or weight are incorporated. As an example for a gradient textile process, Fig. 9.4 shows an extreme lightweight carbon fiber reinforced plastic robot-arm of the German company Kuka Roboter GmbH, produced by a process called tailored fiber placement. This is a stitching process, where, on a slightly altered textile stitching machine, up to 10 stitching heads place every single carbon fiber strand next to the preceding fiber strand (Fig. 9.5).

Manufacturing of these ultra-light composites was made possible by the development of adequate 'finite element' computing methods, which facilitate the calculation of curved and irregular shapes. Together with physicists, biologists and engineers from the Forschungszentrum Karlsruhe, Claus Mattheck investigated biological design rules, triggering the development of an optimized shape of naturally growing biological constructions. They developed computing methods to simulate force-controlled biological growth, which help to optimize technical constructions by a similar 'organic' growth (as in trees) or even help to remove unnecessary volume and weight (as in bones) (Mattheck, 1990, 1996, 1998). His propagation of using tension force loaded machine elements instead of using pressure loaded elements under the motto 'Thinking in Ropes' for lightweight construction will further advance the use of custom-made composites (Mattheck *et al.*, 2004).

9.3 Using biomimetics to boost the performance of composites

For the development of fiber-reinforced plastics, biomimetics can enhance the performance of composites. In the future, traditional engineering will still be the basis of most new technical developments. Biomimetics can not and should not replace this established and well-tested approach. But new developments, whenever possible and ingenious, should be stimulated by solutions from nature and compared with nature's wisdom, thus generating a pool of ideas and knowledge for further use. The mostly superficial, functional knowledge gained from past research can now be supplemented with new findings about the fine structure of materials or the functions of boundary layers using new measuring methods.

Usually, there are two approaches to biomimetics (Speck *et al.*, 2006a, b, 2007): top-down and bottom-up, as described in the following subsections.

9.3.1 Top-down approach

Engineers are searching for ways to optimize existing products or processes with the aid of biologists and their pool of biological knowledge. Because of the differing technical languages of the researchers involved, it is very helpful if biologists acquire knowledge of various physical and engineering contexts, whereas engineers should be equally open-minded and willing to think in unusual directions. After identifying the most promising solutions with additional, and sometimes very extensive, structural and functional analyses, biologists and engineers will abstract nature, deduce the functional principles, and create a modified and appropriate technical solution. Then engineers have to look for an optimal translation into techniques with appropriate production methods and materials. This strategy is also usable for optimizing already existing biomimetic technical solutions.

9.3.2 Bottom-up approach

Biologists do fundamental research into nature's structures, processes, and functional modes of operations. New principles are discovered and analyzed, then communicated to engineers, and the two groups work together to abstract and transfer insights into new technical solutions.

Conscious that the knowledge of biological structures, processes, and functionality in plants and animals will deeply enrich engineering work, biologists from the universities of Freiburg and Tuebingen and engineers from the Institute of Textile Technology and Process Engineering in Denkendorf (ITV) founded the Competence Network Biomimetics (Speck and Speck, 2003, 2006). The interdisciplinary approach of the network members ensures that results from basic research are transferred into industrial products throughout the whole value chain. The aim of the cooperation between the biologists of the Plant Biomechanics Group and the engineers of ITV Denkendorf is the conversion of natural principles into technical applications by means of textile technologies. Textiles techniques are most suited for this purpose, because textiles techniques, like nature, also assemble from small to big, from (nanoscale-) fibres to big superstructures (Fig. 9.6).

Biological production method:

Construction from small to large:

molecule → cell → tissue → organ → living being

➤Increase in complexity by hierarchical growing

➤ Constructing based on structures

Traditional technical production method:

Construction from large to small:

workpiece-blank made of one material → sawing, milling etc.

➤No hierarchical structure

➤ Constructing based on material

Production methods based on technical textiles:

Construction from small to large:

fiber → fiber bundle → braiding, knitting etc. → textile preform
→ composite preform → complex formed final product

➤Increase in complexity by hierarchical composition

➤ Constructing based on structures: similar to biology

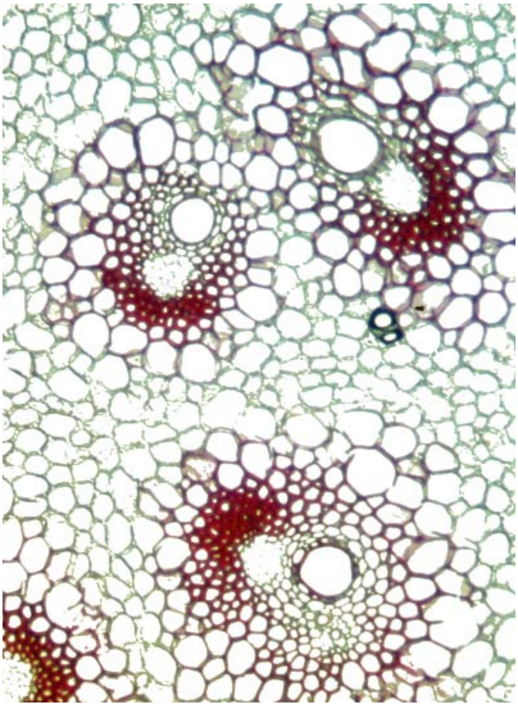
9.6 Comparison of biological, technical, and textile construction methods.

Because of the superior mechanical and lightweight properties of their stems, Dutch rush (*Equisetum hyemale*, Equisetaceae) (Fig. 9.7) and giant reed (*Arundo donax*, Poaceae) (Fig. 9.8) were identified by biologists from the Plant Biomechanics Group Freiburg and engineers from ITV Denkendorf as particularly promising biomimetic role models for the construction of ultra-lightweight technical structures with an interesting combination of mechanical properties (Speck and Spatz, 2001; Speck *et al.*, 2006a). With those natural examples in mind, in a joint brainstorming, biologists from Freiburg and engineers from ITV Denkendorf recombined and abstracted those natural functionalities and searched for possibilities for transferring them into technical structures.

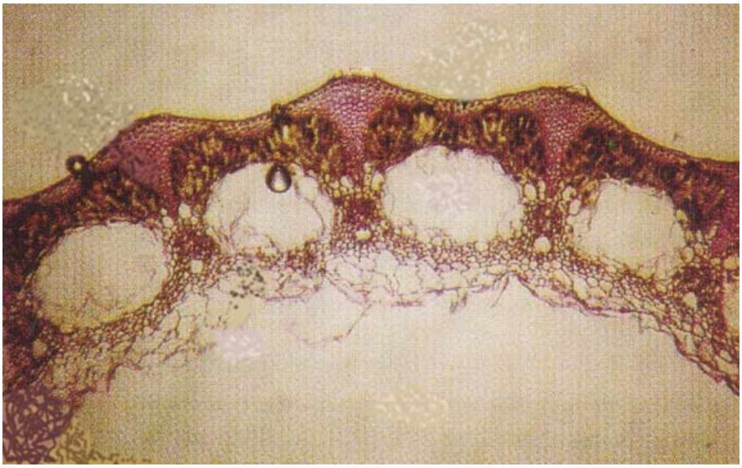
9.4 Learning from a role model: horsetail (*Equisetum hyemale*)

The hollow aerial stem of horsetail (*Equisetum hyemale*) represents an extremely lightweight construction. Functional analyses identified a double ring structure in strengthening tissues, consisting of an outer ring of fibrous collenchymatous tissue that is connected to the inner, double-layered endodermis by ‘pillar-like structures’ having the appearance of T-struts in cross-section in the stem periphery

9.7 Cross-section of the stem of horsetail *Equisetum hyemale*.



9.8 Cross-section of the stem wall of giant reed (*Arundo donax*).

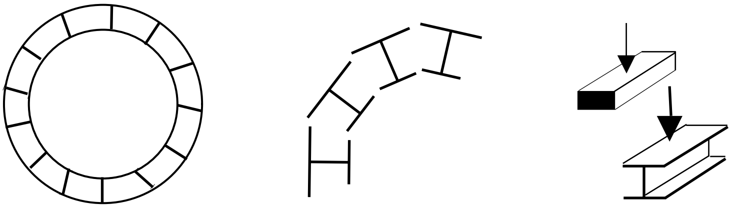


9.9 Detail of cross-section of the stem of horsetail *Equisetum hyemale*.

(Fig. 9.9). Between the collenchyma and the endodermis, which resemble a technical sandwich structure, is a thicker layer of parenchymatous tissue with remarkably large so-called vallecular canals, significantly reducing the weight of the hollow stem (Speck *et al.*, 1998; Spatz and Emanns 2004). The hollow stems of the giant reed A*rundo donax* grow up to a height of 6 m with a basal outer diameter of approximately 2 cm. They also have excellent mechanical properties under both static and dynamic loading conditions (Spatz *et al.*, 1997; Speck, 2003; Speck and Spatz, 2003). If the dense stands are subjected to dynamic wind loads, the slender culms respond with bending vibrations and pronounced damping (Speck, 2003; Speck and Spatz, 2004).

Several structural design principles, which are fundamental to theoretical mechanical engineering, contribute to these outstanding mechanical properties. The most obvious optimized structural design is the double ring structure of *Equisetum hyemale*. This principle is well known in mechanical engineering. In load-carrying beams, most of the material of the beams should be placed (or spaced) at the utmost possible distance from the center of the beam (neutral line), this being the reason for developing the double T-beams. The structure of Equisetum hyemale anticipated one of the most applied structural principles in building bridges and houses and just looks like welded together double T-beams (Fig. 9.10).

The same principle is also applied in building cars (space frame structure) or airplanes. In airplanes, the honeycomb or foam cores in 'spacer' sandwich composites multiply the bending resistance of structures. Figure 9.11 illustrates this principle. The left, thin side of the specimen is comprised of two layers of glass woven fabric embedded in a matrix material and has a bending resistance defined as 1. In the thicker, right side of the specimen, a foam core is included between the



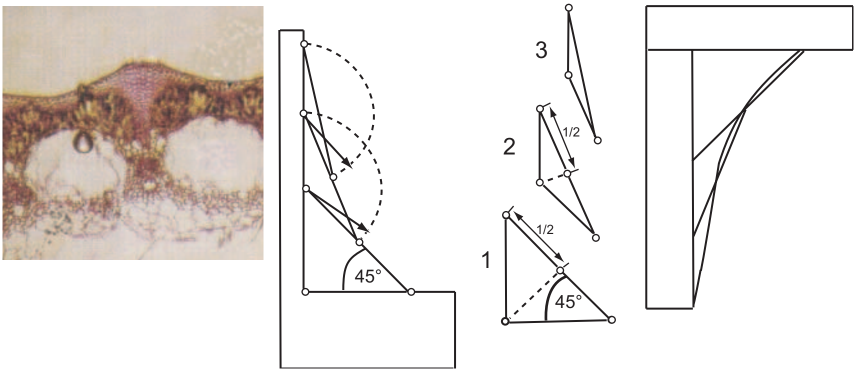
9.10 Double-ring structure with connecting beams, similar to *Equisetum hyemale,* 'constructed' out of welded double T-beams.

9.11 Increasing bending stiffness of composites using a foam core.

9.12 Cut-away view of an 'Isogrid' bicycle frame tube to show inner stitched fiber core reinforcement (courtesy Vyatek Corp.).

skin layers. This part has a bending moment 40 times higher than the left side without the core.

For the same reason, hollow tubes also have very good specific bending resistance. But, if the skin of the tube is very thin, buckling will arise, and the structure will need a supportive inner framework, either a foam core or a fibrous



9.13 Optimally shaped connection between pillars and rings, shaped similarly as with trees to avoid notch stress (courtesy of Prof. Mattheck).

core (Niklas, 1989, 1992, 1997; Mattheck, 1996, 1998, 2006; Spatz and Speck, 1994; Spatz *et al.*, 1997; Speck *et al.*, 1998; Mattheck *et al.*, 2006).

9.4.1 First bionic transfer

With its double-ring structure with connecting cross-beams, *Equisetum hyemale* represents a superior lightweight construction with high compression and bending stiffness. So far, fibrous cores in tubular composites are very seldom applied, and never before in pultruded tubular composites. However, Fig. 9.12 shows a newly developed lightweight tubular composite material, where fiber strands are stitched helically onto the inner side of a thin tubular skin, the part being yet very expensive. The nearly exact structure of *Equisetum hyemale* can be produced with braid-pultrusion technology, the basic equipment already installed at ITV Denkendorf. For producing a similar effective structure the braid-pultrusion line was specially adapted.

9.4.2 Second bionic transfer

The curved shape of the cross-beams of *E. hyemale* offers a continuous and organic connection with better stress distribution between the inner and outer ring than analogous technical constructions with a right angle bonding. Thus notch stress is largely avoided. One can see this principle just everywhere in nature, most notably in trees with specially adapted, shape-optimized connections from trunk to branches and to the root (Mattheck 1990, 1996, 1998). In the technical realization, the connection between pillars and rings will be shaped similarly (Fig. 9.13).

9.4.3 Third bionic transfer

Vallecular canals between inner and outer ring and the connecting cross-beams of

E. hyemale work as an additional means of gas exchange and store water from the cells to prevent frost damage. As technical analogs of the vallecular canals, the so-called functional canals could be used to transport electrical power via power supply lines or liquids and gases via pipes (see Fig. 9.9).

9.5 Learning from a role model: giant reed (*Arundo donax*)

The hollow stems of *Arundo donax* offer another astonishing sort of 'core': a sophisticated, weight-optimized structure with a material optimized to dynamic loads. The stems are composed of strengthening elements such as vascular bundles with accompanying fiber caps, which are embedded in a matrix of basic parenchyma (Fig. 9.8). In cross-section, at least four structural gradients on different hierarchical levels can be found, which meet all theoretical considerations and needs of composite structures.

In the periphery of the hollow stems, the area of highest stress, most of the load-carrying fiber material is placed. Then, the amount of load-carrying material is gradually reduced in the direction of the stem's hollow pith, in keeping with the gradual decrease in bending stress as the distance from the periphery increases.

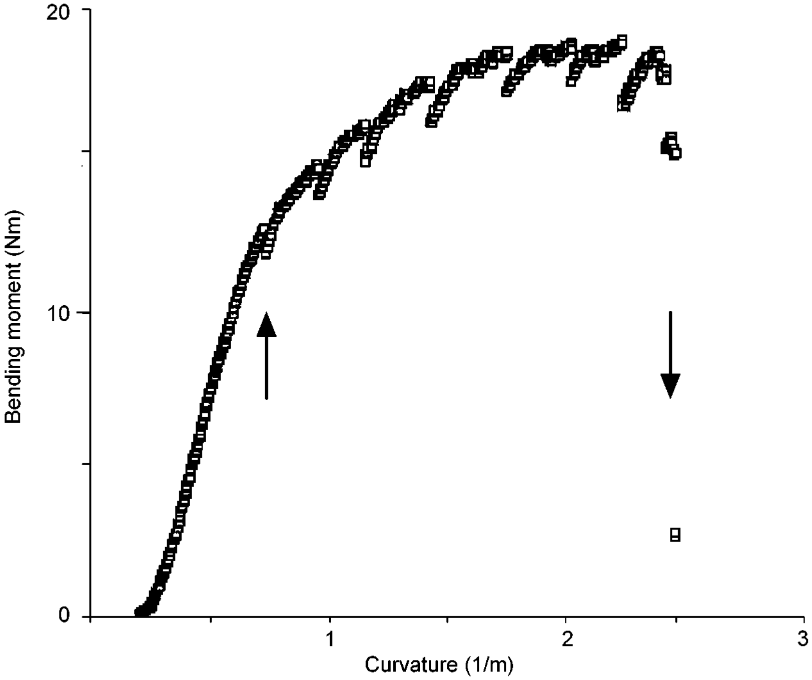
This mechanical grading is also exemplified by the lignification of the parenchymatous basic tissue as it decreases in a radial direction from the outside toward the center.

An additional gradient in the basic parenchyma can be found: the increasing size of the parenchyma cells is accompanied by gradually thinner cell walls from the outside to the inside of the stem wall, causing a reduction of the relative cell wall amount.

The macro superstructure finds its counterpart in a micro-structural phenomenon. The pronounced difference in stiffness between natural fibers and the surrounding parenchyma matrix is equalized by a gradual transition in stiffness. This results in a very high damping of oscillating wind forces and a high bending ability with optimal distribution of stress before the connection between fibers and matrix finally fails and the structure disintegrates. This is illustrated by Fig. 9.14, which shows a bending test of an internode of the hollow stem of *Arundo donax*. After each of the 10 smaller ruptures, the structure stabilizes itself through the distribution of stress and can then tolerate even more stress until the final failure. This graph is a very good example of a mechanically benign, ductile rupture failure and could be a model for any load-carrying technical structure (Spatz *et al.*, 1997; Speck *et al.*, 2006a).

9.5.1 Fourth bionic transfer

According to the gradually decreasing bending stress with increasing distance from the outer periphery of the plant stem, the amount of load-carrying material is



9.14 Bending test of an internode of *Arundo donax* to show the relationship between bending moment and curvature. Arrows mark initial failure and final failure. In between, a series of several partial collapses can be found.[19]

also gradually reduced concurrent with a gradual reduction of cell wall thickness and an increase of cell size of the parenchymatous basic tissue.

As 'gradient textile technologies' already demonstrate, fibers should only be incorporated where they are useful in carrying loads. In less stressed parts of a construction, polymer foam will be used for spacing out fibers. With the braid-pultrusion technique, this principle can be applied very easily into the structure.

9.5.2 Fifth bionic transfer

The angle of strengthening fibers in the stem walls and of cellulose micro-fibrils in cell walls is optimized according to the types and combinations of mechanical loading occurring in the plant stem (e.g. static or dynamic bending and torsion, energy damping). The angle of fibers and fiber bundles can be adjusted to the predominant loading situation(s) of the application mode of the finished component by using computer-controlled braiding techniques available at ITV Denkendorf. Optimally designed technical structures can thus be produced.

9.5.3 Sixth bionic transfer

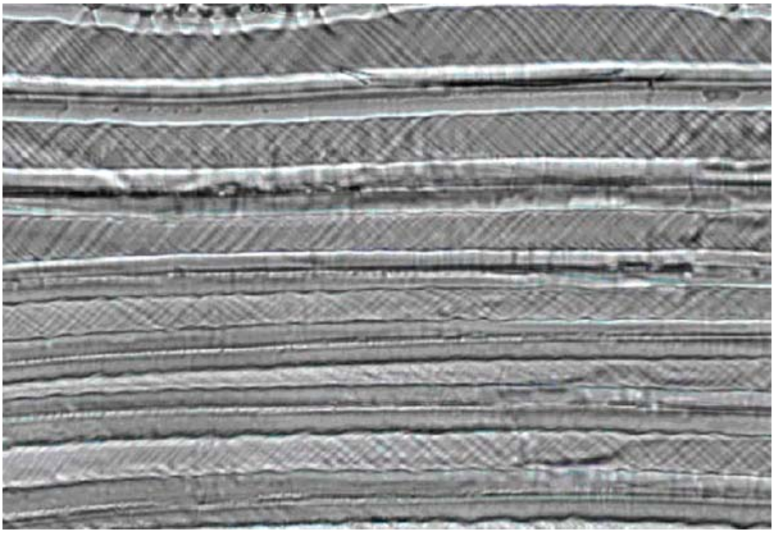
In summary, the structural basis of graded transition of Young's modulus between stiff fiber and less stiff parenchyma matrix is a gradient in lignification between fibers and parenchymatous cells and of variations in cell size and cell wall thickness. Transferring this knowledge into techniques, the stiffness between fibers and matrix will also be graded using a matrix material that can be provided by varying Young's modulus.

9.6 Learning from a role model: wood

Another interesting structure can be found in wood (Fig. 9.15). Helically arranged cellulose micro-fibril bundles, as found for example in the different layers of conifer tracheids, may result in a diagonally 'braided' structure improving (torsional) stability and oscillation damping (Mark and Gillis, 1973; Cave and Walker, 1994; Reiterer *et al.*, 1999; Burgert *et al.*, 2004, 2005).

9.6.1 Seventh bionic transfer

Tracheids with spirally arranged micro-fibril bundles improve torsional stability and oscillation damping. Using the braiding technology developed at the ITV Denkendorf, helically wound fibers can be easily incorporated into the structure.



9.15 Polarized light microscopy of compression wood of spruce (*Picea abies*), image of helical cellulose fibers in adjacent cell walls (courtesy of Dr I. Burgert, Max Planck Institute of Colloids and Interfaces, Potsdam/Golm, Germany).

9.7 Combination of different principles of role models into the 'technical plant stem'

9.7.1 Eighth bionic transfer: creating the 'technical plant stem'

Whereas other bionic solutions in the field of composites are mostly founded on a single natural function, the above-mentioned seven different natural functionalities were combined and translated into one technical structure, creating a totally new technical fiber composite material with superior mechanical properties.

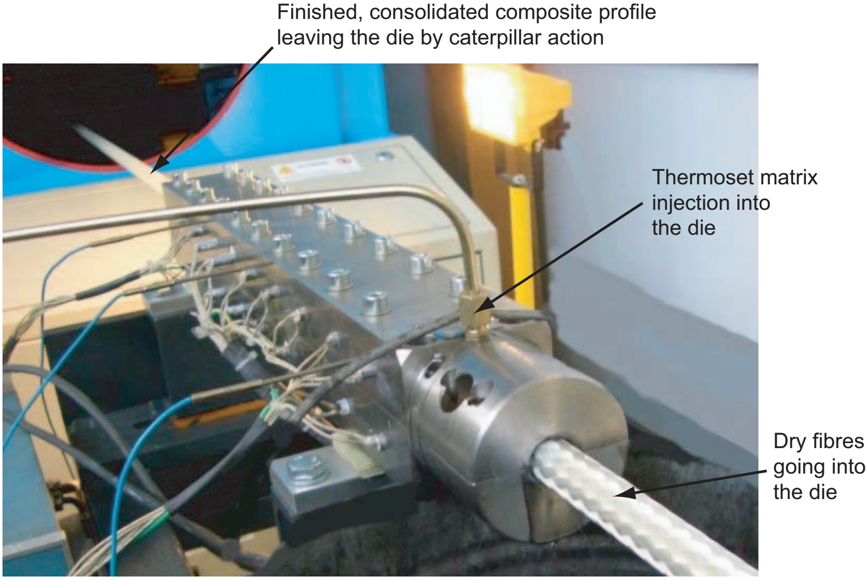
The advantages of the new composite material were self evident in such a way that specialists from prominent composite companies – seeing first prototypes of the technical plant stem – encouraged the inventors to patent it. The now-patented material, called the 'technical plant stem', has generated interest from several composite companies from the fields of aerospace, automotive, building, and sporting goods, which are willing to finance future research work.

9.8 Production methods and machinery equipment for the 'technical plant stem'

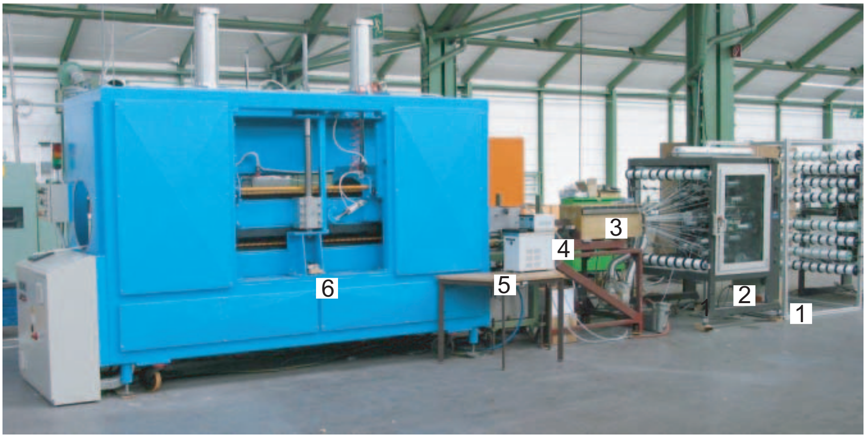
Nevertheless, the production costs for combining these functionalities into a new, unique product, must always be considered. For composite beams, the pultrusion process is a cost-efficient production method for endless-fiber-reinforced plastics. Compared with metals, the profiles are corrosion resistant and to a large degree maintenance free. They are very safe in having good electrical and thermal isolation, installation costs are lower and lighter foundations can be realized. In thermo-set pultrusion, impregnated high-performance fibers are pulled through a form-shaping die and are consolidated by heat and pressure during the transit through the die (Fig. 9.16). To incorporate diagonal fiber bundles into the technical plant stem, a braiding machine was installed into the pultrusion process (Fig. 9.17 and 18).

The braiding technique (Fig. 9.19) helically winds two different counter-rotating sets of intertwining fiber strands around a core system and an inner layer of unidirectional fibers. Deriving from ancient arts, braiding is now a process with ever-increasing fields of applications, such as composites, technical, or smart textiles. By varying the density, arrangement, and angles of the fibers in the different layers of the technical plant stem, technical structures optimally designed for a given load situation can be produced. The targeted structure and line production of the technical plant stem are only feasible with computer-controlled braiding line equipment.

In a first approach, different hollow profiles with glass fiber reinforcement were pultruded and braid-pultruded, optimizing the process and machinery (Fig. 9.20 and 21).

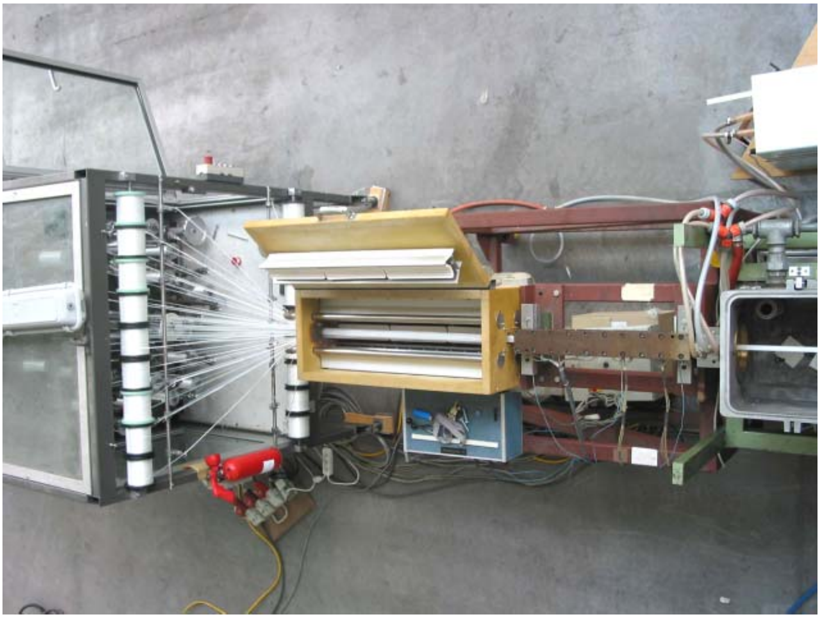


9.16 ITV thermoset braid-pultrusion.

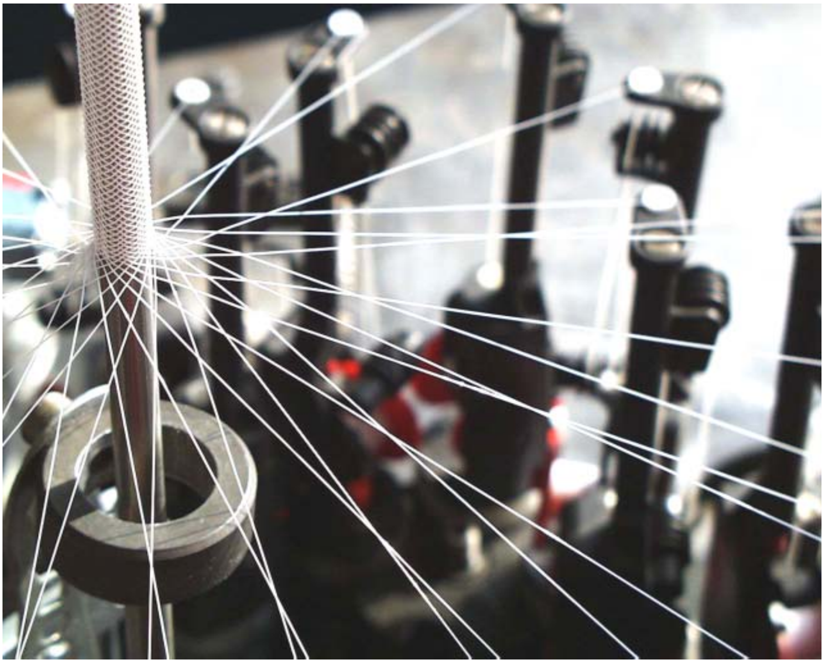


9.17 ITV braid-pultrusion: (1) reel for core- and axial-yarns, (2) braider with braiding yarns, (3) preheating device, (4) heated die, (5) water cooling, (6) caterpillar.

Parallel to this process, first samples of technical plant stems were braided and resin impregnated (Fig. 9.22). In the next step of optimization, the usual polyurethane matrix was used to encase micro-fibrils and fiber bundles. But to mimic the porous, optimized weight potential of the plant–matrix system, a polyurethane foam matrix was applied between the fiber bundles, resulting in a very lightweight



9.18 ITV braid-pultrusion system, seen from above.



9.19 Detail of braiding technique.

9.20 Thin-walled, unidirectional, reinforced thermoplastic profile produced by pultrusion.

9.21 Braid-pultruded tubular profile with thermoset matrix.

9.22 'Technical plant stem' with double-braid textile construction.

9.23 'Technical plant stem' with partial polyurethane foam matrix.

9.24 Braid-pultruded 'technical plant stem.'

specimen (Fig. 9.23). The first sample of a braid-pultruded technical plant stem can be seen in Fig. 9.24, showing the principle applicability of the braid-pultrusion process. By combining this cost-efficient production method with the several advantages of the technical plant stem, this unique material will rapidly spread into manifold applications in the composite world.

9.9 Applications of the 'technical plant stem'

There are numerous applications for the technical plant stem. Usually, where tubular rods are used – and there is an abundance of applications for tubular rods – the structure of the technical plant stem will enhance the performance of the original rod regarding mechanical properties like pressure resistance or bending stiffness. Either the rods will be stiffer and stronger, or the rods will be lighter than other composite materials.

In the building industry, if the rods are used to build a load-carrying structure under the roof, the structure is assembled very rapidly with less manpower and the foundations are made lighter (Fig. 9.25). This is the same as in telescopic structures, which need a stiff yet lightweight construction, because the whole structure will be moved in a desired direction.

9.25 Application of the 'technical plant stem': lightweight load-carrying roof substructure (courtesy Exel-Oy).

In other instances, the multi-channel system will offer new functionalities like an integrated gas, fluid or power transport, or using the structure as a pre-tensioned system.

9.10 Conclusions and future trends

Many other astonishing plant functionalities are waiting to be discovered. The transdisciplinary collaboration of researchers with biological, chemical, physical and engineering backgrounds and a systematic biomimetic approach to comprehend biological structures, processes, and functionality will bring new insights for the development of new technical solutions. In our opinion, technical textiles and fibrous composite materials offer a brilliant opportunity for transferring ideas inspired by biological models via biomimetic approaches into innovative technical structures, because composite materials based on technical textiles allow production processes similar to those used by nature (Milwich *et al.*, 2006, 2007).

For composites, the way into the future is already predetermined by nature: combining the lightweight nature and energy-saving potential in production and use of composites with a better recycling ability. Improving the recycling ability e.g. with the use of biodegradable natural fibers and bio matrix systems, the future use of composites will quickly increase. The development of the technical plant stem will strongly contribute to future developments.

9.11 Acknowledgement

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10

Bionic developments based on textile materials for technical applications

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Abstract: Developments in the production of self-cleaning textiles based on the 'Lotus Effect' are presented and topical bionic research activities being undertaken in this area at ITV Denkendorf are described. The biological models have been analyzed in detail to allow definition of the construction requirements and tube-filter development, assembly of filtration test equipment and determination of characteristic filtration data. A general model for lightweight tubular structures with high bending stiffness was defined, and this formed the basis for studying potential industrial applications, including solar-thermal materials that mimic the pelts of polar bears for use in energy technology.

Key words: biomimetics, bionic textiles, nano technology, self-cleaning surfaces, 'Lotus Effect'.

10.1 Introduction

Fiber technologies based on natural models of growth processes, hairy structures and reinforcement show great potential for the development of bionic materials. Biologists and engineers have conducted intensive bionic research and development activities at ITV Denkendorf for about eight years, and research areas include:

- surface technology, exploring possibilities for self-cleaning surfaces and boundary layers that retain air and reduce friction in water, based on the lotus leaf;
- environmental technology, studying self-adapting filtration systems as potential models for energy-independent liquid transport;
- energy technology, developing new solar–thermal materials that mimic the behavior of polar bear pelts;
- climate control through the use of adaptive and breathable membranes; and
- lightweight construction products with load-bearing properties based on fiber orientation and micro-macro-graduation created by pultrusion.

10.2 Potential of fiber-based materials in bionics

The term 'bionics' encompasses the areas of biology and technology, and describes the creative transfer of findings from the living world of nature into technical products and systems. An intensive and interdisciplinary cooperation between natural scientists (e.g. biologists) and engineers/technicians is essential for this type of research.

10.2.1 From micro- to macro-structures

Technology tends to start with large volumes of raw materials, which are gradually processed into smaller functional units and subsequently assembled, whereas nature does the opposite. Genetic information and environmental influences control growth processes that start with the smallest units – atoms and molecules – and generate larger structures. This growth can result in very complex systems with functionality and efficiency that far exceeds any of our technical products, especially in terms of consumption of materials and energy.

Textile-processing technologies offer remarkable analogies to natural growth processes. Starting from small units of single fibers, down to nanometer dimensions, larger elements can be 'composed' in staged processes. This method in principle functions without producing much waste and requires relatively small amounts of energy.

10.2.2 Hairy surfaces

Many surfaces in nature are hairy. Hairs can be found on the upper and under sides of insects, between the parts of an insect exoskeleton, in the feathers of birds, in the coats of animals, and in spiders' webs. These surfaces have functions that we know a lot about, but we are far from knowing everything. The many different methods of fiber processing, fiber orientation and finishing are suitable for meaningfully transferring biological functions to technical products.

10.2.3 Fibers in composites

Nature has many forms of fiber-reinforced materials. The more closely these materials are analyzed, the more astonishing the findings are. Fibers at the nanoscale, gradual transitions, high-tensile materials, and functional cross-sections can be found in natural constructions.

Composites occur in soft and hard forms in bones, stalks, leaves, and surfaces, and are composed of organic and inorganic materials.

Topical bionic R&D activities being undertaken in these areas at ITV Denkendorf are described below.

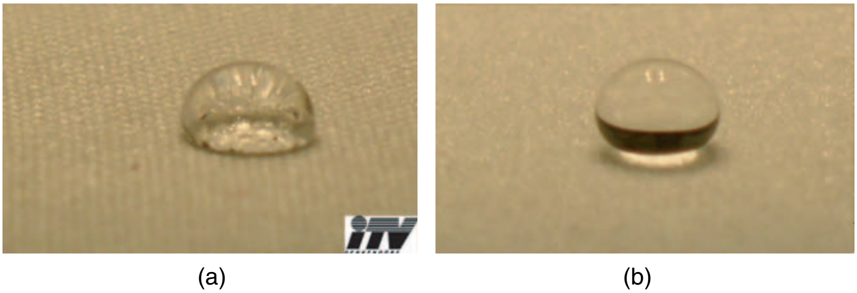
10.1 Spherical water drops on fabric with Lotus Effect.

10.3 Research activities in the field of surfaces

10.3.1 Self-cleaning surfaces according to the model of lotus leaves

Self-cleaning textiles based on the 'Lotus Effect'[1] are being developed at ITV Denkendorf using our understanding of the basic correlations between textile constructions, surface topographies and wetting behavior after water-repelling functionalization.

Previous investigations, for example, have shown that wetting behavior is considerably influenced by topography, which results from weave and type of yarn. The type of yarn – staple fiber or filament yarn – determines the extent to which water drops roll off textiles. Long, protruding fibers, which, for example, occur with increasing frequency in ring yarn samples, prevent water drops from rolling off. Short, protruding fibers at high fiber density, as for example in the case of nonwovens, promote rolling off because they present a smaller surface area to the water drops (Fig. 10.1). Self-cleaning ability is determined by the ability of water drops to access dirt particles. Thus, good water-repellent behavior, which results from the hairiness of the sample, does not automatically lead to good self-cleaning behavior. Lotus leaves exhibit a hydrophobic micro- and nano-structure


(a)
(b)

10.2 Water drop on hydrophobic, flocked textiles with (a) low and (b) high flock density.

10.3 Textile made of bulky special yarn with especially good air-storing property.

without any hair which leads – due to superhydrophobicity – to outstanding self-cleaning properties. The opposite is the case with lady's mantle, where the hairs are located above the hydrophobic surface of the leaf. These are able to keep the rain drops away from the surface of the leaf, but prevent smaller drops from rolling off.

We are now at the stage where a seal of approval for self-cleaning textiles based on the Lotus Effect can be awarded.

10.3.2 Air-storing boundary layers under water

In order to prevent wetting, plants and animals use surfaces with hydrophobic, hairy coverings. Nature pursues several strategies that permit birds and animals to swim and dive without getting wet, but hairy surfaces are the most distinct. Textiles, with their fiber-based construction, have a large potential for developing boundary layers with lasting air-storing properties. Textiles with hairy surfaces are flocked. The transition from a hydrophobic but wettable surface of low flock density to a non-wettable, superhydrophobic surface of high flock density – where a stable air layer forms between drop and flocked substrate – is illustrated in Fig. 10.2.

Investigations have shown that optimized textile surfaces generated from particularly bulky, hydrophobically finished special yarns remained dry after up to four days' storage in water (Fig. 10.3).

10.4 Research activities in environmental technology

10.4.1 Self-adapting micro-filtration systems

Adaptive filtration plays an important role in nature, especially for food ingestion in sponges (Fig. 10.4). Water is sucked into the sponge through fine pores placed over the entire surface, food particles and oxygen are extracted from the water and then it is ejected via larger, collective channels. The water stream is driven by special cells called choanozytes, which are located in groups along the pore

10.4 Cushion-shaped sponge.

channels. Freely mobile cells (amoebozytes) take up the food in the interior of the sponge and distribute it to the rest of cells, which are incapable of nourishing themselves independently. The sponges can change the pore size of the channels using a tissue similar to muscle, so the water stream and pressure ratios can be adjusted. This method of filtration is extremely energy-efficient, and effective pressures from 10^{-4} to 10^{-5} bar result in up to half of the body volume in water being moved per second.[2, 3]

What nature performs so successfully is difficult to replicate, but low-energy and efficient separation processes that worked reliably over a long lifetime and did not clog would be highly valuable in the field of micro-filtration, so we initiated a feasibility study. The first step was to use fiber innovations to develop an adaptable and low-energy cross-flow micro-filtration system. A specially braided tube filter with pore sizes that adapted over time was developed. Twined monofilaments were found to increase the filtration efficiency due to their micro-roughness, a considerable advantage for surface cleaning.[4]

Examinations and tests performed

The biological models were analyzed in detail, and the following steps were carried out:

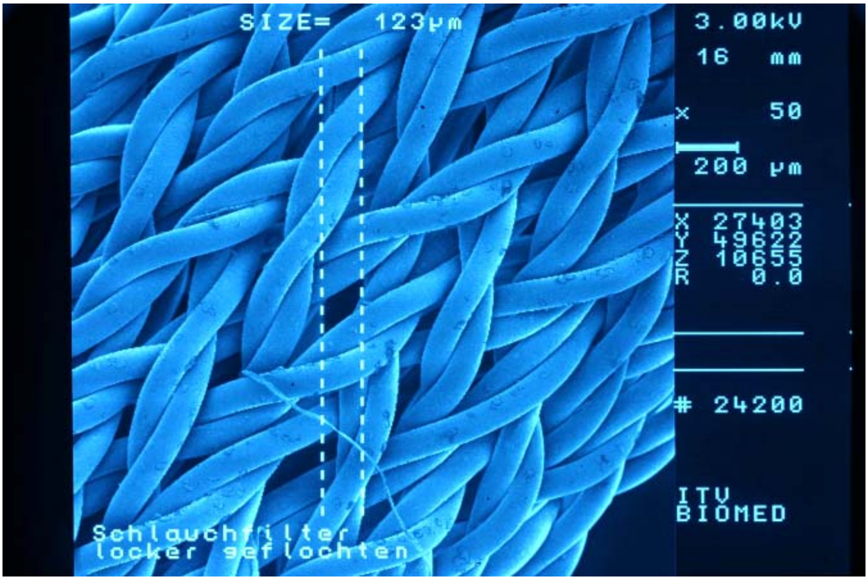
- definition of the construction requirements and tube filter development;
- assembly of filtration test equipment;
- determination of characteristic filtration data.

Construction requirements and tube filter development

Filtration took place through the tube cover in one braided tube filter prototype. In principle, filtration from the outside to the inside and vice versa is possible, corresponding to requirements. The innovation here was to use twisted monofilament fibers instead of the normal multifilament fibers of the polyamide (PA) fiber material studied. The helical fiber contour with no round form results in microporosity along the partially parallel twisted contours in the wickerwork (Fig. 10.5). The additional micro-porosity produces an increased pore surface, which facilitates filtrate flow and reduces the pressure losses substantially.

Bending resistant and twisted monofilaments make the tube filter more stable, and the braid form is significantly more stable against external pressure. This is very favorable, especially in the case of external to internal filtration, when filtration can take place under a significantly increased pressure difference. Introducing a stranded or twisted core into the braid provides additional support for the braid tube under higher pressures.

The filter effect can be modified by adjusting the tube length, which defines the angle of the braid fibers to each other and thus the pore size. Fig. 10.6 shows the geometry for pore size calculation of a cylindrical braid tube.



10.5 SEM photograph of a developed tube filter braid with twined monofilament fibers.

Figure 10.6 shows a rhombic structure with four equal sides of length b. If tractive forces F_Z are applied, the braid contracts, changing the braid angle and thus the pore size ΔU. Figure 10.7 shows the dependence of the pore size ΔU (in mm) on the braid angle of a tube filter ($d = 2.2$ mm, $b = 193$ µm). The particle separation barrier is principally defined by the diameter of the monofilament fiber and can be realized technically up to a fineness of 40 µm.

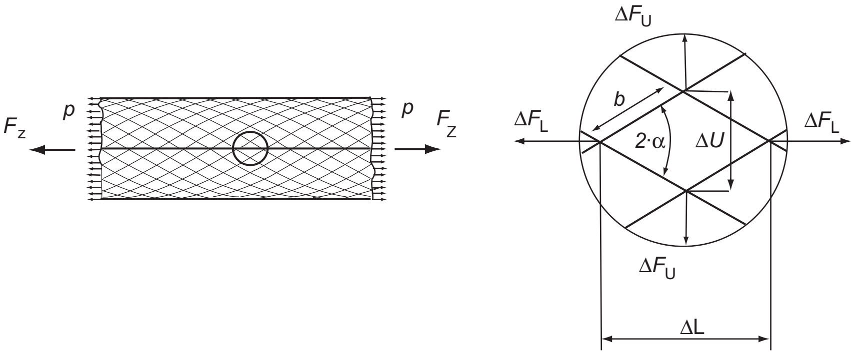
Assembly of filtration test equipment and production of filter tubes

A filtration test device consisting essentially of an inlet pump, a collection container and the filtration unit was assembled for wet filtration experiments. The sample to be filtered is pumped from the collecting container through a filtration circuit, which consists of the tube filter and a transparent acrylic pipe, and which demonstrates the filtration effect very effectively. The nominal diameters of the manufactured filters initially were 3, 4 and 5 mm.

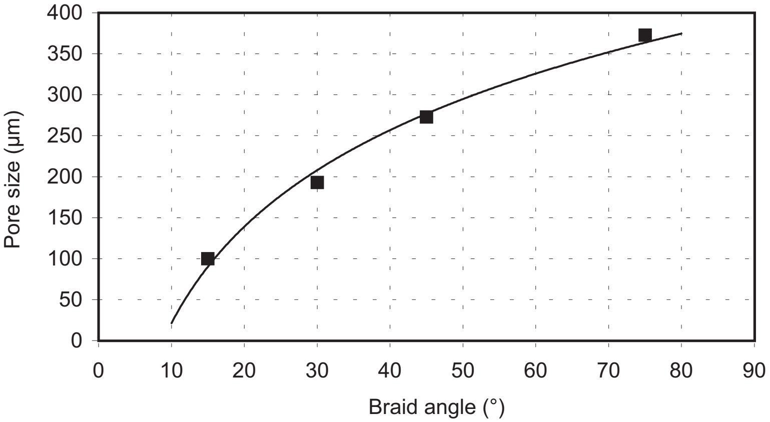
The filtration unit is characterized by the fact that the pore size and thus the separation barrier can be modified by a factor of 3 by using clamps to alter the length of the tube filter in the piping module.

Determination of characteristic filtration data

A wet filtration system was used to attempt to separate different particles (e.g. coal



10.6 Geometrical analysis of a tube filter.

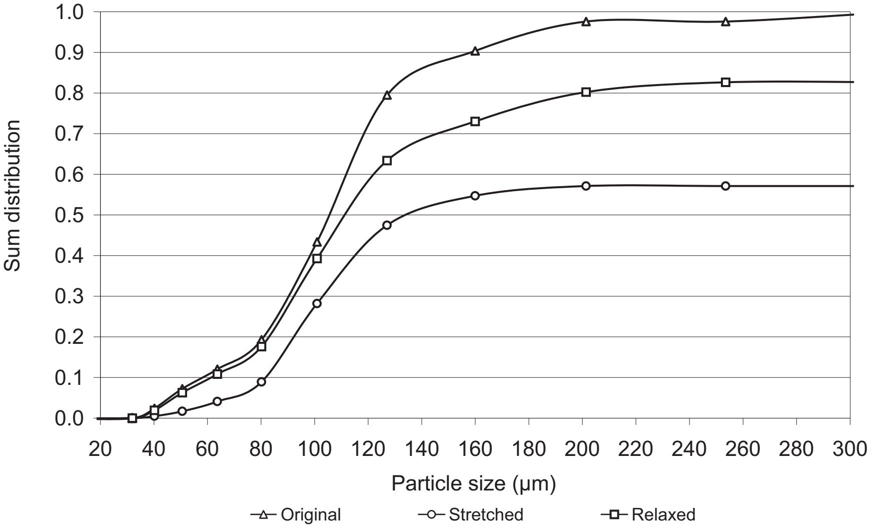


10.7 Pore size ΔU as a function of the braid angle α.

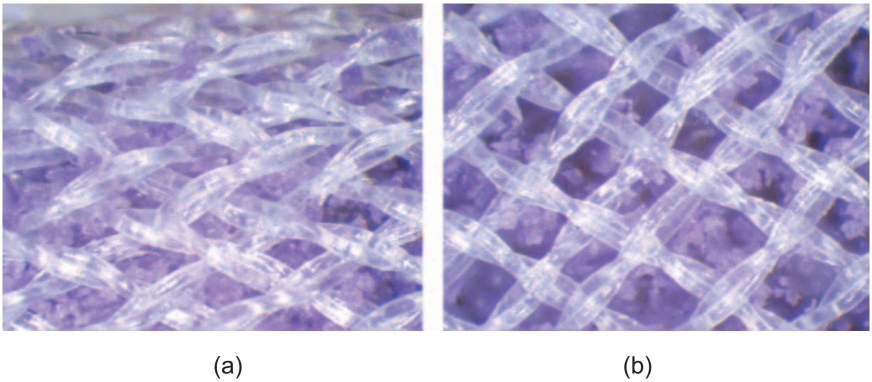
dust, polymer particles) with distinct particle sizes (15 to 355 µm). Figure 10.8 shows the sum distribution curve for a filtration trial with polymer particles. The characteristic curves for the collecting container and the filtrate are shown with stretched and relaxed tube filters. The external to internal filtration took place under a pressure difference of 10 to 50 Pa, a flow rate of 0.8 l min^{-1}, and a filter surface of approximately 0.04 m^2; the specific flow rate was 20 l min^{-1} m^{-2}).

Comparing the filtration characteristics demonstrates that, with the tube in a stretched condition, separation took place starting from a particle diameter of 30 µm. In a relaxed condition, separation begins at approximately 100 µm. Figure 10.9 shows the tube filter in stretched and relaxed conditions during filtration.

An additional process engineering advantage emerged during the filtration. Dynamic movements of the filter elements led to an effective separation of the surface layers formed and provided a cleaning function.



10.8 Sum distribution curve for a filtration experiment with polymer dust.



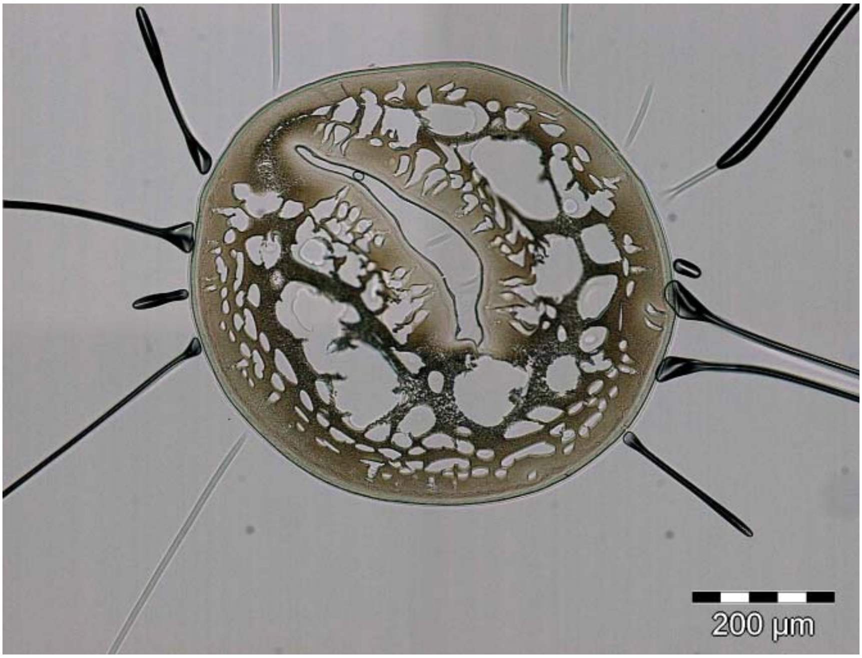
10.9 Tube filter (a) stretched and (b) relaxed.

Outlook

Variable pore size and good cleaning behavior suggest that these adaptive tube filters can offer new micro-filtration methods in the fields of waste water, and food and chemical technology. Current work is aimed at producing industrial modular filter elements for these different applications.

10.4.2 Liquid transport without the use of pumps

Liquid can be transported in fiber-based systems without the use of pumps. New



10.10 Cross-section of polymer hollow fiber.

technical textiles for long-distance transport of low-viscosity liquids are being developed in cooperation with Tübingen University, based on the model of water transport systems in plants (Fig. 10.10).

Trees and vines can transport water over great heights and distances without mechanical pumping systems and without requiring additional energy input. The energy necessary is supplied by the sun, suction being provided by transpiration (evaporation) at the end of the system – the pores, or stomata, in the leaves. In terms of utilizing this in biomimetically inspired textile materials, the following properties are of interest:

- the transport volume exclusively regulates itself according to need: only the water required for metabolism processes in the plant and transpiration is transported;
- transport security is maintained by preventing embolism.

Climbing vines can efficiently and securely transport water over several hundred meters via specialized water-carrying cells in the xylem, and serve as an interesting source of creative ideas for new technologies. There is a danger that gas bubbles might develop in the xylem because of high internal negative pressure, which would interrupt the flow and thus stop water transport (embolism). Various mechanisms contribute significantly to the prevention of embolism, based on the micro-morphology and biochemistry of the inner surfaces of the xylem cells and the membrane valves which connect them. To date, we have yet to develop technical solutions to the challenge of transporting liquid over long distances without mechanical pumping systems.

Possible applications of biomimetically inspired textiles include underground irrigation systems that do not require active pumping mechanisms and which provide more economical, tailored water release, textiles that transport large volumes of liquid for medical use, the clothing industry and fuel cells (carrying away the water formed at the fuel cell membrane).

10.5 Research activities in energy technology/management

10.5.1 Transparent heat insulation for solar–thermal applications

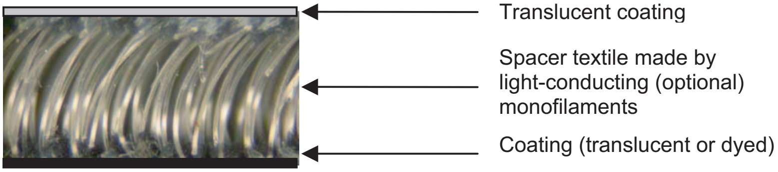
Solar energy

Fossil energy sources are finite, and the development of efficient solar heating is an essential task of our time. Solar radiation at the earth's surface contains about 3% ultra violet (UV), 46% visible (UV–VIS) and 51% infra red (IR) radiation. The insolation power at a particular point on the earth's surface corresponds to its latitude. The annual insolation power for Munich shows a maximal value of 1.1 kWh m^{-2}, whilst in the Sahara it amounts to 2.2 kWh m^{-2}.

Thermal solar collectors change the sun's radiation power into usable heat. There are two different types of collector, concentrating high-temperature collectors (HT collectors), where the solar radiation is reflected by one or more hollow mirrors and collected in a receiver, and non-concentrating flat or low-temperature collectors (NT collectors), which collect solar radiation by means of an absorber layer or tubes. The absorbers, which consist of efficient heat-conducting metals or plastics, transfer the heat via a carrier medium (air, water, glycol water mixtures). Absorbers should have a high absorption rate and convert solar radiation as completely as possible into heat.

Materials used for the covers of solar collectors and translucent thermal insulation (TTI) on buildings have to have high translucence and, at the same time, high thermal insulation characteristics. Insulation glasses with excellent optical characteristics and insulating materials with fine capillaries or honeycombs arranged side by side are used as TTIs. They are most effective when the incidence of the sunlight is vertical.

To date, the materials used for absorbers and TTIs are plate-shaped, inflexible and rigid. They are also heavy and fragile due to the panes of glass, and so only suited for local use. A new, flexible transparent heat insulation material has been



10.11 Construction of a spacer textile composite.

developed based on the solar–thermal functions of the pelt (skin and fur) of the polar bear.

Development of translucent thermal insulation material based on polar bear pelt

The possibilities for the development and production of flexible collectors were analyzed under a European Union research project.[5] Flexible materials for absorbers are already well known in principle, but they are unsuitable for TTI.[6] Polar bears have to survive in the arctic cold.[7] They have a black epidermis and opaque skin, and incident sunlight is transmitted by means of the yellowish white hair to the skin and transformed into heat.

At ITV Denkendorf, this principle was analyzed in detail. Solar power was transferred to textiles, which could be used in industrial solar–thermal applications (heating water and air) as flexible, translucent heat insulators. The product, based on coated spacer structures, can be manufactured on a large, industrial scale. Spacer textiles with translucent and/or dyed coatings showed particularly good performance. Figure 10.11 shows schematically the structure of a spacer textile with a double-sided coating.

The spacer textile is characterized by the following properties:

- highly light-resistant polymers,
- highly translucent and/or black pigmented silicone coating,
- translucence to incident light in the visible spectrum and impermeability to UV radiation,
- heat loss by convection strongly reduced,
- coating to prevent heat loss via long-wave (thermal) radiation,
- dirt-resistant coating, providing good translucence and high thermal efficiency.

The TTI textile shows some special advantages compared with other thermal insulation materials:

- relatively low weight,
- high mechanical stability (unbreakable, tearproof, elastic),
- high thermal stability (approximately up to 160 °C),
- flexibility, i.e. arched structures are feasible,
- deep-drawable within certain limits,

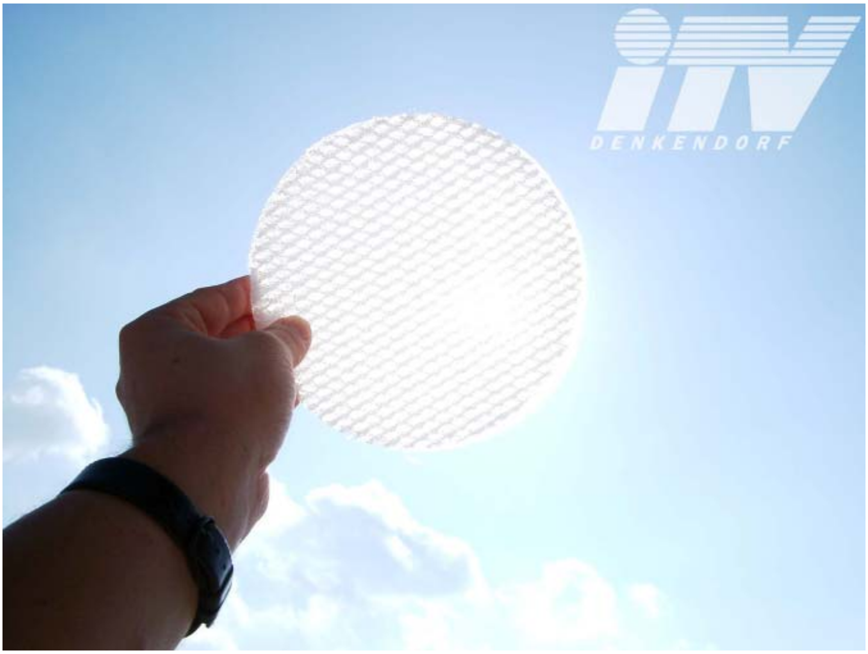
Table 10.1 Technical data of different translucent heat insulation materials

	Spacer textile	Hollow chamber panel	Comb structure
Thickness (mm)	5–60	6–16	20–60 (28–68[1])
Mass per unit area (kg m^{-2})	1.2–2.0	1.3–3.1	0.32–0.96 (20.32–20.96[1])
Light transmission (%)	80–≤95	77–82	84
Thermal transition coefficient *U*-value (W K^{-1} m^{-2})	2.2–3.0	2.6–3.6	1.3–2.2

[1] With double panes of glass.

- chemical resistance due to the silicone rubber coating,
- dirt resistance due to a special surface treatment (for self-purification, water is sufficient).

Table 10.1 shows the technical data for a translucent spacer textile coated on both sides (Fig. 10.12) and for commercially available TTI hollow chamber panels and structures, which are inserted in double panes of glass. The properties of the spacer textiles can be adjusted over a wide range by their construction and the coating conditions. Comparing the materials shows that the flexible spacer textiles, having



10.12 Translucent coated spacer textiles.

a low weight, high light transmission and low thermal transition coefficient (*U*-value), have advantages over the TTI materials used at present.

Potential applications

The company Solarenergie Stefanakis, one of the project partners, is using this new, flexible, textile-based construction for a new generation of solar collectors. Solarenergie Stefanakis has been developing and building spherical, hemispherical and parabolic thermal solar collectors for warm water production for many years. The spherical and hemispherical forms give the collectors the largest aperture areas possible, and the collectors do not have to be aligned according to the sun's position. The new materials have several advantages, including low prices, low assembly and maintenance costs and wind insensitivity. The spherical and hemispherical collectors are used as tank and tube absorbers, consisting of copper tubes or fabric hoses, and are suitable as continuous flow water heaters (Fig. 10.13).

In earlier models, the absorber was covered with a heat insulating acrylic glass cupola to prevent heat losses (particularly at night), providing TTI due to the included air layer and prevention of convection (Fig. 10.13). The new spacer textiles were tested as substitutes for the acrylic glass cupola (Fig. 10.14). A translucent spacer textile coated on one side was tested. The lighter, elastic and unbreakable spacer textiles show high thermal insulation effects. The textile can also be used as an absorber with integrated thermal insulation (Fig. 10.15), if one side is translucent and the other side is coated with a black absorbing layer. These materials are not only useful for collectors, but also have applications in the construction industry with a modified structure, as front elements and for roof constructions that allow an architecturally free design.

10.5.2 Adaptive breathable membranes for climate regulation

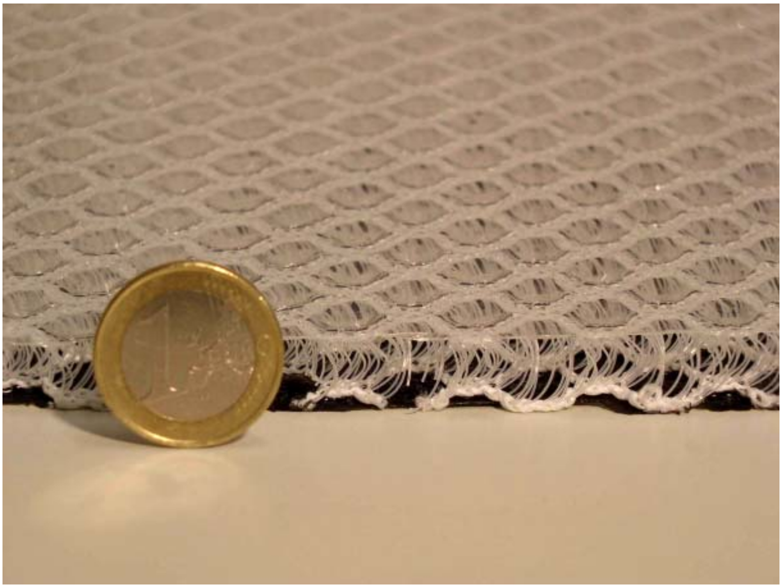
In cooperation with Tübingen University, we have analyzed the possibility of using the mechanism that controls water evaporation in plants to develop new materials with the potential to optimize liquid transport via self-regulating micro-pores, e.g. for clothing, upholstery, and wound dressing. Detailed anatomical studies of the stomata (plant pores) were carried out using SEM and 3-D microscopy, paying particular attention to the micro-structures responsible for optimizing the transport of liquids. Computer simulations of transpiration at the stomata were then developed, and revealed the effect of the different features on liquid transport. This enabled us to identify the structures that are of functional importance for evaporation-induced liquid transport, resulting in two basic conceptions:

10.13 Hemispheric collector with tube absorber from the company Solarenergie Stefanakis.

- Lamination to create humidity-sensitive coating systems using a combination of layers of different materials. According to the basic idea, two porous materials must be stacked in such a way that the pores of one layer are covered by the corresponding pores on the other. These materials are coated with swelling media which expand in the presence of humidity and thus promote evaporation through the pores.
- Combination of two fiber types, one that is very sensitive to humidity and lengthens in the presence of humidity, and one that is not sensitive to humidity.

Samples were produced and the adaptive function regarding permeability to air and steam was proved. Impermeability to water penetrating from the outside was achieved by including an external water-repellent layer.

10.14 Deep-draw (formed with heat and pressure) spacer textile as collector cover.



10.15 Spacer textile with translucent and black coating.

10.6 Research activities in the field of lightweight construction

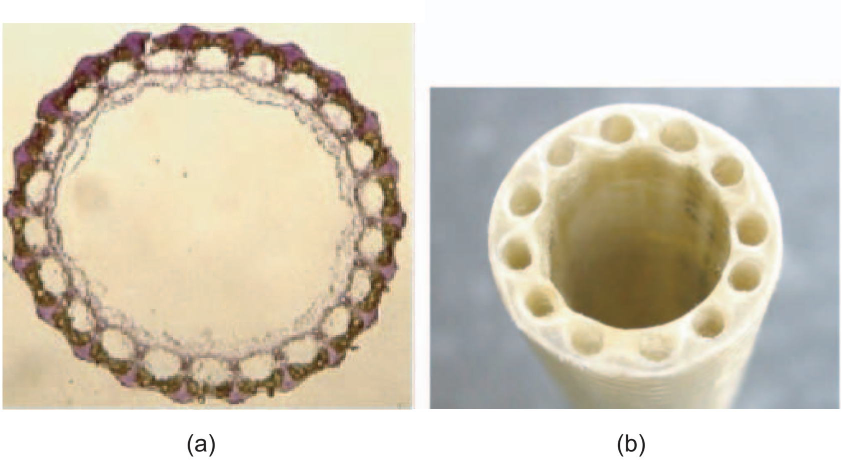
The search for lightweight construction materials led us to look at natural, weight-optimized structures such as bones and plant stems. In nature, the fibers are orientated optimally according to the main direction of stress, and the number of fibers is just sufficient to provide the necessary strength. Research activities were aimed at developing cheap textile technologies that made it possible to include reinforcing fibers in response to the expected distribution of forces, for instance for the production of tubes that must withstand bending, buckling or torsional stress. Findings from the Freiburg University Plant Biomechanics Group concerning the structure of stalks were used to produce profiles of composites with optimized weight-related bending stiffness/strength and high dynamic load capacity and damping behavior.[4]

Plant stems can be understood as composite, fibrous materials that are composed of various materials with different mechanical properties. The bionic potential of hollow, cylindrical plant stems, including those of the horsetail (*Equisetum hyemale*) and giant reed (*Arundo donax*), were investigated.

The stem of the horsetail plant (Fig. 10.16) is composed of external and internal pressure cylinders and connecting spacers. There are variations at different hierarchical layers; for instance, an optimal fiber layout includes a higher fiber volume fraction and thicker cell walls in the outer parts of the cross-section. This structure represents a lightweight construction with high, specific bending stiffness and buckling stability using the minimal amount of materials. The horsetail stem demon-strates the well-known fact that, similar to double T-supports, the main mass of the supports is stored in the pull and pressure belts, respectively, at a distance as large as possible from the neutral bending fiber. Based on the different biological models, a general model for lightweight tubular structures with high bending stiffness was defined, and this formed the basis for studying potential industrial applications.

The giant reed plant (*Arundo donax*), as well as optimizing fiber weight, shows excellent damping behavior towards mechanical vibrations along with favorable breaking behavior (with several pre-failure events). This is because there is a gradual transition in stiffness between fibers and basic matrix.

A braid pultrusion technology, specially adapted and suitable for large-batch applications, was developed and installed at ITV Denkendorf to utilize this ultra-light sandwich structure. The yarns stored on the bobbin creel and on the braiding carriers are led through a matrix-impregnation bath and a heated pultrusion tool. The matrix of impregnated fibers is cured while being led through the tool. Spiral-shaped fibers can be produced in the profile by integrating a braiding machine into the pultrusion line, and the braided fibers impart desired properties such as torsional stiffness, high vibration damping and favorable structural integrity. Using this braid pultrusion technology, sandwich structures for fiber composite


(a) (b)

10.16 (a) Horsetail plant (*Equisetum hyemale*) (b) technical plant stems (both in cross-section).

profiles with tubular cross-sections, so-called 'Technical plant stems', were produced.

There is a wide range of technical applications for these innovative high-performance fiber composite profiles, covering all applications which require tubular fiber composite structures, including aerospace technology, vehicle construction, building technology, instrument building, medical engineering (prosthetics) and sports equipment.

10.7 Future trends

Nature provides technicians with a very broad field of highly interesting models. Continuous development of instruments, detectors and sensors will enable us to understand the functions and mechanisms of the natural world, and translate this information into useful technologies. Nanoscience, in particular, should lead to significant advances.

10.8 Conclusions

Bionic research in fiber-based materials has great potential for innovation and optimization. At ITV Denkendorf, bionics is a strategic pillar of future research aimed at developing new materials and opening up new markets.

Thanks to the support of public funding, it has become possible to conduct the necessary basic research and take important steps in product development. Applied research activities with potential partners from industry have made it possible to bring the first bionic products to market. This collaboration will continue.

10.9 Sources of further information and advice

www.itv-denkendorf.de
www.biokon.de
www.kompetenznetz-biomimetik.de

10.10 Acknowledgements

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